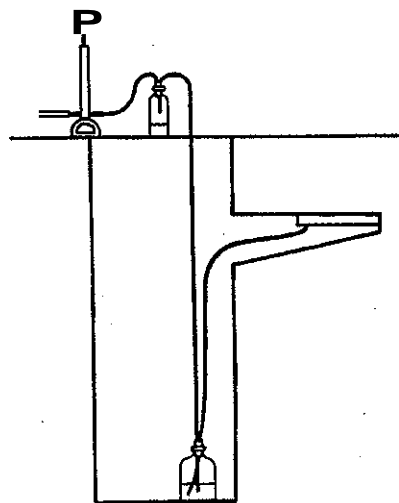
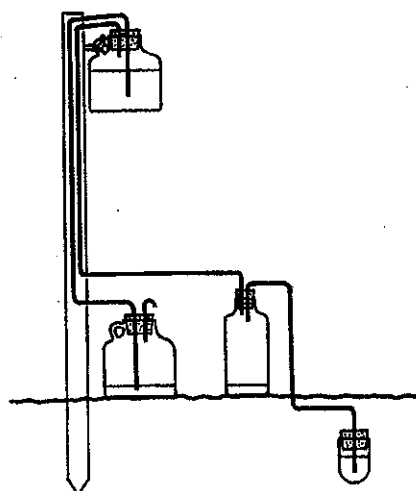
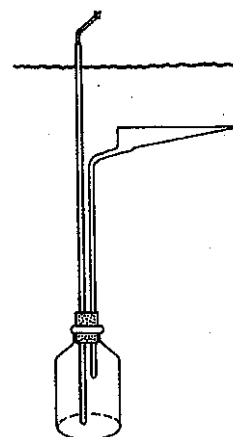
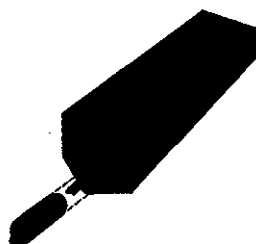
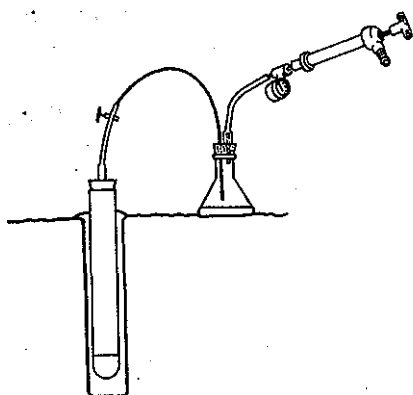


Lysimeter System Designs Used in Soil Research: A Review

B.D. Titus and M.K. Mahendrappa
Newfound and Labrador Region – Information Report N-X-301



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LYSIMETER SYSTEM DESIGNS USED IN SOILS RESEARCH: A REVIEW

by

B.D. Titus
Canadian Forest Service
Newfoundland and Labrador Region
Bldg. 304, Pleasantville
St. John's, Nfld.
A1C 5X8

and

M.K. Mahendrappa
Canadian Forest Service
Maritimes Region
P.O. Box 4000
Fredericton, N.B.
E3B 5P7

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NATURAL RESOURCES CANADA
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ABSTRACT

Lysimeter systems have been used for many years to obtain, with a minimum of disturbance, soil solution samples for use in nutrient cycling studies in agriculture and forestry. Recent methodological studies and improvements in technology have led to a great diversification in lysimeter system designs and installation methods. This review considers the agricultural, forestry, and ground-water monitoring literature and reports on the current designs that are relevant for use in forestry nutrient cycling studies. A brief history of lysimetry is given, and a functional classification scheme is presented and then used as a framework for discussing variations in lysimeter system design. The impact of lysimeter system design on sampling artefacts is briefly discussed, and the literature on the effect of construction materials on soil solution contamination is tabulated. Statistical considerations are discussed, especially regarding determination of sample size and distribution of the data. As the review is primarily concerned with design, some of the wider aspects of lysimetry are not discussed. However, a broad range of references is cited so that workers, particularly ones new to the topic of lysimetry, can follow up areas of interest and concern.

RÉSUMÉ

On utilise les systèmes lysimétriques depuis plusieurs années dans les milieux agricole et forestier pour obtenir, en provoquant le moins de perturbations possible, des échantillons de solution du sol destinés à l'étude du cycle des éléments nutritifs. Des études méthodologiques et des progrès techniques réalisés récemment ont donné lieu à une grande diversification des méthodes de conception et d'installation des systèmes lysimétriques. Le présent rapport traite de la documentation relative à la surveillance effectuée dans les domaines de l'agriculture, de la foresterie et des eaux souterraines; il fait état des concepts actuels qui conviennent aux recherches forestières axées sur le cycle des éléments nutritifs. Il donne une courte description de la lysimétrie et expose une méthode de classification fonctionnelle qui sert ensuite de cadre à la discussion de divers modèles de systèmes lysimétriques. L'incidence de la conception des systèmes lysimétriques sur les outils d'échantillonnage est abordée brièvement, et la documentation concernant l'effet des matériaux de construction sur la contamination de la solution du sol est tabulée. Des questions d'ordre statistique sont examinées, surtout en ce qui a trait à la détermination de la taille des échantillons et à la diffusion des données. Compte tenu que le présent ouvrage porte essentiellement sur la conception, certains des aspects plus généraux de la lysimétrie ne sont pas explorés. Toutefois, un grand nombre de travaux sont cités de sorte à permettre aux travailleurs, en particulier à ceux qui s'intéressent à la lysimétrie pour la première fois, de suivre les sujets d'intérêt et de préoccupation dans la documentation.

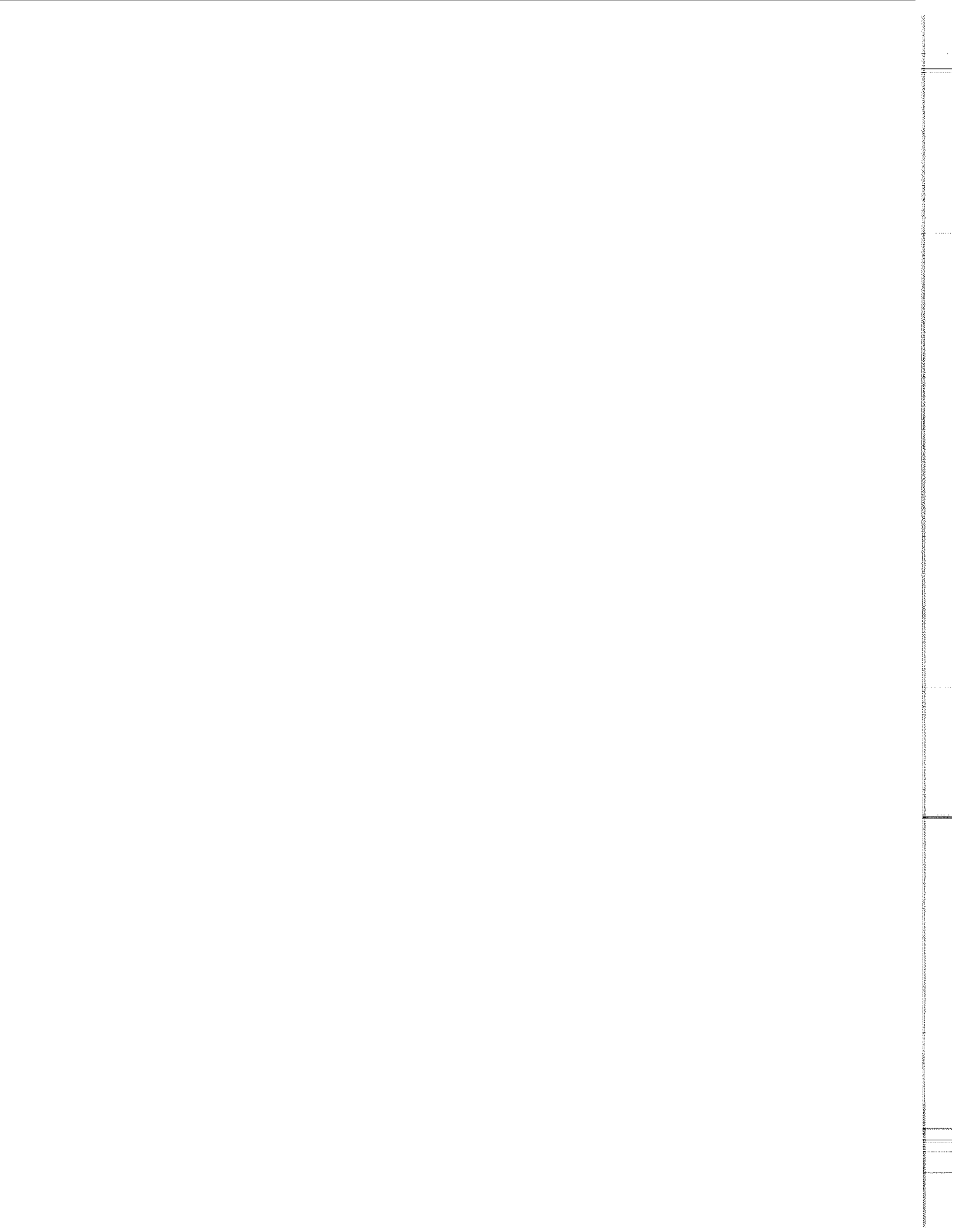


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LYSIMETER SYSTEM DESIGNS USED IN SOILS RESEARCH A REVIEW

by

B.D. Titus and M.K. Mahendrappa

1. INTRODUCTION

In recent years concerns have arisen in forestry that intensive harvesting practices may deplete soil nutrient reserves and thus reduce site productivity. There are two main sources of nutrient losses as a result of intensive harvesting: (i) additional biomass removal, and (ii) increased leaching losses of nutrients beyond the rooting zone. Although the removal of nutrients in biomass from a site can be determined through destructive sampling, changes in the leaching of nutrients out of the rooting zone and the concomitant loss of soil productivity are not so easily quantified. One class of instruments often used to monitor nutrient changes in the soil solution¹ are called *lysimeters*, from the Greek roots

lys- or *lysi-* meaning "loosening" or "dissolution", and *metron* meaning "measure" (Gove 1966).

While planning a series of studies in Atlantic Canada for evaluating the potential impact of whole-tree harvesting on site quality it became apparent that although numerous improvements have been made over many decades to lysimeter systems used in agriculture to suit them for use in forestry studies, further modifications could be made to ensure the successful functioning of these lysimeter systems under local soil and weather conditions. This report is the result of a literature survey conducted to seek out the latest developments in lysimeter system designs and to identify systems most suited to intensive forest harvesting studies in Atlantic Canada. The intent of this report is to present the various aspects of lysimeter system use that require consideration by researchers embarking upon new studies on the movement of nutrients through the soil. The range of available lysimeter system designs is documented, and the advantages and disadvantages of different design features are discussed. References containing more detailed analyses of specific points of interest are also presented. The review begins with a brief historical overview of lysimeter systems development. A classification scheme for lysimeter systems is outlined, followed by a more detailed discussion of each individual category.

¹ A variety of terms are used to describe the water samples obtained from lysimeters, including "soil solution" (Litaor 1988, Homung 1989), "soil water" (Creasey and Dreiss 1985, Starr 1985, Anderson 1986, Grossmann and Udluft 1991), "soil pore wafer" (Momsen 1983), and "aqueous pore-liquid" (Wilson *et al.* 1994a). (The more general term "bore-liquid" is often used in the ground-water monitoring literature to indicate that the liquid may also be organic liquids other than water, such as oil.) Strictly speaking, the term used depends on the type of lysimeter and the class of soil water that is sampled:

Three major types of soil water can be identified in the context of sampling soil water: (i) macropore or gravitational water, which flows through the soil relatively rapidly in response to gravity (excess of 0.1 to 0.2 bars [10 to 20 kPa] suction); (ii) soil-pore or capillary water, which is held in the soil at negative pressure potentials from around 0.1 to 31 bars [10 to 3100 kPa] of suction; and (iii) hygroscopic water that is held at tensions greater than 31 bars [or 3100 kPa] suction. Soil-pore water moves through the vadose zone, but at much slower rates than gravitational water, whereas hygroscopic wafer moves primarily in the vapor form. The term soil solute or solution sampling has been used loosely in the literature to describe most sampling methods, whereas the term soil pore liquid is typically used in a more restricted sense, to apply to the sampling of capillary water. (after Anon. 1993b)

References from agricultural, forestry, and ground-water monitoring studies were compiled after scanning for relevant citations in published bibliographies on lysimetry by Anon. (1978) and Doeny (1984), computerized reference data bases, and recent journal issues. This present work builds upon the general

The Soil Science Society of America (1987) defines soil solution as "the aqueous liquid phase of the soil and its solutes". For the purposes of this review the general term soil solution will refer to all water in the soil, whether it is held under tension or not. The term leachate will be used sparingly to refer to soil solution that freely drains (or leaches) through soil under the force of gravity alone.

reviews of lysimetry as applied to agriculture and forestry by Kohnke *et al.* (1940), Yamasaki and Kishita (1970), Litaor (1988), Homung (1989), Addiscott (1990), Angle *et al.* (1991), and Führ and Hance (1992). Specific works related to porous cup lysimetry have been prepared by Linden (1977), Stevens (1981), Grossmann *et al.* (1987), Everett *et al.* (1988), Peters and Healy (1988), Morrison and Lowery (1990a,b), Grossmann and Uhlir (1991) and Lord and Shepherd (1993). Much valuable information is also contained in general reviews on ground-water monitoring techniques, especially for the vadose zone², and includes works by

² *The vadose zone is the geological profile from the ground surface to the upper surface of the principal water bearing strata... The term "vadose zone" is preferable to the often-used term "unsaturated zone" for this region because saturated conditions are frequently present. The term "zone of aeration" is also often used as a synonym for vadose zone.*

The vadose zone has been subdivided into three regions, designated as the soil zone, the intermediate vadose zone, and the capillary fringe (Davis and de Wiest 1966). Weathering of native geological material, together with the process of eluviation and illuviation of colloidal materials, to develop more or less well-developed soil profiles is generally recognized to take place and thus defines the limit of the soil zone. Water movement in the soil zone is generally in the unsaturated state, i.e., that state in which the soil water exists under pressures that are less than atmospheric. The principal transport mechanisms associated with unsaturated flow are infiltration, percolation, redistribution and evaporation. Saturated regions may develop in the soil zone in response to surface flooding, especially in soils that contain horizons of low permeability...

The soil zone gradually merges with the underlying intermediate vadose zone through a transition from weathered to generally unweathered native material... [T]he intermediate vadose zone is rarely uniform throughout. In some regions it may be practically non-existent, when soils merge with bedrock...

*The base of the vadose zone, the capillary fringe, merges with underlying saturated material of the principal water bearing formation. This zone is not characterized as much by the nature of geological materials as by the presence of water under conditions of saturation or near saturation. In general, the thickness of the capillary fringe is greater in fine materials than in coarse deposits. (after Everett *et al.* 1984a)*

Everett (1980), Momson (1983), Wilson (1983), Everett and Wilson (1984), Everett *et al.* (1984a,b), Everett and McMillion (1985), Everett (1990), Wilson (1990), Ballesterio *et al.* (1991), Dorrance *et al.* (1991), Anon. (1993b), Wilson and Dorrance (1994), and Wilson *et al.* (1994b).

Not all aspects of lysimetry are covered in the present report, and other reviews of wider interest in sampling the soil solution include Wilson (1980, 1981, 1982, 1983), Uhlir *et al.* (1984), Anon. (1986), and Starr *et al.* (1991). A review of methods for determining water flux and budget models for use with lysimeter systems can be found in Anon. (1993b). Models of transport flow in the vadose zone are also reviewed by Foggetal. (1994) and Kramer and Cullen (1994).

Only a small selection of diagrams of lysimeter system designs have been included as many of these can be viewed in Morrison (1983), Dorrance *et al.* (1991) and Anon. (1993b), or in the original works.

1.1 Historical Overview

Studies on the movement of water through soil-plant systems have been carried out in the Western World for over 300 years. One of the first recorded quantitative experiments was conducted by J.B. van Hehnont (1577-1644) who compared the weight of a pot of soil and a willow tree before and after a 5-year period of growth. He found that while the tree gained 75 kg the soil only lost 57 g and therefore he attributed the tree growth to uptake of water alone (Kramer 1949, Anon. 1957). De la Hire (1720) examined water movement down the soil profile in the late seventeenth century (this work was carried out in 1688, presented in 1703, and published in 1720; see Appendix 1 for a translation from the original French). Although he could obtain no drainage water from lead trays buried at a depth of approximately 2.4 m or 40 cm, he did obtain flow at a 20-cm depth following snow melt or rainfall. Not long after this, water movement from soil through plants and into the atmosphere was studied by Hales (1677-1761),

Cullen *et al.* (1994) likewise differentiate between vadose zone and unsaturated zone, as "[f]low in the vadose zone is dynamic and characterized by periods of unsaturated flow at varying degrees of partial saturation punctuated by episodes of preferential, saturated flow in response to hydrologic events or releases of liquids".

who repeatedly weighed a potted plant with its soil sealed against water loss to determine its transpiration rate (Hales 1727 in Kramer 1949). With the advent of analytical chemistry in the nineteenth century it became possible to examine the movement of water and associated nutrients in the soil solution (e.g. Way 1850). Research in these areas of the soil-plant system expanded as the scientific foundation for modern hydrological and nutritional research in agriculture and forestry was established in the nineteenth and early twentieth century.

For 300 years there was little change in the fundamental concepts underlying the designs of the equipment used to study rates of movement of water down the soil profile, nutrient leaching from soil, or transpirational water loss from soil, and the various instruments used became commonly referred to as *lysimeters*. In their classic review of 489 publications on lysimeters Kohnke *et al.* (1940) noted that lysimeter *"is an accepted term for a device to study the rate, amount, and composition of natural precipitation percolating through soil"*, and defined a lysimeter as *"an instrument that contains soil and receives natural rainfall or irrigation and is provided with an arrangement for collecting and measuring the percolate"*. Up to this time the designs of lysimeter systems were such that only water in excess of field capacity could be collected. The leachate from these lysimeter systems could be used, by and large, for either hydrological or nutrient movement studies.

Unease with the accuracy of data obtained from these lysimeter systems (Kittredge 1940) because of the potential barrier to gravitational water movement caused by the soil-air interface (Kittredge 1941) helped to stimulate interest in the development of lysimeter systems which draw soil solution from the soil through porous materials into a collection vessel by the application of a greater tension than that with which soil water is held within the soil matrix. These new designs for sampling water in the vadose zone led to a further expansion in research utilizing lysimeter systems (reflected in the production figures for one type of lysimeter system in Fig. 1) so that recently Doeny (1984) was able to list approximately 1800 publications in an extensive bibliography on the subject (Fig. 2). The proliferation of designs has been such that a wide array of equipment is now available commercially or can be constructed, depending on the nature of the topic under

investigation. While advances in weighing lysimeter system designs are often associated with the mechanisms for sensing and recording changes in the amount of water with a system (see review by Aboukhaled *et al.* 1982), new designs for lysimeter systems used for sampling the soil solution for subsequent chemical analysis are taking place constantly with regard to materials used in construction, shape and size of sampling device, and application of tension. It is the intent of this review to describe and categorize the present designs available that can be used for sampling the soil solution for nutrient cycling studies, rather than weighing lysimeter systems.

As the term *lysimeter* has sometimes been used in the past to refer only to encased soils (or monoliths) but not necessarily to associated tension-generating and soil solution collecting systems, for the purposes of this review a *lysimeter system* will be defined as:

a device used to measure the volume flow of water with or without the application of tension, or to obtain water samples from the soil for analysis of solutes and/or suspended substances of either natural or anthropogenic origin'.

Lysimeter systems basically consist of: (i) a *lysimeter* (or soil solution sampler) which causes soil solution to move from the soil into some form of a collection vessel by directing freely moving gravitational water to a drainage port, or by causing the movement of soil water through a porous wall under a tension (or suction) greater than that with which it is held in the soil;

Morrison (1983) defines a lysimeter more narrowly as an instrument *"used to measure percolation and leaching losses from a column of soil under controlled conditions, or for measuring gains and losses by collecting soil pore water via suction in the unsaturated zone. Lysimeters are capable of retaining the accumulated water within the sampling vessel"*.

The Soil Science Society of America (1987) define a lysimeter as "(i) A device for measuring percolation and leaching losses from a column of soil under controlled conditions. (ii) A device for measuring gains (irrigation, precipitation, and condensation) and losses (evapotranspiration) by a column of soil".

The term *system* has been added to describe the entire apparatus (e.g. Ranger and Nys 1994), as some authors use *lysimeter* to describe the soil solution sampler only, while others use it to describe the complete apparatus, including tension-generating and collection systems.

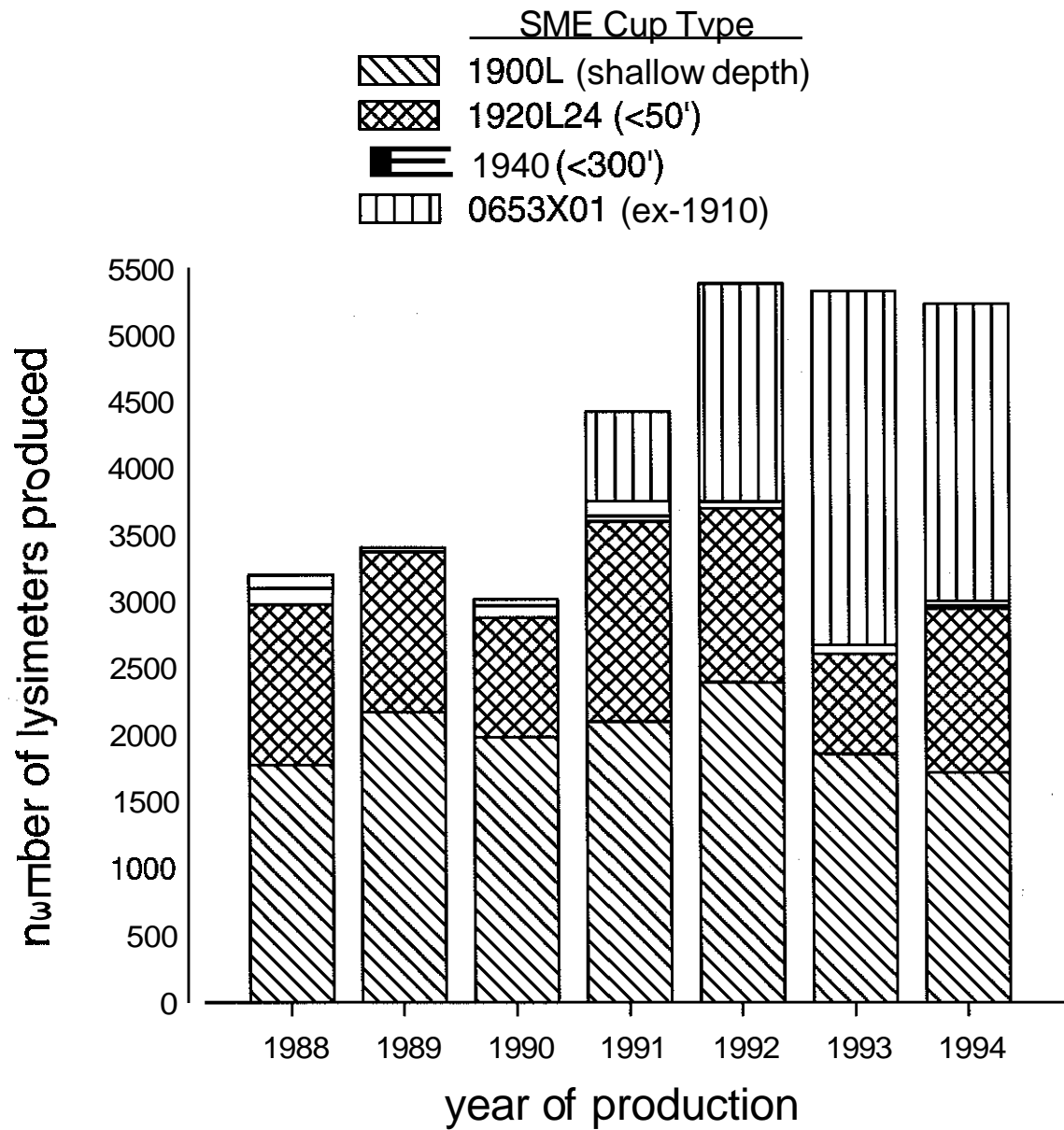


Figure 1. Rate of porous cup production (from Soilmoisture Equipment Corp.)

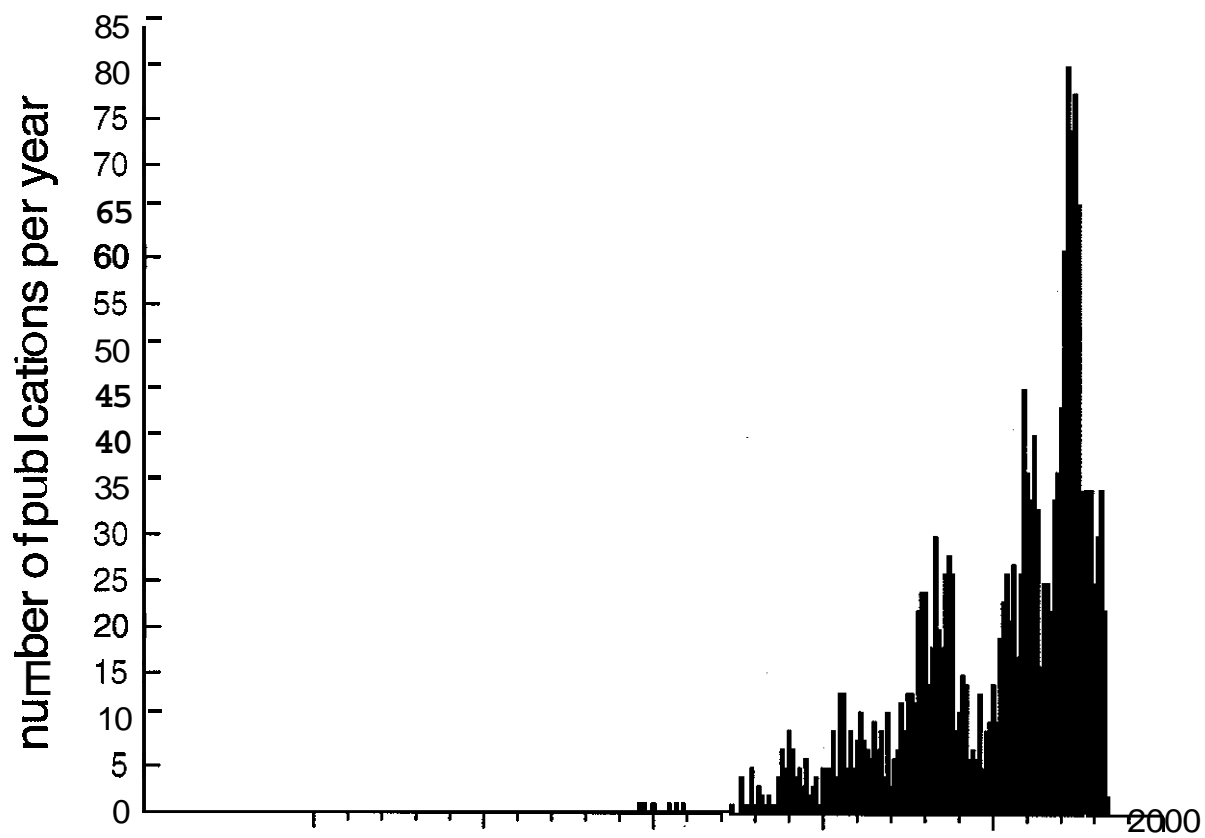


Figure 2. Frequency histogram of lysimeter system publications 1720-1984 (from Doeny 1984)

(ii) a *tension-generating system* (or vacuum-generating system) for applying a negative pressure to the soil (where applicable) through the soil solution sampler to cause soil solution movement; and (iii) a *collection system* for holding the sampled soil solution in a reservoir from which it can be periodically retrieved.

1.2 Classification of Lysimeter Systems

Lysimeter systems can be broadly divided into non-hierarchical categories based upon: (i) *confinement* of soil; (ii) *disturbance* of soil; (iii) the *type of tension* used to obtain the soil solution sample; and (iv) the use of *weighing* devices.

Based on the continuity of the surrounding soil with that being sampled, lysimeter systems can be classified depending on whether the sampled soil is: (i) confined; or (ii) *unconfined*. *Confined* lysimeter systems include “*monoliths*” and “*filled-in*” lysimeter systems (*sensu* Kohnke *et al.* 1940), which can conveniently be considered as one group because of their *similarity*. Within this category, known volumes of soil are bounded by walls of impermeable material so that the amount of soil water sampled can be related to precipitation inputs. However, with *unconfined* lysimeter systems lateral movement of water and growth of roots can take place from outside the sampling zone, and thus the volume of soil being sampled cannot be so easily defined.

With both confined and unconfined lysimeter systems the soil can be either: (i) *undisturbed*; or (ii) *disturbed*⁵. In *confined, undisturbed* situations soil cores ranging in diameter from a few centimeters up to several meters, or blocks of soil, can be isolated and left in the field or moved to a laboratory or greenhouse. Alternatively, large undisturbed blocks can be trenched in the field and impermeable barriers built to encase the block without moving it. At the largest scale, and under

specific circumstances, entire watersheds with impermeable underlying geological formations can be considered to be confined, undisturbed lysimeter systems. In *unconfined, undisturbed* situations there are two main methods of installation: (i) lysimeters can be placed vertically in the soil after augering an access hole from the soil surface; or (ii) lysimeters can be placed horizontally into the soil from the face of access pits or trenches.

Although both confined and unconfined lysimeter systems are used in undisturbed soils, the use of *disturbed* soils is largely restricted to confined (or filled-in) lysimeter systems where soil from the field is placed in tubes or tanks, often after some combination of air-drying, sieving, and/or mixing. In some cases an attempt is made to simulate natural conditions by rebuilding horizons within containers. However, in others disturbed soil is placed in unconfined lysimeter systems either by refilling pits with mixed, uniform soil (Patric 1961), or by reconstituting soil by horizon in a pit over a large buried tray (Will 1977, Knight and Will 1977).

Regardless of the degree of confinement or disturbance of soils being sampled, lysimeter systems can be classed as either (i) *zero tension*⁶, or (ii) *tension*⁷ lysimeter systems. These classes differ largely in the kind of soil water sampled, with *zero tension* lysimeter systems being better suited to sampling water moving by preferential flow⁸ through macropores⁹ (cracks, root

⁶ Also known as “*free-drainage*” (Wilson 1990, Anon. 1993b), “*tensionless*”, or “*tension-free*” lysimeters; includes Ebermayer lysimeters (*sensu* Kohnke *et al.* 1940); van Bavel (1961) refers to the “*zero-pressure plane*” at the bottom of freely draining lysimeters.

⁷ Also known as “*suction*” lysimeters (Everett and McMillion 1985, Anon. 1993b).

⁸ *Preferential flow* can account for the transport of large volumes of soil solution rapidly down the soil profile, and 69-83%, 90% and 96% of the total flow of water through soils can occur at water potentials of -0.06 to -1.4 kPa, 0 to -2.0 kPa, and 0 to -1.5 kPa, respectively (Dunn and Phillips 1991, Shaffer *et al.* 1979, Watson and Luxmore 1986). Preferential flow and its implications on water movement and solutes are further discussed by Aubertin (1971), Thomas and Phillips (1979), Bevan and Germann (1981), Germann and Bevan (1981a,b), Megahan and Clayton (1983), White (1985), Watson and Luxmore (1986), Lauren *et al.* (1988),

⁴ *Confined* soils within lysimeters are also recognized by van Bavel (1961) in a categorization of methods of determining evapotranspiration.

⁵ These terms are also recognized by van Bavel (1961) when categorizing methods of determining evapotranspiration using lysimeters, by Shaykewich (1970) regarding hydraulic properties, and by Cassel *et al.* (1974) regarding solute movement.

channels, invertebrate **tunnels**), down fingers arising from wetting front instability especially in coarser textured soils, or down funnels formed in interbedded and inclined soil layers which concentrate water flow, and **tension** lysimeter systems being better suited to sampling water held more firmly by smaller pores and therefore moving by matrix flow. However, tension samplers can withdraw water from larger pores if the soil is sufficiently wet for these pores to contain water.

References directly or indirectly comparing the performance of **zero** tension and tension lysimeter systems are listed in Table 1, along with references giving a wider range of comparisons between lysimetry and other techniques for sampling the soil solution. The aspects of the soil solution that were compared using the techniques listed in Table 1 are presented in Table 2.

Tension lysimeter systems can be **further** subdivided based on the continuity of the tension applied over the sampling period into: (i) **constant** tension; (ii) **decreasing** tension; or (iii) **variable** tension lysimeter

Parlange *et al.* (1988), Philip (1988), Richard and Steenhuis (1988), Steenhuis and Muck (1988), Wilson and Luxmore (1988), Kung (1988, 1990a,b), Andreini and Steenhuis (1990), Kung and Donohue (1991), Li and Ghodrati (1994), Steenhuis *et al.* (1994a), Fleming and Butters (1995), and Phillips *et al.* (1995).

⁹ Macroporosity is specified by Skopp [1981] as that pore space that provides preferential paths of flow so that mixing and transfer between these and other pores is limited. Matrix or microporosity is characterized as that pore space which transmits water and solute at a rate slow enough to allow transfer of molecules between the different pores. The term mobile water as used by Addiscott (1977) and Van Genuchten and Wieringa (1976) is that water in the macropore space. The retained or immobile water is contained in the micropore volume. According to Watson and Luxmore (1986), macropores make up only a small percentage of the total pore space, yet they account for the bulk of the water movement. They found that under ponded conditions on a forest floor, 90% of the water flux was through 0.32% of the soil volume. For agricultural soils the macropore space is in the order of 0.5 to 5% (Germann and Bevan 1981[a], Kneale 1985) (after Steenhuis and Muck 1988).

See Luxmore (1981) and Skopp (1981) for further discussion of definitions of macropore.

systems. With **constant** tension lysimeter systems a given tension is maintained through the **use** of such devices as "hanging water columns", and automated pressure gauges linked to evacuated **reservoirs** or vacuum pumps. With **decreasing** tension lysimeter systems a collection vessel (**or** the tubular part of the lysimeter system to which a porous cup is attached) is evacuated to a certain level at the beginning of the collection period, and as the vessel fills with water the vacuum concomitantly decreases. With **variable** tension lysimeter systems no standard tension is applied. Rather, just enough tension to induce a slow movement of water into a collection vessel is used, and the tension applied is varied depending on the moisture potential in the surrounding soil brought about by drying or wetting cycles.

Finally, lysimeter systems can be classified according to whether they do or do not incorporate weighing devices. Weighing lysimeter systems all utilize confined soil, either disturbed or undisturbed. As the intent of this review is to examine lysimeter systems used in nutrient cycling studies, weighing lysimeter systems will not be discussed **further**.

Other variations in design arise with regard to: (i) the materials used in construction; (ii) the **size** and shape of materials used for the soil solution sampler; (iii) the methods used to apply or maintain tension (where applicable); (iv) the location **of** sample collection vessels; and (v) the methods of emptying collection vessels. However, these variations do not all warrant inclusion within distinct classes when discussing lysimeter system designs for nutrient cycling studies, although they have been usefully applied in the ground-water monitoring literature (e.g. see **vacuum**, **pressure-vacuum** and **high pressure-vacuum** lysimeter systems in Appendix 2).

Taxonomies **are** only useful in that they provide a convenient method of organizing concepts, and are a means to an end rather than an end in themselves. However, the above categories and terminology allow for a reasonably unambiguous definition and description of most lysimeter system designs found in the literature. Lysimeter system designs will be reviewed within the non-hierarchical categories outlined above, moving from lysimeter **systems** that are relatively simple in concept to those that are more complex, and from small- to large-scale systems. However, many permutations and

Table 1. Comparison of methods of obtaining samples of the soil solution with lysimeter systems: types of methods compared

Reference	Soil wring	Centri- fugation	Zero tension	Wick	Tension								Water balance
					Ceramic cup	Ceramic plate	Alundum® plate	Fritted glass	PTFE	Stainless steel	Nickle	Hollow fibres	
Alberts <i>et al.</i> (1977)	core				ceramic c								
Artiola and Crawley (1994)			zero t ¹		ceramic c								
Barbarick <i>et al.</i> (1979)	core ²				ceramic c								
Barbee and Brown (1986)			zero t		ceramic c								
Beier and Hansen (1992)					ceramic o				PTFE				
Boll <i>et al.</i> (1991)			zero t	wick	ceramic c								
Brown (1987)	core				ceramic c								
Daliparthi <i>et al.</i> (1993)				wick	ceramic c								
Everett <i>et al.</i> (1988)					ceramic c ³				PTFE				
Faber and Nelson (1984) ⁴		centrif			ceramic c								
Fernandez <i>et al.</i> (1995)			zero t					glass					
Fleming and Butters (1995)	core				ceramic c								
Hädrich <i>et al.</i> (1977)					ceramic c ⁵						ni		
Haines <i>et al.</i> (1982)			zero t			ceramic p ⁶							
Hergert (1986)					ceramic c ⁷								w balance ⁸
Hornby <i>et al.</i> (1986)			zero t	wick	ceramic c								w balance ⁹
Jemison and Fox (1992)			zero t										
Johnson <i>et al.</i> (1981)	core		zero t ¹⁰		ceramic c								
Jones and Edwards (1993)			zero t ¹¹		ceramic c							h fibre	∞
Joslin <i>et al.</i> (1987)			zero t		ceramic c								
Krejzl <i>et al.</i> (1994)			zero t ¹²		ceramic c			glass					
Levet <i>et al.</i> (1985)			zero t				Alundum®						
Levin and Jackson (1977)			zero t		ceramic c							h fibre	
Lord and Shepherd (1993)	core				ceramic c								
Magid <i>et al.</i> (1992)			zero t						PTFE				
McGuire and Lowery (1992)					ceramic c			glass	PTFE	ss			
Miller (1981)			zero t		ceramic c	ceramic p ¹³							
Montgomery <i>et al.</i> (1987)			zero t ¹⁴		ceramic c ¹⁵								
Nemeth and Bittersohl (1981)					ceramic c ¹⁶						ni ¹⁷		
Radulovich and Sollins (1987)			zero t ¹⁸										
Ranger <i>et al.</i> (1993)		centrif	zero t										
Rasmussen <i>et al.</i> (1986)			Zero t		ceramic c ²⁰				PTFE				
Raulund-Rasmussen (1989)		centrif			ceramic c ²¹								
Ripp and Villauve (1985) ¹⁹			zero t		ceramic c				PTFE				
Russel and Ewel (1985)			zero t										w balance ²³
Shepard <i>et al.</i> (1990)			zero t ²⁴					glass ²⁶					
Sheppard <i>et al.</i> (1992)	core ²²	centrif				ceramic p ²⁵							
Shuford <i>et al.</i> (1977)	core					ceramic p ²⁸							
Silkworth and Grigal (1981)					soil solution samplers (material or type not defined)								
Silkworth and Grigal (1981)					ceramic c ²⁹			glass				h fibre	
Steenhuis <i>et al.</i> (1994)	core		zero t	wick	ceramic c								
Swistock <i>et al.</i> (1990)			zero t		ceramic c								
Turner <i>et al.</i> (1985)			zero t ³⁰				Alundum®						

Tyler and Thomas (1977)	core		zero t		
Watanabe <i>et al.</i> (1988)		centrif		ceramic c ³¹	
Webster <i>et al.</i> (1993)	core		zero t ³²	ceramic c	
Zabowski and Ugolini (1990)		centrif		ceramic p ³³	
Zimmermann <i>et al.</i> (1978)				ceramic c	PTFE

¹ *"Glass brick"* lysimeters.

² And saturated paste method.

³ Both **high-** and low-flow ceramic cups.

⁴ Also compared with methanolic extraction and column displacement.

⁵ Ceramic cup (manufactured by Schumacher, Bietigheim) *after* Czeratzki (1971b), and sintered Al₂O₃ plate ("*Al₂O₃-Sinterplatten*", manufactured by Haldeuwanger, Berlin) *after* Mayer (1971).

⁶ *"Porous ceramic"* plates from Pacific Lysimeter.

⁷ Ceramic *"candle"* (α tube) in bottom of trough.

⁸ Weekly volumes of water collected by lysimeters were. compare with estimates of soil percolation where weekly percolation = initial **soil** water content at beginning of week (as determined by **neutron** probe) + irrigation water applied **during** week + rainfall during week - evapotranspiration (from modified Penman equation) - soil water content at end of week.

⁹ Compared measured leachate output with predicted output from Mather model based **on** monthly average temperature, incoming precipitation, potential evapotranspiration from Thomthwaite equation, surface **run-off**, **soil** moisture storage potential (Mather 1978 *in* Jemisou and **Fox** 1991) and LEACHM model (**Wagenet** and **Hutson** 1989 *in* Jemisou and **Fox** 1991).

¹⁰ Ground water monitoring well.

¹¹ Leachate out bottom **of** encased **soil** sample.

¹² Sand-tilled funnel and *"perforated tube well"*.

¹³ Described **as** "SME *non-vitreous porcelain*".

(...Cont'd.)

Table 1. (Concl'd.)

- ¹⁴ Drainage tiles.
- ¹⁵ Ceramic tube in bottom of trough.
- ¹⁶ Sintered Al_2O_3 candle ("*Aluminiumoxid-Sinter*", SKA100FF, manufactured by Haldenwanger, Berlin) and ceramic candle (Diapor 8 G, manufactured by Schumacher, Bietigheim).
- ¹⁷ "*Nickel-Sinter*" candle (manufactured by Krebsöge; 1.9 cm i.d., 2.5 cm o.d. x 6.0 cm length).
- ¹⁸ 162 vs. 500 vs. 2500 cm^2 surface area.
- ¹⁹ Column displacement.
- ²⁰ Both SME ceramic cups and P80 porcelain cups.
- ²¹ P80 porcelain cups.
- ²² Describes experimental design, but **no data** presented, and reference therefore omitted from Table 2; used zero tension lysimeters (*after* Barbee and Brown 1985), SME ceramic cups, and Timco PTFE samplers.
- ²³ Compares *water flux* (where **flux** (q) during big storm events was calculated using Darcy's Law $q = K(\theta) dH/dz$ where K is the hydraulic conductivity at the volumetric content θ , and dH/dz is the rate of change in total hydraulic potential (H) with respect to depth z ; this required determining the relationships between soil moisture tension and volumetric water content, and between volumetric water content and hydraulic conductivity) and *water balance* (where water balance during big storm events = total rainfall - change in **soil** water storage resulting from the rainfall; this assumes that during large storms vegetation interception is low, that all water flow through the **soil** is vertical, and that evapotranspiration losses were negligible).
- ²⁴ Trough-like lysimeter (*after* Jordan 1968).
- ²⁵ 15 cm diameter ceramic plate; 2.5 μm pore size; 160 kPa air entry tension.
- ²⁶ Fabricated from Pyrex[®] immersion tube and fritted glass **disk** (60 mm diameter; 4 to 5.5 μm pore size; 67 kPa air entry tension) .
- ²⁷ Immiscible displacement.
- ²⁸ Three bar pressure plate cell, Cat. #1690, Soilmoisture Equipment Corp., CA.
- ²⁹ Also compared SME cups of two different sizes: 2.2 cm o.d. x 5.7 cm vs. 4.8 cm o.d. x 6.2 cm.

³⁰ Both

Jordan 1968) and funnels filled with acid-washed sand.

³¹ Both "*alumina and siliceous ceramic cups*".

³² The "*zero tension*" percolate came from a monolith which also had porous ceramic cups inserted in it; in addition, ceramic cups were installed in the field from which the monoliths came.

³³ Porous ceramic plates with average pore diameter 14 μm .

Table 2. Comparison of methods of obtaining samples of the soil solution with different lysimeter systems: nutrients and compounds assessed.

Reference	Location ¹	Flow	pH	EC ²	NH ₄ ⁺	NO ₃ ⁻	NO ₂ ⁻	PO ₄ ³⁻	K	Na	Ca	Mg	Mn	Al	Fe	Zn	Cu	Cd	Ni	SO ₄ ²⁻	Cl	Si	C ³	Other
Alberts <i>et al.</i> (1977)	field	flow	pH		NH ₄ ⁺				K	Na	Ca	Mg		Al						Cl				
Artola and Crawley (1994)	lab ⁵	flow	ec							Na ⁴	Ca	Mg												
Barbée and Brown (1986)	field	flow																						
Belier and Hansen (1992)	field	flow																						
Boll <i>et al.</i> (1991)	field	flow																						
Brown (1987)	field ⁶	flow																						
Daliparthi <i>et al.</i> (1993) ⁸	lab ⁹	flow																						
Baverfuit <i>et al.</i> (1988)	lab ⁹	flow	pH	ec	NH ₄ ⁺				K		Ca	Mg		Al						SO ₄ ²⁻	Cl	Si		
Fabre and Nelson (1984)	lab ⁹	flow																						
Fernandez <i>et al.</i> (1995)	field	flow																						
Fleming and Butters (1995)	field	flow																						
Hädrich <i>et al.</i> (1977)	lab	flow							K	Na	Ca	Mg	Mn	Al	Fe	Zn	Cu	Cd	Ni					Br
Haines <i>et al.</i> (1982)	field	flow	pH		NH ₄ ⁺															SO ₄ ²⁻	Cl	Si		Co, Be, Pb
Hergert (1986)	field	flow																						
Hornby <i>et al.</i> (1986)	field	flow																						
Jennison and Fox (1992)	field	flow								Na														
Johnson <i>et al.</i> (1981)	field	flow	pH	ec	NH ₄ ⁺				K	Na	Ca	Mg	Mn	Al	Fe	Zn				SO ₄ ²⁻	Cl	Si		Pb, Hg
Jones and Edwards (1993)	lab	flow	pH	ec					K	Na	Ca	Mg		Al						S				coliform, streptococcus
Joslin <i>et al.</i> (1987)	field	flow																						
Krejel <i>et al.</i> (1994)	lab	flow																						
Levet <i>et al.</i> (1985)	field ¹⁰	flow	ec																					
Lord and Shepherd (1993)	field	flow																						
Magid <i>et al.</i> (1992)	field	flow							K	Na	Ca	Mg		Al	Fe					SO ₄ ²⁻	Cl			
McGuire and Lowery (1992)	lab	flow	pH						K	Na	Ca	Mg												
Miller (1981)	field	flow																						
Montgomery <i>et al.</i> (1987)	field ¹¹	flow																						
Nemeth and Bittersohl (1981)	lab	flow																						
Radulovich and Solters (1987)	field	flow	pH		NH ₄ ⁺				K	Na	Ca	Mg	Mn	Al	Fe	Zn	Cu	Cd						Pb, Hg
Ranger <i>et al.</i> (1993)	field	flow	pH						K	Na	Ca	Mg												
Rasmussen <i>et al.</i> (1986)	field	flow	pH						K	Na	Ca	Mg	Mn	Al	Fe									
Raulund-Rasmussen (1989)	field	flow	pH						K	Na	Ca	Mg												
Russell and Bwel (1985)	field	flow	pH						K	Na	Ca	Mg												
Shepard <i>et al.</i> (1990)	field	flow	pH	ec	NH ₄ ⁺				K	Na	Ca	Mg		Al						SO ₄ ²⁻	Cl			F, CO ₂
Shurford <i>et al.</i> (1992)	lab	flow							K	Na	Ca	Mg												
Shurford <i>et al.</i> (1977)	field	flow	pH						K	Na	Ca	Mg												
Silkworth and Grigal (1981)	field	flow							K	Na	Ca	Mg												
Steenhuis <i>et al.</i> (1994)	field	flow																						
Swistock <i>et al.</i> (1990)	field	flow	pH	ec	NH ₄ ⁺				K	Na	Ca	Mg	Mn	Al	Fe					SO ₄ ²⁻	Cl			Br
Turner <i>et al.</i> (1985)	field	flow	pH																					
Tyler and Thomas (1977)	field	flow	pH																					
Valanac <i>et al.</i> (1988)	field	flow							K	Na	Ca	Mg												
Weber <i>et al.</i> (1993)	field ¹²	flow																						Br, F
Zabowski and Ugoilini (1990)	field	flow	pH		NH ₄ ⁺															SO ₄ ²⁻	Cl	Si		DOC
Zimmermann <i>et al.</i> (1978)	field	flow																						

¹ Location where comparisons were made (field or laboratory).

² Electrical conductivity.

³ Includes total organic carbon (TOC), dissolved organic matter (DOM) and dissolved organic carbon (DOC).

⁴ As "sodium adsorption ratio".

⁵ A confined, disturbed soil; soils re-packed to simulate profile after being air-dried, crushed and sieved.

⁶ Confined, undisturbed soil.

⁷ 30 organic compounds from API separator sludge, solvent recovery sludge, and wood preserving waste, including 11 alkanes and 11 phenolic compounds.

⁸ Only NO₃-N results for porous cup lysimeter systems are presented, as the wick lysimeter systems generally failed to collect soil solution samples under the fine sandy loam soils tested because the wicks did not generate high enough tensions.

⁹ Tested in 1:1:1 mix of clay loam:sand:peat moss as used in horticulture.

¹⁰ Confined, undisturbed soil.

¹¹ Confined, disturbed soil.

¹² Confined, undisturbed soil.

combinations of categories exist". Lysimeter system categories derived by other reviewers are presented in Appendix 1. Other methods of obtaining soil solution for analysis such as ceramic points (Shimshi 1966) and sponges (Tadros and McGarity 1976) are not considered as they have not been widely used.

2. ZERO TENSION LYSIMETER SYSTEMS

2.1 Introduction

Perhaps the simplest and in many cases cheapest types of soil solution samplers to build and use are zero tension lysimeter systems, in which only freely draining water can be collected. Indeed, the earliest lysimeter systems used by de la Hire (1720) were of the zero tension type, with one being an unconfined tray buried approximately 2.5 m beneath the soil, and the other confining the approximately 20-cm upper horizons within a pan with side walls that extended to the soil surface. After this date virtually all lysimeter systems were of the confined type, with soil bounded in containers of different sizes, until Welbel in Russia in 1903 used funnels with a surface area of 100 cm², buried at 25, 50, 75 and 100 cm beneath the soil surface (Kohnke *et al.* 1940). Earlier, Ebermayer had also used funnels (but beneath blocks of soil isolated by concrete walls), and hence these early zero tension funnel designs are sometimes known as "Ebermayer", or "Russian" lysimeter systems (Kohnke *et al.* 1940)". Tile drains were also used to collect freely draining soil solution, especially under agricultural fields (Kohnke *et al.* 1940). After a fairly long period with few innovations in lysimeter system designs, improvements were made to methods of collecting soil solution with a minimum of disturbance to the solum. The first improvement was accomplished by pushing three-sided trays laterally into

soil pit faces (Shilova 1955)¹², and another followed with the use of a meshed drainage bed held against the roof of a horizontal installation tunnel dug into soil pit faces (Jordan 1968). These two designs are illustrated in Figure 3.

A wide range of materials have been used to construct the soil solution sampling portion of zero tension lysimeter systems, including concrete, galvanized metal, zinc tinplate, stainless steel, glass, PVC, vinyl plastic, plastic, polyethylene, rigid polystyrene and plexiglass. Concerns for the choice of materials for zero tension samplers, as well as tubing and collection or storage vessels, are restricted largely to whether the sampler adsorbs or releases contaminants. For example, PVC is a relatively inert material (Quin and Forsythe 1976), while some plastics such as polyethylene and polycarbonate may take up small amounts of phosphate (Heron 1962, Ryden *et al.* 1972). Metal materials may corrode, and the use of more inert materials such as plexiglass is recommended (Laukajtyš 1968). In some cases, soil solution samplers may be treated with plastic coatings such as Krylon® acrylic to prevent leaching of elements to sample solutions (Vitousek 1977). References to different materials used in constructing zero tension lysimeter system samplers are presented in Table 3. Other reviews of zero tension lysimetry can be found in Kohnke *et al.* (1940), Momson (1983), Hornung (1989), Everett (1990), Dorrance *et al.* (1991), and Wilson and Dorrance (1994).

¹⁰ E.g. an undisturbed, confined soil core in the field may either rest on a zero tension funnel lysimeter (Rosén 1986), or on a tension plate lysimeter (Krause 1965); porous plates under tension may be used to sample unconfined soil (Krause and Wilde 1960) or confined soil (Krause 1965); the tension in porous cup lysimeters can decrease over time (Wagner 1962) or be held constant with a vacuum tank (Reeve and Doering 1965).

¹¹ Hornung (1989) credits Ebermayer (1878) with being one of the earliest workers to use a "trough-like collector" to sample freely draining percolate; however, it is not clear if walls were used to confine the soil or not.

¹² Shilova (1959), an English translation in Soviet Soil Science from the original Russian, cites Shilova, Ye. I. (1955) for construction and operation of these lysimeters, as do Laukajtyš (1968) and Levett *et al.* (1985). However, variations in translation from the original Russian can be found, and Ponomareva *et al.* (1968) cite this same reference as Shilova, E.I. (1955).

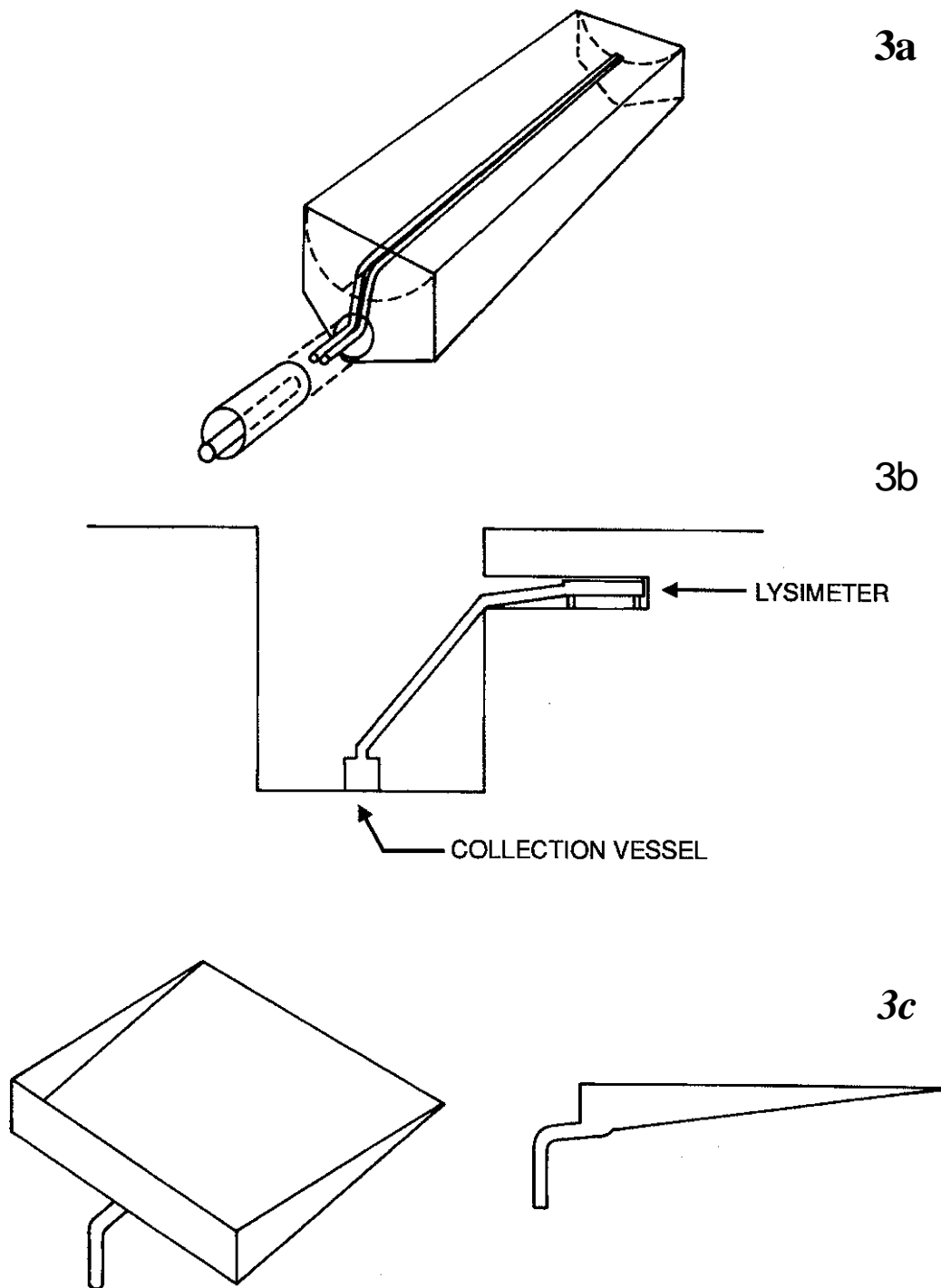


Figure3 Zero tension lysimeter systems: (a) typical sampler designed (*after* Jordan 1968) to be pushed against roof of (b) horizontal installation tunnel (*after* Jordan 1968); (c) typical sampler designed to be inserted by pushing horizontally into vertical pit or trench face (*after* Shilova 1955).

Table 3. Materials used in the construction of soil solution samplers in zero tension lysimeter systems.

Material	Reference
aluminum	Jemison and Fox (1992)
concrete	Knight and Will (1977), Will (1977)
galvanized metal	Parizek and Lane (1970), Radulovich and Sollins (1987)
glass	Barbee and Brown (1986)
plastic	Miller (1981), Shepard <i>et al.</i> (1990), Swistock <i>et al.</i> (1990), Fernandez <i>et al.</i> (1995)
plexiglass	Boemer (1982), Turner <i>et al.</i> (1985)
polyester	Rasmussen <i>et al.</i> (1986) ¹ , Thompson and Scharf (1994) ²
polyethylene	Turner <i>et al.</i> (1985), Nys <i>et al.</i> (1990), Rangeretal. (1993)
polystyrene (rigid)	Titus and Malcolm (1992)
PVC	Mayer (1971) ³ , Joslin <i>et al.</i> (1987), Rosén and Lundmark-Thelin (1987), David <i>et al.</i> (1989), Stevens <i>et al.</i> (1990), Vance and David (1991)
stainless steel	Jordan (1968) ⁴ , Haines <i>et al.</i> (1982), Russell and Ewel (1985), Rascher <i>et al.</i> (1987), Tindall and Vencill (1995)
steel	Tyler and Thomas (1977)
vinyl plastic	Ponomareva (1968)
zinc tinplate	Laukajtys (1968)

¹ Polyester net at bottom of plexiglass cylinder.

² Polyester screen over polycarbonate cylinder.

³ PVC screen in PVC funnel.

⁴ With fibreglass screen.

2.2 Zero Tension Lysimeter Systems and Unconfined Soil

Lysimeters that are pushed horizontally directly into the face of a soil pit or trench face usually consist of a tray with **three** vertical walls and an outlet port (*i.e.* designs *after* Shilova 1955)¹³. A drainage mesh cannot be used as it would be crushed on insertion, and a slight incline **ensures** water flows laterally along the soil/sampler interface to the outlet port. Drawbacks to this design include: (i) difficulty in insertion in stony soil, although this can be reduced by hammering in a template before insertion (Parizek and Lane 1970); (ii) lateral flow down steep slopes can flow in over the wall-less back of the tray, although this can be prevented by pushing small plastic plates vertically into the soil a few centimeters **uphill** of the lysimeter (Stevens *et al.* 1989); and (iii) water that is intercepted by the tray must move laterally along the soil-tray interface until the drainage port is reached. The size of trays (Table 4) is limited by the physical difficulty of insertion, and as a result a range of sizes from 129 to 1600 cm² have been used in the field. Reported surface areas include a 129-cm² semicircular trough made by cutting PVC pipe in half (Joslin *et al.* 1987), 250-cm² rectilinear section PVC rain guttering (*e.g.* Stevens *et al.* 1990), 1161-cm² galvanized 16-gauge metal trays (Parizek and Lane 1970), 1200-cm² **neutral** polyethylene (Nys *et al.* 1990), 1600-cm² vinyl plastic (Ponomareva *et al.* 1968), and 1600-cm² zinc tinplate (Shilova 1955, Laukajtys 1968).

Sampler units that **are** pressed against the ceilings of horizontal tunnels dug in from the walls of pits or trenches usually consist of trays with vertical walls, a

drainage bed and a drainage port. Trays (*e.g.* Jordan 1968) or funnels (*e.g.* Bringmark 1980) are often covered with a meshed material to support the overlying soil horizons and to form a drainage bed, although samplers have also been filled with crushed quartzite (Kardos 1948), sand (Roose and des Tureaux 1970, Turner *et al.* 1985, Radulovich and Sollins 1987) or glass wool (Miller 1981). However, the soil-air interface forms a barrier to water movement out of the soil and into the sampler. Jordan (1968) attempted to at least partially overcome this problem through the addition of rods positioned just under the drainage screen to help induce water flow. However, Radulovich and Sollins (1987) found that neither a screen nor filling a tray with sand helped increase drainage **as** much as pressing the lip of the sampler 1 cm into the tunnel **ceiling**¹⁴. A **minor** slope to the floor of the tray, or the use of a funnel will **ensure** that drainage water flows out of the drainage port and into a collection vessel. Backfilling holds the sampler in place, although adjustable wooden supports (Jordan 1968), inflatable tires (Shaffer *et al.* 1979), pneumatic pillows (Duke and Haise 1973), turnbuckles (Jemison and Fox 1992) or screw-jacks (Boll *et al.* 1991, Steenhuis *et al.* 1994) can also be used, and in some wick lysimeter system designs¹⁵ compression springs hold small 6-cm x 6-cm pans against the soil surface (Boll *et al.* 1991, Daliparthi *et al.* 1993, Steenhuis *et al.* 1994). Appropriate diameter piping is then laid down a slope away from the drainage port so that soil solution will freely flow to a collection vessel.

¹⁴ Cf. Hergert and Watts (1977) in Montgomery *et al.* (1987) who similarly found that increasing sidewall heights of **troughs** increased drainage efficiency at higher percolation rates. However, **soil** solution was extracted from troughs under tension through porous ceramic tubes (or candles), and was not collected through zero tension lysimetry.

¹³ Some authors (*e.g.* Momson 1983) define these as **pan** lysimeters, **as** distinct from trough lysimeters (*i.e.* designs *after* Jordan 1968) which are placed against the roof of a horizontal tunnel. However, this terminology can perhaps lead to confusion and **tray**, pun and trough lysimeters will not be differentiated in the present review but will only be used to describe the shape of zero tension lysimeters, with **no** specific methods of installation implied. Lysimeters with shapes other **than** troughs have been placed in horizontal tunnels by Radulovich and Sollins (1987), thus **weakening** the **use** of trough **as** a description; see Tyler and Thomas (1977) where **pan** is used to describe an *Ebermayer* lysimeter, which is **usually** referred to **as** a trough lysimeter; and Levett *et al.* (1985) where a design *after* Shilova (1955) is called a **tray lysimeter**; and Nys *et al.* (1990) where it is called a **plate** lysimeter.

¹⁵ Also **known as** **wick pan**, **capillary-wick** or **passive capillary sampler**. Wick samplers **are** beginning to be used more widely and have many advantages over zero tension and traditional tension lysimeter systems, but can still be thought of being much like a porous plate sampler with a lip to catch vertically moving water, and with a constant tension applied through a hanging water column. In **that** they combine some of the desirable features of both zero tension and tension lysimetry they **are** not unlike the design of Duke and Haise (1973), who used porous ceramic candles laid in a trough **so that** freely draining water that collected in the trough could be extracted at realistic tensions **using** the porous ceramic sampler.

Table 4. Sues of **soil** solution samplers in zero tension lysimeter system designs' for sampling unconfined **soil**.**zero tension in unconfined soil: sampler pushed in soil pit wall**

Area	Dimension	Material	Reference
129 cm ² 250 cm ²	4.3 cm x 30 cm	PVC pipe cut in half longitudinally, with cap on end rectilinear section PVC rain guttering	Joslm <i>et al.</i> (1987) Stevens and Wannop (1987), Stevens and Homung (1988), Stevens <i>et al.</i> (1989), Stevens and Hornung (1990), Stevens <i>et al.</i> (1990)
1161 cm ² 1200 cm ²	30.5 cm x 38.1 cm 30 cm x 40 cm	galvanized 16 gauge metal pans neutral polyethylene pan	Parizek and Lane (1970) Nys <i>et al.</i> (1990)
1200 cm ² 1600 cm ²	30 cm x 40 cm 40 cm x 40 cm	polyethylene pan	Ranger <i>et al.</i> (1993) Shilova (1955)
1600 cm ² 1600 cm ²	40 cm x 40 cm 40 cm x 40 cm	zinc tinplate pan vinyl plastic pan	Laukajtys (1968) Ponomareva (1968)
1600 cm ²	not specified	not specified	Levett <i>et al.</i> (1985)

zero tension in unconfined soil: sampler inserted in horizontal tunnel and held against roof of tunnel

Area	Dimension	Material	Reference
78 cm ² 155 cm ² 156 cm ² 162 cm²	10 cm diameter 5 cm x 30.5 cm 5.2 cm x 30 cm x 4 cm deep 5.4 cm x 30 x 4 cm deep	polyethylene funnel filled with acid-washed sand stainless steel trough stainless steel trough stainless steel trough	Turner <i>et al.</i> (1985) Jordan (1968) Haines <i>et al.</i> (1982) Russell and Ewel (1985), Radulovich and Sollins (1987)
452 cm ² 500 cm ² 638 cm ² 900 cm ²	24 cm diameter 20 cm x 25 cm x 10 cm deep 28.5 cm diameter 30 cm x 30 cm x 1.6 cm deep	PVC funnel with PVC mesh galvanized iron tray plastic funnel filled with glass wool glass "tray", overlain by filter	Mayer (1971) Radulovich and Sollins (1987) Miller (1981) Barbee and Brown (1986), Hornby <i>et al.</i> (1986), Artiola and Crawley (1994)
1110 cm ² 1998 cm ² 2500 cm ² 4648 cm ² 4800 cm ² 4976 cm ² 10000 cm ² unknown	91 cm x 122 cm 54 cm x 37 cm x 3 cm deep 50 cm x 50 cm x 10 cm deep 76.2 cm x 61 cm 60 cm x 80 cm 79.6 cm diameter 1.13 m diameter 7.5 cm V-walls x 50 cm long	steel tray, with gravel drainage bed plastic tray, with nylon cloth galvanized iron tray aluminum tray, with polypropylene pellet bed tray funnel funnel trough	Tyler and Thomas (1977) Swistock <i>et al.</i> (1990) Radulovich and Sollins (1987) Jemison and Fox (1992) Roose and des Tureaux (1970) Roose and des Tureaux (1970) Schroeder (1969) Boemer (1982)

zero tension in *sampler buried beneath undisturbed profile*

Area	Dimension	Material	Reference
52.8 cm ²	82 cm i.d. x 8 cm deep	polycarbonate collection vessel with polyester screen top	Thompson and Scharf (1994)

zero tension in unconfined soil: sampler buried beneath re-constructed profile

Area	Dimension	Material	Reference
1.0 m ² 856 m ²	1 m x 1 m in 1.35 m deep pit 200 m x 205 m x 15 cm wall	stainless steel mesh and perforated plate over pan concrete sloning tray	Tindall and Vencill (1995) Knight and Will (1977) Will (1977)

¹ Not all 3

A larger sampler surface area will ensure that a more representative soil solution sample is collected, but the size of sampler inserted in a horizontal tunnel will be limited by the stoniness and other physical properties of the soil, and the time required for installation. Sizes of surface areas used range from 79 to 4976 cm² (Table 4), and include: 79-cm² polyethylene funnel filled with acid-washed sand (Turner *et al.* 1985), 155-cm² stainless steel tray (Jordan 1968), 156-cm² stainless steel tray (Haines *et al.* 1982), 162-cm² stainless steel tray (Russell and Ewel 1985, Radulovich and Sollins 1987), 452-cm² PVC funnel with PVC mesh (Mayer 1971), 500-cm² galvanized iron tray (Radulovich and Sollins 1987), 638-cm² plastic funnel filled with glass wool (Miller 1981), 900-cm² perforated glass tray (*i.e.* upper surface of hollow glass brick), overlain by fibreglass (Barbee and Brown 1986) or geotextile material (Hornby *et al.* 1986, Artiola and Crawley 1994) to act as a filter, 1000-cm² funnel (Schroeder 1969), 2500-cm² galvanized iron (Radulovich and Sollins 1987), 4648-cm² aluminum tray with polypropylene pellets as a drainage bed (Jemison and Fox 1992), 4800-cm² tray and 4976-cm² tray filled with sand (Roose and des Tureaux 1970).

Collection efficiency¹⁶ can be determined for zero tension lysimeter systems. From data collected by Russell and Ewell (1985) using 162-cm² trays, collection efficiency during storms was shown to vary from 5 to 11%, depending on the water movement model used. The effect of tray size on sample volume is discussed by Radulovich and Sollins (1987) who determined that collection efficiency increased from 10 to 13 to 26% for trays of 162, 500 and 2500 cm² surface area, respectively. However, performance also depended on the soil structure, and large trays were 36% efficient under grass, but only 17% efficient under a forest. Further evidence that large lysimeters are more efficient can be found in Jemison and Fox (1992) who compared the amount of leachate collected from large, 4648-cm² trays with estimates from two different water movement models, as well as recovery of added bromide, and concluded that average collection efficiency was 45, 50, 56 and 58% as determined by bromide mass balance, bromide leaching, a Mather model and a LEACHM model (Mather 1978, Wagenet and Hutson 1991 in

Jemison and Fox 1992), respectively. Individual lysimeter collection efficiencies ranged from 13 to 92%. However, sampler size is not the only factor in determining sampling efficiency. By creating a 32-cm x 32-cm pan-shaped lysimeter made up of a 5 x 5 grid of individual cells, Steenhuis *et al.* (1994b) were able to demonstrate that recovery of bromide added to the surface of a well-drained silt loam soil was highest in the centre of the pan. This suggests that water and solutes bypassed the lysimeter, a sampling artefact also observed by others (Kung 1988) and with implications for approaches to sampling the soil solution (Steenhuis *et al.* 1994a). The zero tension lysimeters intercepted 28% of applied water, and only 7% of applied bromide¹⁷. However, in a clay loam soil recovery of applied water was 93 and 69, and applied bromide was 107 and 104%, respectively, for grass- and moss-covered plots. This high collection efficiency was attributed to the presence of cracks in the clay loam soil, with minimal sideways matrix flow because of the dense soil matrix.

Where lateral rather than vertical water flow has been of interest, Kardos (1948) placed tin funnels with a surface area of 730 cm² (30.5 cm) on their side against the upper slope of a trench. Alternatively, Beasley (1976) used 12.2-m long L-shaped troughs pushed into the sides of trenches to estimate flow down a slope. Homung *et al.* (1986) also measured lateral flow using equipment based on designs by Knapp (1973) and Atkinson (1978), and Hattori (1975) compared results of water movement in lysimeter systems containing 127-cm deep soil horizons at a 30° slope over 4.5 m length with theoretical equations. In another study (Joslin *et al.* 1987), 50-cm long sections of 10-cm diameter PVC pipe were cut longitudinally to create a 6-cm wide opening running their full length, endcaps were installed, and the troughs were placed against pit faces in hardwood and softwood stands to catch lateral flow during storm events.

¹⁷ By contrast, bypass flow around wick samplers on the same well-drained silt loam site was much lower, with virtually 100% of added water and 63% of applied bromide being recovered. For a further discussion of bypass flow around wick samplers see Daliparthi *et al.* (1993), Knutson and Selker (1994) and Rimmer *et al.* (1994). The results for the well-drained silt loam soil are also presented in Boll *et al.* (1991) where they are compared with breakthrough curves for porous cup lysimeters.

¹⁶ Defined as the volume of water collected by a soil solution sampler divided by the water flux leaving the rooting zone, as determined from water balance models.

Variations exist on the above two methods of installing zero tension lysimeters¹⁸. In one, an 8.56-m² (2.90m x 2.95 m with 15-cm wall) concrete sloping tray was built at the bottom of a large pit, a layer of coarse pumice was placed on top for drainage, the soil profile was reconstructed (three horizons of 0.9 m, 0.6 m and 1.2m, for a total depth of 2.7 m) and then the lysimeter system was planted with pines (Knight and Will 1977, Will 1977). Similarly, Drake *et al.* (1980) designed what they termed a "mini-lysimeter" for monitoring soil solution in special cases such as under golf course greens where the soil profile was reconstructed and a perched water table created. An 18-cm thick horizon of pea gravel was laid down, and a 79-cm² (10cm diameter) plastic bucket was placed at the desired sampling location with the lip level with the top of the pea gravel to create the sampler unit of the lysimeter system. A 71-cm long piece of PVC pipe was placed with one end at the bottom of the sampler unit, and piece of Tygon® tubing led to the bottom of the bucket for extraction of sample. The PVC pipe was installed in the soil at an angle of 45° to minimize the channelling of rainfall down the PVC access tube into the sampler unit.

In a combination of tray types, Boemer (1982) constructed a 50-cm long V-shaped trough (7.5-cm walls) similar to the rectilinear PVC rain guttering used by others (e.g. Stevens and Wannop 1987). However, it was installed against the roof of a tunnel dug at a 20° slope rather than pushed in horizontally. A "slump plate" was put against the disturbed soil face after backfilling, allowing more flexibility in installation than might be attained with a rigid front wall.

All of the above examples require an access pit or trench to be dug for lysimeter installation which is then used for access to soil solution collection vessels¹⁹.

¹⁸ Sampler pushed horizontally into pit face after Shilova (1955); sampler pressed against ceiling of tunnel after Jordan (1968).

¹⁹ Hence some authors (e.g. Morrison 1983) refer to these as trench lysimeters. However, this does not seem to be a useful term as virtually all zero tension lysimeters used to sample unconfined soils (i.e. trays, pans, troughs, funnels) are inserted from the sides of pits or trenches, which are then used for continued access to collection vessels. The term trench therefore refers more to the mode of access for installation and collection vessel servicing than it does to the shape or size of the soil solution sampler or its method of

However, in one unique design a 5-cm diameter hole was augered from the soil surface at a 45° angle for sampler placement. The sampler consisted of a screened mid-section built into a 5-cm diameter PVC pipe that extended around the pipe for half of its circumference (Simmons and Baker 1993). A smaller diameter internal spring-loaded pipe behind the screen was activated once the lysimeter was installed to hold the screen mesh firmly against the soil surface. Soil solution entered the pipe through the screen, and drained into the lower capped section of the pipe, which formed the collection vessel.

Tile drains can also be used to sample freely flowing soilwater (e.g. Richard and Steenhuis 1988, Scholefield *et al.* 1993; Jayachandran *et al.* 1994; see also references pertaining to tile drains in Steenhuis *et al.* 1994a), and because of their length and the area of soil drained can potentially form some of the largest unconfined zero tension lysimeter systems²⁰. While soil disturbance during installation can be relatively severe as compared to other methods of zero tension lysimetry, the possibility exists of sampling a large area of soil and thus integrating differences in soil solution within the same treatment as a result of spatial variability factors. However, while this may be of benefit for representative sampling, replicating treatments can be problematic.

2.3 Zero Tension Lysimeter Systems and Confined Soil

Under certain circumstances investigators have chosen to isolate the volume of soil (either disturbed or undisturbed) under investigation by encasing it with walls, and with a floor if the bottom horizon is permeable. These isolated and confined soils (sometimes called monoliths²¹) may be left *in situ*, or

insertion into the face of an exposed soil profile.

²⁰ Although tile drains can also be used in smaller, confined lysimeter designs such as the 2.4-m x 2.4-m x 2.3-m deep confined, reconstituted disturbed soils sampled by Montgomery *et al.* (1987).

²¹ The Greek roots for the term *monolith* (*monos* alone, sole, single + *lithos* stone) do not specifically describe shape or infer size, although the word can be defined to mean a "single block of stone, esp. shaped into pillar or monument" (Fowler and Fowler 1956). Kohnke *et al.* (1940) include *undisturbed soil-blocks* in their definition of *monolith*

moved to more convenient field sampling locations or to the laboratory. Various techniques have been developed to collect intact blocks (Brown *et al.* 1974) or cylinders (Mielke 1973, Belford 1979, Brown *et al.* 1985, Harris and Stone 1990, Cameron *et al.* 1992) of soil from the field, and will not be reviewed in this report.

Large confined soil lysimeter systems are usually of the zero tension type as a result of the difficulties that would be encountered in applying tension to a large surface area using plates or cups. However, smaller diameter cylindrical soil samples can be placed in tubes with a tension plate attached to the bottom (e.g. Czeratzki 1959, Krause 1965, Cronan 1978, Harris and Stone 1990), and larger soil cores can be sampled with porous cups or "candles" inserted horizontally through access holes (e.g. Brown *et al.* 1974, 1985, Harris and Stone 1990, Cameron *et al.* 1992). Applications of tension lysimetry to confined soils is discussed further in Section 3.5, with the exception of methodologies that are also appropriate to zero tension lysimetry.

Advantages in isolating soil include being able to work with a known volume or surface area of soil, thereby making nutrient flux calculations more straightforward. When large enough areas of soil are isolated, agricultural and even forestry crops can be planted in the lysimeter systems (e.g. Patric 1961). Moving confined soil samples to a central access trench (e.g. Overrein 1968) also simplifies field collection of soil solution samples while retaining some measure of site variability.

Although there are advantages in using confined soil the rapid movement of water down the walls of containers can be a problem. However, this can be minimized by: (i) the use of heat shrink casings (Bondurant *et al.* 1969, Mielke 1973); (ii) obtaining the soil core in such a manner that a small gap is left

between the casing and the core, which can then be filled with hot liquid petrolatum that gels on cooling (Cameron *et al.* 1992), plaster of paris (Andreini and Steenhuis 1990), liquid polyurethane foam (Quisenberry *et al.* 1994, Phillips *et al.* 1995) or concrete (Buchter *et al.* 1995); (iii) the construction of an interior lip just below the soil surface (Brown *et al.* 1974, 1985) or a series of lips (or "annular-ring baffles") at various depths (Corwin and Le Mert 1994) to move rainfall or irrigation water away from the wall; (iv) calibration of the movement of ions through the soil (Till and McCabe 1976); (v) roughening the interior walls of containers with sandpaper to improve contact with the soil (Powelson and Gerba 1994); or (vi) collection of soil solution from only the central core of the soil sample (Cronan 1978, Smith *et al.* 1993).

It has also been recognized that soil water conditions may not be the same inside confined soil samples as in unconfined soil. To overcome this, tension lysimeters can be used to withdraw water from the base of confined soil cores at tensions equivalent to those found in the field (Cameron *et al.* 1992). Experience has also shown that when large lysimeter systems of this kind are planted with trees, the changes in water movement arising from confining the soil can result in reduced tree growth as compared to trees growing in unconfined soil (Patric 1961, Tollenaar and Ryckborst 1975). Walls also block lateral water movement and the growth of roots into the lysimeters. However, Anderson *et al.* (1990) introduced roots into isolated soil blocks to help determine the role of macrofauna in forest soils, and the roots may be thought of as living tension lysimeter systems withdrawing water and nutrients, and also contributing exudates to the soil sample. The inclusion of overflow pipes is important in lysimeter systems where the rim extends above the soil surface, unless the aims of the experiment are not compromised by the possible ponding of water, or the inclusion of water that may have flowed over the surface in the field. For example, Jones *et al.* (1974) constructed lysimeter systems from 1932-cm² x 559-cm deep galvanized cans with a drainpipe in the centre of the bottom to serve as an outlet port, and with an overflow pipe inserted at the soil surface. Another serious artefact that can be introduced by confining soils is the long-term release of nitrogen as a result of soil disturbance. While this is especially a problem if soils are sieved, homogenized and then reconstituted (Johnson *et al.* 1995), it is also a potential artefact with intact soil cores, as the release of

lysimeters, and likewise Brown *et al.* (1974) describe a 203 cm x 152 cm x 150 cm deep block as a monolith. However, use of the term *monolith* often suggests an undisturbed cylindrical soil sample of a size that can be transported, bounded by an impermeable material. To avoid confusion over questions regarding shape, size, and degree of soil disturbance, the term "monolith" will be avoided in this review and instead soil samples will be described as being confined or unconfined, and disturbed or undisturbed (i.e. soil horizons reconstituted inside impermeable barrier, or soil bounded with minimum of disturbance).

nitrogen may obscure treatment effects. Similarly, repacking disturbed soils can result in unrealistic water movement through confined lysimeter systems (Montgomery *et al.* 1987).

2.3.1 Undisturbed Soil: Confined, undisturbed soils were first used in lysimeter systems at Rothamsted, U.K., in 1870²² (Lawes *et al.* 1881, Kohnke *et al.* 1940), and a variety of early designs are individually summarized in Kohnke *et al.* (1940). A great range in dimensions, construction materials and applications of isolated soils have been used since. Within Scandinavian forestry experiments it is common to place undisturbed soil cores in cylinders with funnels attached to the bottoms, and to put these back in the boles from which they came, often with a collection vessel in a cavity directly below the confined soil sample. This simple arrangement has been used by Bergkvist (1987) with undisturbed soil cores of two surface areas (660 cm² x 5 and 15 cm long, and 284 cm² x 35 and 55 cm long) in plexiglass tubes with funnels on the bottoms, based upon a design by Tyler (1981). Bringmark (1980) also used this type of lysimeter system (based on a design by Mayer 1971), but only placed the litter layer and associated mosses and lichens in a 314-cm² funnel over a plastic net. Again, the collection bottle was located in a cavity beneath the lysimeter. Alternatively, Rosén (1986) initially used a confined soil core lysimeter system technique beneath both litter and mineral horizons similar to that of Bringmark (1980), but later modified the collection system so that water from the 314-cm² PVC pipes over polythene funnels flowed to IO-L polythene collection vessels housed in an adjacent trench with a lid over it (Rosen and Lundmark-Thelin 1987). This type of system was also used by Nys *et al.* (1990) who enclosed undisturbed soil cores in cylinders (707 cm² x 35 and 60 cm deep), but with a nylon mesh overlying a quartz sand drainage bed in the bottom, leading via an outlet tube to a collection vessel in a pit. In a shallower design, Titus and Malcolm (1992) placed excised forest floor litter layers in 881-cm² rigid polystyrene trays over a mesh so that soil solution would drain by gravity into nearby darkened 25-L collection vessels.

Once obtained, confined soil samples can also be moved to more convenient locations. Overrein (1968) gathered 707-cm² x 48-cm deep samples encased in fibreglass tubes with a layer of porous inert pebbles in the bottom and set them up in two rows along a trench to facilitate soil solution collection. Likewise, Belford (1979) also moved undisturbed cores of 5026 cm² surface area x 135 cm deep in fibreglass cases to a central location. Cameron *et al.* (1992) collected undisturbed cores in steel plate cylinders of 5026 cm² surface area x 120 cm deep and moved them to a laboratory site. Small soil samples can be more easily returned to the more controlled environment of a greenhouse or laboratory. For example, Ausmus and O'Neill (1978) wrapped intact forest floor cores (5 cm diameter x 5 cm deep) in shrinkable polyvinyl chloride sheeting and leached them weekly in a laboratory microcosm experiment. Bengtson and Voigt (1962) used 324-cm² x 30.5-cm length pieces of stove-pipe with metal funnels soldered to the bottom in a greenhouse study in which the lysimeter systems were planted with seedlings. De Walle *et al.* (1985) placed frozen forest floor horizons in 960-cm² plastic trays for subsequent use in laboratory leaching studies. Where transparent materials such as plexiglass are used to confine soils, and where lysimeter systems are not buried again but are moved to a greenhouse or laboratory, blocking light (*e.g.* by wrapping the system in aluminum foil) to prevent algal growth is recommended (Powelson and Gerba 1994).

If the required volume of soil is too large to move, a block may be isolated by trenching and building watertight walls around it *in situ*, so long as the underlying horizon is impermeable. For example, Malcolm and Cuttle (1983) trenched around three sides of a 2.25-m² (1.5 m x 1.5 m) block of peat (the fourth side being the side wall of a drainage ditch) and used plastic sheeting to isolate it from the surrounding peat to a depth of 0.8 m. A gutter was pushed into the fourth side at the bottom of the drainage ditch which led to collection bottles. A roof and front cover were added to keep rainfall from mixing with the soil solution. On a larger scale, Law (1956) built a concrete wall around part of a small dense plantation of Sitka spruce. Remezov (1958) trenched 30 to 40 cm down to underlying impermeable clay loam around a 35-m² (5-m x 7-m) plot and built a brick wall around the plot, coated with concrete on the outside. Drainage was to a collection vessel in a second pit, and the lysimeter

²² These "drain gauges" still function, and provide valuable insights into long-term nutrient leaching (*e.g.* Addiscott 1988).

system was big enough to contain six oak (15 to 16 cm dbh²³, 16 m high) and four Norway maple trees (6 to 12 cm dbh, 10 m high). More recently, Calder (1976) created an 84-m² "natural" lysimeter system enclosing 26 *Picea abies* trees in a stand in Hafren Forest, Wales. Part of the stand was isolated using drainage ditches in which an impermeable wall of corrugated iron supported by concrete was constructed, with the underlying clay forming a naturally sealed bottom. Polythene sheets have been used to isolate large plots in agricultural fields with impermeable subsoil (Catt *et al.* 1992 in Webster *et al.* 1993), and are sometimes called "[field] lysimeters" (Webster *et al.* 1993). The use of resin sealants has not been successful, but polythene sheets have been used in hydrological studies to encase 100-m² blocks of soil (Kitching and Bridge 1974). Steenhuis and Muck (1988) used berms to prevent overland flow entering a 2507-m² (23 m x 109 m) field plot on a slope that was isolated from the surrounding soil by a plastic barrier. Backfilled "interceptor drains" have been used to isolate 1-ha "lysimeter plots" in agricultural fields overlying clay shales of low hydraulic conductivity in which mole drains were used to collect leachate (Scholefield *et al.* 1993). As with large lysimeter systems containing disturbed soil, soil moisture conditions inside and outside lysimeter systems may not be comparable. In hydrological studies wells and submersible pumps have been installed within large lysimeter systems to keep ground-water levels the same both inside and outside the installations to minimize differences in moisture conditions (Kitching and Bridge 1974).

On a larger scale, geographic relief can define boundaries so that complete watersheds can be considered to be lysimeter systems. Larger watershed studies include Hubbard Brook in New Hampshire (Likens *et al.* 1977, Likens and Bormann 1995), three watersheds in Sweden (Rosen 1982), and the Coweeta Hydrological Laboratory in North Carolina (Gaskin *et al.* 1983). Although the use of natural lysimeter systems has advantages in that their scale integrates spatial variation, the required geological properties (impermeable base) are exacting and difficult to verify. However, Homung *et al.* (1986) used a 4.1-ha, 6.2-ha, and six 2-ha catchments in Plynlimon, Beddgelert and Kershope, U.K. to monitor nutrient outputs. They compared measured stream discharge with modelled

outputs and concluded that there were no leaks out the bottoms of their large catchment or watershed lysimeter systems.

A range of dimensions of zero tension lysimeter systems using confined, undisturbed soils is presented in Table 5.

2.3.2 Disturbed Soil: In some cases soil profiles are reconstructed within walled containers. Although reconstructed profiles can be criticized as being unrepresentative of natural conditions (*see* Flodquist 1936, Shaykewich 1970, Cassel *et al.* 1974, Montgomery *et al.* 1987, Johnson *et al.* 1995), they can be very useful under specific circumstances. For example, Sundaram *et al.* (1985) repacked soil horizons in 7.8-cm² x 30-cm deep PVC tubes with a protective layer of Teflon FEP® on vinyl backing applied to the interior to prevent adsorption of materials by the PVC. A metal screen overlain by a mat of glass wool was attached to the bottom of the tube. The fate of added ¹⁴C-mexacarbate insecticide was then monitored. Upchurch *et al.* (1973) used a 1648-cm² x 152.5-cm deep stainless steel tank filled with a 56-cm deep drainage bed of pea-gravel in the bottom, overlain with 5 cm of sand, and then crushed and mixed soil horizons and tamped them within the tank to the same bulk density as in the field. The lysimeter systems were placed in the soil in pits to examine the pedological role of the exchange complex. In a similar design, Bormann *et al.* (1993) constructed large pits (2.5 m x 2.5 m x 1.5 m deep; 7.5 m x 7.5 m x 1.5 m deep), lined the sides with an impermeable reinforced membrane (Hylapon, DuPont), installed bottom drains for leachate collection, and placed a 15-cm layer of stone (1.9-cm to 3.8-cm diameter) in the bottom before backfilling with screened sand of known origin and chemistry. These Hubbard Brook "sandboxes" were then used for detailed mass-balance studies. Jones *et al.* (1974) constructed lysimeter systems by filling 1932-cm² x 559-cm deep galvanized cans painted with black "rustoleum" with two screened horizons of soil. King *et al.* (1977) used soil mixed with sewage sludge and/or landfill refuse in 6362-cm² x 124-cm deep lysimeter systems to determine the feasibility of utilizing agricultural land for waste disposal.

Some larger lysimeter systems using confined, disturbed soils have been maintained for over 50 years (Jürgens-Gschwind and Jung 1979), but these earlier

²³ Diameter at breast height (1.3 m).

installations will not be dealt with, as they were adequately reviewed by Kohnke *et al.* (1940) as 'fill-in' lysimeter systems. However, large lysimeter systems have also been built post-1940. For example, a major installation was constructed by the Provincial Waterworks of North Holland (Minderman and Leeftang 1968) with individual lysimeter systems covering an area of 625 m² each x 2.25 m deep with free drainage from bottoms, and were planted in 1940 and 1941. In dry periods the drainage pipes emptied and air could penetrate the soil from below, so valves were therefore added in 1947 to prevent drains from emptying completely. This ensured that the minimum water level in the lysimeter systems was the top of the gravel drainage bed in the bottom, which underlay the soil. However, Patric (1961) demonstrated with the San Dimas lysimeter systems in California that trees did not grow as well in these confined lysimeter systems as in adjacent pits with no confining walls filled with the same soil, thus clearly demonstrating the limitations of confined lysimeter systems. This same effect has been observed in the Castricum lysimeter systems in the Netherlands (Tollenaar and Ryckborst 1975). Other recent lysimeter systems of this type include ones of 78.5 m² x 2.1 m deep in Sellenburen, Switzerland (Kappeli and Schulin 1988). These were built in 1970 of concrete, with a gravel layer overlain with 1.5 m of soil and planted with *Populus canadensis*, *Alnus incana* or grass. Much smaller lysimeter systems 9 m² in area and with a volume of 13.5 m³ were also built in Russia, and were similarly planted with trees (Vinnik and Bolyshev 1972). A range of zero tension lysimeter systems using confined, disturbed soil is presented in Table 5.

2.4 Collection Vessels and Sample Retrieval

All that is required to transport soil solution from samplers in unconfined soil to collection vessels in most zero tension lysimeter systems is lengths of pipe of adequate diameter laid with a slight incline to allow for unimpeded soil solution movement by gravity. Collection vessels can be located in pits or trenches that may be covered (Parizek and Lane 1970, Ranger *et al.* 1993) or open (Titus and Malcolm 1992). Closed pits and trenches offer the advantage that the soil temperature will create a cooler, dark environment that will help limit microbial growth. If pits are open, collection vessels should be darkened (*e.g.* Sollins and McCorison 1981, Titus and Malcolm 1992). In either

case, microbial inhibitors such as mercuric iodide (Laukajty 1968), mercuric chloride (Marvin *et al.* 1972), phenyl mercury acetate (Duke and Haise 1973, Montgomery *et al.* 1987), sulphuric acid and sodium thiosulphate (Stollar 1990) can also be added to the vessel to prevent microbial growth, although consideration must be given to health and environmental issues when collecting, analyzing and disposing of the soil solution. Other preservatives such as nitric acid, hydrochloric acid and sodium hydroxide can be used to prevent salt formation with organic bases or volatile compounds, or to inhibit oxidation (Stollar 1990). If a preservative is to be used, its lack of interference with planned chemical analyses must first be ascertained. For example, Sollins and McCorison (1981) found that preservatives interfered with nitrate analyses at the low concentrations found in the forest watersheds they were studying, although 1 N H₂SO₄ could be added to give a pH of 3 when vessels were emptied, thus retarding microbial activity and minimizing ammonium volatilization.

A small diameter hole in the lid of the collection vessel will allow air to escape while soil solution flows into the vessel. However, in soils with a high water table the access pit can fill with water and the collection vessels can float, which prevents soil solution flow. Furthermore, the air-vent hole can allow water from the pit to contaminate the leachate. These conditions can be prevented by weighing the collection vessel down with heavy stones or bricks, using an air-tight lid and connection to the soil solution drainage pipe, and using an air-vent tube that runs from the collection vessel lid to a secure fastening above the soil surface to allow displaced air to escape as soil solution flows in. Alternatively, the pit can be lined with water-tight walls through which the drainage tubes lead from the samplers to collection vessels which are located within this caisson²⁴ (*e.g.* Schmidt and Clements 1978, Merkel *et al.* 1982) which can be constructed of concrete (Vaughn and Landry 1978) or steel (Aulenbach and Clesceri 1980). The caisson must be secure enough that it cannot float up out of the soil at times of high water tables.

Samples are easily removed from collection vessels which are located in open pits and trenches. However,

²⁴ "[A] large water-tight case used in laying foundations under water" (Fowler and Fowler 1956).

Table 5. Sizes of soil solution samplers in zero tension lysimeter system designs' for sampling confined soil.

undisturbed, confined soil in zero tension design: soil encased over base, and may be movable

Area	Dimension	Material	Reference
20 cm ²	5 cm diameter x 5 cm deep	shrinkable PVC around intact soil core	Ausmus and O'Neill (1978)
79 cm ²	10 cm diameter x 25 cm deep	plexiglass tube	Hempel <i>et al.</i> (1995)
82 cm ²	10.2 cm diameter x 122 cm deep	heat shrinkable insulation Alpha FTE 220 tubing	Mielke (1973)
95 cm ²	11 cm diameter x 20 to 40 cm deep	plexiglass tube'	Insam and Palojarvi (1995)
284 cm ²	19 cm diameter x 35 and 55 cm deep	plexiglass tube over funnel	Bergkvist (1987)
314 cm ²	20 cm diameter	plastic net over funnel	Bringmark (1980)
314 cm ²	20 cm diameter	PVC tube over polythene funnels	Rosen (1986), Rosén and Lundmark-Thelin (1987)
324 cm ²	20.3 cm diameter x 30.5 cm deep	stove-pipe over metal funnel	Bengtson and Voigt (1962)
452 cm ²	24 cm diameter x 3 cm lip	PVC funnel with lip above PVC mesh	Mayer (1971)
660 cm ²	29 cm diameter x 15 cm deep	plexiglass tube over funnel	Tyler (1981)
660 cm ²	29 cm diameter x 5 and 15 cm deep	plexiglass tube over funnel	Bergkvist (1987)
661 cm ²	29.2 cm diameter x variable length	plexiglass tube over polyethylene funnel	Rasmussen <i>et al.</i> (1986)
707 cm ²	30 cm diameter x 35 and 60 cm deep	nylon mesh overlying quartz sand	Nys <i>et al.</i> (1990)
707 cm ²	30 cm diameter x 48 cm deep	fibreglass tubes; porous inert pebbles for drainage	Overrein (1968)
881 cm ²	23.5 cm x 37.5 cm x 5.5 cm deep	rigid polystyrene trays with mesh drainage bed	Titus and Malcolm (1992)
960 cm ²	24 cm x 40 cm	plastic tray	DeWalle <i>et al.</i> (1985)
5026 cm ²	80 cm diameter x 120 cm deep	steel plate	Cameron <i>et al.</i> (1992)'
5026 cm ²	80 cm diameter x 135 cm deep	fibreglass cases	Belford (1979)
10 800 cm ²	90 cm x 120 cm x 12 cm deep	PVC tray	Vance and David (1991)
12 000 cm ²	100 cm x 120 cm x 12 cm deep	PVC tray	David <i>et al.</i> (1989), Vance and David (1992)
28 000 cm ²	120 cm x 240 cm	stainless steel tray	Rascher <i>et al.</i> (1987)

undisturbed, confined soil in zero tension design: *encased, but with no base and therefore non-movable (includes catchments and watersheds)*

Area	Dimension	Material	Reference
2.25 m ²	1.5 m x 1.5 m	plastic sheeting around block of peat	Malcolm and Cuttle (1983)
35 m ²	5 m x 7 m	30-40 cm brick/concrete wall over clay loam	Remezov (1958)
84 m ²		corrugated iron/concrete wall over clay	Calder (1976)
100 m ²		polythene sheet	Kitching and Bridge (1974)
2507 m ²	23 m x 109 m	plastic barrier, and berm	Steenhuis and Muck (1988)
1 ha		back-filled ditches over clay	Scholefield <i>et al.</i> (1993)
2 ha		catchment at Kershope, U.K.	Homung <i>et al.</i> (1986)
4.1 ha		catchment at Plynlimon, U.K.	Hornung <i>et al.</i> (1986)
6.2 ha		catchment at Beddgelert	Hornung <i>et al.</i> (1986)
12-43 ha		catchments at Hubbard Brook	Likens and Bormann (1995)
40-150 ha		catchments in Sweden	Rosén (1982, 1984)
		catchments at Coweeta Hydrological Laboratory	Gaskin <i>et al.</i> (1983)

disturbed, confined ~~soil~~ in zero tension design

Area	Dimension	Material	Reference
19.6 cm ²	5 cm diameter x 100 cm deep	clear plexiglass, wrapped in aluminum foil	Powelson and Gerba (1994)
24.6 cm ²	5.6 cm diameter x 30 cm deep	Teflon FEPC+membrane over PVC tube; metal screen /glass wool bottom	Sundaram <i>et al.</i> (1985)
177 cm ²	15 cm diameter x 53 cm deep	PVC tube with sand/gravel drainage bed	Smith <i>et al.</i> (1993)
1648 cm ²	40.6 cm x 40.6 cm x 152.5 cm deep	stainless steel tank with sand/gravel drainage bed	Upchurch <i>et al.</i> (1973)
1932 cm ²	49.6 cm diameter x 559 cm deep	galvanized cans painted with black "rustoleum"	Jones <i>et al.</i> (1974)
6362 cm ²	90 cm diameter x 124 cm deep	un-specified lysimeter materials	King <i>et al.</i> (1977)
7854 cm ²	1 m diameter x 1 m deep	high density polyethylene with sloping bottom	Nilsen (1995)
6.25 m ²	2.5 m x 2.5 m x 1.5 m deep	Hypalon® membrane (DuPont polymer) liner in pit	Bormann <i>et al.</i> (1993)
9 m ²			Vinnik and Bolyshev (1972)
20.5 m ²	3.2 m x 6.4 m x 1.83 m deep	concrete walls and floor	Patric (1961)
56 m ²	7.5 m x 7.5 m x 1.5 m deep	Hypalon® membrane (W o n t polymer) liner in pit	Bormann <i>et al.</i> (1993)
78.5 m ²	10 m diameter x 2.1 m deep		Kappeli and Schulin (1988)
625 m ²	25 m x 25 m x 2.25 m deep	tanks with free drainage from bottom	Minderman and Leeftang (1968)

¹ Not all references listed in Tables 1-3 are included, as dimensions are not always reported.

² Also "artificial roots" inserted horizontally into tube for tension lysimetry.

³ Perforated pipe in bottom to collect "fast-drainage" water; porous plastic tension tubes in bottom to collect "slow-drainage" water.

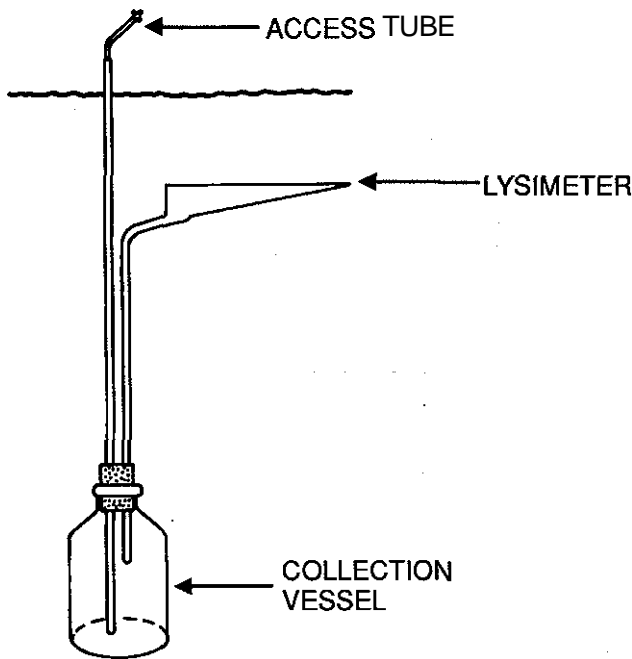


Figure 4. Typical installation method for sample retrieval from buried collection vessel for zero tension lysimeter system (after Shilova 1955).

the pit or trench can be filled in if access tubes are included that extend from the soil surface to the bottom of the collection vessel (Shilova 1955, Laukajtys 1968). A second venting tube will allow air to pass into the collection vessel as samples are withdrawn from the access tube under vacuum (Fig. 4). The venting tube can be short and terminate in the soil itself in light, sandy soils or gravels, or can extend to the soil surface in heavy or wet soils (Laukajtys 1968). However, care must be taken that access tubes are placed in the bottom of collection vessels in such a manner that dead space and resultant sample carry-over are minimized. If collection vessels are buried deep enough that samples will not freeze (e.g. Laukajtys 1968) then the sampling season can be extended through the winter months.

The same types of collection systems used with unconfined soils can also be used for confined soils. For example, in Scandinavia small soil cores are often placed in tubes with funnels on the bottom and are replaced back in the holes from which they came. The collection vessels can be placed in cavities beneath the encased cores, or can be in adjacent pits (e.g. Rosen 1986). In another design, Thompson and Scharf (1994) placed a cylindrical collection vessel with an air intake and sample collection tube beneath an undisturbed core (10-cm diameter), and collected the leachate samples with a vacuum trap system.

Where large volumes of water flow have occurred, sample splitters (Cuttle 1979) have been used to prevent collection vessels from overflowing (Malcolm and Cuttle 1983, Hornung *et al.* 1986). Tipping bucket recorders have also been placed in outlet lines so that the rate of volume flow of leachate can be automatically recorded (Roose and des Tureaux 1970). Alternatively, an apparatus can be added to collection vessels that siphons out all but a small amount of soil solution every time the vessels fills, and automatically records each siphoning event (Hazlett *et al.* 1990). Although the remaining solution can be analyzed for nutrients, it is not a proportionally split sample (cf. Cuttle 1979) and therefore may not be truly representative of all the solution that has passed through the lysimeter system since the previous sampling.

Consideration must also be given to the diameter and the positioning of the outlet pipes. If the pipe is too narrow and becomes filled with water then a hanging water column can develop, creating a small amount of tension. This is likely to take place especially if the sampler is placed under wet, fine textured mineral soils.

Once collected, samples should generally be refrigerated and analyzed immediately, depending on the analyses being carried out, as microbial transformations can take place. Harr and Fredriksen (1988) found that storing stream water samples in a cool location in the field for 3 weeks reduced $\text{NO}_3\text{-N}$ concentration by 17% as compared to samples analyzed within 2 days of collection. A table of recommended sample bottle materials, preservatives and maximum holding times for a wide range of organic and inorganic substances can be found in Stollar (1990). As an alternative to collecting water samples *per se*, some workers have used ion exchange resins to capture cations and anions as the soil

solution flows through the resins (*e.g.* Sakadevan *et al.* 1993). The resins are then removed and returned to the laboratory for extraction and analysis at the end of collection periods.

Installation of lysimeter systems can cause soil disturbance, and a stabilization (or equilibration) period may be required so that the soil can return to pre-disturbance conditions, and so that ions in the soil solution can saturate any exchange sites on the materials used to construct the lysimeter systems. Rascher *et al.* (1987) confined forest humus in large 1.2-m x 2.4-m stainless steel trays in October and therefore initiated sample collection in the spring after a 5-month stabilization period. Vance and David (1991), using similar large (90 x 120 cm) PVC trays, began biweekly sample collection in June, but discarded samples for 4 months until September before initiating chemical analysis of the soil solution.

2.5 Recommendations

Zero tension lysimeter systems generally sample a different component of the soil solution than tension lysimeter **systems**. By definition, zero tension lysimeter systems are required to sample rapidly moving soil solution, especially preferential flow. In forestry applications, zero tension lysimeter systems should generally be used at least under the litter layer and should be seen as complementary rather than **as** an alternative to the use of tension lysimeter systems in the field.

Care should be taken to ensure that all materials used in the construction of lysimeter systems do not adversely affect or contaminate soil solution samples. Although **cleaning** procedures for zero tension lysimeter systems have not been widely reported, it would seem prudent to wash all components thoroughly with dilute acid and then deionized water to remove dust and contaminants before installation. Although not well defined for zero tension lysimetry, allowing for a stabilization period during which soil solution samples are collected but then discarded would also seem prudent. This would allow the soil to return to pre-disturbance conditions, and ions in the soil solution to saturate any exchange sites on the materials used to construct the lysimeter systems.

With **unconfined** zero tension lysimeter systems the surface area of the sampler should be **as large as** local conditions permit so that soil solution is collected from as representative a portion of the soil as possible. Collection efficiency of these lysimeters systems also generally increases with increasing sampler surface area. However, **bypass** flow can still occur. Pressing a lip into an access tunnel ceiling may help reduce bypass flow in some soils, although use of a drainage bed or mesh pressed against the soil should also be beneficial. Collection efficiencies can vary from **5** to 100%, depending upon the design, size, and soil being sampled. Because of the occurrence of bypass flow around these lysimeters, it cannot be assumed that multiplying soil solution concentrations by sample flow rates **will** necessarily give accurate estimates of nutrient fluxes. Water flow models should be used with nutrient concentration data to estimate nutrient fluxes.

Under special circumstances, **confining** the soil and leaving it in the field or returning it to a laboratory or greenhouse may be warranted. **Confined** zero tension lysimeter systems eliminate bypass flow problems, but may **introduce** other sampling artefacts. Techniques that minimize disturbance during removal of soil samples must be used. Poor contact between container walls and the soil may allow for rapid water movement down container sides, and **this** can be reduced by **filling** the space with expanding foams or hardening agents, or by sampling only the middle of the bounded soil. In the absence of application of tension at the base of confined soil, ponding of water may occur, creating unrealistic soil moisture conditions. Increasing the size of confined soil even up to a watershed level may not improve the reliability of samples if there is leakage out the bottom of the system. The use of disturbed soils in confined lysimeter systems for nutrient cycling studies is to be discouraged, **as** increased nitrogen mineralization **as** a result of sieving and soil preparation can persist over long periods, and can be of a large enough **magnitude** to mask treatment effects.

Collection vessels should be darkened and preferably shaded or buried in the soil to discourage algal and microbial activity through elimination of light and reduction of temperature. Microbial inhibitors can be used, but these should be tested first to ensure that they will not interfere with sample analysis. Burial of collection vessels has the added advantage that soil solution samples can be obtained for a longer period in

northern climates. Sample splitters can be used to reduce sample volume if water flow rates are high.

3. TENSION LYSIMETER SYSTEMS

3.1 Introduction

The major innovation in lysimetry since the review of Kohnke *et al.* (1940) has been the advent of tension lysimetry, which developed because of unease with the impedance to movement of soil water through zero tension lysimeter systems caused by the soil-air interface. Briggs and McCall (1904) first extracted soil water under tension²⁵ in the field by burying an unglazed porcelain tube (Pasteur-Chamberland filter tube) and connecting it with lead tubing to an evacuated 2-L bottle. They used this apparatus to collect soil water samples almost daily for a 6-week period, and analyzed their samples for electrical conductivity. Cole (1932) then used an Alundum® filter cone attached to a (3.4-cm diameter x 25.4-cm long glass tube) to sample water in mud at the bottom of lakes for determination of dissolved oxygen content. However, no tension was applied, and water passively filled the instrument under pressure that was dependent on the water depth as air was displaced through a long glass air vent tube. Foreshadowing the wider use of ceramic porous cups as soil solution samplers, Krügel *et al.* (1935) used "Berkefeld's Liliput filter-candles" made of "silicious marl" in the laboratory to sample a suspension of soil for phosphoric acid determination, and Kapp (1937) sampled submerged soil solutions in the field. Wallihan (1940) then used porous ceramic cups under constant tension in the laboratory to draw soil solution from a confined soil core in a tube, although this was done to make the moisture conditions in the soil sample more realistic rather than to sample the soil solution. Richards (1941) reversed tensions and forced the soil solution out by application of gas pressure to a closed cylinder with a permeable cellophane membrane over a brass screen. The work of Wallihan (1940) was taken further by Colman (1946) who used an 81-cm² (10-cm diameter)

"porous fired clay plate" sealed to the rim of a glass funnel and pressed against the bottom of a 182-cm² (15.24-cm diameter x 213-cm deep) soil column to apply tensions equivalent to 0, 50, 55 and 160 cm of water using a partially evacuated carboy or a hanging water column to maintain the different tensions. Krone *et al.* (1952) then tested porous cups and tubes in the laboratory, in preparation for monitoring effluent in the field. Fifty-four years after the first field sampling by Briggs and McCall (1904), Brooks *et al.* (1958) and Cole (1958) produced tension lysimeter systems for collecting soil water in the field, the former using porous cups inserted horizontally in disturbed, confined soil, and the latter by placing an Alundum® disk²⁶ of 616 cm² (28 cm diameter) against the roof of a tunnel with a 110-cm hanging water column to produce a tension to draw soil solution sample into a collection vessel (Fig. 5). Wagner (1962) then glued ceramic cups of 4.8 cm o.d. x 6.35 cm length to plastic pipe which was inserted in a vertical augered hole, and a tension applied by evacuating the lysimeter system with a hand-pump (Fig. 6).

By this time the major steps in the development of tension soil solution samplers (*i.e.* plates, cups) were completed, and new developments over the past 35 years

²⁶ Alundum® is a "porous media... composed of fused alumina grains held together by a porcelainic bond" (Norton Co., pers. comm.), or a "porous alumina oxide resembling corundum in hardness. It is manufactured by fusing alumina in an electric furnace, and is used chiefly as an abrasive and as a refractive" (Morrison 1983). It consists "primarily of aluminum silicate/aluminum oxide with Fe, K, Li and Gt as potential contaminants" as determined by energy-dispersive X-ray fluorescence analysis (Neary and Tomassini 1985) in the following proportions: 82.0% Al₂O₃, 13.0% SiO₂, 2.5% TiO₂, 1.0% Fe₂O₃, 0.8% CaO, 0.5% MgO, 0.2% Na₂O, and trace MnO (Norton Co., pers. comm.). Alundum® is a trademark of Norton Company who supplied the disks used in the original Alundum® tension lysimeter (Cole 1958). Alundum® disks are available from Norton Company, Worcester, MA 01615-0008, tel. (508) 795-5000.

²⁵ The tensions applied are reported in various units in lysimetry literature, depending on the publication medium and the country in which the work was done. Reporting tensions in SI units as kPa is recommended by the Canadian Society of Soil Science, and as Pa or MPa by the Soil Science Society of America. A table of conversions to SI units is presented in Appendix 3.

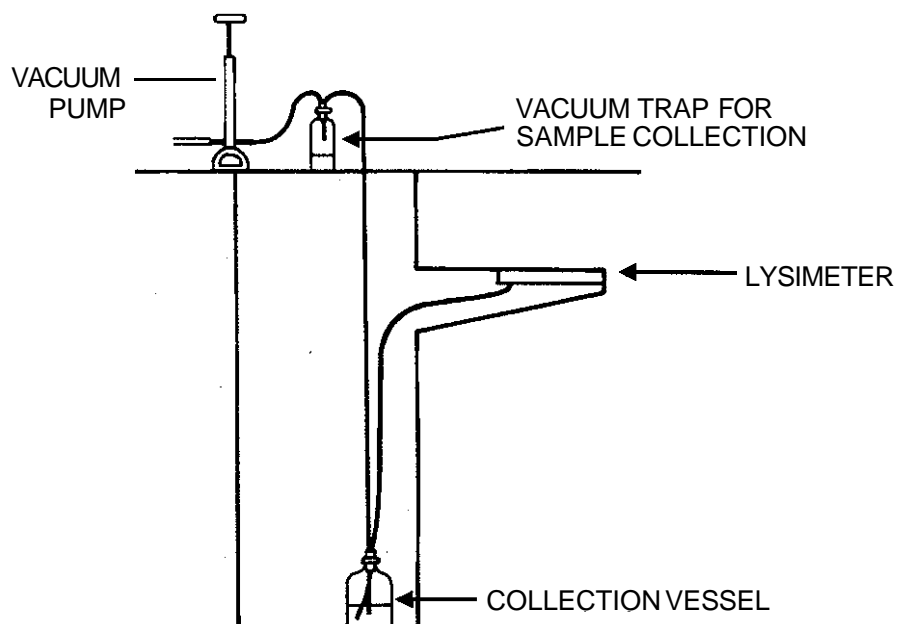


Figure 5 Typical installation method for porous plate tension solution sampler installed in side of pit, with hanging water column to generate constant tension, and sample retrieval from buried collection vessel using vacuum trap (*after* Cole 1958).

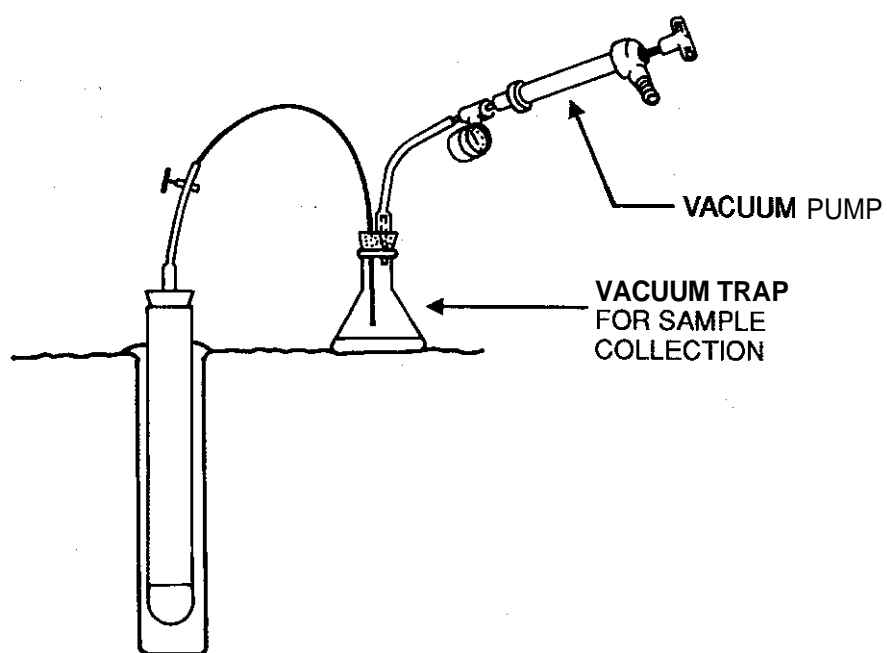


Figure 6 Typical installation method for porous cup tension solution sampler installed vertically from soil surface in augered hole (after Wagner 1962), with decreasing tension generating system and one-line sample retrieval using vacuum trap.

have consisted largely in choice of construction materials, pore diameter²⁷ (or size), dimensions of samplers, modifications of methods of applying tension, methods of retrieving samples from collection vessels, and applications.

A wide range of materials have been used to construct soil solution samplers for tension lysimeter systems (Table 6). Porous, hollow fibres made of cellulose-acetate (Jackson *et al.* 1976), non-cellulosic polymers (Levin and Jackson 1977), cellulose (Silkworth and Grigal 1981) and polysulfone²⁸ (Jones and Edwards 1993) have been used to extract the soil solution under tension. Porous cups have been made of Alundum® (Bottcher *et al.* 1984, Creasey and Dreiss 1985, 1988), ceramic²⁹ (Wagner 1962),

Carborundum®³⁰ (Krone *et al.* 1952), fitted glass" (MacLeod 1964, Chow 1977a, Long 1978, Bottcher *et al.* 1984, Starr 1985, Shepard *et al.* 1990, Roberts and Titus 1994, Fernandez *et al.* 1995), porcelain (Hetsch *et al.* 1979), polyethylene (Harris and Stone 1990), porous plastic (Hossner and Phillips 1973), nylon and PVC (Quin and Forsythe 1976), PVC (Merkel and Promper 1984), PVDF (polyvinylidene fluoride) or nylon (Grossmann *et al.* 1985) membrane with polyethylene support, PTFE³² (Zimmermann *et al.* 1978, Morrison

³⁰ Carborundum® is an abrasive, and is available in disks from 2.5 to 100 cm diameter, in a variety of thicknesses and porosities. It is a tradename of Carborundum Abrasives Co. North America, 6600 Walmore Rd., Niagara Falls, NY 14304; tel. 1 (800) 472-2200, FAX 1 (800) 542-0347.

³¹ To "fritter" is to "break into small fragments", to "frit" is "v.t. to fuse partially", and to "sinter" is "to heat a mixture of powdered metals to the melting-point of the metal in the mixture which has the lowest melting point, the melted metal binding together the harder particles [with a higher melting point]; to coalesce under heat without liquefaction" after the German "sinter" cf. English "cinder" (Macdonald 1972). Fritted glass can be made by melting glass beads in a mold (Nielsen and Phillips 1958, Chow 1977a) or by crushing Pyrex® to a powder, sieving it to give different grades of porosity, mixing it with a binding agent, creating disks under pressure in a mold, and then firing the disks (Coming 1993, pers. comm.). The term *sintered glass* is used synonymously by MacLeod (1964), Ripple and Day (1967), Marvin *et al.* (1972), and Starr (1985) for *fritted glass*.

³² PTFE, the usual abbreviation for polytetrafluoroethylene, was first marketed under the registered DuPont tradename of Teflon®PTFE (polytetrafluoroethylene). However, three other copolymers are also produced by DuPont: Teflon®PFA (perfluoroalkoxy), Teflon®FBP (fluorinated ethylene propylene, or tetrafluoroethylene hexafluoropropylene), and Tefzel®ETFE (ethylene tetrafluoroethylene). Unless explicitly stated to the contrary, authors who refer to Teflon® are usually referring to PTFE. Other companies also produce PTFE and its copolymers, so for the purposes of this review all Teflon^m samplers will be referred to by this generic abbreviation. PTFE is obtainable as rods that can be machined into cups from Fluorocarbon, Anaheim, CA (Zimmermann *et al.* 1978), or as completed lysimeters from Timco Mfg. Inc., P.O. Box 8, 851 Fifteenth St., Prairie du Sac, WI 53578, U.S.A.; tel. (608) 643-8534, FAX (608) 6434275. In Europe, PTFE cups are available from Prenart Equipment, ApS BUEN 14, 2000 Frederiksberg, Denmark. More information on Teflon^m can be obtained from DuPont de Nemours & Co., Inc., Specialty Polymers, P.O. Box 80713, Wilmington, DL 19880-0713, U.S.A.; tel. (302) 999-5080.

²⁷ Diameter assumes that pores are cylindrical in shape and have a circular cross-section, but pores are generally irregular in shape. The term pore size is often used synonymously for pore diameter", but will be avoided in the present review, as size is commonly associated with three-dimensional volume rather than cross-sectional area. Pore volume can become important in its own right under special circumstances, especially if the effects of soil solution resident time in the sampler material, or sample carry-over, are important.

²⁸ CHOS polymer; hollow, thin walled, semipermeable, flexible fibre tubing (150 mm long fibre x 2.5 mm diameter) sealed at one end with epoxy resin and attached at the other to 0.5 m of thin bore nylon tubing to which a suction was applied; fibre tube consists of dense inner layer (0.5-1.5 µm thick, <0.1 µm pores) surrounded by thicker (50-250 µm thick, 10 µm pore size) open celled spongy layer; MW rejection level of 100,000; commercially available as Diaflo hollow fibre tubing with macrosolute rejection levels of between 500 and 100,000 MW from Amicon Ltd., Laboratory Ultrafiltration Selection Guide, Upper Mill, Stonehouse, Gloucestershire, U.K.

²⁹ Wagner (1962) used porous ceramic cups manufactured by Soilmoisture Equipment Corp., who make only two kinds of ceramics: standard (or low flow) ceramics (M1) consisting of 56% SiO₂, 15% Al₂O₃, 12% MgO, and small amounts of Fe₂O₃, CaO, TiO₂, K₂O and Na₂O, and highflow ceramics (M2, M3) consisting of >90% alumina (Al₂O₃) and small amounts of SiO₂, Fe₂O₃ and TiO₂ (Soilmoisture Equipment Corp. 1992). Soilmoisture Equipment Corp. do not make porcelain cups, and recommend the use of highflow ceramics for nutrient work as there is less leaching/adsorption (Soilmoisture Equipment Corp., 1993 pen. comm.).

Table 6. Range of materials used in construction of soil solution samplers in tension lysimeter systems.

Type	Material	Reference
hollow fibres	cellulose	Silkworth and Grigal (1981)
	cellulose-acetate	Jackson <i>et al.</i> (1976)
	non-cellulosic fibre	Levin and Jackson (1977)
	polysulfone	Jones and Edwards (1993)
wicks	quartz-fibre'	Gee and Campbell (1990)
	plastic ²	Gee and Campbell (1990)
	glass fibre	Holder <i>et al.</i> (1991)
porous cups ³	Alundum®	Cole (1932), Creaser (1971), Bottcher <i>et al.</i> (1984), Creasey and Dreiss (1985,1988)
	Al ₂ O ₃ (sintered)	Grossmann <i>et al.</i> (1990)
	Carborundum®	Krone <i>et al.</i> (1952)
	ceramic	designs after Wagner (1962), Soilmoisture Equipment Corp. (1994)
	glass (fitted)	MacLeod (1964), Chow (1977a), Long (1978), Silkworth and Grigal (1981), Bottcher <i>et al.</i> (1984), Starr (1985)
	nickel (sintered)	Hädrich <i>et al.</i> (1977), Hetsch <i>et al.</i> (1979), Nemeth and Bittersohl (1981)
	nylon	Grossmann <i>et al.</i> (1985, 1990)
	nylon mesh ⁴	Quin and Forsythe (1976)
	plastic	Hossner and Phillips (1973), Cameron <i>et al.</i> (1992)
	polyethylene	Harris and Stone (1990)
	porcelain	Raulund-Rasmussen (1991), Rasmussen <i>et al.</i> (1986)
	PTFE ⁵	Zimmermann <i>et al.</i> (1978), Morrison (1982), Bottcher <i>et al.</i> (1984), Everett and McMillion (1985), Rasmussen <i>et al.</i> (1986), Creasey and Dreiss (1988), McGuire and Lowery (1992), McGuire <i>et al.</i> (1992), Beier and Hansen (1992), Magid <i>et al.</i> (1992)
	PVC membrane'	Merkel and Promper (1984)
	PVDF	Grossmann <i>et al.</i> (1985)
	stainless steel	McGuire and Lowery (1992), McGuire <i>et al.</i> (1992)
porous plates	acrylic copolymer	Driscoll <i>et al.</i> (1985)
	Alundum®	Cole (1958), Levett <i>et al.</i> (1985), Turner <i>et al.</i> (1985)
	Al ₂ O ₃ (sintered) ⁷	Mayer (1971), Hädrich <i>et al.</i> (1977), Bringmark (1980)
	ceramic	Haines <i>et al.</i> (1982), Shepard <i>et al.</i> (1990), Soilmoisture Equipment Corp. (1994)
	filter paper	Shaffer <i>et al.</i> (1979)
	glass (fritted)	Chow (1977a), Kirda <i>et al.</i> (1973), Shepard <i>et al.</i> (1990), Mahendrappa (1991), McGuire and Lowery (1992), McGuire <i>et al.</i> (1992), Roberts and Titus (1994), Johnson <i>et al.</i> (1995), Fernandez <i>et al.</i> (1995)

linear polyethylene	Cronan (1978)
polyamide membrane	Hantschel <i>et al.</i> (1994)
polyethylene sheet	Harris and Stone (1990)
nylon membrane*	Rambow and Lennartz (1993)
SiC ⁹ powder	Bourgeois and Lavkulich (1972a,b) ¹⁰ , Feller (1977) ¹¹
stainless steel	Gaber <i>et al.</i> (1995)

¹ Although used as "wick" tensiometer materials, these ~~data~~ are indicative of values that should be obtainable from "wick" lysimeters made of similar materials.

² Although used as "wick" tensiometer materials, these ~~data~~ are indicative of values that should be obtainable from "wick" lysimeters made of similar materials.

³ Includes "cones" and "candles", as well as "tubes" and membranes used to construct samplers in the general shape of a "cup".

⁴ Over perforated PVC.

⁵ Polytetrafluoroethylene, or Teflon[®].

⁶ Over porous polyethylene (PE).

⁷ SKA100FF "highly sintered ceramic material consisting of more than 99% Al₂O₃" ("eine hochgesinterte Keramik, die zu über 99% aus Al₂O₃ besteht"; Mayer 1971).

⁸ Over perforated PTFE.

⁹ Silicon carbide.

¹⁰ Over rigid disks of acrylic.

¹¹ Over rigid disks of plexiglass.

1982, Bottcher *et al.* 1984, Everett and McMillion 1985, Maitre *et al.* 1991, McGuire *et al.* 1992), sintered nickel³³ (Hadrich *et al.* 1977, Hetsch *et al.* 1979) and stainless steel (McGuire *et al.* 1992, Powelson *et al.* 1993). Porous cones have been made of Alundum®, but function much like porous cups (*e.g.* Creaser 1971). Porous plates have been made of Alundum® (Cole 1958, Levett *et al.* 1985), ceramic (Haines *et al.* 1982), fritted glass (Kirda *et al.* 1973, Chow 1977a, Shepard *et al.* 1990, McGuire *et al.* 1992, Roberts and Titus 1994, Johnson *et al.* 1995), acrylic copolymer (Driscoll *et al.* 1985), porous nylon membrane over a perforated PTFE plate (Rambow and Lennartz 1993), linear porous polyethylene (Cronan 1978), filter paper (Shaffer *et al.* 1979), and silicon carbide (SiC) powder over rigid disks of acrylic (Bourgeois and Lavkulich 1972a,b) or of plexiglass (Feller 1977).

The smallest samplers made to date have been constructed of hollow fibres (*e.g.* Jackson *et al.* 1976). Ceramic cups can range in outside diameter (o.d.) from 0.599 cm (*e.g.* SME³⁴ 652X01, 652X02) to 6.033 cm (*e.g.* SME 653x05). When elongated into candles, ceramic cups can be up to 25 cm long (*e.g.* SME 653x07). Likewise, polyethylene candles can be 1 cm in diameter but 7 cm long (Harris and Stone 1990). PVC filter membrane can be sandwiched between two pieces of porous polyethylene tubing of concentric diameters to form a filter tube of 2.5 cm diameter x 5 cm length positioned directly behind a cap to form a cup-like soil solution sampler with minimal interior dead space (Merkel and Promper 1984). This design was modified slightly by Grossmann *et al.* (1985), and nylon and PVDF (polyvinylidene fluoride) membranes over a porous polyethylene support have also been used to make sampling cups. Glass cups of 2.5 to 3.0 cm o.d. x 6 cm (Starr 1985), 2.5 cm o.d. x 20 cm (Silkworth and Grigal 1981) and 1.6 cm o.d. x 9.5 cm (Bottcher *et al.* 1984) have been used. PTFE cups of 5.1 cm o.d. x 6.4 cm (Bottcher *et al.* 1984) and 5.1 cm o.d. x 8 cm (Zimmermann *et al.* 1978) have been made, and with the rounded part of the cup removed, tubes of porous PTFE in Timco Mfg., Inc. lysimeter systems are 4.8 cm o.d.

and 14 cm long (Creasey and Dreiss 1985, 1988). Stainless steel tubes used have been 3.8 cm o.d. x 15.1 cm long (McGuire *et al.* 1992). Porous plates can range in diameter from 6 cm to 28 cm (Cole 1958, Dawson and Hrutford 1976, Chow 1977a, Cronan 1978).

Both the shape and dimensions of the sampler will have implications on the soil volume from which soil solution can be drawn (van der Ploeg and Beese 1977, Warrick and Amoozegar-Fard 1977, Warrick *et al.* 1980, Narasimhan and Dreiss 1986, Momson and Lowery 1990b). Hendrickx *et al.* (1994) compared the effect of tensiometer ceramic cup size on variability and concluded that larger cups gave more representative readings with less variability, and the same may be true of ceramic cups used as soil solution samplers. However, soil physical properties and difficulties encountered in installation (especially stoniness) may also influence choice of sampler size. A range of sampler sizes used in tension lysimetry under unconfined conditions are presented in Table 7.

As with zero tension lysimeter systems, care must be taken that no parts of the system, from samplers and tubing through to collection or storage vessels, leach or adsorb an unacceptable level of compounds that are under investigation. However, with tension lysimeter systems there is the additional concern that the materials used in soil solution samplers will define pore diameter, which places limitations on the passage of substances to be measured. However, pore diameter is often more important in determining the ability of the sampler to retain a tension during periods of soil drying than in causing a sample screening effect.

3.2 Pore Diameter Considerations

Parizek and Lane (1970) warned that the small pore diameter of ceramic samplers might screen out suspended solids and most soil bacteria. This was confirmed by Dazzo and Rothwell (1974) who demonstrated that faecal coliform bacteria do not move through 3- to 8-µm pore diameter ceramic (SME 1900-A sampler), and Bell (1974) who demonstrated that *E. coli* do not move through a 100-kPa SME porous ceramic cup. Quin and Forsythe (1976) thus designed a

³³ Glass is usually referred to as *fritted*, and metals as *sintered*.

³⁴ Soilmoisture Equipment Corp., P.O. Box 30025, Santa Barbara, CA 93105, U.S.A.; tel. (805) 964-3525, FAX (805) 683-2189.

PVC cup with 5-mm diameter holes that was covered with 2 layers of 1-mm mesh nylon curtain material for sampling microbiological samples under low tension (0.1-0.3 bar). In a comparison of soil solution samplers, Krejzl *et al.* (1994) found that high-flow ceramic and high-flow fitted glass recovered 6% and 85% of total coliforms, 2.2% and 69% of faecal coliforms, and 0% and 42% of faecal streptococcus, respectively, as compared to concentrations of these microbes in added sewage effluent³⁵ (the pore diameters of the samplers were not reported).

Similarly, choice of pore diameter will determine the passage of chemicals, especially larger molecular weight organic compounds. However, this is of most concern when fibres or other materials designed as screening filters for organic compounds are used, and molecular weight screening sizes of 500-2,000, >30,000, and >50,000 for hollow fibres have been used by Silkworth and Grigal (1981), Jackson *et al.* (1976) and Levin and Jackson (1977), respectively. The polysulfone hollow fibres with <0.1-µm pore diameters (100,000 MW rejection level) used by Jones and Edwards (1993) were found to screen very small amounts of total organic carbon from a test solution, but no screening took place when test solutions were pre-filtered through a 0.45-µm filter first. It has been suggested that nitrate screening can also take place with cellulose acetate fibres and porous ceramic (Levin and Jackson 1977 in Dorrance *et al.* 1991), but alternatively Nagpal (1982) suggested that the observed retention of nitrogen probably took place because of its diffusive transfer to an immobile solution phase rather than because of a screening effect.

Apart from potential screening effects, pore diameter will determine the degree to which a tension can be maintained in unsaturated soil, with tension being inversely proportional to pore diameter. While pore volume, average or range of pore diameter, and air entry tension (air entry value, or bubbling pressure³⁶) of porous materials are variously reported in the literature, the latter is one of the most important features of porous soil solution samplers. The maximum pore diameter must be of a small enough diameter that, under soil drying conditions, the surface tension of a meniscus in a pore is greater than the tension, generated within the lysimeter system for regular soil solution sampling. If the pores are too large, the internal tension in the lysimeter system may draw air from the soil into the evacuated system of the lysimeter system, thus releasing the tension and causing the lysimeter system to fail. Pore diameter, as well as thickness of the material, pore diameter distribution, total porosity and the tension applied, will also determine the rate of water flow (hydraulic conductivity) through the porous material. A fuller discussion of the implications of pore diameter on tension samplers can be found in Everett and McMillan (1985), Everett *et al.* (1988), Everett (1990), Dorrance *et al.* (1991), Grossmann and Udluft (1991) and Wilson *et al.* (1994a).

The physical limitations of the material used will determine pore diameter and thus air entry tensions (Table 8) and flow rates. For example, the smallest pores can generally be found in ceramics, with pore diameters of individual products ranging from 0.16 µm to 6.0 µm, with corresponding bubbling pressures of 48.3 kPa to 1516.8 kPa and flow rates (through 0.635 cm of ceramic at 101.35 kPa) of 180 to 0.015 mL hr⁻¹ cm⁻² (Soilmoisture Equipment Corp. 1994).

³⁵ Results from trials with fibreglass wick samplers also suggest that screening of bacteriophages can take place with these lysimeter systems, and that the air-water interface may retain and/or inactivate viruses during transport through unsaturated soil (Poletika *et al.* 1995).

³⁶ Air entry tension (air entry value, or bubbling pressure) is the pressure required to force air through a thoroughly wetted porous material. This measurement can be used to estimate pore diameter (*i.e.* pore size) in hydrophilic materials. Because of their differences in properties, pore diameters of hydrophilic (Alundum[®], ceramic, glass) materials are determined in water, and hydrophobic (PTFE, some plastics) materials in alcohol (methanol or ethanol) or with mercury. However, in practice the tension at which air can be drawn through water-filled pores determines the limitations of the use of a material in the field. The relationship between pore diameter and air entry tension can be determined from formulae presented in Appendix 4, and is illustrated in Figure 7.

Table 7. Sizes of soil solution samplers in tension lysimeter system designs' for sampling unconfined soil.

Material	Dimension	Reference
Fibres		
<i>hollow fibres</i>	variable sizes available 15 cm long x 2.5 mm diameter tube with 0.5 m nylon tube attached	Jackson <i>et al.</i> (1976), Levin and Jackson (1977), Silkworth and Grigal (1981) Jones and Edwards (1993)
Cups, cones and tubes		
<i>Alundum® cups/cones</i>	3.8 cm o.d. cone 4.4 cm diameter x 11.4 cm long cup 4.5 cm diameter cone	Creaser (1971) Bottcher <i>et al.</i> (1984) Cole (1932)
<i>aluminum oxide (sintered) cups</i>	2.5 cm o.d. x 6 cm long cup	Nemeth and Bittersohl (1981)
<i>ceramic cups</i>	0.599 cm (SME 652X01, 652X02) to 6.033 cm (SME 653x05) outside diameter (o.d.); “candles” (elongated ceramic cups) can be up to 25 cm long (SME 653x07)	Soilmoisture Equipment Corp. (1994)
<i>glass cups</i>	2.5-3.0 cm o.d. x 6 cm long 2.5 cm o.d. x 20 cm long 1.6 cm o.d. x 9.5 cm long 1.6 cm o.d. x 10 cm long”	Starr (1985) Silkworth and Grigal (1981) Bottcher et al. (1984) Long (1978)
<i>nickel cups</i>	4 cm long with 27 cm ² surface area	Hetsch <i>et al.</i> (1979)
<i>plastic filters</i>	1.2 cm diameter x 4 cm long	Hossner and Phillips (1973)
<i>polyethylene “candles”</i>	1 cm diameter x 7 cm long	Harris and Stone (1990)
<i>porcelain cups</i>	2 cm o.d. x 5 cm long (model P80 ³)	Rasmussen <i>et al.</i> (1986), Raulund-Rasmussen (1989, 1991)

<i>PTFE cups</i>	2.1 cm outside diameter (o.d.) x 5 cm long 4.8 cm o.d. x 14 cm long 5.1 cm o.d. x 6.4 cm long 5.1 cm o.d. x 8 cm long	Beier and Hansen (1992) Creasey and Dreiss (1988) <i>Bottcher et al.</i> (1984) <i>Zimmermann et al.</i> (1978)
<i>PVC membrane-PE "cups"</i>	2.5 cm diameter x 5 cm long	Merkel and Promper (1984)
<i>stainless steel tubes</i>	3.8 cm o.d. x 15.1 cm long	McGuire <i>et al.</i> (1992)

Plates

<i>acrylic copolymer plates⁴</i>	103.9 cm ² (11.5 cm diameter)	Driscoll <i>et al.</i> (1985)
<i>Alundum® plates</i>	176.7 cm ² (15 cm diameter) 615.8 cm ² (28 cm diameter)	Dawson and Hrutfiord (1976), Rambow and Lennartz (1993) Cole (1958)
<i>aluminum oxide (sintered) plates</i>	452 cm ² (24 cm diameter) 615.8 cm ² (28 cm diameter)	Bringmark (1980) Mayer (1971)
<i>ceramic plates</i>	2.0 to 599 cm ² (range of 1.6 to 27.6 cm diameter) 176.7 cm ² (15 cm diameter ceramic)	Soilmoisture Equipment Corp. (1994) Shepard <i>et al.</i> (1990)
<i>glass cloth "wick"</i>	900 cm ² (30 x 30 cm)	<i>Holder et al.</i> (1991)

Table 7. (Concl'd.)

Material	Dimension	Reference
<i>glass fritted) plates</i>	7.1 cm ² (3 cm diameter) 28.3 cm ² (6 cm diameter) 78.5 cm ² (10 cmdiameter)	McGuire <i>et al.</i> (1992) Shepard <i>et al.</i> (1990), Mahendrappa (1991), Roberts and Titus (1994), Fernandez <i>et al.</i> (1995), Titus <i>et al.</i> (submitted) Chow (1977a)
<i>polyethylene plates</i>	44.2 cm ² 7.5 cm diameter linear porous polyethylene	Cronan (1978)
<i>SiC powder on plates</i>	81.7 cm ² (10.2 cmdiameter) 400 cm ² (20 x 20 cm); also other sizes	Feller (1977) Bourgeois and Lavkulich (1972a)

¹ Not all references listed in Tables 1-3 and 8-10 are included, as dimensions are not always reported.

² Filter tube, with non-porous, rounded end.

³ Note that Hetsch *et al.* (1979) refer to these P80 cups as ceramic cups ("Keramische Kerzen"), as do Beier and Hansen (1992)

⁴ Over polypropylene base.

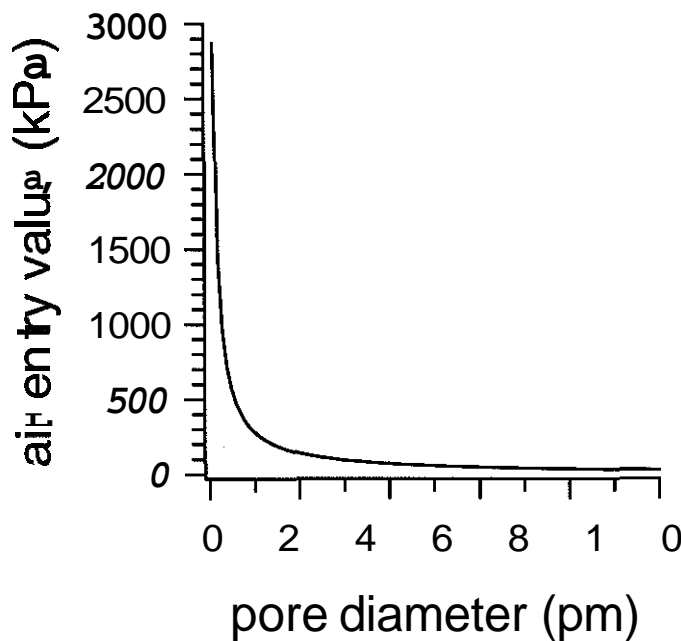
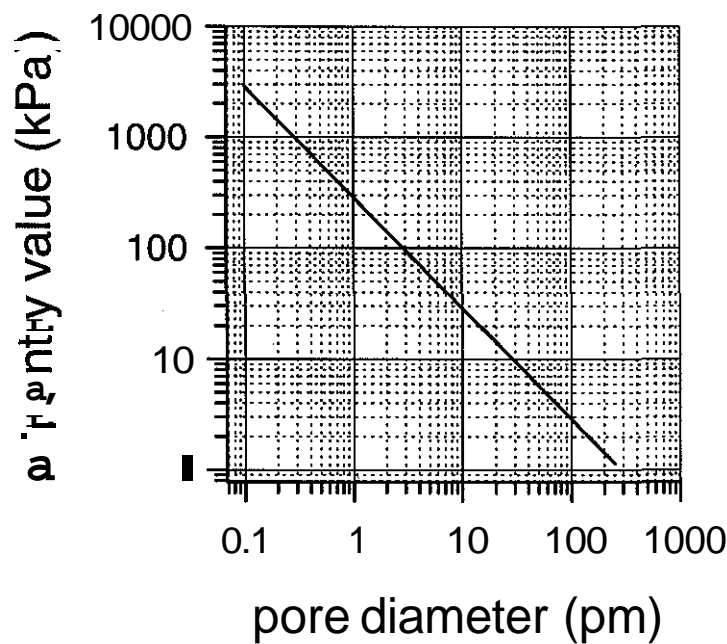


Figure 7 The theoretical relationship between pore diameter and the maximum tension that can be applied to porous soil solution samplers (air entry value) as derived from $D = 30\gamma/P$, where D = pore diameter (pm), γ = surface tension of water (= 72 dynes cm^{-1} at 20°C) and P = air entry value (mm Hg; then converted to kPa) (after Momson 1982, Everett and McMillion 1985, Soilmoisture Equipment Corp. 1992).

Table 8. Pore diameters and air entry tensions' of various porous soil solution samplers.

Material	Reaction with Water	Pore Diameter (μm)	Air Entry Tension (kPa)	Reference
polysulfonetube	n.a.	<0.1 ²	n.a.	Jones and Edwards (1993)
ceramic	hydrophilic	0.16 to 3.6.0	1517 to 48	Soilmoisture Equipment (1994)
ceramic (SME 15 bar)	hydrophilic	0.16	1517	Soilmoisture Equipment (1994)
non-cellulosic polymer	n.a.	0.3 ⁴	n.a.	Levin and Jackson (1977)
ceramic (SME B5M1)	hydrophilic	0.5	552	Soilmoisture Equipment (1994)
ceramic (P80)	hydrophilic	n.a.	392	Hetsch <i>et al.</i> (1979)
ceramic (low flow)	hydrophilic	n.a.	310-241	Everett and McMillion (1985), Everett <i>et al.</i> (1988)
fritted glass	hydrophilic	n.a. ⁵	250	Silkworth and Grigal (1981)
ceramic (high flow)	hydrophilic	n.a.	145-124	Everett and McMillion (1985), Everett <i>et al.</i> (1988)
acrylic copolymer ⁶	n.a.	0.2	n.a.	Driscoll <i>et al.</i> (1985)
PVDF ⁷	n.a.	0.22	345	Grossmann <i>et al.</i> (1985)
nylon membrane	hydrophilic*	0.45	210	Grossmann et al. (1985, 1990)
polyamide membrane	n.a.	0.45	n.a.	Hantschel <i>et al.</i> (1994)
sintered Al ₂ O ₃	hydrophilic	0.5	600 ⁹	Nemeth and Bittersohl (1981)
sintered Al ₂ O ₃ ¹⁰	hydrophilic	0.5	n.a.	Merkel <i>et al.</i> (1982)
aluminum oxide''	hydrophilic	0.6	n.a.	Mayer (1971)
aluminum oxide	hydrophilic	0.6	n.a.	Bringmark (1980)
ceramic (SME B3M1)	hydrophilic	0.8	483-317	Soilmoisture Equipment (1994)
ceramic (Czeratzki)	hydrophilic	0.8	n.a.	Czeratzki (1971a,b)
PVC filter membrane	n.a.	0.9	>300	Merkel and Prömper (1984)
fritted glass ¹²	hydrophilic	<1.0 to 200	n.a.	Schott Corp. (pers. comm.)
PTFE''	hydrophobic	1.0	n.a.	Momson (1982)
stainless steel	n.a.	1.0	n.a.	Powelson <i>et al.</i> (1993)
ceramic	hydrophilic	1.0	400 ¹⁴	Grossmann <i>et al.</i> (1990)
ceramic (SME B2M2)	hydrophilic	1.2	310-241	Soilmoisture Equipment (1994)
ceramic (SME B2M2)	hydrophilic	n.a.	>196	Bottcher <i>et al.</i> (1984)
ceramic (SME 1910)	hydrophilic	n.a.	196-104	Bottcher <i>et al.</i> (1984)
fritted glass	hydrophilic	1-2	n.a.	Johnson et al. (1995)
nylon membrane	n.a.	1.2	<25	Rambow and Lennartz (1993)

ceramic	hydrophilic	1.2	>70	McGuire and Lowery (1992)
ceramic	hydrophilic	1.2-3.0	>100	Dorranceetal. (1991)
ceramic	hydrophilic	1.8-3.0	100	Nemeth and Bittersohl (1981)
fritted glass"	hydrophilic	1.4 to 200	n.a.	Corning Inc (pers. comm.)
ceramic (SME B1M1)	hydrophilic	2.1	207-138	SoilmoistureEquipment (1994)
ceramic (SME B1M3)	hydrophilic	2.5	193-131	SoilmoistureEquipment (1994)
ceramic	hydrophilic	2.5	160	Shepard <i>et al.</i> (1990)
cellulose-acetate	hydrophilic	<2.8	>100	Dorranceetal. (1991)
non-cellulosic fibre	hydrophobic	<2.8	>100	Dorranceetal. (1991)
ceramic (SME B1MC)	hydrophilic	n.a.	108-90	Bottcher <i>et al.</i> (1984)
unspecified	n.a.	n.a.	100	Suarez (1986)
ceramic (Czeratzki)	hydrophilic	n.a.	98	Hetsch <i>et al.</i> (1979)
nickel (sinter)	n.a.	n.a.	88	Hetsch <i>et al.</i> (1979)
nickel (sinter)	n.a.	3.0	90	Nemeth and Bittersohl (1981)
polyethylene	n.a.	2.5-5.0	n.a.	Momson (unpublished)
fritted glass	hydrophilic	4.0-5.5	67	Shepard <i>et al.</i> (1990)
quartz-fibre "wicks" ¹⁶	n.a.	n.a.	59	Gee and Campbell (1990)
plastic "wick"	n.a.	n.a.	59	Gee and Campbell (1990)
fritted glass	hydrophilic	4.0-5.5	50	Dorranceetal. (1991)
stainless steel	n.a.	5.0	35-26"	McGuire and Lowery (1992)
PTFE¹⁸	hydrophobic	5	n.a.	Beier and Hansen (1992)
fritted glass	hydrophilic	5.0	40	McGuire and Lowery (1992)
Alundum®	hydrophilic	5	14.7-7.8	Bottcher et al. (1984)
ceramic (SME B.5M2)	hydrophilic	6	62.1-48.3	SoilmoistureEquipment (1994)
ceramic (SME B.5M3)	hydrophilic	n.a.	45.1-13.7	Bottcher et al. (1984)
stainless steel	n.a.	n.a.	24.5	Gaber <i>et al.</i> (1995)
fritted glass	hydrophilic	6.8 to 16.6¹⁹	21.1 to 8.7	Chow (1977a)
Alundum®	hydrophilic	7	20	Dorrance et al. (1991)
stainless steel	hydrophilic	7	20	Dorranceetal. (1991)
polyethylene	n.a.	10	n.a.	Merkel and Promper (1984)
fritted glass	hydrophilic	10-16	30-20	Starr (1985)

(...Cont'd.)

Table 8. (Concl'd.)

Material	Reaction with Water	Pore Diameter(μm)	Air Entry Tension (kPa)	Reference
fritted glass	hydrophilic	n.a.	15.7-13.7	Bottcher <i>et al.</i> (1984)
PTFE	hydrophobic	15-30	10-5	Dorrance <i>et al.</i> (1991)
fibreglass wick	n.a.	n.a.	5.4	Holder <i>et al.</i> (1991)
polyethylene ²⁰	n.a.	20	n.a.	Grossmann <i>et al.</i> (1985)
plastic	n.a.	20	n.a.	Cameron <i>et al.</i> (1992)
PTFE	hydrophobic	30	n.a.	Timco Mfg. Inc. (pers. comm.)
polyethylene ²¹	n.a.	35	n.a.	Cronan (1978)
polypropylene	n.a.	40	n.a.	Driscoll <i>et al.</i> (1985)
polyethylene	n.a.	70	n.a.	Harris and Stone (1990)
PTFE	hydrophobic	n.a.	3	McGuire and Lowery (1992)
PTFE	hydrophobic	n.a.	12.1-2.6 ²²	Everett and McMillion (1985), Everett <i>et al.</i> (1988)
PTFE	hydrophobic	n.a.	1.18-0.29	Bottcher <i>et al.</i> (1984)
PTFE	hydrophobic	70	n.a.	Creasey and Dreiss (1988)
nylon ²²	n.a.	1000	n.a.	Quin and Forsythe (1976)

¹ Or *air entry* value, *bubbling pressure*.

² Screening *size* of >100,000 MW; *cf.* pore size of 0.3 μm and >50,000 MW screening size for Diaflo hollow fibre tubing (Levin and Jackson 1977); see also hollow fibre molecular weight screening sizes of 500-2,000 MW (Silkworth and Grigal 1981) and >30,000 MW (Jackson *et al.* 1976).

³ "To" is used to indicate the range of values for which samplers of different discrete values may be found; by contrast, "-" is used to indicate the range within a single sampler.

⁴ Molecular weight screening size of >50,000 MW.

⁵ N.a. = information not available.

⁶ Acrylic copolymer sheets.

⁷ Polyvinylidene fluoride filter membrane.

- ⁸ "Nylon ~~is~~ not perfectly hydrophilic" (Grossmann *et al.* 1990).
- ⁹ Reported as "6000 mbar".
- ¹⁰ "Kerzenmaterial [candle material] wird 99.5% Aluminium-Oxid-Sinter (SKA100FF der Fa. Haldenwanger)", also called " Al_2O_3 -Keramik".
- ¹¹ Sintered >99% Al_2O_3 .
- ¹² Available in eight different pore sizes from 0.9-1.4 μm to 170-200 μm .
- ¹³ Made in ~~ten~~ different pore diameters, from 1 to 10 μm , in 1 μm increments
- ¹⁴ Reported as "4000 hPa".
- ¹⁵ Available in six different pore sizes from <1.0 to 150-200 μm .
- ¹⁶ Although used as "wick tensiometer" materials, these data are indicative of values that should be obtainable from wick lysimeters made of similar materials.
- ¹⁷ Air entry tension determined with samplers installed in columns filled with sand (35 kPa) or silt loam (26 kPa).
- ¹⁸ Made by Prenart Equipment Aps., Frederiksberg, Denmark; note that these cups are manufactured using "glass pellets" as a component, giving rise to "mineral needles" (Maitre *et al.* 1991)
- ¹⁹ 6 different porosities made, depending on glass bead size and length of time fritted at 655°C.
- ²⁰ Pore size of polyethylene sinter reported here, but ~~was~~ used as a support for a nylon membrane with a smaller pore size.
- ²¹ Linear porous polyethylene.
- ²² Using full range of data presented in Figs. 2 from ~~both~~ publications.
- ²³ 1 mm nylon mesh curtain over perforated PVC cups.

Fritted glass products can also be manufactured with small pore diameters. Glass plates with six different porosities ranging from 0.9-1.4 μm to 170-200 μm can be obtained in Pyrex® glass (Corning Inc.³⁷, pers. comm.) or glass plates with eight different porosities from <1.0 to 150-200 μm can be obtained in Duran 50® glass (Schott Corporation³⁸, pers. comm.). The smallest grade of glass made by Corning has an air entry tension of 250 kPa (Silkworth and Grigal 1981). Glass plates with pore diameters of 1-2 μm (Johnson *et al.* 1995), glass plates with pore diameters ranging from 4 to 5.5 μm and an air entry tension of 67 kPa (Shepard *et al.* 1990), glass cups³⁹ with 10- to 16- μm diameter pores and an air entry tension of 20-30 kPa (Starr 1985), and glass cups with air entry tensions of 13.7-15.7 kPa (Bottcher *et al.* 1984) have all been used as soil solution samplers.

Pores of 0.2 μm diameter were achieved with acrylic copolymer sheets which were then lain over polypropylene with 40- μm diameter pores (Driscoll *et al.* 1985). Likewise, porous PVC membrane filter sheets with 0.9- μm diameter pores were sandwiched between two lengths of concentric porous polyethylene tubing with 10- μm diameter pores to construct a sampler (Merkel and Promper 1984). This design was later modified to construct cups with a layer of either polyvinylidene fluoride (0.22- μm diameter pores) or nylon (0.45- μm diameter pores) membrane over a porous polyethylene support. Polyamide membranes with 0.45- μm diameter pores (Hantschel *et al.* 1994), and nylon membranes with 1.2- μm diameter pores over supporting disks of 1-cm thick perforated PTFE with 1-mm diameter holes have been used to construct sampling plates (Rambow and Lennartz 1993). Polyethylene

samplers with 2.5- to 5- μm (Momson, unpublished⁴⁰) and 70- μm (Harris and Stone 1990) diameter pores have been used, as well as linear porous polyethylene with 35- μm diameter pores (Cronan 1978). An unspecified porous membrane with a 100-kPa air entry tension threshold over a perforated PVC cup has been used (Suarez 1986), as well as stainless steel filter tubes with 5- μm diameter pores (McGuire *et al.* 1992).

By mixing sacrificial fatty acids with granular PTFE, Momson (1982) was able to consistently make PTFE samplers with pore diameters ranging from 1 to 10 μm , in 1- μm increments. Pore diameters of 70 μm were initially achieved for Timco PTFE samplers (Creasey and Dreiss 1988), although improvements in the patented process have led to a reduction so that the range within a single sampler is now 1.5 to 30 μm , as determined by the mercury penetration porosity method (Timco Mfg., Inc. 1992). Botcher *et al.* (1984) used PTFE samplers with 0.29- to 1.18-kPa bubbling pressures.

The largest pores used were perhaps those in 1-mm nylon mesh curtain over perforated PVC cups to which only 10 kPa of tension could be applied for sandy soils and gravels, and 33 kPa for heavy soils (Quin and Forsythe 1976). However, in this case the limit to the tensions applied must have been a function of the porosity of the soil surrounding the soil solution sampler, rather than the nylon mesh itself. Further, limitations in sampler materials as a result of pore diameter can be partially overcome by bedding the sampler in fine silica flour or quartz (silica, silica dioxide) powder on installation (e.g. Beier and Hansen 1992), and this procedure is recommended using 99.8% pure 200-mesh silica for PTFE soil solution samplers to increase the range of tension that can be applied to them (Timco Mfg., Inc. 1992). Some researchers have even designed plate samplers where a raised lip allows for the retention of a layer of silicon carbide (SiC) powder over rigid disks of acrylic (Bourgeois and Lavkulich 1972a,b) or of plexiglass (Feller 1977) so that the powder can be pressed against the soil, and thus the powder effectively determines the pore diameter of the sampler. An added benefit is that contact between the sampler and the soil is improved with the use of powders.

³⁷ Corning Inc., Science Products Division, Big Flats Plant, Corning, NY 14831, U.S.A.; tel. 1 (800) 222-7740, FAX (607) 974-0345.

³⁸ Schott Corporation, 3 Odell Plaza, Yonkers, NY 10701, U.S.A.; tel. (914) 968-8900, FAX (914) 968-4422 in North America. For head office and manufacturing plants contact Schott Glaswerke, Hattenbergstrasse 10, D-55122 Mainz, Germany; tel. 49 (Germany) 6131 (Main) 66 0, FAX 49 6131 66 2000.

³⁹ Manufactured by Siljander Oy Lasipuhaltamo, Luotsikatu 3, SF-00160 Helsinki 16, Finland; tel. Helsinki 780633.

⁴⁰ R.D. Morrison, Modified vacuum-pressure lysimeter for vadose zone sampling (unpublished, no date).

Not surprisingly, the performance of lysimeter systems made with samplers of different materials and porosities is ultimately dependent on field moisture tensions. For example, McGuire and Lowery (1992) found that samplers with large pore diameters collected soil solution samples at a faster rate than samplers with smaller pore diameters. However, samplers with small pore diameters were required when soil moisture tensions were high and samplers with large pores failed. The authors therefore concluded that choice of sampler is dependent on the aims of the study, and site and soil conditions.

3.2.1 Pore Clogging: The plugging or clogging of porous materials was observed by Krügel *et al.* (1935) while filtering soil suspensions, and by Krone *et al.* (1952) while testing porous cup solution samplers in the laboratory. It was shown that this can also occur over time with tension lysimeter systems in the field (Creaser 1971, Hansen and Harris 1975) and reduce sampling efficiency. Likewise, Talsma *et al.* (1979) found that sample volumes collected with porous ceramic cups decreased 23-fold over an 8-week period as a result of plugging. Although Johnson *et al.* (1981) found a small reduction in yield with porous cups in the laboratory using leachate from landfill sites because of plugging, this did not occur when the samplers were used in the field, presumably because particulate matter in the soil solution was filtered out before coming into contact with the buried samplers. Levin and Jackson (1977) also did not find plugging to be a problem with ceramic cups or fibres over a 5-week period, and Parizek and Lane (1970) found no apparent loss in efficiency over a 6-year period, although their cups were packed in fine-grained pulverized quartz which may have prevented migration of suspended solids. Morrison (1982) found that plugging of PTFE samplers was reduced in the field through packing with silica flour; this procedure is also recommended by Everett and McMillion (1985). PTFE, low- and high-flow ceramic samplers embedded in a silica flour slurry in potted soils of five different textures have also been tested for clogging (Everett and McMillion 1985, Everett *et al.* 1988). Daily flow rates were measured over a 4-month period until a cumulative total of 60 L had been drawn through the samplers (the equivalent of 30 years of sampling for pollutants at a sampling rate of 500 mL per quarter). Flow rates rapidly decreased over the first 15 L of sampling, but then stabilized at a rate which would still yield 500 mL of soil solution sample over a 24-hour period. It was

therefore concluded that plugging would not render the samplers inoperable, even after extensive sampling in the field. However, use of silica flour may introduce adsorption problems if trace metals are being monitored (McGuire *et al.* 1992). Alternatively, DeByle *et al.* (1988) recommended monitoring intake rates for signs of reduced efficiency and removing cups that clog for cleaning and reinstallation. They also recommended acid washing and flushing cups at the end of an experiment to clean clogged pores before installing used samplers on a new site, especially if conditions are markedly different. If ceramics are acid washed, however, pore diameter may increase somewhat; Johnson *et al.* (1981) found in the laboratory that acid-washed porous ceramic cup samplers had a slightly higher intake rate than uncleaned cups. Although to date only plugging of ceramics and PTFE has been investigated there is no reason to assume that sampler units of a similar pore diameter but made of different materials would not also potentially clog.

3.2.2 Contamination: Contamination of water samples can occur as the soil water moves from the soil through the sampler: (i) as dust remaining from the manufacturing process of ceramics (El Bassam 1972, Neary and Tomassini 1985); (ii) through leaching of contaminants from the sampler material; (iii) through adsorption and/or subsequent release, as sampler material may have its own CEC⁴¹ (Parker 1925, El Bassam 1972, England 1974, Wood 1974, Hughes and Reynolds 1988); (iv) through diffusive transfer to an immobile water phase (for NO₃-N and NO₂-N) along pore walls in ceramic tension samplers (Nagpal 1982); (v) through uptake by micro-organisms adhering to the sampler (Quinn and Forsythe 1976); or (vi) by weathering of the sampler material itself. Contamination may be minimized by: (i) judicious choice of sampler material (Dorrance *et al.* 1991, Wilson *et al.* 1994a); (ii) employing appropriate washings prior to use (*e.g.* El Bassam 1972, Hetsch *et al.* 1979, Bottcher *et al.* 1984); (iii) allowing the sampler to stabilize in the soil environment and discarding initial water samples (El

⁴¹ Very low exchange capacity of 2.05 mval/100 g as determined for ground porous ceramic material (El Bassam 1972); CEC of 80 microequivalents per SME cup tested (Hughes and Reynolds 1988).

Bassam 1972, Dawson and Hruttford 1976, DeByle *et al.* 1988); or (iv) withdrawing multiple samples on each sampling occasion, but only retaining the last for analysis (Nagpal 1982).

Washing tension soil solution samplers before installation to minimize contamination is recommended, especially for ceramic materials. Procedures commonly consist of placing the sampler in a 1 N HCl acid wash (although Watanabe *et al.* 1988 compared 0.5 N HCl and 0.5 N NaOH washes, and Wood 1973 used 8 N HCl) and drawing a volume of the acid through the sampler under tension, followed by rinsing with distilled or deionized water. Specific washing procedures used include: (i) leaching ceramics with 50-60 pore volumes of 1 N HCl and rinsing with 10 pore volumes of deionized water (Grover and Lamborn 1970); (ii) passing 500 mL (70 pore volumes) of 1 N HCl through ceramics, 750 mL (60 pore volumes) through Alundum®, and 500 mL through PTFE, and then rinsing with distilled water until the pH of output is equal to the pH of input water (Creasey and Dreiss 1988); (iii) leaching ceramic cups with 1 L of 1 N HCl and rinsing with 1 L of distilled water (DeByle *et al.* 1988); (iv) leaching Alundum® plates with 1 N HCl followed by large volumes (4-5 L) of distilled water (Neary and Tomassini 1985); (v) passing 1 L 8 N HCl through ceramic cups and rinsing with 15-20 L distilled water (Wood 1973); (vi) flushing sintered aluminum oxide, ceramic and nylon cups with 0.1 L 1 M HCl, then 0.1 L 1 M NaOH, and then 0.5 L distilled water at a low flow rate (Grossmann *et al.* 1987 in Grossmann *et al.* 1990); (vii) soaking ceramic cups in 0.1 N HCl for 24 hours and then drawing through deionized water (Jones and Edwards 1993); and (viii) rinsing porous ceramic samplers at least ten times with distilled water, and then discarding the first three samples obtained after installation (El Bassam 1972).

Acid washing and leaching does not solve all contamination problems, especially with ceramics. For example, Wolff (1967) found release of Ca, Mg, Al, Na, and SiO₂ from a ceramic cup that had been acid washed and rinsed. Bottcher *et al.* (1984) determined that acid washing increased subsequent adsorption of P by ceramics, although PTFE and glass did not adsorb P, whether washed or not. Grover and Lamborn (1970) concluded that washing ceramics reduced Na and K contamination, but that Ca leaching continued to be a problem, and that P adsorption was low. Zimmermann

et al. (1978) acid washed PTFE and ceramic cups, and found complete recovery of NH₄-N, NO₃-N, NO₂-N, PO₄-P and Si when two solutions of different concentrations were drawn through PTFE cups. However, Maitre *et al.* (1991) found that unacceptable amounts of Na, Ca, Mg, Fe and Si were still leached from PTFE cups even after two acid leachings and concluded that this may be a function of mineral needles in the PTFE cups arising from the use of glass pellets in the manufacturing process (*cf.* use of sacrificial fatty acids with granular PTFE by Momson 1982). There was a great reduction in recovery of solution drawn through ceramic cups for NH₄-N (11-28% recovery) and P (43-80%), but results were better for NO₃-N (94-97%) and NO₂-N (85%). Regarding trace elements, McGuire *et al.* (1992) determined that acid washing and leaching reduced trace element adsorption in PTFE, flitted glass, ceramic and stainless steel samplers, and that the general pattern of metal adsorption on samplers was ceramic > stainless steel >> flitted glass = PTFE. The general order that trace metal adsorbed to samplers was Zn >> Co > Cr > Cd. The authors concluded that PTFE, flitted glass and stainless steel were preferable to ceramic because of smaller adsorption-desorption errors, but that packing silica around these samplers in the field to give a wider operational range of tensions in the soil would compromise their non-reactive characteristics. As acid washing may increase subsequent P adsorption, Bottcher *et al.* (1984) recommended as an alternative that ceramic and Alundum® samplers be rinsed with a solution of orthophosphate at the concentration expected in the soil. Similarly, Hetsch *et al.* (1979) recommended pre-conditioning ceramic cups with a P solution before use. Grover and Lamborn (1970) also concluded that the passage of a small amount of solution through the sampler unit would quickly lead to equilibrium of P. By contrast, Jones and Edwards (1993) found that aluminosilicate (60% Al, 30% Si, 5% K, 1% Fe, 1% Ca) ceramic cup samplers which were soaked in 0.1 N HCl for 24 hours, rinsed in deionized water, and then pre-conditioned by drawing through soil solution equilibrated rapidly and after several samplings no further changes took place in concentrations of ions of concern (P, K, Na, Ca, Mg, Al, Mn, Zn, Si) except for Fe. Wick samplers have been tested for contamination effects, and it has been shown that the fibreglass wicks do not adsorb or desorb significant amounts of inorganic or organic compounds (Holder *et al.* 1991). Furthermore, cleaning fibreglass wicks using combustion at 400°C for 3 hours removed >98% of

impurities and increased capillary rise from 22 to 93 cm, or 67 to >150 cm, depending upon the type of wick (Knutson *et al.* 1993). The latter authors recommended that appropriate cleaning methods should be verified for particular wicks before use. With polysulfone hollow fibres, washing with deionized water alone was sufficient to remove contaminants except for S, with Mg, Cu, Zn, Fe, Mn, Al and Si being present in washings below analytical detection limits (Jones and Edwards 1993).

A list of papers which directly compare contamination effects of samplers and nutrients are presented in Tables 9 and 10. As few of these papers employed the same methodology and are therefore not necessarily directly comparable, the original references in these tables should be consulted by workers interested in either a specific sampler material or specific nutrients. References on adsorption/desorption and screening effects for different tension soil solution samplers are also collated in Dorrance *et al.* (1991) and Wilson *et al.* (1994a).

3.3 Installation

Porous samplers can be installed in a number of ways. Plates are usually pressed against the surface of horizontal tunnels where they can be held in place by backfilled soil (Cole 1958), pneumatic pillows (Duke and Haise 1973), or tire inner tubes (Shaffer *et al.* 1979). Porous cups on the ends of tubes are usually installed in holes augered vertically from the soil surface (Wagner 1962). However, these samplers can also be placed at an angle of 30° to the vertical (Richardson and Lund 1975, Lord and Shepherd 1993), horizontally from the sides of soil pits (Grossmann and Udluft 1991), or into confined soil columns (Harris and Stone 1990), at an angle greater than 90° from the vertical so that soil solution flows to the bung end (Wolff 1967), or even upside-down (Knighton and Streblow 1981a). A slurry of sieved soil material, silica flour or quartz powder is used to ensure hydraulic continuity and a good contact with the soil. Where boreholes are deep and it is difficult to ensure good placement of silica flour around samplers, the sampler can be frozen in the flour using a mold, and then inserted in the soil (Brose *et al.* 1986). With porous cups on the ends of tubes installed from the soil surface, a bentonite seal (Soilmoisture Equipment Corp.

1994) or a plastic collar (Brown 1987, Grossmann and Udluft 1991) can be used to reduce water movement down the stem of the tube to the porous cup.

Although freezing and subsequent damage to lysimeter system equipment can occur in colder climates, the extent of this problem has not yet been well documented (Everett *et al.* 1984a, Everett 1990). Laukajytis (1968) recommended burying collection bottles for zero tension lysimeter systems beneath the frost zone. Other problems associated with working in soils subject to freezing conditions include soil heaving and breaking of good contact between the soil solution sampler and the soil, freezing of samples within lysimeter systems so that they cannot be retrieved, and lack of ability to sample the frozen soil solution (Everett *et al.* 1984a). Frost heaving effects may be dependent on soil conditions. Czeratzki (1959) found that no soil solution was collected under tension from loamy sand and sandy-clayey loam soils encased in a 50-cm diameter x 50-cm deep metal tube with a ceramic plate attached to the bottom and set up in the field, and no damage was reported. However, frost heaving damaged the lysimeter systems set up in loam soil. Regarding porous cup solution samplers, Czeratzki (1971a,b) found that winter operations were possible, and that any soil solution frozen in extraction lines could be removed after each sample removal by flushing the lines with alcohol. A fritted glass plate sampler with an extra access port was also designed (Mahendrappa 1991) that allowed for 95% ethanol to be added before the winter and then drained out again in the spring (Roberts and Titus 1994). In a year with an unseasonably early and heavy frost, several of the glass samplers installed at shallow depths were broken (B.A. Roberts and B.D. Titus, pers. comm.). By contrast, porous ceramic cup samplers installed at 50 cm on the same sites (Roberts and Titus 1994) were not winterized with alcohol, and no losses as a result of freezing damage from amongst 108 samplers over four consecutive winters have occurred. If alcohol is to be used for winterization, then all parts of the lysimeter system should first be tested for a number of weeks to ensure that the alcohol will not cause deterioration of components⁴².

⁴² 95% ethanol added to SME Series 1900 porous cup solution samplers for winterization caused polycarbonate tubing that had been installed to extend to the bottoms of the samplers to dissolve, and rubber corks to shrink slightly; it can also cause Nalgene® to turn brittle after prolonged exposure (B. Titus, pers. comm.).

Table 9. Washing, contamination and screening effects of different porous soil solution samplers: comparison of samplers'.

Reference	Ceramic cup	Ceramic plate	Fritted glass	Alundum® disk	Sintered Al ₂ O ₃	PTFE	Nylon	PVDF	Stainless Steel	Ni	Silica	Miscellaneous
Anderson (1986)	cc ²											
Beier and Hansen (1992) ¹	cc					PTFE						
Bell (1974)	cc											
Bottcher <i>et al.</i> (1984)	cc ⁴		fr gl	Alun ⁵		PTFE						
Creasey and Dreiss (1985, 1988)	cc ⁶					PTFE						
Dawson and Hrutford (1976)				Alun								
Dazzo and Rothwell (1974)	cc ⁷											
DeByle <i>et al.</i> (1988)	cc ⁸											
Driscoll <i>et al.</i> (1985)												acrylic copolymer ⁹
El Bassam (1972)	cc ¹⁰											
Faber and Nelson (1984)	cc ¹¹											
Finger and Hojaji (1991) ¹²			fr gl									
Gillham and O'Hannesin (1990) ¹³						PTFE			ss			
Grossmann <i>et al.</i> (1985)					al ox		nylon ¹⁴	PVDF ¹⁵				
Grossmann <i>et al.</i> (1990) ¹⁶	cc ¹⁷				al ox ¹⁸		nylon ¹⁴					
Grover and Lamborn (1970)	cc											
Hädrich <i>et al.</i> (1977)		cp ²⁰								Ni		
Hansen and Harris (1975)	cc											
Hetsch <i>et al.</i> (1979)	cc ²¹									Ni ²²		
Holder <i>et al.</i> (1991)			gl wick ²³									
Hughes and Reynolds (1988)	cc ²⁴											
Hughes and Reynolds (1990)	cc ²⁵											
Jackson <i>et al.</i> (1976)												cellulose acetate ²⁶
Johnson and Cartwright (1980) ²⁷	cc											
Johnson <i>et al.</i> (1981)	cc											
Jones and Miller (1988) ²⁸						PTFE						
Jones and Edwards (1993)	cc ²⁹											polysulfone ³⁰
Krejslet <i>et al.</i> (1994)	cc		fr gl									
Law Engineering Testing Co. (1982) ³¹	cc											
Litaor (1987)	cc					PTFE						
Maitre <i>et al.</i> (1991)	cc					PTFE						
Mayer (1971) ³²		cp	fr gl	Alun								
McGuire <i>et al.</i> (1992)	cc		fr gl			PTFE			ss		silica	
Miller (1981)	cc ³³	cp ³⁴	gl wool ³⁵									polyester fibre ³⁶
Momson (1982)						PTFE						
Nagpal (1982)	cc											
Neary and Tomassini (1985)				Alun								
Nemeth and Bittersohl (1981)	cc ³⁷			Alun						Ni		
Peters and Healy (1988)	cc ³⁸											
Powelson <i>et al.</i> (1993)									ss			

Rasmussen <i>et al.</i> (1986)	cc ³⁹							PTFE ⁴⁰
Raulund-Rasmussen (1989)	cc ⁴¹							
Raulund-Rasmussen (1991)	cc ⁴²							
Reynolds and Gillham (1985) ⁴³								PTFE
Schimmack <i>et al.</i> (1984) ⁴⁴			Alun					polypropylene
Severson and Grigal (1976)	cc ⁴⁵							
Sheppard <i>et al.</i> (1992)		cp						
Silkworth and Grigal (1981)	cc ⁴⁶		fr gl ⁴⁷					cellulose fibres ⁴⁸
Smith and Carsel (1986)	cc ⁴⁹							
Sommer (1976) ⁵⁰	cc							
Strebel <i>et al.</i> (1973) ⁵¹	cc						Ni	
Tsai <i>et al.</i> (1980) ⁵²	cc							
Turner <i>et al.</i> (1985) ⁵³			Alun					
Wagner (1962)								
Watanabe <i>et al.</i> (1988)	cc ⁵⁴							
Wolff (1967)	cc							
Wood (1974)	cc ⁵⁵							
Zimmermann <i>et al.</i> (1978)	cc							PTFE

Equipment	Reference	Cellulose Nitrate	Cellulose Acetate	Esters of Cellulose	Paper	Millipore	Fritted Glass	Glass Wool
Filters	Marvin <i>et al.</i> (1972) Wagemann and Graham (1974)	cn	ca ca	ec	pa	Mi	fr gl	gl w gl w

Equipment	Reference	Glass	Polyethylene	Polypropylene	Polycarbonate	Polyvinyl Chloride	PTFE	Silicone
Vials and Tubes	Barcelone <i>et al.</i> (1988) Hassenteufel <i>et al.</i> (1963) Heron (1962) Murphy and Riley (1956) Ryden <i>et al.</i> (1972)	gl gl	pe pe pe pe	PP PP	pc	pvc pvc	PTFE PTFE	silicone

(...Cont'd.)

Table 9. (Cont'd)

- ¹ References in Tables 1 and 2 may also be examined for differences between samples obtained using lysimetry and other techniques, but direct contamination effects cannot necessarily be deduced (*e.g.* Barbarick *et al.* 1979, Hossner and Phillips 1973, Levin and Jackson 1977).
- ² SME 1900 Series.
- ³ Compared cups in paired sampling in the field; see also Maitre *et al.* (1991) who tested the same PTFE cups in the laboratory.
- ⁴ SME models B.5M3, B1MC, 1910 and B2M2 (listed in decreasing order of pore diameter).
- ⁵ Two different pore diameter (5 and 20 μm) products tested.
- ⁶ Two types of cups were compared, described as being made of "ceramic" and "alundum"; the "ceramic" were SME 2-bar flow cups, with 1.2 μm pore size, and composed of 55% Al_2O_3 and 35% SiO_2 plus trace amounts of other materials; although recorded as being composed of "alundum", the second type of cups were purchased from SME, who do not make "Alundum®" products; the description of size matches those made by SME; the recorded 1-bar high flow rate, 2.5 μm pore size, and composition of 90% Al_2O_3 suggests that the cups were made of B1M3 1 bar high flow ceramics, which are described by SME as being composed of over 90% Al_2O_3 , or alumina.
- ⁷ SME Model 1900-A, wall thickness 0.24 cm, pore size 3-8 μm .
- ⁸ SME 1900 series; 2-bar cups, 1.2 μm pore size.
- ⁹ Acrylic copolymer filter over porous polypropylene support.
- ¹⁰ Unspecified ceramic tubelike sampler (pore size 0.8 μm ; 29-30 cm in length; internal volume of 180-235 cm^3 ; wall thickness 6-9 mm).
- ¹¹ "Ceramic cups" as "used to construct tensiometers"; 1.9 cm o.d. x 7 cm long.
- ¹² Cited in Wilson *et al.* (1994).
- ¹³ Cited in Wilson *et al.* (1994).
- ¹⁴ Nylon membrane Pall filter over polyethylene sinter.
- ¹⁵ Polyvinylidene fluoride, or "polyvinylidenefluorid" (Ger.) Millipore filter over polyethylene sinter.
- ¹⁶ Results from Grossmann *et al.* (1990) also summarized in Grossmann and Ullrich (1991).
- ¹⁷ P80 ceramic cup (manufactured by Staatliche Porzellanmanufaktur, 1000 Berlin, Germany).
- ¹⁸ Aluminum oxide sinter SKA100FF (manufactured by Haldenwanger, 1000 Berlin, Germany).
- ¹⁹ "Self-made sandwich of a nylon membrane filter (manufactured by Pall, 6072 Dreieich, Germany) and a polyethylene sinter (manufactured by Wolftechnik, 7252 Weil der Stadt, Germany).

- ²⁰ "*Keramik*" (manufactured by Schumacher) and "*Al₂O₃-Sinterplatten*" (manufactured by Haldenwanger).
- ²¹ P80 porcelain (manufactured by Staatliche Porzellanmanufaktur, 1000 Berlin, Germany) and "Czeratzki" (manufactured by Schmidt, Braunschweig, Germany).
- ²² Manufactured by Krebsöge, Radevormwald, Germany.
- ²³ Fibreglass used in wick lysimeter.
- ²⁴ SME (63 mm x 48 mm diameter; 12 mL pore volume; model not given).
- ²⁵ SME (63 mm x 48 mm diameter; 12 mL pore volume; model not given).
- ²⁶ Cellulose acetate hollow fibres.
- ²⁷ Cited in Dorrance *et al.* (1991), "*porous ceramic*".
- ²⁸ Cited in Dorrance *et al.* (1991), "*porous PTFE*".
- ²⁹ SME ceramic cups.
- ³⁰ Polysulfone hollow fibre.
- ³¹ Cited in Dorrance *et al.* (1991), "*porous ceramic*".
- ³² P42 and P80 ceramic plates (manufactured by Staatliche Porzellanmanufaktur, 1000 Berlin, Germany); sintered glass plates (manufactured by Schott & Gen., Mainz, Germany); SKA100FF "*highly sintered ceramic material consisting of more than 99% Al₂O₃*" (manufactured by W. Haldenwanger, Berlin, Germany); listed in present table as "Alundum" because it is highly sintered.
- ³³ SME 2-bar ceramic; *equal* portions of kaolin, alumina, ball clay.
- ³⁴ SME 0.5 bar, 9 mm ~~thick~~ 90% Al₂O₃.
- ³⁵ Glass wool used as filter bed in funnel-shaped zero tension lysimeter; repeated acid and distilled water washings did not remove cation ~~contaminants~~.
- ³⁶ Polyester fibre used as filter bed in funnel-shaped zero tension lysimeter; repeated acid and distilled water washings did not remove cation ~~contaminants~~.
- ³⁷ Diapor 8G ceramic (manufactured by Haldenwanger), SKA100FF aluminum oxide sinter (manufactured by Schumacher) and sintered nickel (manufactured by Krebsöge); examined sorption properties.
- ³⁸ "*Porous ceramic cups... composed of 55 percent Al₂O₃, 35 percent SiO₂...*".
- ³⁹ SME 1900 ceramic and P80 porcelain cups.

(...Cont'd.)

⁴⁰ **40** mm diameter PTFE disc ~~on~~ **45** mm o.d. PVC tube, after C.S. Cronan.

⁴¹ P80 porcelain cups.

⁴² SME ceramic and P80 porcelain cups.

⁴³ Cited *in* Nielsen and Schalla **(1991)**, and *in* Wilson *et al.* **(1994)**.

⁴⁴ ~~cited~~ *in* Grossmann *et al.* **(1987)**; examined sorption properties.

⁴⁵ SME catalogue no. **2133** (6 cm length x 6 mm outside diameter, air entry tension of **2** bars).

⁴⁶ Both large and small SME 1-bar cups.

⁴⁷ coming ultrafine ~~fritted~~ glass cup.

⁴⁸ 500 to 2,000 MW units cutoff; Spectrum Medical Industries, Inc.

⁴⁹ SME high flow.

⁵⁰ Cited *in* Hetsch *et al.* **(1979)**, and *in* Grossmann *et al.* **(1987)**.

⁵¹ Cited *in* Grossmann *et al.* **(1987)** as having used P80 ceramic and sintered nickel; examined sorption properties.

⁵² Cited *in* Morrison and Tsai **(1981)**, and *in* Everett *et al.* **1984a**.

⁵³ Plexiglass and polyethylene zero tension lysimeters were **also** tested.

⁵⁴ Two types of cups were tested, made of *alumina* (**90%** Al₂O₃, **5%** SiO₂, **4%** CaO + MgO, **1%** other; pore sue **2** μm), and *siliceous* (**9%** Al₂O₃, **78%** SiO₂, **10%** CaO, **2%** MgO, **1%** other) material.

⁵⁵ SME; **no** model number or further description given.

Table 10. Washing, contamination and screening effects of different porous soil solution samplers. nutrients and compounds assessed'.

Reference	Flow	pH	EC	NH ₄ ⁺ , NO ₃ ⁻ , NO ₂ ⁻	PO ₄ , K	Na	Ca	Mg	Mn	Al	Fe	Zn	Cd	Cu	Cr	Co	SO ₄ , Cl	others
Anderson (1986)															Cr			
Beier and Hansen (1992) ²	flow	pH		NH ₄ ⁺		K	Na	Ca	Mg	Al								non-purgeable organic C
Bell (1974)																		<i>E. coli</i>
Bottcher <i>et al.</i> (1984)					PO ₄													
Creasey and Dreiss (1985, 1988)							Ca	Mg	Mn	Al	Fe		Cd	Cu	Cr	Co		
Dawson and Hrutford (1976)																		organics'
Dazzo and Rothwell (1974)																		fecal coliform
DeByle <i>et al.</i> (1988)	flow			NO ₃ ⁻		K	Na	Ca	Mg									
Driscoll <i>et al.</i> (1985)										Al								
El Bassam (1972)				NH ₄ ⁺ NO ₃ ⁻		K	Na	Ca	Mg		Fe	Zn		Cu			SO ₄ Cl	Pb, Ni
Faber and Nelson (1984)						K												
Finger and Hojaji (1991) ⁴																		organics'
Gillham and O'Hannesin (1990) ⁶																		organics'
Grossmann <i>et al.</i> (1985) ⁸												Zn	Cd	Cu				Pb, Ni
Grossmann <i>et al.</i> (1990)												Zn	Cd	Cu		Co		Be, Mn, Ni, Pb, humic
Grover and Lamborn (1970)					PO ₄ , P	Na	Ca											
Hadrich <i>et al.</i> (1977)					K	Na	Ca	Mg	Mn	Al	Fe	Zn	Cd	Cu		Co		Ni, Be, Pb, Si
Hansen and Harris (1975)					PO ₄													
Hetsch <i>et al.</i> (1979)		pH		NH ₄ ⁺ NO ₃ ⁻ NO ₂ ⁻		K	Na	Ca	Mg	Mn	Al						S	Cl
Holder <i>et al.</i> (1991)													Cd					Br, organics ⁹
Hughes and Reynolds (1988)						K	Na	Ca	Mg									
Hughes and Reynolds (1990)										Al								
Jackson <i>et al.</i> (1976)													¹⁰⁹ Cd					
Johnson and Cartwright (1980) ¹⁰						K	Na	Ca	Mg		Fe							Cl
Johnson <i>et al.</i> (1981)						K	Na	Ca	Mg		Fe	Zn		Cu				Cl
Jones and Miller (1988) ¹¹																		Pb, Hg
Jones and Edwards (1993)		pH			P	K	Na	Ca	Mg	Mn	Al	Fe	Zn				S	organics ¹²
Krejzl <i>et al.</i> (1994)																		Si, TOC
Law Engineering Testing Co. (1982) ¹³																		coliforms, streptococcus
Litaor (1987)																		high MW organics ¹⁴
Maitre <i>et al.</i> (1991)						K	Na	Ca	Mg		Al	Fe						
Mayer (1971)		pH			P	K	Na	Ca	Mg	Al	Fe						S	Cl
McGuire <i>et al.</i> (1992)												Zn	Cd		Cr	Co		
Miller (1981)		pH	ec ¹⁵			K	Na	Ca	Mg									
Momson (1982)						Na	Ca	Mg	Mn		Fe	Zn						Pb, organics ¹⁶
Nagpal (1982)				NO ₃ ⁻ NO ₂ ⁻	PO ₄ , K													
Nemeth and Bittersohl (1981)									Mn			Zn	Cd	Cu				Pb, Hg

56

(...Cont'd.)

¹ Does not include Schimmack *et al.* (1984) or Strebel *et al.* (1973), which were cited in Grossmann *et al.* (1987) as the originals were unobtainable for the present review.

² Compared cups in paired sampling in the field; see also Maitre *et al.* (1991) who tested the same PTFE cups in the laboratory.

³ Natural organic acids found in soils.

⁴ Cited in Wilson *et al.* (1994).

⁵ Un-defined in Wilson *et al.* (1994).

⁶ Cited in Wilson *et al.* (1994).

⁷ "Studied the sorption of six monoaromatic hydrocarbons onto seven materials. The hydrocarbons included benzene, toluene, ethylbenzene, and *o*-, *m*- and *p*-xylene. The materials examined included stainless steel and PTFE..." (from Wilson *et al.* (1994).

⁸ Authors also cite Hadrich *et al.* (1977), Hetsch *et al.* (1979), Nemeth and Bittersohl (1981) and Schimmack *et al.* (1984) as having determined that transport of iron, phosphate and humic substances through aluminum oxide sinter and ceramic samplers is problematic.

⁹ Ethylbenzene, toluene, trichloroethylene, naphthalene.

¹⁰ Cited in Dorrance *et al.* (1991).

¹¹ Cited in Dorrance *et al.* (1991).

¹² "4-nitrophenol, chlorinated hydrocarbons, diethylphthalate, naphthalene, acenaphthene".

¹³ Cited in Dorrance *et al.* (1991).

¹⁴ "Highmolecular weight compounds".

¹⁵ Specific conductance at 25°C.

¹⁶ Sacrificial organic compounds used in manufacturing process

¹⁷ Used bacteriophages MS2 and PRD1 to model human enteric viruses

¹⁸ Cited in Nielsen and Schalla (1991), and in Wilson *et al.* (1994).

¹⁹ Cited in Hetsch *et al.* (1979)

²⁰ 'according to Morrison *et al.* (1981), 'Laboratory studies by Tsai *et al.* (1980) found that several pesticide species were substantially reduced when leached through a 0.32 cm thick ceramic cup with a pore size of 2.5 micron. Concentrations of the chlorinated hydrocarbons pp DDD: pp DDE', and pp DDT" were reduced 90 percent, 70 percent and 94 percent respectively'" (from Everett *et al.* 1984a).

²¹ Author does not specify *ions*, but states that after washing with HCl and rinsing with tap water, the "output of major cations and anions equaled the input quality within analytical error".

²² Total dissolved nitrogen and total dissolved phosphorus.

²³ Chloroform, trichloroethylene, trichloroethane, tetrachloroethylene

Once soil solution samplers are installed, a "settling in" period is required so that artefacts such as increased N concentrations as a result of soil disturbance are minimized. This time period will vary from site to site, and disturbance effects can be minimal (e.g. Beier and Hansen 1992, Lord and Shepherd 1993) or can last for 2 to 3 months (Vitousek *et al.* 1982) up to 1 (Montgomery *et al.* 1987) or 2 (Shepard *et al.* 1990) years.

3.4 Systems for Applying and Maintaining Tension

Porous samplers need to have a tension applied to them before soil water can be drawn through them and into a collection vessel. This tension must be greater than the tension with which water is held in the soil. To date the majority of tensions applied have been either (i) **constant**, or (ii) **decreasing**, as the evacuated space that supplies the tension also serves as the collection vessel. Although constant tension systems are often used with porous plates (e.g. designs after Cole 1958) and decreasing tensions with porous cups (e.g. designs after Wagner 1962), there is no practical reason why any combination of sampler and tension system cannot be used (e.g. Reeve and Doering 1965, Riekerk and Moms 1983). However, in either case the lysimeter system tension does not necessarily reflect changes in the actual soil tension over time. In several recent designs tension can be (iii) **variable**, and changed via feedback mechanisms so that the lysimeter system tension is always the same or marginally greater than the actual soil tension.

The aim with all three tension systems (constant, decreasing, variable) is to obtain as representative a sample of the soil solution as possible. As decreasing tension systems may quickly fill and lose their tension they may be better suited to making spot samplings. Conversely, both constant and variable tension systems will collect sample continuously over time, and the collection interval will be determined by (i) the length of time that samples can be left in the field without undergoing chemical changes or microbial transformations, and (ii) the volume of the collection vessel.

Because of inherent differences between the three tension systems, they may sample different proportions of soil pore size classes at different times, depending on the differential between lysimeter system tension and soil moisture tension. This tension differential will vary

depending on both soil wetting-drying conditions and the type of tension-generating system used. If different proportions of pore size classes in the soil are sampled then some variation in results from different lysimeter system classes can be expected, and will be dependent on the degree of equilibrium between the solid phases of the soil and the soil solution, which is dependent on the rate of movement of soil water through the soil system, which in turn is partially dependent on soil pore size. For example, in a review of the effects of lysimeter system tension on solute concentrations, Grossmann *et al.* (1987) concluded⁴³ that increases in lysimeter system tensions generally result in increases in solute concentrations. Intuitively, this would suggest that if falling and constant tension-generating systems were set to the same initial tension, then constant tension systems would yield samples that were higher in solute concentrations because average lysimeter system tensions over the sampling interval would be higher. With variable tension-generating systems, results would be dependent on soil tension conditions over the sampling period. If soil drying caused a variable tension system to sample at a higher tension than a constant tension system, then it is reasonable to predict that solute concentrations in samples would be higher. Although there are very few studies that compare soil solutions from different systems, Beier and Hansen (1992) found that changing from a decreasing to a variable tension-generating system in the field actually had no effect, except for K, on solute concentrations. In contrast to Grossmann *et al.* (1987), Wu *et al.* (1995) found no difference in solute concentrations using porous cup lysimeter systems at 25, 35 and 45 kPa in the field. Similarly, Webster *et al.* (1993) cite Lord and Shepherd (unpublished data) as having demonstrated that a range in tension from 10- to 70-kPa porous cups had no effect on NO₃-N concentrations.

Defining the soil volume sampled by tension samplers is problematic. The movement of water through the soil towards various kinds of porous samplers has been considered by van der Ploeg and Beese (1977), Warrick and Ammoszegar-Fard (1977), Warrick *et al.* (1980), Morrison and Szecsody (1985), Narasimhan and Dreiss (1986), and Morrison and Lowery (1990b). This convergence of the soil solution towards tension samplers constitutes one of the

⁴³ Based on work by Mayer (1971), Hansen and Harris (1975), and Walter (1980).

fundamental differences between tension and zero tension lysimeter systems. To partially overcome this problem, Duke and Haise (1973) used porous ceramic candles laid in a trough so that freely draining water that collected in the trough could be extracted at realistic tensions using the porous ceramic sampler. Linden (1977) suggested that such a combined system would help to **define vertical** flow patterns of soil solution, thus making sampling more representative. Hergert (1986) also used this design after increasing side walls to 45 cm, as did Montgomery *et al.* (1987) who called it a "**vacuum trough extractor**". Watts *et al.* (1991) increased the side walls to 60 cm so that entrapment of percolating soil solution improved, allowing the lysimeter system tension to be reduced from 40 to 30 kPa (*cf.* Hergert 1986), thus further minimizing convergence of soil solution. These types of lysimeter systems were also used by Shaffer *et al.* (1979) to sample a wet, dual-pore soil system where rapidly moving water flowing through macropores was caught in a 29.2-cm diameter funnel with a 6.4-cm lip before being drawn **under** tension through a porous soil solution sampler and into the lysimeter system. Traditional tension designs would fail to sample this rapidly moving water in **well-structured** soils. To partially overcome the problem of sampling rapidly moving water in macropores with a tension lysimeter system, Czeratzki (1959) recommended that a groove might be added to the perimeter of the mounting for a porous ceramic plate so **that** fast moving, freely draining soil solution that was intercepted by the plate could be drained off into a collection vessel **separately** from soil solution collected **under** tension, rather than flow laterally around the plate and bypass the lysimeter system.

One problem with tension lysimeter systems is that water can potentially move from the collection vessel back into the soil if the soil dries enough that the soil moisture tension becomes greater than that within the lysimeter system itself. To help prevent total sample loss, Cole (1958) added a small well to the bottom of the collection vessel into which the hanging water column outlet ended. Where a vacuum trap was used, Cole *et al.* (1961) placed the end of the input tubing in a small **cylinder** that **filled** with soil solution before it overflowed **into** the collection vessel. This retaining tube held a reservoir of 50 mL of soil solution that would be pulled into the soil should the vacuum fail, or the tension in the soil increase to levels greater than that in the vacuum trap. One-way flow or check valves can also be placed in sampler lines so that reverse flow of soil solution

samples is minimized (M.K. Mahendrappa, pers. comm.).

Alternatively, lysimeter systems can be designed so that collected soil solution is not in direct contact with the porous sampler by moving the position of the sampler unit above the bottom of the tube (Knighton and Streblow 1981a, Morrison 1982 in designs after Wagner 1962), or by the **use of** vacuum trap systems for collecting sample. However, the loss of sample is not as important as the loss of vacuum if air is pulled through the porous sampler and into the soil. To a certain extent this can be prevented through the choice of samplers with a higher air entry tension value than that expected in dry periods in the soil under study. Although lysimeter systems where porous surfaces are separated from soil solution (Knighton and Streblow 1981a) rarely experience failure because of drying⁴⁴, tubing can be fixed to the tops of ceramic cups which are inserted horizontally (Duke and Haise 1973), or access ports can be added to fritted glass plates (Mahendrappa 1991, Roberts and Titus 1994) which can be used to rewet surfaces without removing samplers.

To prevent the problem encountered when vacuum traps over-fill and water enters the evacuation system, Czeratzki (1971a,b) installed a float valve in the suction line to prevent soil solution entering the tension-generating container. Similarly, Chow (1977b) developed a mercury-pressure control device in which enough mercury to fill the evacuated line up to the tension being applied is placed in a hollow Styrofoam **cylinder**. When the collection vessel fills, the Styrofoam cylinder floats until the mercury comes in contact with the evacuated line and is drawn up, thus effectively blocking the line. However, in many cases increasing the size of the collection vessel would likely be an easier solution to this problem.

With all tension lysimeter systems, a single evacuated tank can be used to apply tension to a number of sampler units at the same time. This can be achieved by having lines feed to the tank and join it either singly or through a junction manifold (Cole *et al.* 1961, Chow 1977b).

⁴⁴ < 1% in the use of over 400 lysimeter systems at one time (D. Streblow, pers. comm. 1993).

3.41 Constant Tension: The first practical field tension lysimeter system utilized a constant tension⁴⁵ produced by a hanging water column 110 cm in length (Cole 1958). In this design, the soil solution sampler plate and attached drainage pipe were filled with water prior to installation, and then the collection vessel was placed in the bottom of a pit 110 cm below the sampler plate, producing a siphoning action. Soil water filled the collection vessel, and a vent concomitantly allowed for the escape of air from the vessel so that water flow was not impeded. Since that time hanging water columns of 90 cm (Haberland and Wilde 1961, Feller 1977) and 100 cm (Haines *et al.* 1982, Levett *et al.* 1985) up to 425 cm (Starr 1985) have been used, corresponding to tensions of 8.8, 9.8 and 41.7 kPa, respectively. However, the amount of tension required will depend on the texture of the soil being sampled (Cole 1958). Wick samplers can also be considered to be under virtually constant tension as the tension is in essence maintained by a hanging water column (Brown *et al.* 1986 in Steenhuis *et al.* 1994b, Homby *et al.* 1986, Boll *et al.* 1991, Holder *et al.* 1991, Boll *et al.* 1992, Magid *et al.* 1992, Poletika *et al.* 1992, Daliparthi *et al.* 1993, Knutson *et al.* 1993, Knutson and Selker 1994, Rimmer *et al.* 1994, Steenhuis *et al.* 1994b, Rimmer *et al.* 1995, Knutson and Selker 1996).

Although the principle is very simple, a deep pit was originally required to accommodate a hanging water column. This problem was overcome by Riekerk and Moms (1983) who moved the hanging water column above ground and attached it to a post (Fig. 8). Water samples could then be collected in a vacuum trap consisting of a collection vessel placed in the line between the sampler unit and the siphon which intercepted the soil water before it could enter the siphoning apparatus. This entire tension-generating system can also be placed below ground in covered pits in areas where small mammals can cause damage by chewing tubes (M.K. Mahendrappa, pers. comm.). However, the system does not deliver a true constant tension, as the hydraulic head will decrease by the amount that the water level drops within the upper vessel as water moves from the upper to the lower vessel. This decrease in tension will be proportionately small if the initial siphon head is large, and can be further reduced if

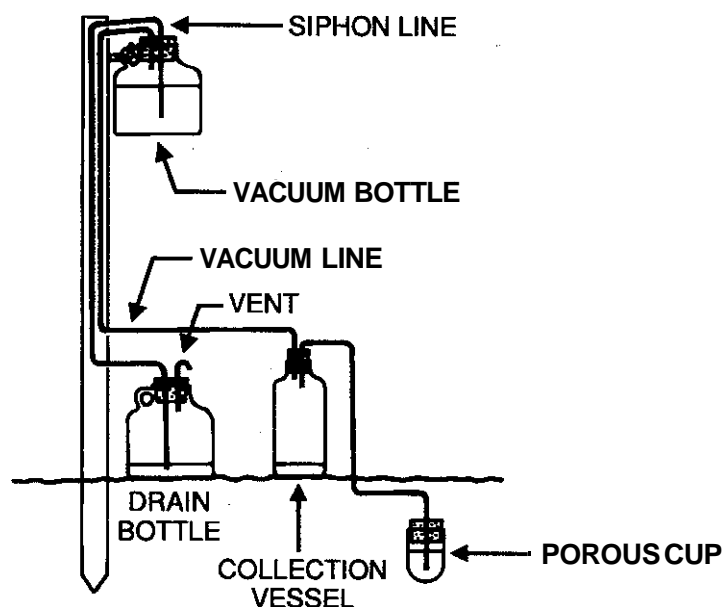


Figure 8 Modified hanging water column to generate constant tension, showing position of porous solution sampler, collection vessel, and tension-generating system installed above ground level (after Riekerk and Morris 1983).

the siphon line terminates at the bung of the lower bottle rather than continuing to the bottom of the vessel. Also, the use of wide diameter vessels will allow for a longer siphoning action relative to a smaller potential loss of head. The decrease in tension could be eliminated entirely by rearranging the upper vessel so that the neck of the up-side-down vessel is immersed in an open dish into which the siphon tube begins, thus eliminating the head effect within the upper vessel. The head will then begin in the open dish. When the water level in the dish drops below the mouth of the inverted upper vessel, air will enter the vessel and allow water to flow into the dish until the mouth is again covered. Depending on materials and funds available, a number of modifications could thus be made to reduce or eliminate the small falling tension in these systems.

⁴⁵ "Constant-potential" (Riekerk and Moms 1983), "constant vacuum" (Hansen and Harris 1975, Suarez 1986), "constant-suction" (Anderson 1986).

A second common way of maintaining a constant tension is by using an evacuated reservoir controlled by pressure gauges and **connected** to samplers via a vacuum trap collection bottle. Manifolds may be used so that more than one sampler can be connected at one time. The earliest design was by Cole *et al.* (1961); similar designs followed by Reeve and Doering (1965), Cole (1968), Cochran *et al.* (1970), McColl (1970), Bourgeois and Lavkulich (1972a,b), Chow (1977b), and Brown *et al.* (1985). The main problem is in maintaining an adequate evacuated reservoir for the duration of the study period. Hand pump (McColl 1970, Chow 1977b), or generator-driven (Chow 1977b) or battery-powered (Rasmussen *et al.* 1986) electric pumps may be used to evacuate tanks in remote locations.

3.4.2 Decreasing Tension: The first practical and widely used porous cup lysimeter system⁴⁶ for field application (Wagner 1962) had a design that inherently led to the use of a decreasing tension⁴⁷. This design consisted of a ceramic cup attached to the end of a length of pipe, capped with a rubber bung. A glass tube was inserted through a single hole in the bung, and a flexible neoprene hose was attached. A hand pump was attached to the neoprene hose, air within the length of pipe was evacuated, and the hose was pinched off with a clamp. As soil water entered the cup the vacuum inside the lysimeter system concomitantly decreased. The rate of decrease of tension is thus dependent on initial tension, porosity, porous surface area, and evacuated volume (e.g. Hansen and Harris 1975). When the porous samplers are too small to retain sufficient sample for analysis, evacuated flasks (or other vessels) can be

attached (Harris and Hansen 1975). Partially evacuated carboys have also been used to produce tension (Colman 1946). Small micro-tensiometer cups (0.6 cm o.d. x 3 cm long) can also be used as tension lysimeter systems when attached by syringe needles to 15-mL "vacutainers" (de Jong 1976). As with constant tension systems, the initial tension chosen will vary with the texture of the soil being sampled. Some tensions used range from 67.7 kPa (Harris and Hansen 1975) to 80 kPa (Alberts *et al.* 1977, Hipp *et al.* 1979, Anderson 1986).

Porous ceramic cups are widely used, with annual sales in excess of 5000 units in 1992 (Fig. 1 after Soilmoisture Equipment Corp., pers. comm.), and have received much attention in the literature. Various aspects of their use are reviewed and discussed in Hansen and Harris (1975), Linden (1977), Shaffer *et al.* (1979), Talsma *et al.* (1979), Stevens (1981), Anderson (1986), Grossmann *et al.* (1987), Peters and Healy (1988), Morrison and Lowery (1990a,b), Grossmann and Udluft (1991), and Lord and Shepherd (1993). A "Porous Cup Users Group" has also recently been established in the U.K. to facilitate communication amongst workers there⁴⁸.

3.4.3 Variable Tension: The above two types of applied tensions (*i.e.* constant, decreasing) do not reflect the reality of the spatial and temporal variations in tension in the field as soils dry and are rewetted, and are a practical compromise between what is theoretically desirable and what can operationally be achieved. However, several workers have developed methods for varying the tension in their lysimeter systems, depending on actual soil conditions. For example, Duke and Haise (1973) used tensiometers in the vicinity of porous candles which were laid in a trough (one tensiometer near the open top of the trough, and one at the same depth as the solution sampler, adjacent to the trough) and maintained a variable tension that was 0.5 kPa greater than that of the surrounding soil, thereby minimizing convergence of the soil solution towards the sampler. A similar methodology was proposed by Linden (1977). Smith and Carsel (1986), using conventional porous cups modified for burial, installed

⁴⁶ Grossmann and Udluft (1991) propose that the term "suction cup" refer only to the porous ceramic cup, "suction probe" to the ceramic cup plus the tube to which it is attached, and "suction-cup method" to the entire soil solution sampling technique. However, possible variations in the use of suction cups and suction probes in lysimetry are such that the term suction-cup method is perhaps too limiting and does not adequately define the entire lysimeter system. Although more cumbersome, "large-volume, falling suction soil-matter samplers" (Anderson 1986) better describes the size of the overall system and the type of tension, but omits any reference to cup. Soilmoisture Equipment Corp. refer to these lysimeter systems as "sail water samplers".

⁴⁷ "Falling-suction" (Anderson 1986), "falling vacuum" (Hansen and Harris 1975), "dropping vacuum" (Suarez 1986), or "transient vacuum" (Momon and Lowery 1990a).

⁴⁸ Contact Dr. Keith Goulding, IACR, Rothamsted Experimental Station, Harpenden, Hertfordshire, U.K., AL5 2JQ; tel. 44 (U.K.) 582 (Harpenden) 763133, FAX 44 582 760981.

a tensiometer at each monitoring site and applied a tension similar to that with which water was held in the soil (15-20 kPa) to obtain soil solution samples. Spalding (1988) in Steenhuis *et al.* (1991) and Tindall and Vencill (1995) also used this kind of system.

These methods require manual checking of tensiometers and adjustment of tensions in lysimeter systems. However, Duke *et al.* (1970) designed a fully automated vacuum system that would adjust the tension in a ceramic plate at the bottom of a confined soil core every 5-10 minutes to ensure maintenance of a tension only marginally greater (as low as 0.27 kPa = 2 mm Hg) than that in the surrounding soil. Brown *et al.* (1974) likewise used regulation manometers to keep porous cups in a confined soil core at the same tension as the surrounding soil, based on the design by Duke *et al.* (1970). However, this concept need not be limited to use in confined soils in the field; Rasmussen *et al.* (1986) used valves and differential switches connected to a tensiometer to control a 12-volt pump, which in turn supplied the vacuum required to draw soil water through a ceramic cup at a slightly greater tension than that in the soil itself, with a differential that was adjustable between 2.25 to 20.6 kPa. This same system was also used by Beier and Hansen (1992), who maintained a variable lysimeter system tension that was 10 kPa greater than the soil tension. Similar automated variable tension designs have been developed and used by Tiktak *et al.* (1988), Beier *et al.* (1989) in Beier and Hansen (1992), Tietema *et al.* (1993), and Aderhold and Nordmeyer (1993, 1995). These designs represent perhaps the optimal concepts to date in the application of tension lysimetry, as objections to the unrepresentativeness of constant or decreasing tensions are minimized. Advances in electronics may make the use of automated variable tension lysimeter systems more widespread in the future. However, although there may intuitively be an attraction to the use of variable tension lysimeter systems that sample the soil solution held at tensions just slightly greater than soil moisture tension, the choice of tension-generating system must ultimately depend on the aims of the study. Bypass flow around variable tension lysimeter systems may still be a problem in soils where preferential flow predominates,

3.5 Tension Lysimeter Systems and Confined Soil

As with zero tension lysimetry (see Section 2.3), tension can be applied to isolated, confined soils in

either the field or the laboratory through the choice of appropriate porous samplers. Typically, a plate may be attached to the bottom of a confined soil core, or small porous samplers may be inserted horizontally through holes in the sides of the container. A variety of tension and collection systems similar to those for unconfined soils have been used, and are presented in Table 11.

Czeratzki (1959) attached a 1963-cm² (50-cm diameter) porous ceramic plate to the bottom of a 50-cm deep metal cylinder for extraction of soil solution under tension in either the field or laboratory. In addition, he proposed that a groove could be added to the base of the lysimeter system to drain off fast moving gravitational water, especially after high rates of water input from storms or irrigation. In the field, Krause (1965) sampled a 613-cm² x 30.5-cm deep confined soil core encased in a polythene tube using an Alundum® disk and a hanging water column. Brown *et al.* (1974) used porous cups to sample the bottom of an undisturbed 3.1-m² x 150-cm deep confined soil sample in the field. Tension was controlled using a regulation manometer so that moisture potential gradients similar to those found in nature were automatically maintained. Brown *et al.* (1985) similarly sampled the soil solution from the bottom of 2552-cm² x 85-cm deep steel cylinders using porous cups, but with a continuous rather than variable tension. Likewise, Kissel *et al.* (1974) placed undisturbed 3.56-m² x 107-cm deep confined soil cores 25 cm below the soil surface so that the fields could be ploughed, with a constant tension of 1.5 kPa applied through unspecified samplers. Cameron *et al.* (1992) used a combination of zero tension (perforated copper pipe covered with 0.2-mm nylon mesh) and tension (porous plastic tubes with 20-μm diameter pores in <70-μm silica sand) sampling techniques to withdraw "fast" and "slow" drainage water from the bottom of large (5027 cm² x 120 cm deep) soil cores encased in steel plate cylinders.

In the laboratory, Bondurant *et al.* (1969) used a ceramic plate at the bottom of an undisturbed 52.8-cm² x 24-cm deep confined soil core to apply 49 kPa of tension in the laboratory to test the efficacy of heat shrink tubing for sealing the sides of a soil core. In a similar design, Harris and Stone (1990) attached a polyethylene sheet with 70-μm diameter pores over a corrugated plastic drainage mat to the bottom of a soil core, and also inserted small porous polyethylene filter candles at different distances down the 150-cm deep soil core. Likewise, Rambow and Lennartz (1993) used a

Table 11. Sues of soil solution samplers in tension lysimeter system designs¹ for sampling confined soil.**undisturbed, confined soil with tension samplers**

Area	Dimension	Material	Reference
162.9 cm ²	14.4 cm inside diameter	polyamide membrane on bottom of plexiglass cylinder	Hantschel <i>et al.</i> (1994)
182.4 cm ²	15.24 cm diameter x 30 cm deep	PVC pipe; stainless steel plate	Gaber <i>et al.</i> (1995)
314 cm ²	20 cm (approx.) diameter x 150 cm	PVC pipe; polyethylene filter "candles" and sheet	Harris and Stone (1990) ¹
1963 cm ²	50 cm diameter x 50 cm deep	unspecified metal; ceramic plate on bottom	Czeratzki (1959) ³
2500 cm ²	50 cm x 50 cm x 50 cm deep	unspecified metal; ceramic cups installed at 20 cm	Knight <i>et al.</i> (1992)
2551 cm ²	57 cm diameter x 85 cm deep	painted 20 gauge steel; ceramic cups in bottom	Brown <i>et al.</i> (1985)
5026 cm ²	80 cm diameter x 120 cm deep	steel plate; porous plastic tubes in bottom	Cameron <i>et al.</i> (1992) ⁴
30856 cm ²	203 x 152 x 150 cm deep	cold-rolled steel plate; ceramic cups in bottom	Brown <i>et al.</i> (1974)

disturbed, confined soil with tension samplers

Area	Dimension	Material	Reference
23.8 cm ²	5.5 cm diameter	Buchner funnel with filter paper	Fyles and Bradley (1992)
167 cm ²	14.6 cm diameter x 15 to 45 cm deep	PTFE-lined PVC pipe; nylon membrane/PTFE plate	Rambow and Lennartz (1993)
613 cm ²	28 cm diameter x 38 cm deep	polyethylene sheeting with Alundum® plate at bottom	Krause (1965)
1257 cm ²	40 cm diameter x 175 cm deep	ceramic cups in soil encased in PVC pipe	Bell (1974)
2827 cm ²	60 cm diameter x 183 cm deep	PVC funnel with gravel and sand (low tension)	Corwin and LeMert (1994)

¹ Not all references listed in Tables 1-3 and 8-10 are included, as dimensions are not always reported² Soil solution down profile sampled with porous polyethylene filter candles (70 µm pore size); polyethylene sheet filter (70 µm) over corrugated plastic drainage mat attached to bottom of core; all soil solution sampling done under tension.³ Porous ceramic plate as base, with potential for zero tension drainage as well⁴ Perforated pipe in bottom to collect "fast-drainage" water; porous plastic tension tubes in bottom to collect "slow-drainage" water.

porous nylon membrane over a perforated PTFE disk to withdraw soil solution samples from the bottom of a cylinder of soil. They also covered the inner wall of the 15-cm diameter PVC tube used to confine the soil with a 0.5-mm thick adhesive PTFE liner to help reduce adsorption and contamination problems. Although small porous cups can easily be inserted in confined soil cores (e.g. Barbarick *et al.* 1979, Harris and Stone 1990), care must be taken when using repacked soil, as settling may cause outlet lines to become pinched against the wall of the container.

Cronan (1978) minimized edge-effect problems in a laboratory experiment by placing a porous polyethylene disk against the bottom of a 113-cm² (12-cm diameter) confined soil core from a forest floor. However, the disk (7.5-cm diameter) did not extend to the edges of the core, which freely drained to waste. In another laboratory application, Fyles and Bradley (1992) placed a suspension of forest floor material in a Buchner funnel with a glass fibre filter of 23.8 cm² surface area. Tension was provided using a 30-cm hanging water column (2.94 kPa). The sample settled under tension, and could be rewetted to obtain soil solution while it incubated for periods of up to 9 months. In a similar design, Matson and Vitousek (1981) incubated 50-g samples of mineral soil in 100-mL plastic funnels lined with glass-fibre filter paper at 20°C in the dark and leached the "microlysimeters" weekly with 50 mL of deionized water at a tension of 20 kPa.

Soil columns need not have only one solution sampler at the bottom. For example, a large composite sampler plate composed of many individual smaller samplers (or cells) can be constructed and attached to the bottom of soil cores, to examine especially the heterogeneity of water flow through soils. Quisenberry *et al.* (1994) attached a composite sampler to the bottom of a 32.5-cm x 32.5-cm undisturbed, encased soil block. This composite sampler was made up of a grid of 144 cells (12 x 12), each 3.05 cm x 3.05 cm in size. Each smaller sampler tapered conically to an outlet tube, was filled with glasswool and covered with 2-3 mm of fine sand, and had a tension of 2.0 kPa applied. The outer edge of cells were positioned under the container walls and were not used for analysis, giving a total of 100 (10 x 10) operational cells. A similar apparatus was used by Phillips *et al.* (1995). Buchter *et al.* (1995), after Andreini and Steenhuis (1990), applied a multicelled sampler to the bottom of a 30-cm diameter column that

consisted of 19 individual porous ceramic plates of two sizes (5- and 6-cm diameters). Each individual plate was then sampled separately to examine the heterogeneity of flow through the soil as determined from breakthrough curves for added chloride solutions. Other systems consisting of a 16-cm diameter base divided into 4-cm x 4-cm cells have been designed by Aderhold and Nordmeyer (1994) and Nordmeyer (1994).

3.6 Collection Vessels and Sample Retrieval

There are three main methods by which soil solution accumulates in collection vessels: (i) by gravity flow into a collection vessel when a hanging water column is used (e.g. Cole 1958); (ii) by suction into a collection vessel when the collection vessel is located between the sampler and the source of tension and acts as a vacuum trap (e.g. Cole *et al.* 1961, Riekerk and Mome 1983); and (iii) when the space inside the porous sampler and sampler body itself is evacuated and forms the collection vessel (e.g. Wagner 1962). As with zero tension lysimetry, tubing and vessels should be arranged so that carry-over problems are minimized. Sampling intervals should not be so great that microbial transformations can take place in the collection vessel. For example, Vitousek *et al.* (1982) found no change in NH₄-N or NO₃-N in soil solution in porous cup lysimeter tubes over a 1-week period and therefore used this as a sampling interval. Also, samples should generally be refrigerated and analyzed immediately after collection, depending on the analyses being carried out. Recommended sample bottle materials, preservatives and maximum holding times for a wide range of organic and inorganic substances can be found in Stollar (1990).

3.6.1 Gravity Flow: Collection bottles in accessible pits and trenches for hanging water column tension-generating systems are easily removed and emptied into appropriate sample bottles for return to the laboratory. However, a small vent hole or tube to allow air to escape as the bottle fills with soil solution is required. When collection bottles are inaccessible, a permanent sampling tube that extends to the bottom of the bottle through which samples can be removed under tension and retained in a vacuum trap can be used, along with air-vent tubes, in a manner analogous to that required for buried zero tension collection bottles (e.g. Laukajtys

1968). Vacuum can be applied using portable hand pumps, electric- or gas-driven pumps, or evacuated containers.

3.6.2 Vacuum Traps: With the advent of evacuated tanks and above-ground hanging water columns, the collection vessel itself becomes part of the evacuated lysimeter system, with soil solution samples accumulating in vacuum traps. Retrieval requires access to the vessels so that inlet and outlet tubes can be clamped for sample removal. Collection vessels can be emptied into sample vessels for return to the laboratory, or can be exchanged.

3.6.3 Porous Cup Samplers: When the air space in a lysimeter system forms not only the source of tension but also the collection vessel (e.g. porous ceramic cups on the ends of lengths of pipe), a number of designs can be used to facilitate sample collection. Originally, Wagner (1962) fed a small diameter capillary tube through a short length of tube in a bung (access port) at the top of the lysimeter system down to the bottom. Accumulated soil solution could then be withdrawn using a vacuum trap, with air entering the lysimeter system through the gap between the capillary and access tubes as water is withdrawn. One drawback to this method of sample retrieval is that the fine capillary tubing can become caught on the rim of the porous cup, leading to problems with dead space and sample carry-over (Everett and McMillion 1985, Everett 1990). Also, sample movement through the capillary tube is relatively slow. Alternatively, a single rigid tube that extends through the bung and to the bottom of the porous cup can be used. Sample is withdrawn into a vacuum trap until air bubbles indicate that the sampler is empty. As there is no way for air to displace the removed soil solution, the sampler is also under a greater tension than required for regular sampling. This tension can be slowly released until the correct tension is required, and the clamp tightened. In this way, sample can be collected and tension applied in a single operation. The method is speedy, and there is little sample carry-over⁴⁹.

Other workers (e.g. Reeve and Doering 1965, Parizek and Lane 1970, Zimmermann *et al.* 1978, Knighton and Streblow 1981a, Stevens 1981, Nagpal

1982, Smith and Carsel 1986, Hamid 1988) have installed two tubes through the bung: one air vent tube that terminates just beneath the bung, and one sample removal tube that extends to the bottom of the sampler⁵⁰. This two-line method of sample retrieval allows for faster sample recovery through larger diameter tubing either by pressurizing the interior of the tube and forcing the water sample out, or by drawing the sample out under vacuum into an external vacuum trap. It also minimizes sample carry-over. Czeratzki (1971a,b) developed a similar two-line system, except that the large diameter pipe that forms the sampler body in designs after Wagner (1962) is greatly reduced in diameter so that the soil solution is largely retained in the ceramic cup only. The long sampling tube that runs to the bottom of the cup is enclosed by an outer concentric tube of small diameter that is connected to an evacuated container on the soil surface for application of vacuum. This collection system design was further modified by El Bassam (1972) who added a second external evacuated vessel so that the original floating valve that prevented water entering the vacuum generating system when the collection vessel filled was no longer needed. In minor modifications of the two-line system, Quin and Forsythe (1976) attached an exterior sample bottle as an integral part of the evacuated lysimeter system. Long (1978) and Talsma *et al.* (1979) also effectively use a two-line system, but with sample bottles situated on the soil surface. Riekerk and Moms (1983) also used a two-line method of sample retrieval with the collection vessel on the soil surface, but the tubing did not extend to the bottom of the cup. However, to minimize sample carry-over errors the porous cups were filled with glass beads, and the minimum length of pipe necessary to connect the porous cup to a bung was used, thereby further minimizing potential dead space.

Two-line systems of sample retrieval also allow samplers to be installed at considerable depths in the soil. Parizek and Lane (1970) first modified the basic design of Wagner (1962) by adding two tubes so that soil solution samplers could be installed at depths of up to 14 m. Air was then pumped into the air access tube, forcing soil solution out under pressure into a sample bottle, and hence these are sometimes referred to as "pressure-vacuum" lysimeter systems. However, these

⁴⁹ Method developed by Dr. N. Foster, Ontario Region, Forestry Canada, P.O. Box 490, 1219 Queen St. East, Sault Ste. Marie, ON, Canada, P6A 5M7.

⁵⁰ A two-line system was also originally used by Brooks *et al.* (1958), although their cups were installed horizontally.

lysimeter systems must be air-tight (Everett and McMillion 1985). Further, if the sampler is buried at too great a depth then there is the possibility that the sample will be forced back out through the porous sampler and into the soil again before air pressure will lift it to the surface. Wood (1973) introduced poppet check valves in the outlet line just above the porous cup so that an initial tension applied to the outlet line with a hand pump would **lift** the sample above the valve. Subsequently, a steady application of pressure just great enough to **lift the** sample was applied from a pressurized cylinder, allowing samples to be collected from 33 m; hence these are sometimes referred to as **"high pressure-vacuum"** lysimeter systems. Likewise, Morrison (1982) used a porous tube with an impervious end-cap so that soil solution drained down into the cap and was not in direct contact with the porous material. A series of check valves were used to **minimize** carry-over errors by allowing samples to be **lifted** over 30 m without draining back down into the lysimeter system (Morrison 1982).

Use of standard porous cup soil solution samplers and their associated **lines** for sample retrieval may lead to the loss of volatile organic pollutants⁵¹; where these are being monitored a purging apparatus such as that used in standard **"purge-and-trap"** methods for collecting volatile pollutants in water and wastewater can be used (Wood *et al.* 1981). Straub *et al.* (1988) also developed a tension lysimeter system to prevent degassing of volatile organic compounds. Likewise, as the CO₂ content of soil air is several orders of magnitude greater than that of the atmosphere, exposure of soil water to atmospheric environments will cause CO₂ **degassing** and a subsequent increase in pH (Grossmann *et al.* 1988). To **minimize** degassing errors, Suarez (1986) reduced the volume of the sampler cup⁵² to 3 mL by addition of Pyrex® rods. The outlet tube was placed flush with the bung in the top of the sampler so that air volume was minimized. A two-chambered vacuum trap was used and sample was only taken from the first sample trap once enough soil solution had flushed through the collection apparatus and the second reservoir trap to ensure that a non-degassed sample could be

collected. If depths greater than 10 m are to be sampled, the two-chambered vacuum trap can be modified to fit within the lysimeter system tube itself. The inclusion of one-way flow valves allows for sample retrieval, not unlike the arrangements of Wood (1973) and Momson (1982). Takkar *et al.* (1987) also used a multiple chamber arrangement like Suarez (1986) to more accurately determine pH, and Straub *et al.* (1988) used a **syringe** to sample water without the presence of air. Grossmann *et al.* (1988) used a number of designs to prevent degassing, including a hanging water column that fed from a soil solution sampler into a flexible plastic sampling bag rather than an open vessel. However, Grossmann *et al.* (1988) concluded that microbial activity also affected pH values, and that it is therefore **necessary** to ensure that there is **no** microbial activity in samples when **using** degassing systems so that the integrity of the samples is maintained.

In all of the above cases, tension or pressure can be supplied using pressure or vacuum from a variety of pumps. In **one** particular case, **lines** from 16 porous cups were fed into a **single** manifold system that allowed for remote collection of soil solution samples without causing site disturbance by trampling (Wengel and Griffin 1971). This system also utilized a portable electric vacuum-pressure pump. In another design, a portable unit containing vacuum trap samplers and an evacuated reservoir was designed to minimize sample retrieval time in the field (Knighton and Streblow 1981b).

3.7 Some Unique Design Features

A variety of existing design variations have application in specialized circumstances. For example, Smith and Carsel (1986) added stainless steel shafts to porous cups (**after** Parizek and Lane 1970) for pesticide monitoring. In addition, access tubes coiled in brake drums allowed for relocation of lysimeter systems with a metal detector **after** systems were buried for application of ploughing treatments. Other workers found that wire mesh buried **at** 25 cm could not be found with a metal detector, so used a ring magnet and a magnetic detector to relocate lysimeter systems after burial for ploughing (Lord and Shepherd 1993).

Porous ceramic cup soil solution samplers have also been modified to withstand crushing in soil compaction field trials. Stone and Roble (1996)

⁵¹ See Pettyjohn *et al.* (1981) and Lewis *et al.* (1991) for a wider review of sampling methodologies for volatile organic compounds.

⁵² Suggested materials include PTFE, ceramic, or 100-kPa air entry tension membrane over perforated PVC pipe.

attached ceramic cups with 4-mm thick walls to PVC pipe with 6.4-mm thick walls in an inverted design *after* Knighton and Streblow (1981a) and installed the lysimeter systems 30 and 60 ~~cm~~ beneath the soil surface. The plots were then compacted with about 60 kPa of static ground pressure (with a 19 400-kg D-7 Caterpillar tractor) or 110-120 kPa (with a 20 455-kg front-end loader). Only minimal damage occurred, and much of this was to sampler tubing, which was easily repaired.

In saturated conditions, porous ceramic cups (4.8 ~~cm~~ diameter x 6.3 cm long) on the end of lengths of pipe were inserted in columns filled with a sandy loam soil at a depth of 30 ~~cm~~ as part of a laboratory experiment. No tension was applied to the cups. However the soil columns had a constant water head **above** the soil surface of 5 cm, giving a total head of 35 cm (3.4 kPa). The cups filled passively with 21.5 to 23 mL of soil solution in 24 hours (Hamid 1988).

Where evolved gases from confined soils are of interest (*e.g.* CO₂ evolution from microbial respiration, or pollutants), caps can be manufactured to allow for **gas** sampling in the confined space above soil samples (Overrein 1968, Fyles and Bradley 1992, Hempel *et al.* 1995); some workers refer to these as "*gas lysimeters*".

Morrison and Szecsody (1985) modified a porous cylinder to create a "*sleeve*" lysimeter system which had a hollow centre and could be used **as** a borehole casing. In addition, porous sleeves could be placed at different lengths in the borehole casing, allowing simultaneous sampling at different depths from one access hole. Boreholes are often used to test for the presence or absence of industrial **or** landfill contaminants rather than nutrient work, and will not be discussed further. Equipment used for monitoring soil water with boreholes has been extensively reviewed **by** workers involved in ground-water monitoring (*e.g.* Morrison 1983, Anon. 1993a).

Morrison and Szecsody (1984) also modified a tensiometer so that it could be used to sample the soil solution, as well as to measure the moisture tension in the soil. Another device that can be used for a combination of functions has been designed (Haldorsen *et al.* 1985, Torstensson and Peterson 1988); the BAT® filter tip system consists of a porous filter tip (available as high-density polyethylene, ceramic or PTFE) at the end of a tube that samples the soil solution when an

evacuated cylinder is lowered down the tube and a double-sided hypodermic needle punctures a septum and withdraws soil solution through the filter tip under tension. However, the same filter tip can also be used as an *infiltrometer* and tensiometer.

One of the disadvantages **of** tension lysimetry is the cost of installing enough lysimeter systems to adequately sample the volume of soil of concern. To partially overcome this difficulty, temporary tension soil solution sampler probes have been developed that are easy to install and can be moved to a different location once a soil solution sample is obtained. In one design, a small diameter (9-mm) porous ceramic sleeve is attached to the end of a stainless steel probe that can be pushed into the soil, a tension **applied**, and a soil solution sample obtained in 1 to 10 days (Bredemeier *et al.* 1990). A **similar** commercially available sampling probe ("*Rhizon Soil Solution Sampler*") that is made of a hydrophilic porous polymer tube (2.3-mm diameter, 0.1- μ m diameter pores) attached to a PVC tube that can obtain **10** mL of soil solution in **1** to 16 hours, depending **on** soil water potential (Eijkelkamp Agrisearch Equipment 1992⁵³). A potential disadvantage of these types **of** systems is that pore structure may be disrupted when compaction occurs as the probe is driven into the soil.

Recording devices have also been used in conjunction with lysimeter system installations. For example, tipping bucket recorders have been placed in outlet lines so that the rate of volume flow of leachate can be automatically recorded (Roose and des Tureaux 1970, Knapp 1973). Knight and Will (1977) recorded percolation rate with a chart recorder and an automatic siphoning device. Miller and Miller (1976) also developed a recording, self-priming siphoning device that activated a manual counter which, although developed **for** measuring stemflow, could be adapted to measure flow through a lysimeter system. However, in perhaps the most complex of any lysimeter system installations for nutrient analysis work, Cole (1968) and later workers (*e.g.* McColl 1972, 1973) automatically determined flow rates, pH and conductivity. The use of more complex electronically controlled systems will only increase as the micro-electronic revolution continues.

⁵³ Available from Eijkelkamp Agrisearch Equipment, Netherlands, tel. 08336-31941, FAX 08336-32167.

3.8 Recommendations

Under most circumstances, tension lysimeter systems sample a different portion of the soil solution than zero tension lysimeter systems. The requirement for samplers with a small enough pore diameter to retain a tension under soil drying conditions mitigates against these same samplers being as able to representatively sample rapidly moving preferential flow as **zero** tension lysimeter systems because of the slower flow rate of solution through the porous soil solution sampler. The materials used in sampler construction will determine not only pore diameter but also whether or not there will **be** release of contaminants and adsorption of ions from the soil solution. Chosen samplers must **be** appropriate for the field soil moisture conditions expected so that tension is not lost but yet contamination of samples does not take place, and the choice must therefore **be** dependant on the aims of the study. Appropriate washing, rinsing, pre-conditioning and installation procedures must **be** used, and a stabilization period that may last a matter of days, weeks or months, depending on installation methods and the site is required. Lysimeter systems should **be** tested for air leaks that might lead to vacuum failure before being installed in the field. Alcohol may be added to help prevent damage from freezing, especially in porous samplers, but lysimeter system components should first **be** tested for potential deterioration because of exposure to alcohol. Protection from animals may also **be** required.

Decreasing, constant, and variable tension-generating systems can **be** used with virtually any kind of porous soil solution sampler. The main considerations in choosing between systems are the duration of the sampling, the differential between actual soil tension and applied lysimeter system tension, resultant soil water movement into the lysimeter system from soil pores of different sizes, and therefore the soil volume and the pore size component of the soil volume being sampled. Decreasing systems by definition cannot integrate sampling at a uniform tension over time periods in the order of weeks, but may do so over a matter of hours in wet soils, or days in dry soils. However, daily sampling is likely to **be** impractical, and therefore maximum peaks of solute concentrations may well **be** missed. Decreasing tension lysimeter systems are therefore perhaps best considered to give spot samplings at some point within a matter of hours or days of tension being reapplied after sample collection, even

if the time period between samplings is measured in weeks. Constant tension lysimeter systems will integrate sampling between collection periods, but may sample different components of the soil solution at different rates as tensions change within the soil itself due to wetting and drying. Peak concentrations will **be** sampled, but their relative importance over the sampling period may be lost as more dilute solution is drawn into the collection vessel over **time**. Variable tension lysimeter systems will integrate sampling over the collection period at the same rate, but will sample different components of the soil solution as tensions vary. In practical terms, decreasing tension systems such as porous cup solution samplers are relatively inexpensive, easy to install and maintain, and large numbers can be **used** on relatively inaccessible sites. Above-ground constant tension systems maintained by hanging water columns are more expensive, but not prohibitively so, **whereas** mechanical systems dependent on pumps and automated valves may **be** even more expensive to install, and may require regular maintenance. Variable tension lysimeter systems are likely the most expensive to install and maintain, and this may limit their short-term utility. **Bypass** flow will occur with **all three** systems, and hence fluxes of solutes can only **be** determined from water flow models. All three systems may fail to accurately sample preferential flow, and hence a combination of tension and zero tension lysimetry may **be** required for some studies.

As with zero tension lysimetry, collection vessels should be situated **so** that soil solution temperatures **are** minimized and light excluded, thus reducing microbial transformations. Toxic compounds may be added as well, so long as they do not interfere with chemical determinations.

4. STATISTICAL ANALYSIS OF DATA

4.1 Introduction

While the statistical **tests** used to analyze data from a specific study will depend upon the experimental design used, two **general** statistical issues common to all lysimetry **studies** are determination of (i) an appropriate sample size, and (ii) the frequency distribution of the data. Sample size will determine the confidence with which true means of measured parameters can **be** estimated, and the frequency distribution of the data will determine if transformations are required to normalize

the data before parametric statistical tests are performed. Although some information is available from the lysimetry literature, general statistical considerations for other soil sampling techniques that have ramifications on soil solution sampling methodologies can be found in Pratt *et al.* (1976), Hajrasuliha *et al.* (1980), Warrick and Nielsen (1980) *in* Wilson (1983), Dahiya *et al.* (1984a,b, 1985), Bouma and Nielsen (1985) *in* Lauren *et al.* (1988), Riha *et al.* (1986), Miyamoto and Cruz (1987), White *et al.* (1987) and Scott-Wendt *et al.* (1988).

4.2 Spatial Variation and Determination of Sample Size

For random sampling, the sample size required to obtain an estimate of the mean within a given percent of the true population mean can be determined from:

$$n = t^2_{(\alpha, df)} s^2 / d^2$$

where n = the sample size required, t = the student t -value for a given α -value (or significance level, or probability level) and a given df (or degrees of freedom), s^2 = sample variance, and d = the allowable error, or desired confidence interval expressed as a percentage of the mean (Payandeh and Beilhartz 1978)⁵⁴. A

⁵⁴ A thorough discussion of the topic, including exceptions and examples, is given by the authors. Variations on this method in the lysimetry literature include:

- (i) $\alpha = t\sigma/\sqrt{n}$, or $n = t^2\sigma^2/\alpha^2$, where α = precision requirement (proportion of mean), t = ordinary t -value (at $p = 0.05$), σ = standard deviation and n = number of samples required. This can be reduced to $\alpha = t(0.4\mu)/\sqrt{n}$, or $n = t^2 0.16\mu^2/\alpha^2$, because α = proportion of mean (e.g. $\alpha = 0.5\mu$) the values for μ cancel out so that (at the 0.05 level) $0.05 = t(0.4)/\sqrt{n}$, or $n = t^2 0.16/0.0025$, or $n = t^2 (64)$ (after Snedecor and Cochran 1967 *in* Alberts *et al.* 1977; see also Petersen and Calvin 1986);
- (ii) $n = 4\sigma^2/L^2$ where n = number of samples required, σ = population standard deviation and L = allowable error in sample mean (after Snedecor and Cochran 1978 *in* Holder *et al.* 1991);
- (iii) $n = MS_{pit}(z)^2/p^2x_{bar}^2$ where n = required sample size, MS_{pit} = mean square due to variation between different sampling locations, z = ordinate of the normal curve ($n-1$ degrees of freedom, $1-\alpha/2$ confidence level), p = pre-specified probability that the sample outcome could be larger than the observed value (e.g. 0.05), and x_{bar} = mean (after

significance level (or the probability of a Type I error) is commonly set at $\alpha = 0.05$ (or 5%). When there are fewer than 20 actual observations or when the desired confidence levels are less than 2% then the degrees of freedom used to locate the t -value from t -distribution tables is $df = n-1$. In all other cases it is usually sufficient to use $df = n$, or the number of actual observations. To determine the confidence interval ($\pm d$) it is necessary to know the observed mean. If a confidence interval of 10% is desired for a mean of 50 then the confidence interval would be $50 \pm 10\%$, or between 45 and 55, and hence $d = 5$. Although determination of sample size assumes that data is distributed normally and that sampling is random, Payandeh and Beilhartz (1978) suggest that knowing how the population is distributed need not be a major problem, so long as the sample size is large enough⁵⁵. This is an important consideration, as data derived from lysimeter systems is rarely normally distributed (see Section 4.4).

The spatial variability of soil properties in general is reflected in the relatively high variability of soil solution concentrations determined by lysimetry. This in turn leads to the general requirement of a large number

Gilbert 1987 *in* Swistock *et al.* 1990);

- (iv) $n_{xbar} = ((Z_{\alpha}/(x_{bar}-\mu))^2 \times \sigma^2)$ where n_{xbar} = minimal number of samples, Z_{α} = z -value (1.96 for $\alpha = 0.05$), $(x_{bar}-\mu)$ = required precision, and $\sigma = s$ = standard deviation (after Sachs 1984 *in* Manderscheid and Matzner 1995).

⁵⁵

One of the most powerful theorems in statistics, the Central Limit Theorem, makes it possible to justify use of the sample mean as an estimate of the population mean, no matter how the population is distributed, as long as it has a finite variance and the sample size is large enough. Just how large is large enough will depend on how close to normally distributed the population is. [The closer a distribution is to normal, the faster the rate of convergence of the distribution of sample means will be to normality.] In rare cases the parent distribution may be such that the distribution of sample means may not converge to normal at all. In other cases, although the Central Limit Theorem will apply, sample size estimation based on the normality assumption may not be very efficient (Alvo 1977). However, for most natural populations the normality assumption will be satisfied for sample sizes of, say, 25 or larger. (after Payandeh and Beilhartz 1978)

of lysimeter systems, especially if expected treatment differences are relatively small, or if data with a high degree of accuracy is required. For example, Alberts *et al.* (1977), using porous cup soil solution samplers, found the spatial variation in nitrate concentration to be very high. Using combined data for extracts from soil cores and soil solutions obtained from porous ceramic cup samplers, it was determined that 246, 64, 18, 12 and 10 samplers would be required to obtain estimates within 5, 10, 20, 25, and 30% of the true nitrate concentration mean, respectively.

Lord and Shepherd (1993) reported coefficients of variation⁵⁶ ranging from 30-70% for nitrate for a single sampling occasion using porous ceramic cups. Based on these findings and a review of data in Lord (1992) from 43 fields monitored with 10 porous cup solution samplers each, the authors concluded that nitrate differences of 25% in treatment means could be detected with 20-25 replicates, and differences of 50% with 5-7 replicates.

In another field study, Grossmann and Kloss (1994) concluded that the minimum number of porous cup samplers required to obtain values within 20% of the mean with 95% confidence in a spruce stand were 4, 8, 33, 8 and 29 for H⁺, Na, K, Mg and Ca, respectively, at a depth of 0.2 m, and 22, 7, 10, 10 and 11 at a depth of 0.7 m (averaged over 12 sampling periods). For individual sampling collections, the largest sample size ever required was 60, and this was for potassium. Coefficients of variation ranged from 16.5% to 79%, but were mainly between 20% and 60%. The authors concluded that bulk samples may be acceptable to reduce costs of analysis, but only when untransformed data are normally distributed. Samples may be bulked before collection by connecting several lysimeters to a single collection vessel in the field (Mohamed and Ranger 1994).

Manderscheid and Matzner (1995) used the minimum and the maximum CV observed during biweekly sampling with 20 porous cup lysimeter systems in a Norway spruce forest over a 1-year period and the annual mean concentrations of NO₃-N, K, Na, Ca, Mg,

Mn, Al, Cl, SO₄-S and H⁺; they concluded that at least 20 lysimeter systems would be needed to determine most concentrations within $\pm 10\%$ of the true mean with 95% significance (or probability) using the minimum CV observed, but that between 68 and 633 lysimeter systems would be needed using the maximum CV observed. However, reducing the required accuracy to $\pm 20\%$ reduced the required sample size by one-fourth.

Spatial variation in apparent diffusion coefficients and pore water velocities determined with porous ceramic cup solution samplers is even greater than the reported variation for nutrient concentrations. For example, Biggar and Nielsen (1976) established 20 randomly located plots (6.5 m x 6.5 m) within a 150-ha field and installed two tensiometers and two porous ceramic cup solution samplers within each plot at each of six different depths down the soil profile. Plots were ponded to attain a steady state of water content and flow conditions using a standard solution. A solution high in Cl⁻ and NO₃⁻ was then added, followed by the standard solution, and soil solution samples were obtained every hour so that the movement of Cl⁻ and NO₃⁻ down the profile could be measured. The authors concluded that the data were normally distributed after logarithmic transformation, although variations in water content on the same site (Nielsen *et al.* 1973) were normally distributed. Spatial variation was high, and 20, 100 and 1000 samples would be needed to estimate the true mean pore water velocity within an order of magnitude, $\pm 50\%$, or $\pm 10\%$, respectively, of its value. Similarly, 35 and 200 samples would be required to estimate the true mean apparent diffusion coefficient within an order of magnitude and $\pm 50\%$, respectively, of its value.

Tension lysimeter systems consisting of porous cups on the ends of PVC pipe are relatively inexpensive and easily installed in a random fashion, and therefore sample sizes can often be large. However, where pits must be dug to install tension plates the relative increase in cost of lysimeter systems, time required for installation, and amount of site disturbance often limits the number of lysimeter systems that can be used. Typically, one to three soil solution samplers are placed under each horizon of interest in a single pit, but there are rarely more than three pits per treatment or site. David and Gertner (1987) examined the sources of variation in soil solution collected weekly from a study using two tension plates per soil horizon per pit, two pits per site, and two sites. Soil solution was analyzed for

⁵⁶ The coefficient of variation (or CV) is the standard deviation expressed as a percentage of the mean from which it has been calculated (*i.e.* percent coefficient of variation = standard deviation/mean x 100).

specific conductance, H^+ , NO_3-N , K , Ca , Mg , Na , and total S . The sampling design was deemed to be generally adequate for the soil solution parameters measured, and coefficients of variation ranged from 27% for total S to 218% for NO_3-N . Significant differences were found between horizon and collection period, and significant differences for pits within sites were only found for total S . Inter-lysimeter differences were only significant for total S and NO_3-N . It was concluded that accuracy of estimation of total S and NO_3-N concentrations could be improved by increasing the number of pits and samplers per pit, and accuracy of estimation of all other parameters could be improved by increasing sampling frequency. The data also suggested that volume flow could not be used to calculate water flux because of significant lateral flow.

In a similar sampling design, but with six pits on one site and using zero tension lysimeter samplers beneath the Oa horizon, Shepard *et al.* (1990) also determined sources of variation. The lower horizon (B) was buffered more against variations in moisture and temperature, and soil solution chemistry was therefore less variable. Standard deviations for NO_3-N , SO_4-S and Ca were high, and percent coefficients of variation were over 150% for NO_3-N and NH_4-N , but less than 40% for SO_4-S and Ca , which is in general agreement with the findings of David and Gertner (1987). However, differences in mean ion concentrations were usually significantly different among the six soil pits. Also, effects of both tension (zero tension vs. constant 10-kPa tension) and porous solution sampler material (glass vs. ceramic) did not exceed other sources of variation, but results were not consistent for all pits. Although working on the same site as David and Gertner (1987), Shepard *et al.* (1990) concluded that spatial heterogeneity was the largest source of variation in their results, suggesting that having an adequate sample size to take into consideration spatial variability is a major consideration in planning a study that will incorporate lysimeter systems. The authors found that estimating mean concentrations within 10% at the 0.05 probability level would require as few as seven samples for Ca but as many as 774 for NH_4-N . Soluble forms of nitrogen were more spatially and temporally variable than other nutrients studied. Shepard *et al.* (1990) also found high coefficients of variation for NH_4-N and NO_3-N and likewise concluded that this reflected the role of biological processes in the cycling of nitrogen in ecosystems. The high spatial variability of available

forms of nitrogen is also reflected in soil sampling studies, where Arp and Krause (1984) showed that 167 and 1242 LFH soil samples would be required, respectively, to estimate available NH_4-N and NO_3-N concentrations within 10% at the 0.05 probability level. In a field study using bromide as a tracer, Holder *et al.* (1991) found that the number of 30-cm x 30-cm wick samplers required to determine concentrations of soil water constituents with 95% confidence were 31 for sand, 6 for silt loam, and 2 for clay soils. Differences in variation were attributed to irregularities in texture that resulted in preferential flow in the sand soil, and swelling in the clay soil that would have decreased the size of macropores, and hence variability

In some studies, the variability between different types of lysimeter systems has been compared, as in the work by Shepard *et al.* (1990) referred to above. For example, Levett *et al.* (1985) examined variability in a number of nutrient cycling studies, including a direct comparison of the performance of 613-cm² alundum tension lysimeter systems (after Cole 1958) and 1600-cm² zero tension lysimeter systems (after Shilova 1955) at two different depths (beneath the organic horizon and beneath the rooting zone) in a 1- to 2-year old radiata pine stand. Coefficients of variation of annual nutrient fluxes ranged from 16% to 120%. Results from zero tension lysimeter systems were generally two to five times more variable than those from tension lysimeter systems, and results from beneath the rooting zone were more variable than those from beneath the organic horizon. In an examination of the nutrients with the maximum coefficients of variation for any site, soil depth, or lysimeter system, it was determined that the number of collectors required to sample Na , K , Ca , Mg , P or Cl and obtain a standard error within 10% or 20% of the true mean ranged from 39 to 144 and from 1 to 32, respectively.

In another comparison of 1998-cm² zero tension lysimeter systems (E and B horizons) and porous ceramic cup tension lysimeter systems (B horizon only), Swistock *et al.* (1990) determined the sample sizes for range of nutrients (H^+ , SO_4-S , Cl , Ca , Mg , K , Na , Mn , Al) and conductivity. Contrary to the findings of Levett *et al.* (1985), fewer zero tension lysimeter systems were required to sample the soil solution from the B horizon with a predetermined confidence than tension lysimeter systems. Nitrate, K and H^+ were the most variable nutrients when sampled with tension lysimeter systems,

but Cl, K and Na were the most variable nutrients when sampled with zero tension lysimeter systems. Determining nitrate concentrations with 95% confidence levels and p-values of 0.05 would require 1989 porous cup solution samplers and ~~from~~ 147 to 753 zero tension lysimeter systems. At the 70% confidence level, 367 porous cup solution samplers would be required for nitrate determinations. Even at the 70% confidence level the required sample sizes were generally too large to be practical, with the fewest porous cups being 6 ($\text{SO}_4\text{-S}$), 19 (Na), 30 (conductivity), 40 (Ca) and then ranging from 50 up to 367 for other nutrients. However, 20 zero tension lysimeter systems under the B horizon would be adequate for determination of 7 of the nutrients with 70% confidence limits, but all the nutrients from under the E horizon required more than 20 zero tension lysimeter systems at the 70% level.

A tabulation of means and standard deviations for nutrient concentrations from 177-cm² porous ceramic tension and 156-cm² zero tension lysimeter systems collected monthly over a 16-month period are presented in Haines *et al.* (1982). These data show that standard deviations of mean nutrient concentrations were generally greater ~~from~~ zero tension than from tension lysimeter systems, and that standard deviations were generally less for nutrients sampled from 30 cm down the mineral horizon than from under the litter layer. $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ were more variable than other nutrients in that standard deviations were several times as large as means, whereas for other nutrients standard deviations were equivalent to or less than mean values.

Various results from the wider literature on soils confirm the high degree of spatial variability in soil properties. For example, Nielsen *et al.* (1973) concluded that large variations in hydraulic conductivity can be found on apparently uniform sites, although variations in texture, bulk density and water content are much less. However, this variability can be decreased by increasing sample volume (Reeve and Kirkham 1951 ~~in~~ Lauren *et al.* 1988, Baker 1977, Hawley *et al.* 1982 ~~in~~ Lauren *et al.* 1988, Lauren *et al.* 1988) or core height (Anderson and Bouma 1973). Using soil samples taken for nitrate, chloride and soluble salt determination, Pratt *et al.* (1976) found that digging 10 soil pits per plot and then taking between 7 and 13 soil samples per soil pit would give mean values within 20% of the true nitrate mean. In practice, the authors found that for economic reasons it was necessary to compromise and take

multiple samples per soil pit from 10 pits per treatment, but then to composite them by pit before analysis.

Lauren *et al.* (1988) concluded that there was a point of diminishing returns beyond which increasing sample size would not greatly increase the accuracy with which the mean hydraulic conductivity could be estimated, and the same principle would apply to soil solution sampling with lysimeter systems. This principle was explored by Strebel and Bottcher (1989) who graphically illustrated the difference between sample sizes required to achieve given error probability levels for two different confidence intervals (± 10 and ± 20 mg L⁻¹) assuming a normal distribution and a standard deviation of 70-80 mg L⁻¹. They demonstrated that accepting a larger confidence interval will greatly reduce the sample size required to attain the same level of error. This is also demonstrated in Figure 9 using data derived from Manderscheid and Matzner (1995) for annual nitrate and potassium concentrations from 20 porous cup lysimeters installed at a 90-cm depth in a Norway spruce stand, and the minimum CV observed from 26 samplings at 2-week intervals over a 1-year period. It should be noted that the theoretical sample sizes are a minimum, as the CV was the lowest observed on any sampling date, and Manderscheid and Matzner (1995) found that spatial variability at 90 cm was less than at 20 or 35 cm.

Wagenet (1985) ~~in~~ Lauren *et al.* (1985) also examined the spatial variability of leaching processes. The spatial variability of soil processes in general is discussed in Bouma and Nielsen (1985) and Petersen and Calvin (1986), who also discuss random sampling plans. Sample size considerations in lysimetry are also briefly reviewed by Litaor (1988) and Angle *et al.* (1991) who noted a general lack of replication and the use of a small sample size in studies utilizing lysimeter systems and recommended statistical methods that require a minimum number of lysimeter systems, and the use of repeated measures analysis to determine changes in solute concentrations over time.

4.3 Temporal Variation

Concentrations of ions in solution vary over time, depending on the ions under consideration and the mechanisms that control their mobility, and temporal or seasonal patterns of variation in ionic concentrations are evident in most studies utilizing lysimeter systems (e.g.

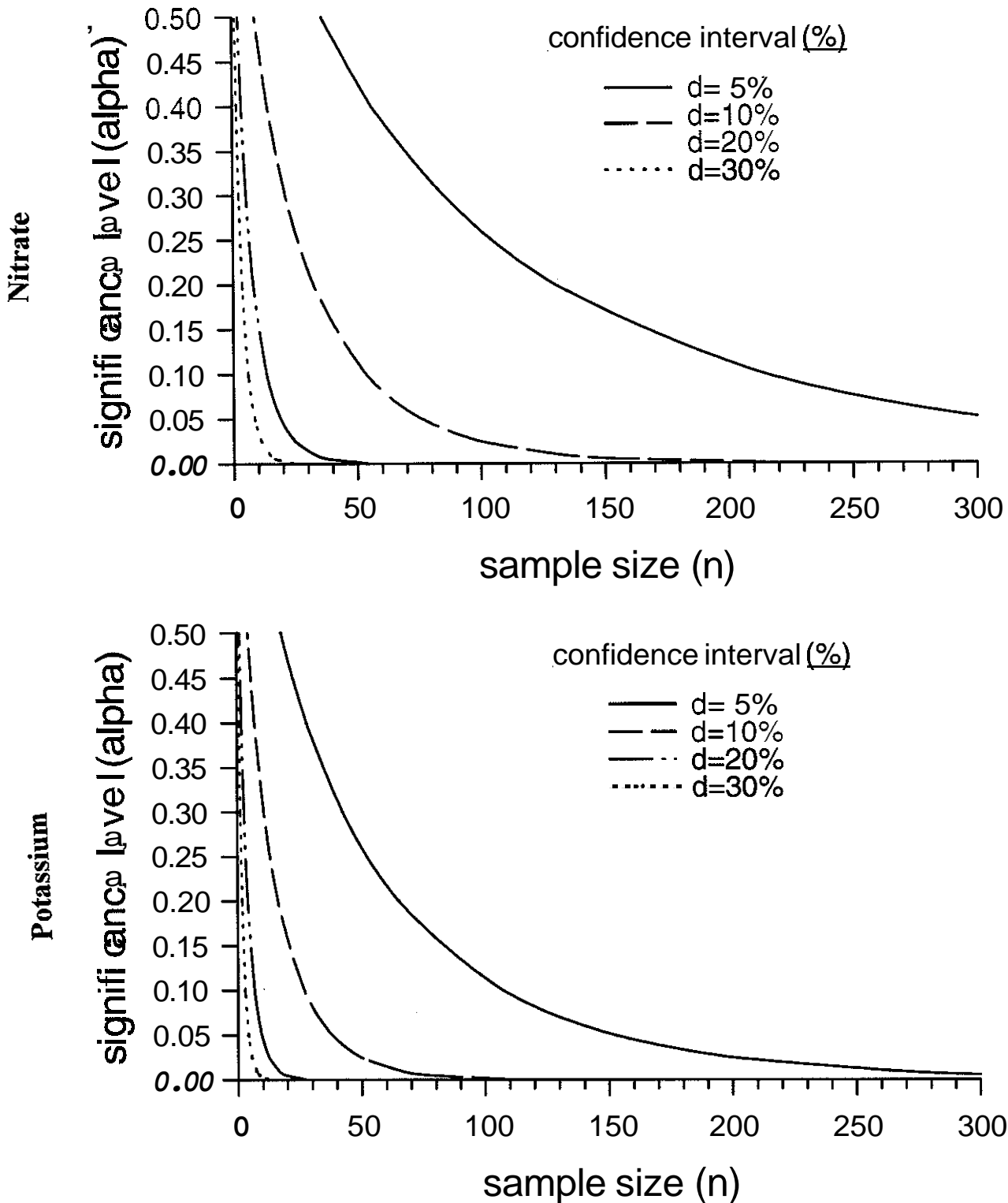


Figure 9. Theoretical sample sizes required for given significance levels (α) at four confidence intervals (5, 10, 20, 30% of mean), derived from annual mean nitrate and potassium concentrations (5.6 and 1.5 mg L^{-1} , respectively) at 90 cm in a Norway spruce stand and the minimum CV observed (44.5% and 31.5% , giving standard deviations of 2.49 and 0.47 , respectively) during biweekly sampling over a 1-year period (derived from data in Manderscheid and Matzner 1995). Curves derived from $n = t^2_{(\alpha, df)} s^2 / d^2$, where n = sample size, t = t-value for given significance level α and degrees of freedom df , s = standard deviation, and d = confidence interval.

Foster *et al.* 1989). However, Starr (1985) used porous glass cups in a forest soil and demonstrated that spatial variability for a set of soil solution samplers also varies over time, with the greatest variation in pH and Ca concentration occurring following high rainfall inputs of these ions. However, the greatest variation in $\text{NH}_4\text{-N}$ and K occurred after a week of low rainfall, and spatial variation in $\text{PO}_4\text{-P}$ was irregular. Notwithstanding relatively large standard deviations, individual lysimeter systems showed similar trends over time. Coefficients of variation for mean chemical concentrations from six lysimeter systems over nine sampling dates ranged from 56% to 181% (n = maximum of 54). Grossmann and Kloss (1994) examined changes in coefficients of variation of mean concentrations of solutes in the soil solution over time, and also concluded that coefficients of variation changed through the season, as well as mean concentrations themselves. This has particular implications when choosing a sampling date for collecting data with which to calculate the number of samplers to be used to achieve a predetermined accuracy when estimating the mean.

An analysis of temporal variation in one study showed that temporal variability was the largest source of variation for most ions, with the exception of total S and $\text{NO}_3\text{-N}$ (David and Gertner 1987). By contrast, Beier and Hansen (1992) found that spatial variability was greater than temporal variability. However, $\text{NH}_4\text{-N}$ was again the most variable ion studied, with variability between 10 samplers being >200% as compared with 20-60% for other variables (volume, K, Na, Ca, Mg, Al, H^+ , C). Potassium was the second most variable ion, and the high spatial variability of $\text{NH}_4\text{-N}$ and K in the very uniform stand studied was attributed to the effects of biological activity. Lord and Shepherd (1993) also found that spatial variability could completely mask temporal variability for nitrate concentrations in agricultural soils. Regarding the temporal variation in mean concentrations, Lord and Shepherd (1993) found that as few as four sampling occasions over the winter months were required to estimate nitrate leaching losses from agricultural fields within 10% of values estimated from samples taken no more than 14 days from each wetting event. However, the authors concluded that sampling at 14-day intervals (and more frequently during unusually wet periods) is required to ensure that the effects of uneven rainfall events are taken into consideration.

4.4 Frequency Distribution of Data and Data Transformations

The use of parametric methods of statistical analysis assumes that data has a normal distribution. When data is not normally distributed, transformations can be carried out to normalize their distribution so that the general assumptions required for parametric statistical tests are not violated. Common transformations include the logarithmic, square root, arcsine, and reciprocal transformations, as well as the more complex Box-Cox transformation. If data are transformed for analysis with parametric methods, then data descriptors such as means, standard errors and confidence limits will all be in transformed units, and, hence, comparisons with previous results are difficult, if not impossible, to make. These transformed units may then be back-transformed (or inverse transformed) to the original units of measurement, but three general rules apply (after Krebs 1989): (i) only means and confidence limits can be converted back to original units of measurement; (ii) variances, standard deviations or standard errors may not be back-transformed, as they will then have no statistical meaning; (iii) means calculated from transformed data cannot be back-transformed and then statistically compared with untransformed data. The issue of whether original data is normally distributed or not therefore has ramifications on whether data should be transformed before being analyzed, and also on whether arithmetic means or back-transformed means should be presented in figures and tables.

It would appear from published studies that, when tested, data from lysimeter systems are usually not normally distributed. For example, with soil solution samples collected from porous cup lysimeter systems, White *et al.* (1987) in Lord and Shepherd (1993) found that nitrate concentrations were positively skewed and that a logarithmic transformation was required to normalize the data. Lord and Shepherd (1993) examined data from Lord (1992) in which 43 fields were each monitored for nitrate with 10 porous cup solution samplers, and also concluded that mean soil solution concentrations with large coefficients of variation often showed distributions which were positively skewed due to a relatively small number of locations with large values. This was further demonstrated for nitrate by

Cuttle (1992) who suggested the use of the Sichel estimator for data analyzed after logarithmic transformations.

Beier and Hansen (1992) concluded that variances for ionic concentration values were heterogeneous, and therefore logarithmically transformed data before analysis. Artiola and Crawley (1994) also found that electrical conductivity (EC) and sodium adsorption ratio (SAR) data from both porous cup and zero tension glass brick lysimeter systems were not normally distributed. While a natural log transformation somewhat improved the goodness of fit for porous cup data, the improvement was still not significant, and the transformation had no influence on zero tension data. Grossmann and Kloss (1994) examined data from Grossmann *et al.* (1991) and concluded that various transformations $x_T^{1/2} = x^{0.5}$, $x_T^{1/3} = x^{1/3}$, $x_T^{1/4} = x^{1/4}$, and $x_T^{1/5} = x^{1/5}$ for concentrations of K, Na, Ca, Mg and H^+ obtained from porous cups all deviated less from the normal distribution than the original untransformed data, but that the logarithmic transformation was usually the best. Similarly, Paré *et al.* (1993) found it necessary to transform soil solution concentration data $x_T^{1/2} = \log(x+1)$ for NH_4-N , NO_3-N , PO_4-P , K, Ca, Mg, Al, Fe and SO_4-S obtained from porous cup lysimeter systems before carrying out statistical analyses. From ground-water samplings, Strebel and Bottcher (1989) concluded that most solute concentrations tested (NO_3-N , K, Na, Ca, Mg, Al, Cl, SO_4-S) were log-normally distributed, with the exception of pH⁵⁷. However, NO_3-N and Al under some conditions were neither normally nor log-normally distributed, and therefore geometric means were derived. Furthermore, the authors concluded that the distribution of K and Na shifted from normal to log-normal with increasing sample size. By contrast, Manderscheid and Matzner (1995) concluded that concentrations of NO_3-N , K, Na, Ca, Mg, Mn, Al, Cl, SO_4-S and H^+ determined with porous cup lysimeter systems in a Norway spruce forest were normally distributed, and no transformations were required.

Regarding the frequency distribution of related soil variables, Nielsen *et al.* (1973) demonstrated that variations in water content are normally distributed but

that values of hydraulic conductivity and soil-water diffusivity are log-normally distributed. Baker and Bouma (1976), Baker (1977) and Lauren *et al.* (1988) also determined that hydraulic conductivity is log-normally distributed. In a study of forest floor properties, Arp and Krause (1984) concluded that only pH is normally distributed, whereas frequency distributions of nutrients (N, P, K, Ca, Mg, Fe, Al, C) and physical properties (weight depth, moisture content) were generally positively skewed. Similarly, Sheppard *et al.* (1992) found that soil solution samples obtained after centrifugation required log-transformation before analysis.

As a result of the difficulties encountered in analyzing non-normal soil solution concentration data, some authors (e.g. Sollis and McCorison 1981) have chosen to simply judge differences between years and treatments by an examination of graphical presentations of the data.

4.5 Stratified Sampling

As indicated above, data sets with large coefficients of variation often have frequency distributions which are positively skewed due to a relatively small number of locations with large values. Where warranted, some form of stratification of the data may therefore be necessary to estimate a more accurate flux of nutrients from a site. For example, Kung and Donohue (1991) have recently drawn attention to the need to understand the non-random patterns of preferential flow through macropores, fingers or funnels in the soil. If soil solution samplers are not placed in the soil to sample this preferential flow then random sampling alone may underestimate both sample volume and peak concentrations.

Systematic sampling may also be of benefit in ecosystems where vegetation imposes a pattern on soil processes. For example, Grossmann and Kloss (1994) systematically installed porous cup solution samplers in a stratified design with equal numbers of samplers in 16 classes based upon distance to the nearest stem in a spruce forest. The authors found that nutrient concentrations were generally positively correlated with the influence of trees, and speculated that this was the result of nutrient inputs in stem flow, litterfall, and the influence of roots. Likewise, Koch and Matzner (1993) and Manderscheid and Matzner (1995) found that the

⁵⁷ As pH is already logarithmically derived from H^+ concentration, it should be converted back to H^+ concentration before determinations of data distribution, transformations, means, or statistical tests are carried out.

spatial heterogeneity of the soil solution in forests can be related to distance to stems.

In specific studies, mammalian behaviour can also create patterns in nutrient cycling processes in the soil. Cuttle (1992) showed that spatial variability of nitrate concentrations in samples obtained from porous ceramic cup samplers in pasture studies could be further confounded by the concentrating of livestock dung and urine in discreet "camping areas" where animals tended to congregate.

In each of the above studies, systematic patterns of nutrient movement may result in skewed data if purely random sampling is used to obtain soil solution samples. As skewing is generally positive, simply transforming the data to improve the goodness of fit to a normal distribution curve may lead to underestimates of the mean, and some form of stratification may be required to more accurately determine nutrient concentrations or fluxes in the soil. Furthermore, where monitoring the transport of highly toxic compounds is of concern, random sampling may even be inappropriate because of spatial variability, and locating samplers in individual preferential pathways may be preferable for determining the presence or absence of the compound (Steenhuis *et al.* 1994a).

4.6 Recommendations

From an examination of the literature it is evident that the magnitude and relative importance of sources of variation will vary, depending on the type and size of soil solution sampler, depth of installation, site, and nutrients or soil solution properties being examined. While determination of sample size is usually carried out a *posteriori* as part of a retrospective analysis, determination of sample size is a necessary (albeit laborious) first step that should be included in major studies where the financial or management consequences of not being able to estimate means with enough accuracy to meet study objectives after the fact are judged to be unacceptable. Coefficients of variation vary through the growing season, so the sample size required to meet specific predetermined accuracies should be calculated at a time of the year when variability is the greatest. From the few available studies, this is likely to be in the spring. Sample size determination will also be a function of the nutrients or parameters under investigation. Nutrients whose

mobilities are largely a function of biological activity are likely to be most variable (e.g. $\text{NH}_4\text{-N}$, $\text{NO}_3\text{-N}$, $\text{PO}_4\text{-P}$, K). The data on differences between the variability of results from tension and zero tension lysimeter systems are contradictory, and the degree of variability will be a function of lysimeter system design and size, as well as soil physical properties and preferential flow patterns. It is apparent from the literature that 10 to 20 soil solution samplers are usually required to estimate population means within 70% of true values for many nutrients. If available forms of nitrogen are of concern, then the sample sizes required for accurate estimates of population means can be extremely large and even as many as >200 samplers may only give estimates within 70% of true values. Realistically, financial constraints will limit the number of samplers that can be used in most studies, and beyond a certain threshold there will be a diminishing return in accuracy for increasing sample size. However, initial capital and installation costs are likely to be only a small proportion of overall maintenance and analytical costs over the duration of a study, and initial investments in an adequate number of lysimeter systems to meet the objectives of the study is essential.

The frequency distribution of the data should be tested for normality before carrying out parametric statistical tests. Although some nutrient concentration data appears to be normally distributed, most data must be transformed, usually by a logarithmic function. Alternatively, untransformed data may be analysed using standard non-parametric statistical methods. If data are not normally distributed, then bulking of samples to reduce analytical costs is not warranted. Furthermore, graphical and tabular presentation of back-transformed means would be more representative than the use of arithmetic means. Use of a Sichel estimator may be helpful in estimating mean values, and in some cases stratification of the data may be warranted, especially when calculating fluxes of nutrients. Where soil solution samples are collected at regular intervals, use of time series analysis (e.g. Chatfield 1989) may prove to be useful.

5. CONCLUSIONS

A large range of lysimeter system designs are available, and many permutations and combinations of soil solution samplers, tension-generating systems, and collection vessels can be used. Studies using lysimeter

systems should be well planned, and consideration should be given to: (i) the overall aims and goals of the study; (ii) the site and soil conditions; (iii) the solutes in the soil solution which are to be measured; (iv) the tension with which the soil solution component of interest is held; (v) the frequency of sampling (*i.e.* length of collection interval) that is feasible or that is required to be able to analyze for the solutes of interest⁵⁸; (vi) analytical laboratory capabilities and costs; (vii) the number of samplers required to obtain statistically reliable data and to carry out the statistical tests required to meet the aims of the study; and (viii) the water flow model to be used to determine solute fluxes. Many studies may require the use of several types of lysimeter systems on the same site in order to sample different components of the soil solution (*i.e.* both zero tension and tension lysimeter systems).

An appropriate sampler unit can then be chosen that will fulfil the aims of the experiment, based upon: (i) sampler size; (ii) sampler material and contamination effects; (iii) pore diameter (for tension lysimetry); and (iv) cost. Once the choice of sampler unit is made, care must be taken before field installation that: (i) the integrity of soil solution samples is not compromised by the non-sampler parts of the lysimeter system; (ii) appropriate pre-installation cleaning procedures are used (especially for tension soil solution samplers); and (iii) tension lysimeter systems are tested in the laboratory for vacuum leaks.

Installation procedures will depend upon site and soil conditions, and the lysimeter system being used. Good sampler-soil contact is important, and with tension samplers this can be improved by placing a slurry of sieved soil around the sampler, or by packing the sampler in silica flour. Installation artefacts that cause channelling of rain water or surface flow down protuberances and into samplers should be minimized by the use of bentonite or plastic shields, where appropriate. Soil disturbance during installation should be minimized, and the area around the soil solution samplers protected from trampling. This inevitable soil disturbance during installation should be followed by a stabilization period during which soil solution samples may be collected to enhance exchange equilibrium between solutes and the

lysimeter systems, but samples may not be representative of the actual undisturbed soil solution. Protection from damage by animals and frost, and ease of future access should be considered when designing installation procedures.

Zero tension lysimeter systems sample freely draining soil water, and hence are usually more useful than tension lysimeter systems for sampling preferential flow. However, tension lysimeter systems are needed to sample the soil solution held more firmly in the soil matrix. Bypass flow can occur around both zero tension and tension soil solution samplers, so fluxes of solutes are best estimated from solute concentration data and water flow models developed for the soils under study, and generally not from the volume of water collected by lysimeter systems.

Constant, decreasing and variable tension-generating systems all sample different components of the soil solution, depending on soil moisture conditions. The use of greater tensions will lead to sampling of components of the soil solution held in smaller pore spaces with greater resident times and usually greater solute concentrations. Solute concentrations in the smaller pores may not necessarily be representative of concentrations in the faster flowing components of the soil solution. Recent advances in the micro-electronic industry may lead to increased application of electronically controlled lysimeter systems for automatically regulating tension, and recording flow, pH and conductivity, as well as other parameters.

The choice of lysimeter system design and resultant cost of installation is likely to be a small proportion of the overall cost of sample collection and analysis, especially if a study is designed to extend over a number of years. A careful review of pertinent literature is therefore a prerequisite to establishing a reliable lysimeter system study, as initial choices will affect the long-term reliability of data.

In all lysimetry work, clear design details should be reported so that work can be easily reproduced or compared. Important information includes (where applicable): sampler size, materials used, pore diameter, air entry tension, pre-installation washing procedure, tension applied, vacuum system, and collection interval. Indicating sources of materials, especially of tension solution samplers, may be of help to other workers.

⁵⁸ This will be shortest for volatile pollutants, then nutrients which might undergo microbial transformations, and longest when only water volume flow is being measured.

In any given study, several lysimeter system designs may be required on one site to adequately monitor the soil solution. There is no universal design that will meet all requirements, and the need for compromise will be inevitable. No lysimeter system will perfectly sample the soil solution, and the relative shortcomings of the designs used must be borne in mind when interpreting results. While great strides have been made in the development of lysimeter systems over the past 50 years, it is still true that

no one construction should be regarded as standard in a lysimeter and... a proper design can be made only by having an accurate knowledge of both the purpose of the experiment and of the pedologic, geologic, and climatic conditions. (Kohnke et al. 1940)

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³ In German, with English summary including figure labels; contains diagram that clearly describes lysimeter design; virtually identical to Czeratzki (1971a) but with several additional paragraphs.

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Appendix 1

Translation of de la Hire (1720)¹.

Observations on rain water and the origin of fountains², with some particulars on the construction of cisterns

by Monsieur de la Hire

18 April 1703

Everything having to do with water, whether for the necessities of life or the embellishment of palaces and gardens, has always been regarded as one of the chief sciences **necessary** to mankind. Great pains have been **taken to make very small rivers** capable of **carrying** large vessels, and by this means to join together seas very **distant from** one another. Very abundant fountains have been brought by long detours and over very high aqueducts to places where no natural ones existed. Finally, a large number of **machines** have been invented to raise water and **carry it** to the tops of mountains, and then distribute it in a thousand different figures with **supernatural** movements, creating a spectacle worthy of admiration. This was enough for most people. But the **curiosity** of those investigating the secrets of nature was not yet **satisfied**; it was necessary to determine the origin of those abundant fountains which are encountered throughout the world, even on high rocks; and this is what has given so much exercise to philosophers, both ancient and modern.

There are two main opinions concerning the origin of fountains, each of them based on experience which it seems impossible to doubt. For it is obvious that many fountains originate in **rain** water and the melting of snow

on the mountains. But how could such rain and snow, which are very rare on steep, high rocks and in very hot countries, provide the very abundant and permanent fountains which are seen there in many places?

This is the strongest objection made by those who are not of the opinion that the rain creates fountains. They only admit of the existence of underground cavities in the form of stills, in which the vapour from the water which flows into the earth at sea level rises up through crevices in the rocks, and is condensed by the cold of the earth's surface.

Monsieur Mariotte, who followed the opinion of those who support the rain theory, did a very careful **study** of the rain and snow water which falls on the part of the earth which provides the River Seine with its waters. He found from his calculations that there was far more such water **than** would be necessary to maintain the river in its average state throughout the course of a year.

While examining the treatise on the origin of fountains by Mr Plot, an Englishman, which was printed in 1685, I made several observations, which I read at that time to the meetings of the Academy. I then undertook to determine for myself what amount of water could be supplied to fountains and rivers by rain and snow. I began determining what quantity of rain water was falling on the earth during a whole year, and since that time I have given memoranda on the subject to the Academy at the end of each year. This shows that the height of water which falls at the Royal Observatory, where I conducted my observations, would be 19 to 20 inches' in an average year, approximately as Monsieur Mariotte had assumed in his study.

But since I doubted that we could count on such a quantity of water for the origin of fountains, I did the following experiments to assure myself of it.

¹ This work was carried out in 1688, presented in 1703, and published in 1720 in the *Memoires de l'Academie Royale des Sciences*, pp. 56-69. It is included for historical interest as it is sometimes cited **as an** example of the earliest published work on **lysime**try. Translated by Translation Services, Public Works and Government Services Canada, Halifax. Typescript of original work in French available on request from the senior author.

² From the context of the entire work, fountain may often be replaced by spring.

³ Pouce (*pouces*) has been translated as inch (inches). Determining the exact SI equivalent to pouces as used in 1720 has not **been** possible; it cannot necessarily be assumed that one pouce is exactly equivalent to a modern inch.

I chose a site on the low terrace of the Observatory, and in 1688 I had a lead basin with an area of 4 feet⁴ buried in the earth at a depth of 8 feet. This basin had sides 6 inches high, and was slightly sloped toward one of its corners, to which I had a lead pipe 12 feet in length soldered. The extremity of this pipe, which had a fairly steep slope, led into a small cellar. The basin was at distance from the wall of the cellar, so that it would be surrounded by a larger quantity of earth similar to that which lay over it, and could not become dried out because of the proximity of the wall. In this lead basin, toward the opening which led into the pipe, I placed several pebbles of different sizes, so that the opening could not become plugged when the earth had been filled in over it to the height of the terrain, that is to say, to a height of 8 feet. This terrain was of an intermediate nature between sand and loam, so that the water could penetrate it quite easily; its outer surface was level.

I thought that if the water from rain and melted snow penetrated the earth until it encountered a loam or clayey earth through which it could not pass, as those who follow the first opinion about the origin of fountains maintain, the same thing should happen to the lead basin I had buried, and that finally I would have a kind of spring, which would flow through the pipe leading into the small cellar.

But as I was not persuaded that this could happen, at the same time I subjected to experimentation another device, at a depth of only 8 inches in the ground: this was a basin with an area of 64 inches and sides 8 inches high. I had chosen a spot where there was no sun or wind, and taken great care to remove all the plants growing on the earth over the basin, so that all the water that fell on the earth could pass without hindrance right to the bottom of the basin, where there were a small hole and a pipe to carry into a vessel all the water which was able to penetrate the earth. This basin was not exposed to the air, but buried in a very large box, filled on the sides and underneath with the same earth as was on the inside, so that the earth in the basin could not be dried out by the air.

⁴ *Pied (pieds)* has been translated as *foot (feet)*. Determining the exact SI equivalent to *pieds* as used in 1720 has not been possible; it cannot necessarily be assumed that one *pied* is exactly equivalent to a modern foot (e.g. one "Paris foot" is equivalent to 1.066 feet, or 32.484 cm).

I first observed that from 12 June until 19 February of the next year, water did not flow through the pipe underneath the basin, and that it *only* did so then because of a large amount of snow which was melting on the ground. Afterwards, the earth in the basin was always very moist, but the water did not flow until a few hours after it had rained, and it ceased flowing when the rain water was exhausted; for a certain amount always remained in the earth, but did not pass through until there was fresh rain on top.

A year later, I repeated the experiment in the small basin; but I placed it at a depth of 16 inches in the earth, which was twice its original depth. There were no plants on the earth over it, and it was again sheltered from the sun and wind. Roughly the same thing happened as before, except only that when a considerable time had passed without rain, the earth dried out somewhat, and a moderate rain occurring subsequently was not capable of wetting it enough, with the moisture that remained in it, to cause a flow of water.

Finally, I planted a few plants in the earth over the basin; but when the plants had achieved some growth, not only did no water flow after the rain, but also all the rain which fell was not enough by itself to sustain them, and they withered and dried out *unless* they were watered from time to time.

I then had the idea of measuring the dissipation or evaporation of water through the leaves of the plants when they were exposed to sunlight and wind. On 30 June, at half-past five in the morning, I placed in a glass vial with a narrow opening one pound⁵ of water, measured very carefully with the vial. I gathered two fig leaves of moderate size, together weighing 5 drams⁶ and

⁵ *Livre (livres)* has been translated as *pound (pounds)*. Determining the exact SI equivalent to *livres* as used in 1720 has not been possible; it cannot necessarily be assumed that one *livre* is exactly equivalent to a modern pound. In British usage, one pound is equivalent to 16 oz. avoirdupois (all goods except precious metals and stones, and medicines), or 12 oz. Troy (used for gold and silver; probably from the town of Troyes in France) where 1 pound Troy = 5760 grains (Fowler and Fowler 1956).

⁶ *Gros* has been translated as *dram*. Determining the exact SI equivalent to *gros* as used in 1720 has not been possible; it cannot necessarily be assumed that one *gros* is exactly equivalent to a modern dram. (In Apothecary weights, one

48 grains', and soaked the ends of the stalks in the water in the vial. These leaves were very fresh and firm when I picked them. Finally, I exposed the vial and the leaves to the sun, which was bright and hot, in a place where there was a little wind, and I carefully plugged with paper the rest of the neck of the vial, which was not filled by the stalks of the leaves, so that the water in the vial could not evaporate through the opening.

At eleven o'clock in the morning I weighed everything together, and found that there had been a decrease in weight of 2 drams, which the air and the sun had drawn in the form of water from the leaf; a decrease which could only be made good, when the leaf was attached to the tree, by the moisture from the earth passing through the roots.

I also did several other experiments on plants, and always found a very great dissipation of moisture; and after measuring the area of the leaves, and considering what usually covers the earth, I judged that the rain, especially in summer, although it was then very abundant, was not capable of maintaining them without assistance from elsewhere. It is true that the night air provides big trees and even plants with a large amount of moisture, which is nearly always seen on the leaves around sunrise, and which by making its way into the roots can maintain the plants for part of the day; but this moisture all by itself would not suffice for their sustenance unless they drew some from the earth itself and from the rain water which enters it, as I observed in my experiments, which I have just reported.

All these experiments showed me that the water from the rains which fall on the earth, where there are always some plants and trees, cannot penetrate two feet into the earth unless it has been collected in sandy or stony places, through which it can easily pass. But these can only be particular cases, from which no general

dram is equivalent to 60 grains, or 1/8 ounces; in avoirdupois, one dram is equivalent to 27 1/3 grains, or 1/16 ounces; after Fowler and Fowler 1956.)

⁷ Grains has been translated as grains. **Determining** the exact SI equivalent to grains as used in 1720 has not been possible; it cannot necessarily be assumed that one grain is exactly equivalent to a modern grain. (One grain is equivalent to 1/5760 of a pound Troy; or 1/7000 of a pound Avoirdupois; after Fowler and Fowler 1956.)

conclusion can be drawn. We can see an example of this at the Rocher de la Sainte Baume, in Provence. The rain that falls on this rock, which is all split and fissured, and where there are no plants, penetrates into the grotto within a very few hours, to a depth of 67 fathoms⁸ below the surface of the rock, and forms a very fine cistern there which would in fact be a fountain if it were filled. And when we encounter on similar rocks, and at considerable depths, large quantities of snow which melt in summer by the sun's heat alone, we observe large flows of water from some fountains for a few hours of the day, and even on several occasions if the sun only shines on the snow at certain hours of the day, with the snow being in the shadow of the peaks of the rocks the rest of the time, and unable to melt easily. This is no doubt why it has been reported that in inland locations there are fountains which ebb and flow like the sea.

These experiments persuaded me that I could not expect the water from the rain and snow to pass through the 8 feet of earth overlying the lead basin which I had buried on the terrace of the Observatory; also, not a single drop of water has flowed through this pipe in 15 years.

We can thus see that there may be but very few fountains which originate with the rain and snow, and we must necessarily resort to other causes to explain how such very abundant springs can be encountered in high places, and at very little depth in the earth, such as the spring at Rungis, near Paris, which cannot be attributed to those grottoes or underground stills by which the water from condensed vapour is distilled; for there are no rocks in the environs, as I have determined from several wells which I had sunk there, and the terrain is only slightly elevated in places where wells have been sunk whose water is very close to the surface of the earth, and higher than the place where the water was collected. This spring provides approximately 50 inches of water, which flows constantly and suffers little change, and the whole space of earth whence it can come is not large enough to provide the water of this spring by collecting rain water, even if none were dissipated; and in addition, it is always cultivated and covered with plants and wheat. There are small valleys quite close to

⁸ Toise (*toises*) has been translated as *fathom* (fathoms). **Determining** the exact SI equivalent to fathoms as used in 1720 has not been possible; it cannot necessarily be assumed that one fathom is exactly equivalent to a modern fathom (*i.e.* 6 feet).

this spot where one has ~~to~~ dig very deep to find water.

It has been thought that these kinds of springs could be explained by natural pipes and channels which brought the water from a small, elevated river, and which, passing through high and low places, and even underneath the rivers which crossed them, were so tightly fused together and plugged that they did not allow the water to escape along the way to the place where it was ~~to~~ emerge from the **earth**. But even if such underground places existed, I am persuaded that they would only have enough slope to allow the water to flow underground over a bottom of loam or clay; but to imagine natural pipes, high and low, that is all that can be achieved by art in the extent of a small garden; and even then, such conduits must ~~often~~ be repaired.

It seems ~~to me that~~ a further ~~serious~~ objection can be made to ~~this~~ hypothesis. For if these large, elevated springs originate in rivers, these same rivers must also draw their water from other even more elevated springs; for the water from rain and melted snow in places with a firm bottom can only form torrents which last but a short ~~time~~, and cannot provide for the continual flow of such rivers. Large ~~bodies~~ of water, such as ponds which are commonly found at the heads of small rivers, prove nothing about the origin of the rivers, for we have done several experiments which show that from water which is exposed to the air in a very broad vessel, far more is dissipated than can fall from the sky.

Therefore only one way remains to explain how these abundant sources can form in the earth; and once again, ~~difficulties~~ are encountered. We have to imagine that through the earth there passes a large quantity of vapour rising from the water, which is usually at the same level as the nearest rivers ~~or~~ the sea, and that this vapour circulates more easily when it encounters a ~~terrain~~ which is more easily penetrated, as we observe in winter at the mouth of certain very deep caves. The ~~particles~~ of such vapour ~~can~~ join together, either because of the coldness of the earth's surface when they begin to approach it, ~~or else~~ when they encounter a terrain already filled with water with which they can combine, or else, finally, if they find matter capable of trapping them, as we see that salts exposed to the air will trap water particles which have been hovering about. Then this water, which is constantly augmented on encountering a bottom solid enough to support it, flows through the earth over ~~this~~ bottom until it escapes onto the surface. of

the **earth** where the bottom terminates, or else falls back into a lower place in the earth, if there are openings in the clay or loam which supports it. That is all that I find probable in ~~this~~ case; and even so, the vapour must have special conduits to pass through, and through which the water it forms cannot escape.

I wished to see by experimentation what could be expected of the manner of condensing the water vapour if it were attached in the **earth** ~~to~~ stones filled with salts, for I had a new idea for explaining how the water from vapour in the earth could be gathered together.

In one of the cellars at the bottom of the quarry of the Observatory I placed a **glass** vase and attached to the lip of the vase a piece of cloth which I had ~~soaked~~ in a little water in which I had dissolved some tartar salt. I chose this salt, because I believed that it was more capable of trapping vapour than any other salt would be. The place appeared very damp, especially in summer. Some time later, I found at the bottom of the vase a fairly large quantity of liquid, which was nothing but water from the vapour in the air which had attached itself to the cloth, the cloth having become filled with it, the ~~surplus~~, which was still increasing, had flowed down the sides of the vase. I could have carried the experiment ~~further~~, to see whether the liquid would have continued ~~to~~ flow, and whether the salt in the cloth had been entirely carried away by the flowing water, although it may ~~be~~ that stones containing salts capable of trapping vapour might be able ~~to~~ permanently retain their salt and even pick up more; but someone entered the cellar in my absence and broke the vase, and my experiment was interrupted.

I am not speaking of particular, extraordinary fountains which are said to be found at the seaside and on high rocks, and which ebb and flow ~~like~~ the sea, but nevertheless contain very fresh water. I have explained in mechanical terms how that could occur, by supposing that there are underground reservoirs somewhat above sea level, and that the cavity in which these reservoirs are located communicates with the sea by means of channels. For it must happen that when the sea rises, it compresses the air in such a cavity, which in turn presses down on the water in the reservoir, and compels it to escape, and even to rise through crevices and conduits in the rocks to the surface. of the earth, where it forms a fountain which must diminish gradually as the sea withdraws and the compressed air which forced it ~~to~~ rise

is reestablished in its earlier state. But with a little knowledge of mechanics and a clear understanding of the effects of liquid bodies, one will not lack means to explain not only the marvels of this kind seen in nature, but also everything that could be imagined.

I have spoken enough of the origin of fountains, and must now explain some particular observations I made at that time on the uses to be derived from rain water. The greatest advantage of rain water is that it can be collected in underground reservoirs called cisterns where, after it has been purified by running through river sand, it keeps for several years without spoiling. This water is usually the best of all the kinds one can use, whether for drinking or for employment for a number of purposes, such as laundering and dyeing, in that it is not mixed with any salt from the earth like nearly all fountain water, even that which is considered to be the best. Such cisterns are very useful in places where there is no spring water or when all the well water is bad. This is not the place to speak of the construction of cisterns or of the choice of materials that should be used for the purpose, since it is simply a matter of having a place which holds the water well, and of the stones and mortar which hold them together not being able to communicate any bad property to the water, which is held for a considerable length of time.

Those who have cisterns and are anxious to have good water take great care not to allow any water from melted snow into the cistern, or any water from rain storms. I believe there is good reason for excluding snow melt from cisterns, not because of the salts people imagine to be contained in it, mixed in with the particles of snow, but only because the snow usually remains for several days, and sometimes whole months, on the roofs of houses, where it is corrupted by the droppings of birds and animals, and even more by the long period of time it remains on the tiles, which are always very dirty. It is for that reason that when it begins to rain, I would recommend that the first water running into the cistern from the roof be rejected as bad, since it has only served to wash the roofs, which are covered with the dust which rises from the dried soil in the streets and high roads, and that only the rain which comes later be collected in the cistern.

There is another very important observation concerning water to be rejected from cisterns, which I learned only by chance. A few years ago, I was

interested in collecting rain water falling at the Observatory with the basin I use for measuring the amount of water which falls during the year. This basin is of well-tinned iron, with an area of 4 feet, and sides 6 inches high. There are a bole and a small pipe soldered to one of its comers, through which the water falling into the basin, which is slightly sloped toward that comer, is carried into a vessel, in which it is collected so that it can later be measured, and the quantity which has fallen can be determined. I cleaned and washed the basin and the vessel which collected the water as promptly as possible at the start of a rain which appeared abundant, and I then collected the water in very clean glass bottles in order to keep it. But when I tasted this water, I was surprised by the fact that it had a very bad taste, and smelt like smoke, which struck me as very unusual, for I had often tasted water which had been collected in the same way but did not have the same taste. I could see nothing that could have communicated such a smoky smell to the rain water, for the place where I collected it was very open and elevated, and there was no chimney that was not very far away. But finally I concluded that the rain water had fallen in a north wind, which was not very usual, for it seldom rains with such a wind; and as the whole city lies to the north of the Observatory, the smoke from the chimneys was mixed into the water which was falling and then passing over the place where I was collecting it; and finally, that this was the real cause of the bad smell of the water; for we know from many experiments that water very readily takes on the smell of smoke. Indeed, I assured myself of this some time later, for having once again collected rain water falling in a south or southwest wind, I observed nothing similar with respect to the taste, for there are only large stretches of countryside extending southward from the Observatory.

From this I concluded that one should also reject from cisterns any rain water brought in by winds passing over places infected with a bad smell, such as sewers, dumps and even large cities, because of the smoke, as I have just pointed out; for the exhalations and bad vapours which are mixed in with the water entering the cistern must corrupt any water that entered it at another time.

Finally, since from all the experiments and tests that have been done we cannot doubt that purifying rain water in river sand to remove the sediment and earthy smell it has as it falls from the sky is the best and most wholesome method of all those which can be used, I

have considered how in all houses cisterns could be built which would provide enough water for the persons living there.

First, it is certain that an ordinary house, with an area of 40 fathoms, and covered with roofs, can collect 2160 cubic feet of water each year, supposing the rainfall to be only 18 inches, which is the smallest amount I have observed. But these 2160 cubic feet are the equivalent of 75 600 pints⁹ of water, at a ratio of 35 pints to the foot, which is the proper measurement for the Paris pint". If, then, this number of pints is divided by the 365 days of the year, it comes to 200 pints per day. We can see from this that if there were 25 persons in a house such as the one I am assuming, they would each have 8 pints of water to expend, which is more than one ordinary bucket, and more than enough for all the usages of life.

The only remaining point is for me to give an opinion about where and how to build cisterns of this kind in private houses. In many cities of Flanders, by the seaside, where all the well water is salt and bitter, because the terrain is only a light sand through which the water from the sea is not purified, we see that people use cisterns in each house for their private purposes. But these cisterns are buried, and are only small cellars in which it is believed that water keeps better than in the air. Now it is true that water, especially rain water, does not keep in the air, because of the sediment it contains, and which is not entirely deposited on passing through the sand, and it becomes corrupted, with a kind of green moss which grows on it and covers it entirely. That is why I would recommend that in each house a small space be built, whose floor would be about 6 feet above the ground floor, and that this place not occupy, at most, more than one-fortieth or one-fiftieth of the area of the house, which would, in our example, amount to roughly one fathom. This space might be 8 to 10 feet high, well vaulted with very thick walls. In it I would place a lead reservoir, which would collect all the rain water after it

had passed through the sand. This space would only have a very small door, very thick and well fitted with straw matting, to prevent the frost from reaching the water. By this means very good water could be readily distributed to the kitchens and washing places. Since the water would be properly enclosed, it would not spoil any more than if it were underground, and it would never freeze. Its slight elevation above the ground floor would be enough to ensure it could readily be distributed in all the lower rooms of the house. Such a reservoir could be placed in a location where it would be no more a nuisance because of its humidity than the fountain water reservoirs found in many houses.

I recently studied the various samples of rain water which I had collected formerly, and had kept in glass bottles. I found that some had a bad taste, but I cannot state whether these are the ones which first had a smoky odour when I had put them in the bottles. The others were quite good and pleasant; they had no more of an earthy taste than any other rain water, and this was perhaps because they had deposited a sediment which is usually seen at the bottoms of receptacles in which rain water has been left to stand for some time.

I will also add an observation I made concerning the water from fountains on the north side of the Butte de Montmartre. This water is very clear and very good to drink. However, if one cooks meat and ordinary pot herbs with this water, the broth is very bitter. This cannot be attributed to the nature of the plants of the place, for if rain water is used to make the broth, it is very good and has no bitterness.

⁹ *Pinte (pintes)* has been translated as *pint (pints)*. Determining the exact SI equivalent to *pints* as used in 1720 has not been possible; it cannot necessarily be assumed that one *pint* is exactly equivalent to a modern pint.

¹⁰ 35 pints = 4.37 gal = 19.86 L, but 1 ft³ = 30.483³ cm³ = 28,319 cm³ = 28 L. Note discrepancies, based on assumption that de la Hire's units are equivalent to modern units.

Appendix 2. Comparison of different non-hierarchical classification schemes for lysimeter system designs by Kohnke *et al.* (1940), Wilson (1980), Momson (1983), Homung (1989), Dorrance *et al.* (1991), Anon. (1993b) and the present review.

Kohnke *et al.* (1940): Tension lysimeter systems were still under development and not yet widely used, so all designs described are zero tension designs. Authors use term “*undisturbed*” to describe soil in monoliths and soil above Ebermayer lysimeter samplers; all other lysimeter systems are “*filled-in*” and therefore by definition the soil is “*disturbed*”.

1. construction
 - 1.1 monolith (or undisturbed soil block, bounded by impermeable material)
 - 1.2 Ebermayer (or “*Russian*”, consists of funnel beneath undisturbed soil in the field)
 - 1.3 filled-in (bounded by impermeable sides; filled with disturbed soil, which is often screened and mixed before adding)
2. run-off
 - 2.1 unlimited run-off (all Ebermayer designs, **plus** some monolith and filled-in designs)
 - 2.2 overflow pipes
 - 2.3 no run-off (the great majority of filled-in designs, and a number of monoliths)
3. provision **for** weighing
 - 3.1 weighing
 - 3.2 non-weighing
4. soil contact (drainage)
 - 4.1 soil rests directly on lysimeter sampler material
 - 4.2 soil rests on drainage bed (sand, gravel)

Wilson (1980): Reviews vadose zone monitoring, and thus not all categories are relevant to nutrient cycling studies.

1. solution sampling in unsaturated media
 1. ceramic-type samplers
 - 1.1 suction cups
 - 1.1.1 vacuum operated soil-water samplers (*e.g.* Wagner 1962¹)
 - 1.1.2 vacuum-pressure samplers (*e.g.* Parizek and Lane 1970)
 - 1.1.3 vacuum-pressure samplers with check valves (or “*hi pressure-vacuum soil-water sampler*”? (*e.g.* Wood 1973)
 - 1.2 filter candle (*e.g.* Duke and Haise 1973)
 2. cellulose-acetate hollow fibre samplers (*e.g.* Jackson *et al.* 1976)
 3. membrane filter samplers (*e.g.* Stevenson 1978)
2. water sampling **from** saturated regions **of** the vadose zone
 - 2.1 tile lines
 - 2.2 collection pans and manifolds (*e.g.* Parizek and Lane 1970)
 - 2.3 wells
 - 2.4 piezometers
 - 2.5 multilevel samplers
 - 2.6 ground-water profile samplers

¹ Inferred from text.

Appendix 2 (Cont'd.) Comparison of different non-hierarchical classification schemes for lysimeter system designs by Kohnke *et al.* (1940), Wilson (1980), Momson (1983), Homung (1989), Dorrance *et al.* (1991), Anon. (1993) and the present review

Morrison (1983): Reviews ground-water monitoring technology and therefore includes many designs for deep wells and boreholes, as well as more traditional lysimeter system designs commonly used in nutrient cycling studies.

1. lysimeters for "soil porewater sampling"²

1.1 vacuum pressure³

- 1.1.1 ceramic cup (*e.g.* Wagner 1962)
- 1.1.2 nylon (*e.g.* Quin and Forsythe 1976)
- 1.1.3 fritted glass (*e.g.* Chow 1977a)
- 1.1.4 Teflon® (*e.g.* Momson 1982)

1.2 vacuum plates and tubes⁴ (plate, ceramic tube, cellulose fibres or tubes)

1.3 membrane filter samplers (polycarbonate or cellulose acetate filters, filter paper)

1.4 absorbant methods (cellulose nylon sponge, ceramic point)

2. lysimeters for "monitoring in the zone of saturation"⁵

2.1 drainage systems⁶ (tiles, perforated PVC drains)

2.2 trench and caisson lysimeters⁷

2.2.1 trench

2.2.1.1 pan (*e.g.* Parizek and Lane 1970)

2.2.1.2 trough (*e.g.* Jordan 1968)

2.2.2 caisson (*e.g.* Aulenbach and Clesceri 1980)

2.3 monitoring wells (single screened wells, well points, well clusters, single wells with multiple sampling points, gas lift samplers, hybrid well systems, piezometers)

Anon. (1986): Review of methods for monitoring unsaturated soil for hazardous waste sites.

1. suction samplers

1.1 ceramic-type samplers

1.1.1 suction cups

1.1.1.1 vacuum operated soil-water samplers (*e.g.* Wagner 1962⁹)

1.1.1.2 vacuum-pressure samplers (*e.g.* Parizek and Lane 1970)

1.1.1.3 vacuum-pressure samplers with check valves (*e.g.* Wood 1973)

1.1.2 filter candle (*e.g.* Duke and Haise 1973)

1.2 cellulose-acetate hollow fibre samplers (*e.g.* Jackson *et al.* 1976)

1.3 membrane filter samplers (*e.g.* Stevenson 1978)

2. free drainage Lysimeters

2.1 pan lysimeters (*e.g.* Parizek and Lane 1970)

samplers installed through the walls of *caissons* (*e.g.* Aulenbach and Clesceri 1980 differentiate between caissons used for installation and access, and the *soil* solution samplers installed through the caisson walls).

⁸ Morrison (1983) states that these are also known as "*Ebermayer designs (also called zero tension lysimeters)*".

⁹ Inferred from text.

² Includes mainly *tension lysimeter* designs.

³ Defined as lysimeters that "*collect soil pore water by creating a vacuum within the sampling vessel; pore water moves toward the sampler and enters the vessel through a porous section of the lysimeter*". Therefore only cups (*after* Wagner 1962) are included in this category, as plates, candles and fibre bundles are included in the next category (1.2). However, the *main* principles of concern in collecting a solution sample include geometry and size of the sampler, porosity, and the type of tension applied; whether the *soil* solution is collected within the lysimeter itself or in external collection vessels is of less importance.

⁴ Includes candles and fibre bundles.

⁵ Includes mainly *zero tension Lysimeter* designs.

⁶ Cf. Dorrance *et al.* (1991) "*drainage samplers*" for sampling "*perched groundwater*".

⁷ This categorization might more usefully refer to installation methods, as *pan* and *trough* lysimeters are both installed in the faces of pits or trenches, and *caisson* lysimeters consist of

Appendix 2 (Cont'd.) Comparison of different non-hierarchical classification schemes for lysimeter system designs by Kohnke *et al.* (1940), Wilson (1980), **Momson** (1983), Homung (1989), Dorrance *et al.* (1991), **Anon.** (1993*b*) and the present review.

Hornung (1989): Review of lysimeter system designs useful for soil solution sampling, with an emphasis on plant nutrients. Includes review of soil solution and sampler interactions, sample contamination, and sampled soil volume and calculation of element fluxes.

1. isolated soil masses'' (soil enclosed in container, in laboratory or field)

- 1.1 disturbed

- 1.2 undisturbed (*e.g.* Caider 1976, Belford 1979)

2. tension/vacuum/suction samplers''

(includes: ceramic cups, ceramic tubes, ceramic plates, Alundum® plates, acrylic plates¹², plastic cups, Teflon® rings, Teflon® cups, sintered nickel cups, cellulose-acetate hollow fibres, fritted glass tubes, non-cellulosic hollow fibre tubing, fritted glass plates, ceramic candles)

- 2.1 cup and (*e.g.* Wagner 1962) and ring-based samplers (*e.g.* Morrison 1982)

- 2.2 porous plate samplers (*e.g.* Cole 1958)

- 2.3 fritted glass tubes (*e.g.* Long 1978)

- 2.4 hollow fibres (*e.g.* Silkworth and Grigal 1981)

3. tensionless collectors

- 3.1 trough, box and funnel-based collectors (*e.g.* Jordan 1968)

- 3.2 sheet or tray-based collectors (*e.g.* Parizek and Lane 1970)

- 3.3 tensionless collectors on sloping sites (*e.g.* Roose 1968)

¹⁰ In distinguishing soils as disturbed or undisturbed, Homung (1989) follows the original classification of Kohnke *et al.* (1940).

¹¹ Hornung (1989) does not categorize lysimeters based on different types of tension (constant, decreasing, variable).

¹² Note that Homung (1989) bases lysimeter design on disk used to support SiC powder rather than on the powder itself (Bourgeois and Lavkulich 1972*a,b*).

Appendix 2 (Cont'd.) Comparison of different non-hierarchical classification schemes for lysimeter system designs by Kohnke *et al.* (1940), Wilson (1980), Momson (1983), Homung (1989), Dorrance *et al.* (1991), Anon. (19936) and the present review.

Dorrance *et al.* (1991): Only review "in situ **pore-liquid samplers**" (*i.e.* tension lysimeter systems) for vadose zone (*i.e.* unsaturated zone, or zone of aeration), with an emphasis on ground-water monitoring. The authors recognize two categories based on sampling soil monoliths (bounded mass of soil) or unbounded soil *in situ*, and only review designs for the latter (see also Wilson *et al.* 1994a).

1. suction **samplers**¹³ (unsaturated/saturated sampling)
 - 1.1 vacuum lysimeters¹⁴ (*e.g.* Wagner 1962)
 - 1.2 pressure-vacuum lysimeters¹⁵ (*e.g.* Parizek and Lane 1970)
 - 1.3 high pressure-vacuum lysimeters¹⁶ (*e.g.* Wood 1973)
 - 1.4 filter tip samplers" (*e.g.* Haldorsen *et al.* 1985)

2. experimental suction samplers" (unsaturated/saturated sampling)
 - 2.1 cellulose-acetate, hollow fiber samplers (*e.g.* Levin and Jackson 1977)
 - 2.2 membrane filter samplers (*e.g.* Stevenson 1978)
 - 2.3 barrel lysimeter¹⁹ (*e.g.* Homby *et al.* 1986)
 - 2.4 vacuum plate samplers (*e.g.* Cole 1958)
3. experimental absorption samplers (unsaturated/saturated sampling)
 - 3.1 sponge samplers (*e.g.* Tadros and McGarity 1976)
 - 3.2 ceramic rod samplers (*e.g.* Shimshi 1966)

¹³ Categories vary based on method of sample retrieval from increasingly greater **soil** depths, rather than on **soil** solution sampling procedure which generally consists of variations on the original porous cup design.

¹⁴ **Vacuum lysimeters**: generally porous cups *after* Wagner (1962), with **a** single tube for access; sample is retrieved by **lifting** to the soil surface by vacuum, so therefore they cannot be placed deeper than 7.5 m, which is the maximum height that water can be lifted **by** suction.

¹⁵ **Pressure-vacuum lysimeters**: **like** vacuum lysimeters, but modified *after* Parizek and Lane (1970); sample collected in the tubular body of the lysimeter under vacuum is retrieved using pressure to force sample up a second tube to the surface.

¹⁶ **Highpressure-vacuum lysimeters**: like pressure-vacuum lysimeters, but modified with one-way check valves and transfer vessels or chambers to lift from greater depths without having to use so much pressure that lysimeters are damaged or sample is pushed back out into the soil.

¹⁷ **Filter tip samplers**: evacuated sample vials used to mechanically retrieve soil solution after **puncturing** septum at permanent tip of sampler with hypodermic needle.

¹⁸ Usually limited to research applications because of fragility; not generally commercially available.

¹⁹ Encased, undisturbed **soil** core with pressure-vacuum cup lysimeters installed in base.

Appendix 2 (Cont'd.) Comparison of different non-hierarchical classification schemes for lysimeter system designs by Kohnke *et al.* (1940), Wilson (1980), Morrison (1983), Hornung (1989), Dorrance *et al.* (1991), Anon. (1993b) and the present review.

4. free drainage samplers'' (saturated sampling)

- 4.1 pan samplers (*e.g.* Parizek and Lane 1970)
- 4.2 glass block lysimeters²¹ (*e.g.* Barbee and Brown 1986)
- 4.3 caisson lysimeters" (*e.g.* Schmidt and Clements 1978)
- 4.4 wicking soil pore-liquid samplers²³ (*e.g.* Homby *et al.* 1986)
- 4.5 trough lysimeters (*e.g.* Jordan 1968)
- 4.6 vacuum trough lysimeters²⁴ (*e.g.* Montgomery *et al.* 1987)
- 4.7 sand filled funnel samplers²⁵ (*e.g.* Brown 1980)

5. perched ground-water samplers (saturated sampling)

- 5.1 point samplers²⁶ (*e.g.* Reeve and Doering 1965)
- 5.2 wells'' (*e.g.* Everett *et al.* 1984b)
- 5.3 cascading water samplers²⁸ (*e.g.* Wilson and Schmidt 1978)
- 5.4 drainage samplers²⁹

²⁰ Could also be termed *zero tension lysimeters*.

²¹ This design is essentially a pan lysimeter made of glass, with the **soil** solution collecting in a chamber beneath the pan, and probably does not warrant a separate category.

²² Caisson refers more to the installation method than actual functioning of the **soil** solution sampler itself.

²³ Unique design that combines attributes of trough lysimeters (**pan** collecting freely draining **soil** solution) and suction samplers (soil solution wicked down a hanging water column of about 4 kPa tension).

²⁴ Unique design consisting of porous ceramic pipe in trough that combines attributes of **trough** lysimeters (samples freely draining soil solution) and **suction samplers** (**soil** solution sampled under tension through porous ceramic pipe); **similar** in concept to **wicking soil pore-liquid sampler** above.

²⁵ No different in concept from **trough** lysimeter above, except that the soil rests on a bed of sand rather than a mesh material.

²⁶ **Point samplers**: open-ended pipes or wells with short screens for sampling a discreet depth interval.

²⁷ **Wells**: like point sampler, but screened over greater depth.

²⁸ For sampling when water from a perched water table "cascades" down a well and mixes with water at the bottom of the well that comes from the water table.

²⁹ **Drainage samplers**: sampling from drainage lines installed to alleviate soil problems caused by perched water tables, rather than to sample soil solution *per se*; *cf.* Momson (1983) "**drainage systems**" under **lysimeters for "monitoring in the zone of saturation"**.

Appendix 2 (Cont'd.) Comparison of different non-hierarchical classification schemes for lysimeter system designs by Kohnke *et al.* (1940), Wilson (1980), Morrison (1983), Homung (1989), Dorrance *et al.* (1991), Anon. (1993b) and the present review.

Anon. (1993b): Main categories are for tension (suction) and zero tension (free-drainage).

direct soil-solute sampling: suction methods

1. suction methods

- 1.1 vacuum-type porous cup (*e.g.* Wagner 1962)³⁰
- 1.2 vacuum-pressure porous cup (*e.g.* Parizek and Lane 1970)³⁰
- 1.3 vacuum high-pressure porous cup (*e.g.* Wood 1973)³⁰
- 1.4 vacuum-plate sampler (*e.g.* Cole 1958)
- 1.5 membrane filter (*e.g.* Stevenson 1978)
- 1.6 hollow fibre (*e.g.* Levin and Jackson 1977)
- 1.7 ceramic tube sampler (*e.g.* Duke and Haise 1973)
- 1.8 capillary wick sampler (*e.g.* Holder *et al.* 1991)
- 1.9 BAT sampler (*e.g.* Haldorsen *et al.* 1985)³⁰

direct soil-solute sampling: other methods

2. free-drainage samplers³¹

- 2.1 trench lysimeter (*e.g.* Parizek and Lane 1970)
- 2.2 caisson lysimeter (*e.g.* Aulenbach and Clesceri 1980)
- 2.3 pan lysimeter (*e.g.* Parizek and Lane 1970)³⁰
- 2.4 glass block lysimeter (*e.g.* Barbee and Brown 1986)³⁰
- 2.5 wicking type sampler (*e.g.* Homby *et al.* 1986)
- 2.6 tile drain outflow (*e.g.* Thomas and Barfield 1974)

3. perched water table

- 3.1 perched water table (*e.g.* Wilson and Schmidt 1978)

4. absorbant methods

- 4.1 nylon sponge (*e.g.* Tadrdo and McGarity 1976)
- 4.2 ceramic rod (*e.g.* Shimshi 1966)

³⁰ Reference deduced from literature but not directly referred to in Anon. (1993b).

³¹ Authors also distinguish between *open trench/caisson* and *buried trench* installations, depending on whether or not the pit used for installation is left open or back-filled.

Appendix 2 (Concl'd.) Comparison of different non-hierarchical classification schemes for lysimeter system designs by Kohnke *et al.* (1940), Wilson (1980), Morrison (1983), Hornung (1989), Dorrance *et al.* (1991), Anon. (19936) and the present review.

Present review: Emphasis is on state of the soil being sampled and tension used to obtain soil solution samples, rather than on description of materials used in construction of samplers or on means of retrieving samples, as the latter include designs that are highly inter-changeable within the four main categories.

1. confinement of soil

- 1.1 confined³² (soil bounded by impermeable vertical walls)
- 1.2 unconfined (no boundary to impede lateral soil water movement)

2. disturbance of soil''

- 2.1 undisturbed (soil left intact; may be either confined or unconfined)
- 2.2 disturbed (soil excavated and placed either in confined vessel or in pit, sometimes after sieving and **mixing**)

³² Includes both "*monoliths*" and "*filled-in lysimeters*" *sensu* Kohnke *et al.* (1940).

³³ *After* Kohnke *et al.* (1940).

3. type of tension applied

3.1 zero tension³⁴

3.2 tension³⁵

- 3.2.1 constant tension (*e.g.* hanging water columns)
- 3.2.2 decreasing tension (*e.g.* Wagner 1962)
- 3.2.3 variable tension³⁶ (*e.g.* Rasmussen *et al.* 1986)

³⁴ No tension applied, and samples freely draining soil solution only; category is not further broken down; "*pan*" and "*trough*" are not used as categories, as images **are** not always clearly distinguishable (see Tyler and Thomas 1977 where pan is used to describe an "*Ebermayer*" lysimeter, which is usually referred to as a *trough*); the difference **between** these two is more in mode of installation rather than operation; "*trench*" and "*caisson*" categories are not recognized as these are methods of installation rather than operation; unique categories **containing** only one lysimeter design such as "*glass block*" are not recognized.

³⁵ Description of type of tension in sampler during sampling interval.

³⁶ Tension differential between **soil** and sampler only large enough to obtain **soil** solution sample is **maintained** over time through tension measurements taken **in** the **soil**, and a feed-back mechanism.

Appendix 3. Conversion of units of soil moisture tension (**pressure**) to SI units (*after* Morrison 1983, Soil Science Society of America 1987, Soilmoisture Equipment Corp. 1994, Campbell Scientific (Canada) Corp. 1994, Wilson et al. 1994a).

<u>1 kPa¹ is equivalent to</u>	<u>to convert to kPa multiply number by</u>
1 centibar (= 10 millibar = 0.01 bar)	1
0.009869 atmospheres	101.327
0.335 feet of water (= 4.016 inches of water)	2.985 (0.2490)
10.200 cm of water	0.09804
0.29530 inches of Hg (at 0°C)	3.38638
0.7500616 cm of Hg (= 7.500616 mm of Hg)	1.33333 (0.13333)
0.14504 pounds per square inch	6.89465
10 ⁴ dynes cm ⁻²	10 ⁻⁴

¹ The Soil Science Society of America (1987) recommends use of MPa, and the Canadian Society of Soil Science recommends kPa.

Appendix 4. Determination of pore diameter and air entry tensions for porous soil solution samplers.

Air entry tension (or air entry value, bubbling pressure) is the pressure required to force air **through** a thoroughly wetted porous material. This measurement is used to calculate pore diameter'. Because of their differences in properties, pore diameter of hydrophilic (e.g. Alundum®, ceramic, glass, stainless steel) materials are ~~determined~~ in water, and hydrophobic (e.g. PTFE, some plastics) materials are determined in alcohol (methanol or ethanol). However, in practice it is the tension at which air can be drawn through water-filled pores that will determine the limitations of the use of a material in the field, and this can be tested by measuring the amount of pressure required for bubbles to form on the surface of a thoroughly wetted sampler submerged in water. The theoretical relation of pore diameter to air entry tension can be determined from the following formula (after Morrison 1982, Everett and McMillion 1985, Everett et al. 1988, Soilmoisture Equipment Corp. 1994):

$$[1] \quad D = 30\gamma/P$$

where: D = pore diameter (pm)
 γ = surface tension of water (dynes cm⁻¹) = 72 dynes cm⁻¹ at 20°C
P = air entry tension (mm Hg; 7.500616 mm Hg = 1 kPa)

Through substitution, P (kPa) = $(30 \times 72/D)/7.501$, or P (kPa) = $287.999/D$ (μm).

Air entry tensions may also **be** calculated from Jurin's Law (Lemon and Ference 1943 in McGuire et al. 1992), also known **as** the "capillary rise equation" (Hanks and Ashcroft 1980 in Wilson et al. 1994a):

¹ Or *pore size* (e.g. Wilson *et al.* 1994a). Note that "pore cross-sectional**area**" might be a better **term**, as pore *diameter* infers that the cross-sectional shape is circular, and pore *size* suggests volume rather than cross-sectional shape.

$$[2] \quad \Delta p = 2\gamma(\cos \alpha)/r$$

where: p = pressure
 γ = solution surface tension
 α = contact angle between **solid** and liquid
 r = radius of pore

or **from** the following derivation (Schubert 1982 in Grossmann and ~~Udlnft~~ 1991):

$$[3] \quad p_c = -2\sigma(T)\cos\alpha(rgD_l)^{-1} \times 10^{-9}$$

where: p_c = capillary pressure (MPa)
 σ = surface tension² (N m⁻¹)
 T = temperature
 α = contact angle
 r = radius of pore (m)
 g = gravitational constant (m s⁻²)
 D_l = density of the liquid (kg dm⁻³)

Equation [1] does not take into account differences between hydrophilic and hydrophobic materials. However, the contact angle (α) in the capillary **rise** equation is <90° for hydrophilic materials and between 90° and 180° for hydrophobic materials (Grossmann and Udlnft 1991). In practice, bubbling pressure should be determined by direct testing in water rather than by derivation from pore diameter formulae (Wilson et al. 1994a).

² Note that **surface tension** is represented as γ in equations [1] and [2], although it **is** represented as σ in equation [1] by Soilmoisture Equipment Corp. (1994).

