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Sampling the vadose zone in stony alluvial gravels using suction cups

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Abstract

Three different techniques were evaluated for installing suction cups in an alluvial gravel vadose zone—a steel spike, a mechanical auger, and an air rotary drilling rig. Soil water samples were collected from suction cups monthly for three years. Nitrate and chloride concentrations in samples taken from the suction cups were similar to those measured from a linear lysimeter installed in the same field. The nitrate and chloride concentrations in the suction cup samples showed significant spatial and temporal variation consistent with leaching from random urine patches. Solute concentrations became less variable as sampling depth increased, so fewer suction cups would be required at greater depths to estimate mean concentrations of solutes leaching to groundwater. Recharge was estimated using a water balance model and combined with the concentration data to give solute fluxes or leaching losses. Averaging the fluxes from all of the suction cups indicates a fairly constant leaching loss of around 50 kg $ha^{-1}yr^{-1}$ for nitrate-N (range = 38–58 kg $ha^{-1}yr^{-1}$) and around 80 kg $ha^{-1}yr^{-1}$ for chloride (range = 79–89 kg $ha^{-1}yr^{-1}$).

The total cost for the construction and installation of the suction cups ranged from $290 for the 1.3 m depth spike installation to $620 for the 5 m depth suction cups installed using an air rotary drilling rig. The major difference in price between the three installation methods relates to their depth limitations and the higher cost of equipment that can install suction cups at greater depths. A significant limitation of the auger installation was the disturbance of the soil profile caused by the large diameter hole that was excavated. For the installation of suction cups in stony alluvial sub-soils, we recommend using spike installation for depths of less than 1.5 m and air rotary drilling for depths of greater than 1.5 m.

Keywords

Porous ceramic suction cups, lysimeter, unsaturated zone, nitrate, chloride.

Introduction

Monitoring of the vadose or unsaturated zone for solutes or contaminants provides an early warning of vadose zone and groundwater contamination. This is particularly important where the water table is deep and where a substantial depth of the vadose zone could become contaminated before there was any indication from groundwater monitoring (Wilson, 1990). The vadose zone is often monitored at waste management sites or in areas where land use is changing. Variations in contaminant sources, in soil properties and recharge amounts often result in spatial

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variability in the leaching of contaminants. Sufficient sample points are therefore required to provide robust estimates of contaminant leaching. A system using relatively low-cost sampling devices would allow an adequate number of sample points to be monitored and would encourage wider use of vadose zone monitoring for contaminants.

Contaminant movement in the vadose zone can be monitored using suction cup samplers, lysimeters, soil cores, or a combination of these devices (Patterson *et al.*, 2000; Wilson, 1983). Lysimeters are generally limited to the upper 1 m of the soil profile. While fine-grained media can be readily cored to some depth, there are major difficulties in coring through stony profiles. Augers of the diameters required for stony profiles may significantly disturb the site, preventing repeat samples at the same location. Because of these restrictions on other devices, porous suction samplers are commonly used to obtain soil water samples in the vadose zone (Wilson, 1990). They can be operated at a range of depths and are relatively cheap to manufacture and install. However, installing and operating suction samplers in an alluvial gravel vadose zone can be difficult. Alluvial gravel profiles are widespread in New Zealand and coarse sand and gravel layers are often encountered within 0.5 m of the surface. Typical d_{50} (median diameter) values range from 13–20 mm, for example (Pang *et al.*, 1998), with gravels exceeding 100 mm in diameter being common. Alluvial gravels are often associated with the most widespread and valuable groundwater resources in New Zealand and more knowledge is required about contaminant transport through their vadose zones.

The stony subsurface creates several major problems for suction samplers. First, the low soil moisture content of the gravels results in very low volumes of soil water being sampled. Second, it is difficult to maintain adequate contact between the matrix and the suction cup. One solution to maintaining good contact is to embed the suction cup in fine silica sand (Wilson, 1990). Silica sand also has the effect of increasing soil water volumes, as the sand acts as a reservoir. Third, the stony nature of the profile makes the installation of suction cups more difficult.

In this paper we evaluate three different techniques for the installation of suction cups into alluvial gravel sub-soils. We report on the effect of different volumes of sand on soil water sample volumes and on the concentration of solutes. We compare soil water concentrations of nitrate and chloride with those measured by the linear lysimeter (an independent measurement technique), and assess the spatial and temporal variability as sampling depth increases.

Materials and methods

Experimental site

The study site is located near Te Pirita, in Central Canterbury (Fig. 1) on a stony Lismore soil (a Typic Dystrustept). The soil consists of 20–25 cm of silt loam over a small transitional sandy layer, with sandy gravels starting at around 25–30 cm, and it is typical of Lismore stony soils that cover a large portion of the Central Canterbury Plains. The gravels are coarse, with the larger cobbles often having diameters that exceed 10 cm. The site is on a farm that was converted in 1998 from dryland sheep farming to a dairy farm, with spray irrigation. The irrigation system used is a Briggs Rotarainer and typically applies 50-60 mm of water per irrigation event, at intervals of 12–28 days, depending on the rainfall and other climatic conditions. A linear lysimeter was used as an independent sampling technique for comparison of nitrate and chloride concentrations in the soil water. The linear lysimeter, which was developed by Lincoln Ventures, samples the drainage from an area of 12 m^2 at a depth of about 1.5 m. The drainage

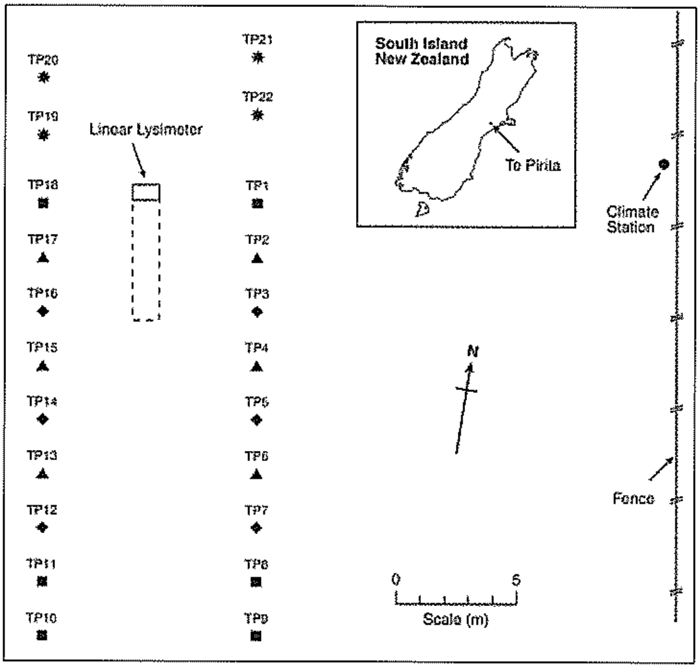


Figure 1 – Layout of the suction cups, linear lysimeter and climate station at the Te Pirita experiment site. ■ = spike installation at 1.3 m; ▲ = auger installation at 1.3 m; ◆ auger installation at 2.5 m; ✱ = air rotary drill installation at 5 m.

is measured separately and collected from 12 × 1 m^2 sub-areas, so spatial variability can be assessed. The linear lysimeter was installed at the site in 1998, and consists of a large steel cylinder that was lowered horizontally into a hole so that the top of the cylinder was at a depth of about 1.5 m. The cylinder was then pushed into the undisturbed gravel profile using hydraulic jacks, and gravels were excavated from the 'cutting' face of the cylinder. The cylinder is 9 m long and 1.2 m diameter, with 'wings' attached to both sides to create a collection gallery. It has an effective cross-sectional sampling area of 12 m^2 (Fig. 2). Drainage percolating down through the profile is intercepted by the cylinder and wings and directed through holes to the inside of the linear lysimeter, where the flux of leachate is measured with a tipping bucket and the leachate is proportionately sampled.

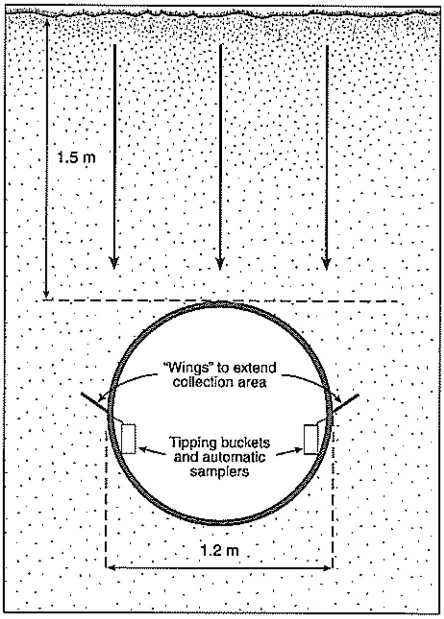


Figure 2 – Schematic of the Linear Lysimeter.

There is an access hatch (0.8 m^2) that is the only significant intrusion of the lysimeter on farming operations such as cultivation. Further details about the linear lysimeter and its testing and calibration are given in Bright (1999).

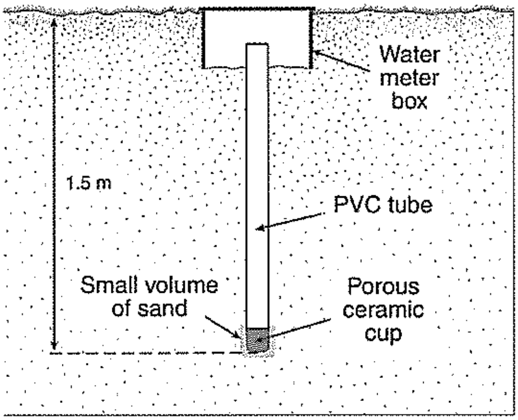
An automatic climate station, installed 40 m from the linear lysimeter (Fig. 1), records rainfall, solar radiation, wind speed and direction, relative humidity, dry bulb temperature and soil temperature at depths of 50 mm, 100 mm and 200 mm.

Installation methods for suction cups

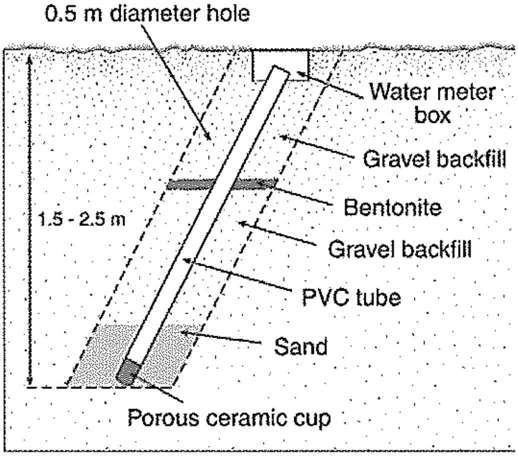
The ceramic suction cups used in the study were 1 bar, high-flow, round-bottomed cups, 56 mm long and 48 mm diameter, consisting mainly of alumina (Al_2O_3). They were leached with 10% HCl and then rinsed through with distilled water prior to use, as recommended by Wilson (1990). The suction cups were attached to lengths of 48 mm rigid PVC pipe and a vacuum seal cap was attached using epoxy resin. Two Teflon tubes were inserted through the cap—one tube for applying vacuum and pressure and the other tube, which extended to the bottom of the suction cup, for the delivery of the water sample. An access tube was used with the suction cup to allow easy access and maintenance of the suction cup. As the experimental site was a working dairy farm, all the suction cups were installed below ground level and were covered with water meter boxes to protect the samplers from stock and farm machinery and to allow access for sampling (Fig. 3).

The key factor that allowed the suction cups to work in alluvial gravel was the fine silica sand that surrounded the ceramic cups. The sand gave good contact with the surrounding gravels and provided a reservoir of soil water for sampling. The sand was Silica Fine Sand screened between 63 and 300 microns, and was obtained from Fulton Hogan. The sand had an average bulk density

A. Installation using spike



B. Installation using auger



C. Installation using air rotary drill

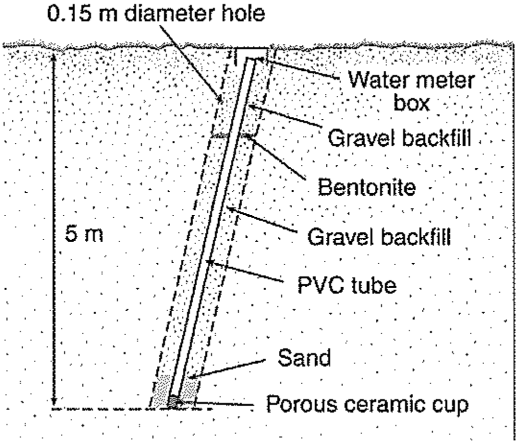


Figure 3 – Installation diagram for the suction cups at Te Pirita (not to scale).

of $1.54\,t\,m^{-3}$ and a total porosity (v/v) of 42%. The water-holding capacity of the sand was low at suction values below 10 kPa. The average volumetric water content at 10 kPa was 5.6%, but this increased to 20.8% at 5 kPa. Depending on the installation method used and size of the hole made, varying amounts of sand were placed at the required sample depth and the access tube was inserted into the top of the sand. The hole was then backfilled with gravel, bentonite, and then more gravel in the case of the auger and drill installation methods. A volume of sand, equal to the suction cup volume, was carefully reamed out and the suction cup was inserted, giving a good contact with the fine sand.

Three different installation methods were tested: a schematic is shown for each method in Figure 3. The first used a 1.6 m long steel spike that had a slightly larger diameter (63 mm) than the access tube (diameter = 60 mm). A hole was drilled through the end of the spike to assist with its removal. The spike was hammered into the ground to a depth of 1.3 m using a post-hole pile driver. A length of chain, together with a bolt through the hole, was used with the pile driver to lift the spike out. The access tube fitted tightly into the hole, and then the sand, suction cup, and water meter box were installed.

The second method used a mechanical auger. A large diameter (0.45 m) auger was required to lift the large stones to the surface. The movement of the auger as it excavated the hole created a much larger hole than anticipated, so a greater volume of sand was required to give the same depth for insertion of the suction cup. The sand was positioned using a funnel with a section of PVC pipe to direct the sand. Native gravels were backfilled on top of the sand, followed by a layer of bentonite, and then gravels up to 0.2 m below the surface. The sand and gravels were compacted several times during backfilling. The water meter box was installed and then a volume of sand was reamed out and the suction cup installed. The mechanical auger was used to install suction cups at depths of 1.3 and 2.5 m below ground level and the cups were installed at an angle of about 20° to maximise the amount of undisturbed profile sampled. The maximum installation depth for the mechanical auger in this type of unsaturated zone was about 2.5 m.

The third installation method used air rotary drilling. A 150 mm casing was used and the rig was tilted at an angle of about 15°. The installation depth was 5 m for these suction cups. The fine sand (5 L) was placed in the bottom of the casing, followed by native gravels, bentonite, then more gravels up to 0.2 m below the surface. The water meter box was installed and then a volume of sand was reamed out and the suction cup installed. In all the installations the gap at the top between the access tube and the suction cup was filled with silicon sealer to prevent the entry of water, dirt or insects.

Sampling and analysis

The suction cups were sampled by applying a vacuum (60 kPa), leaving overnight and then applying pressure to the vacuum/pressure tube and collecting the water from the sample tube. The volume was measured and it was noted whether there was still a vacuum present prior to sample collection. Samples were collected from the suction cups monthly. The linear lysimeter sampled the percolating water every 100 tips of the tipping bucket. The water samples were analysed for nitrate and chloride using ion chromatography.

Estimation of recharge and solute flux

Monitoring and comparison of solute concentrations in isolation can be misleading. Although soil water solute concentrations may be high, at low soil moisture levels they will not result in high fluxes to groundwater. The soil water concentrations need to be linked with recharge measurements or estimates to provide flux information, as it is the flux that would influence groundwater quality. Where suction cups are used for monitoring contaminant concentrations, recharge measurements may often not be available and may need to be estimated using a water balance. A simple soil water balance procedure, SOILMOD, described by Thorpe and Scott (1999), was used to estimate recharge. Rainfall data were obtained from the climate station at the site from July 1999 onwards and, prior to that date, rainfall data from a neighbouring farm approximately 2 km away was used. Potential evapotranspiration (PET) was calculated using the Penman-Monteith equation (Jensen *et al.*, 1990). Data for the potential evapotranspiration calculations were from a climate station at Lincoln, 32 km from the experimental site, for 1998–99 and from the experimental site from 2000 onwards. Actual evapotranspiration (AET) is a function of the potential evapotranspiration rate, soil moisture status and plant development. When potential evapotranspiration is low, actual evapotranspiration may equal potential evapotranspiration, even at relatively low soil moisture levels. At high potential evapotranspiration, actual evapotranspiration may be limited by the transpiration ability of the plant. Actual evapotranspiration decreases as soil moisture levels decrease, with the decrease occurring at higher soil moisture levels as potential evapotranspiration increases. The following approximation describing this relationship is given in Thorpe and Scott (1999):

$$\frac{AET}{PET} = 1 \text{ for } SM \geq WHC(1 - VC/PET) \quad (1)$$

$$\frac{AET}{PET} = \frac{SM/WHC}{1 - VC/PET} \text{ for } SM < WHC(1 - VC/PET) \quad (2)$$

where SM = soil moisture; WHC = water-holding capacity; and, VC is a vegetative cover factor.

The water-holding capacity of the soil was taken from soil moisture monitoring data from an adjacent farm (Lincoln Ventures, unpublished data) and estimated to be 80 mm. The vegetation factor generally ranges from 1.2–1.5 (Thorpe and Scott, 1999); as the pasture was on a well-irrigated dairy farm, the vegetation factor was likely to be at the high end of the range and was assumed to be 1.5 for this simulation. Irrigation events were taken from the farmer's records and the amount of water applied was taken to be 60 mm. The water balance was estimated on a daily basis. Soil moisture was equal to the soil moisture on the previous day plus rainfall and irrigation minus actual evapotranspiration. Recharge was calculated as the soil moisture excess over the water-holding capacity, and the soil moisture was reset to the water-holding capacity when recharge occurred.

Some studies have used a stratified approach to estimate nitrate leaching, for example, Di and Cameron (2002) used lysimeters to obtain measurements for urine-affected and non-urine affected areas, and then combined the results using estimates for the proportion of the field affected by urine patches. However, this approach was not possible in this field-based study, as sample events could not be reliably assigned into either urine-affected or non urine-affected categories. The nitrate concentrations were a continuum between samples definitely affected by urine and those that were unaffected. Some samples may have been partially affected by a urine patch and others affected by two or more urine patches. The non-stratified approach used in this study also gives an estimate of the mean leaching but usually requires more sampling points. The actual number of suction cups that is needed to provide an estimate of nitrate leaching within a given level of precision is discussed later in the paper.

Results and discussion

Soil water volumes

The volume of water collected by each suction cup with time is shown in Figure 4, grouped by depth and installation method, with summary statistics given in Table 1. The volume of water collected depended on several factors. The applied vacuum and the length of time suction was applied were held approximately constant, however, in a few cases the seals on the caps may not have been adequate to maintain the vacuum over the whole sampling time (approximately 20–24 hours). The caps and O-rings were checked periodically, particularly if sample volumes suddenly decreased. Changes in the soil moisture status could have significant effects on the volume of water collected. This can be seen most clearly for the 'spike' suction cups at 1.3 m, where the sample volume is more variable than that for the other installation methods and the sample volumes are highest during the winter period. Changes in the sample volume for the other suction cups are damped by the much larger reservoir of sand for the auger and air rotary drilling installation methods. In addition, soil moisture is expected to vary less at a greater depth. The effect of sand volume on the water sample volume can be seen in Table 1, where the average water volume increased as the volume of sand increased. The other factor that influences sample volume is the volume of the suction cup. For this particular design of suction cup, the deeper suction cups had a much larger volume and consequently a much larger volume of evacuated air. This results in larger sample volumes, other things being equal. This was particularly noticeable for the maximum sampled volumes, which increased with sampler volumes. This indicated that when soil moisture was not limiting, the final collected volume was limited by the capacity of the suction cup.

Soil tension measurements indicated a 'field capacity tension' for the suction cups of between 3–5 kPa. As the suction cups were evacuated to 60 kPa (average volumetric water content of sand = 3.1%) for sampling, the water available for sampling from the sand was 17.7% by volume. This equates to sample volumes from the sand ranging from 0.02–9.2 L (Table 1). Table 1 indicates that the mean sample volume was much greater than the volume associated with the sand for the spike sampler, much less for both auger samplers, and about the same volume for the 5-m-deep drilling rig sampler. This means that the two auger-installed samplers would be expected to show lags in concentration breakthrough curves associated with the large sand reservoirs. The 5 m samplers would, on

Table 1 – Summary of soil water volumes for each suction cup installation method. Available water from sand in the range of 5–60 kPa was 17.7% by volume.

Cup Installation Method	Spike	Auger	Auger	Drilling rig
Depth (m)	1.3	1.3	2.5	5.0
Sampler volume (L)	1.63	1.63	3.14	6.28
Sand volume (L)	0.1	31–42	52	5
Available water from sand (L)	0.02	7.4	9.2	0.9
Mean water volume (L)	0.12	0.84	1.02	0.97
Median water volume (L)	0.09	0.93	1.09	0.77
Range (L)	0.001–1.10	0.005–1.68	0.03–2.11	0.04–2.42

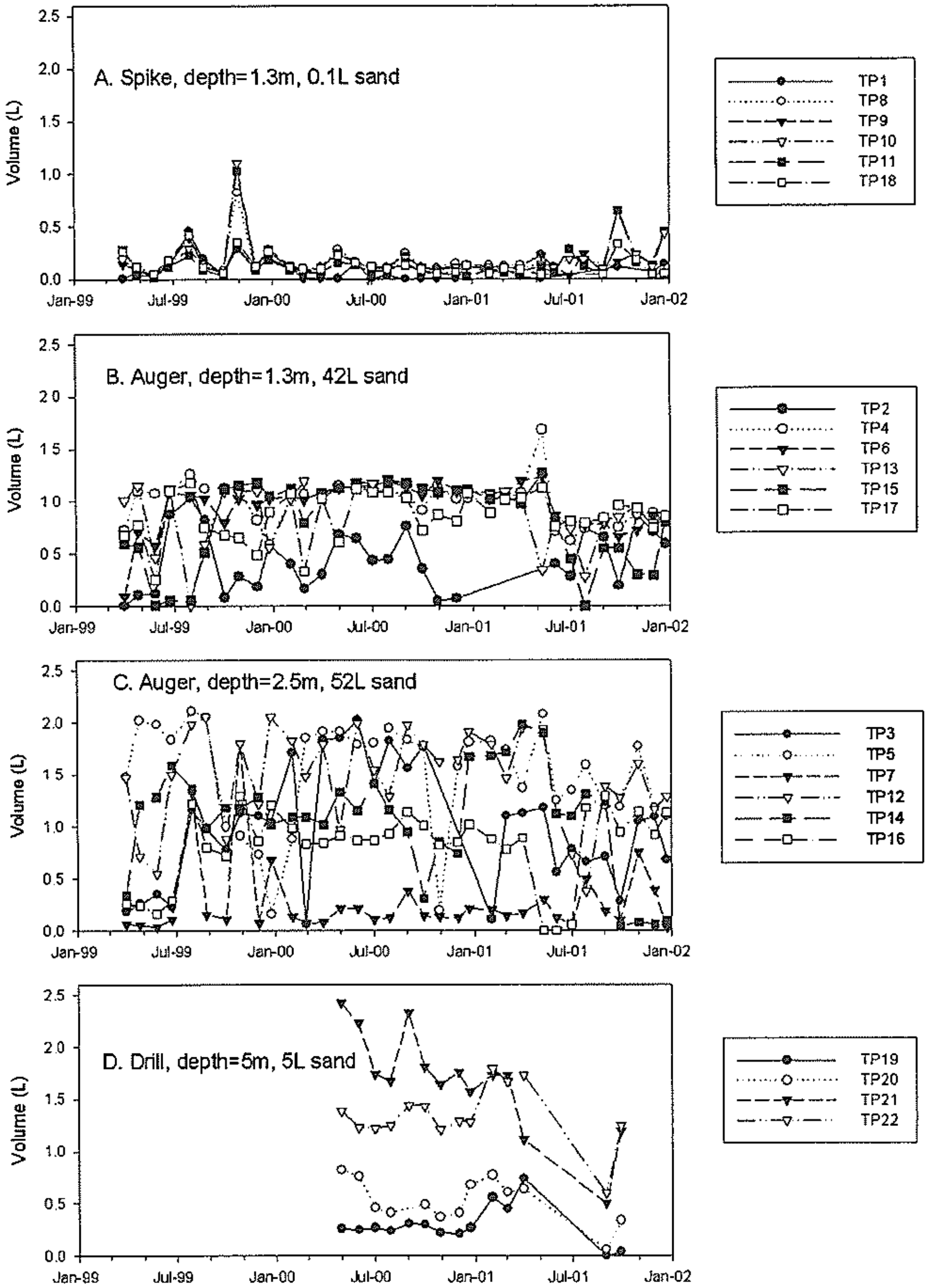


Figure 4 – Soil water volumes collected with time for each suction cup, separated by depth and installation method.

average, sample the water that had collected in the sand since the previous sampling occasion, and most of the water sampled from the spike sampler would be from the gravel media rather than the sand.

Nitrate and chloride concentrations

The nitrate and chloride concentrations over time for each suction cup, separated by depth and installation method are given in Figures 5 and 6. The summary statistics for nitrate and chloride (Table 2) indicate that the median concentrations were less than the mean concentrations. This type of skewed distribution is expected due to random high leaching of nitrate and chloride from urine patches. There was little difference in the mean concentrations of nitrate and chloride for different depths and installation methods. Most nitrate-N concentrations were less than 20 $g\,m^{-3}$, but there were significant peaks, up to 230 $g\,m^{-3}$, in individual suction cups at various times. The peaks could last for 3–6 months and would have been associated with deposition and leaching of urine. A similar pattern was evident for the chloride concentrations (Fig. 6), with the peaks in nitrate concentrations often being slightly preceded by a peak in the chloride concentrations. Nitrogen is excreted as urea, which needs to be transformed to ammonia and then to nitrate before it is readily leached; it therefore takes longer than chloride to leach. The correlation between the nitrate and chloride levels varied considerably, with the correlation coefficients between nitrate and chloride levels for individual suction cups ranging from 0.18–0.93. Some disturbance occurred as the suction cups were installed and it was possible that animal behaviour had an effect on the newly installed suction cups. The natural curiosity of cows resulted in obvious concentrations of dung, and by implication urine, around many of the suction cups for the first month. This effect can be seen in Figures 5 and 6 for several suction cups, with elevated levels of nitrate and chloride at the start of the sampling period. Similar concentrations were observed later in the study as well, but generally only in one or two suction cups at a time, consistent with the random deposition of urine by grazing animals.

Table 2 – Summary of nitrate and chloride concentrations for each suction cup installation method.

Cup Installation Method	Spike	Auger	Auger	Drilling rig	Linear Lysimeter
Depth (m)	1.3	1.3	2.5	5.0	1.5
Nitrate-N (gm-3)					
• Mean	9.6	15.5	11.4	11.0	8.8
• Median	5.2	7.1	7.4	7.8	4.4
• Range	0.4–97	0.9–230	0.1–66	1.6–48	0.4–138
• CV (%)	157	197	105	83	140
Chloride (gm-3)					
• Mean	14.6	19.9	22.0	19.2	15.0
• Median	10.0	12.0	17.3	15.0	10.8
• Range	1.9–77	0.9–140	2.0–85	3.7–64	1.6–121
• CV (%)	83	110	74	64	87

CV – coefficient of variation

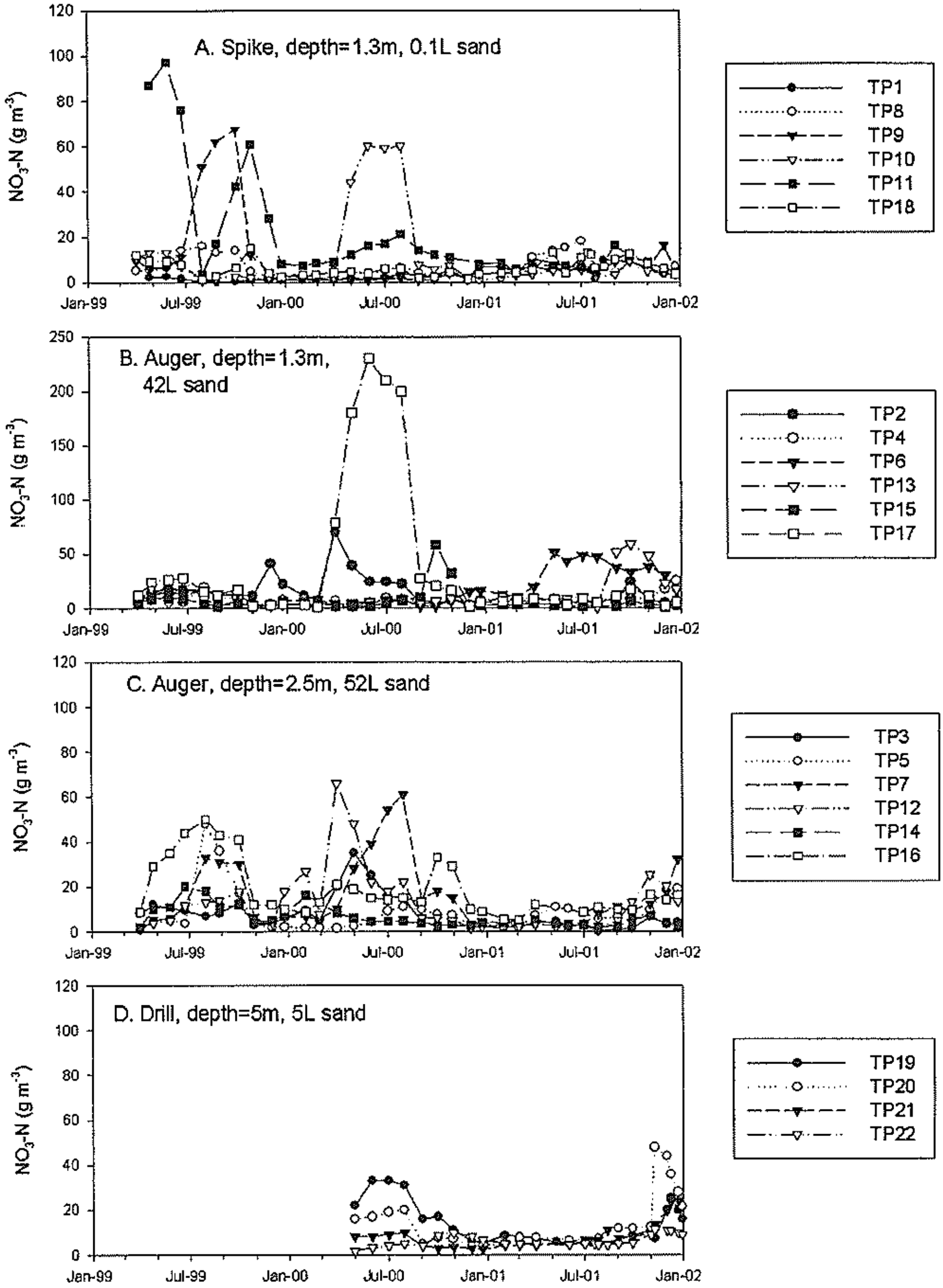


Figure 5 – Nitrate-N concentrations with time for each suction cup, separated by depth and installation method. Note that the y-axis has a different scale for graph B.

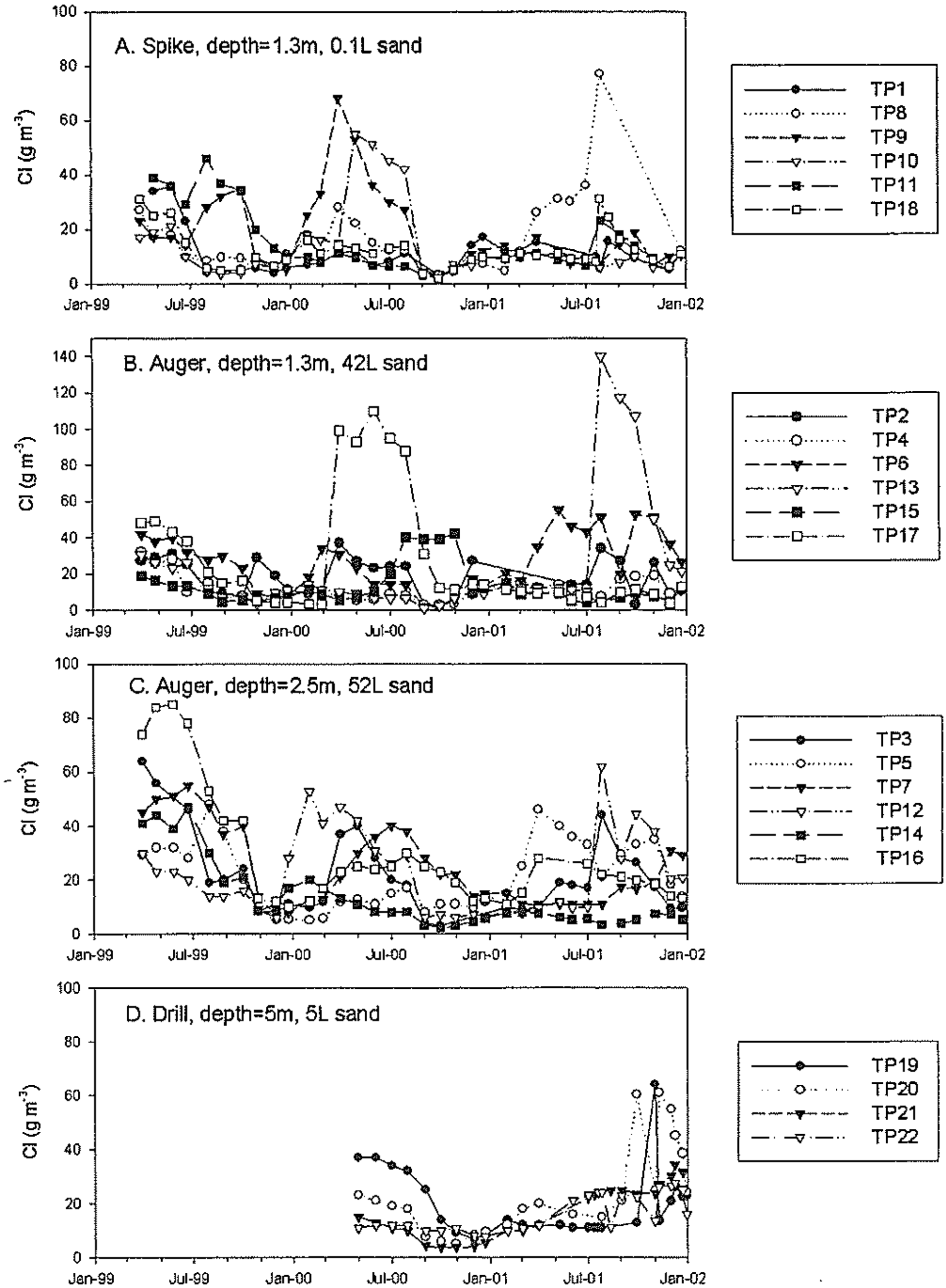


Figure 6 – Chloride concentrations with time for each suction cup, separated by depth and installation method. Note that the y-axis has a different scale for graph B.

The random deposition of urine has significant effects on the variability observed in the nitrate and chloride concentrations from the suction cups (Table 2), as evidenced by the relatively large standard deviations and coefficients of variation. The coefficients of variation decreased with depth for both nitrate and chloride: the coefficients of variation calculated from the individual nitrate data points were 177% (average for spike and auger), 105% and 83%, for depths of 1.3, 2.5, and 5 m depths, respectively. A decrease in coefficients of variation would be expected due to the increased mixing that takes place with transport to greater depths. One implication of this decrease in variability with increasing depth is that fewer suction cups would be required at greater depths to estimate mean concentrations of solutes leaching to groundwater.

The nitrate-N and chloride concentrations observed in the suction cups and in the linear lysimeter were similar (Table 2) and well within the range expected from spatial variability. The range of concentrations was also similar. The coefficients of variation for the linear lysimeter were similar to those observed for the suction cups at 1.3 m, but were greater than the coefficients of variation for the suction cups at greater depths. For the different types of sampler, the median solute concentrations varied slightly less than the mean solute values, which reflects the greater influence of the high concentrations associated with leaching of urine patches on the mean when compared with the median. Magesan *et al.* (1994) compared concentrations of nitrate and chloride measured using suction cups with those from a mole tile drainage system. They found that the suction cups gave mean concentrations and estimated leaching losses similar to those from the tile drain system.

Recharge estimates and nitrate and chloride fluxes

The recharge estimates from SOILMOD are given in Table 3 for 1999–2001. The recharge measurements from the linear lysimeter were not available at the time of writing this manuscript, so some recharge measurements from a nearby study site (Donkers farm) were obtained as a comparison. The Donkers farm site is approximately 9 km away from the Te Pirita study site and has a similar Briggs Rotarainer spray irrigation system. The available water-holding capacity

Table 3 – Summary of annual recharge and flux estimates for 1999-2001.

	1999	2000	2001	Mean
SOILMOD recharge (mm)	471	545	436	484
Donkers recharge L1 (mm)	*404	*532	539	*492
Donkers recharge L2 (mm)	777	791	*551	*706
Te Pirita rain + irrigation (mm)	1459	1472	1271	1401
Donkers rain + irrigation (mm)	1391	1444	1345	1393
Mean NO_3-N flux (kg $ha^{-1}yr^{-1}$)	58	57	38	51
Mean Cl flux (kg $ha^{-1}yr^{-1}$)	89	80	79	83

L1, L2 are lysimeter 1 and 2, respectively from the Donkers site. The Donkers site is an Eyre very stony silt loam with an available water capacity of about 65 mm.

* indicates that there were some missing data from these sites and the true values would be higher

is about 65 mm (Evans, 1999), which is less than the value of 80 mm for the Te Pirita site. Recharge amounts were measured from two lysimeters at the Donkers site, initially as part of an MSc project (Evans, 1999), and data collection was continued by Hugh Thorpe as part of a GNS research project (White *et al.*, 2003). There was consistently more recharge through one lysimeter (L2) compared to the other (Table 3). The reasons for the difference in recharge were an observed difference in surface microtopography and a possible difference in water-holding capacity between the lysimeters (Evans, 1999). Evans (1999) observed some surface runoff from the lysimeters due to the difference in surface microtopography, with the amount dependent on the antecedent soil moisture conditions. There were some periods of missing data from each of the Donkers lysimeters, which limited the comparisons that could be made. In 1999 and 2000 the total input of rainfall plus irrigation was slightly greater at Te Pirita compared with the Donkers site and the SOILMOD estimated recharge amounts were between the recharge amounts measured by the two lysimeters. However, there were missing data for L1, which measured lower recharge amounts, during these periods. In 2001 74 mm more rainfall plus irrigation was measured at the Donkers site than at the Te Pirita site and SOILMOD predicted about 100 mm less recharge than was observed for one lysimeter, with a greater difference for the other lysimeter, which had some missing data. Overall SOILMOD estimates of recharge were less than those observed by the lysimeters at the Donkers site. Some of the under-prediction would result from the difference in assumed water-holding capacity between the two sites. Simulations using the same water-holding capacity as the Donkers site (65 mm) resulted in an increase of between 22 and 35 mm per year in the estimated recharge. The SOILMOD model has been observed to slightly under-estimate recharge in conditions of heavy rainfall or irrigation (H. Thorpe, pers. comm.), which is consistent with these results. However, the spatial variability in observed recharge from the two lysimeters is quite large compared with the difference in recharge estimates, so the recharge estimates obtained from SOILMOD for the Te Pirita site appear to be reasonable for estimating solute fluxes at the Te Pirita site.

The summary of annual nitrate and chloride fluxes (Table 4) indicates that spatial variation, as seen between the suction cups, was quite high, with coefficients of variation for nitrate ranging between 43–98%. If the variation of the flux events instead of the annual totals is considered, then the variation is greater than the variation of the individual concentrations, as would be expected. However, if the fluxes from all of the suction cups were averaged (Table 3), then a fairly constant annual leaching loss of around 50 kg $ha^{-1}yr^{-1}$ for nitrate-N (range = 38–58 kg $ha^{-1}yr^{-1}$) and around 80 kg $ha^{-1}yr^{-1}$ for chloride (range = 79–89 kg $ha^{-1}yr^{-1}$) took place over the three-year period. As with the concentration data (Table 2), less variation was observed in the estimated fluxes in the deeper suction cups (2.5–5 m) compared with the suction cups at 1.3 m.

Nitrate-N leaching losses from dairy farmlets in Waikato were measured in a 3-year study by Ledgard *et al.* (1999). Nitrate-N leaching losses ranged from 20 to 74 kg $ha^{-1}yr^{-1}$ for areas with no additional N fertiliser, 59 to 101 kg $ha^{-1}yr^{-1}$ when 200 kg N $ha^{-1}yr^{-1}$ urea was added, and 100 to 204 kg $ha^{-1}yr^{-1}$ when 400 kg N $ha^{-1}yr^{-1}$ urea was added. Di and Cameron (2002) used lysimeters to estimate nitrate leaching from dairy pasture with flood irrigation. Where no additional nitrogen fertiliser was used, nitrate-N leaching losses were between 112 to 130 kg $ha^{-1}yr^{-1}$. Losses ranged up to 162 kg $ha^{-1}yr^{-1}$ for fertiliser or effluent inputs of 400 kg N $ha^{-1}yr^{-1}$. The estimate of

Table 4 – Summary of annual nitrate and chloride fluxes for each suction cup installation method.

Cup Installation Method	Spike	Auger	Auger	Drilling rig
Depth (m)	1.3	1.3	2.5	5.0
Nitrate-N (kg $ha^{-1}yr^{-1}$)				
• Mean	38.8	60.6	55.2	44.2
• Median	28.3	41.9	47.1	39.0
• Range	3.9–143	11.6–268	13.2–136	22.4–78
• CV (%)	94	98	58	43
Chloride (kg $ha^{-1}yr^{-1}$)				
• Mean	64.2	87.5	98.5	74.1
• Median	50.5	87.1	100.1	81.3
• Range	35–132	35–202	28–199	29–115
• CV (%)	50	57	41	38

nitrate-N leaching of around 50 kg $ha^{-1}yr^{-1}$ from this study reflects conditions immediately after conversion from a dryland farm. Detailed nitrogen fertiliser inputs were not available for the first two years (1999-2000) but soil N analyses in 2000 indicated that the N status of the soil was still in the low-medium range and less than that expected from a fully producing dairy farm (Lincoln Ventures, unpublished data). It is thus likely that nitrate leaching will increase in the future as the soil fertility increases.

Costs, advantages and limitations of different installation methods

A summary of the costs for the different installation methods is given in Table 5. The main difference in the cost of the suction cups is in the different lengths of PVC pipe required for both the suction cups and the access tubes. Many suction cups described in the literature (Dorrance *et al.*, 1991) do not have access tubes and have only a standard length of PVC pipe for the suction cup, with the cups being buried at the required depth. This approach was not used in this study, as we wanted to be able to take the cups out and service them as required. A standard length of PVC pipe and permanent emplacement would make the cost of all suction cups the same, regardless of depth. The other major difference in price among the three methods relates to the depth limitations of each technique, and the higher cost of equipment that can install suction cups at greater depths. As noted in the above section, solute concentrations and fluxes vary less at greater sampling depths, so the lower number of suction cups required to give the same level of confidence for a mean leachate flux may result in similar or even lower overall costs for a monitoring system.

The number of samples required to estimate the mean concentration or flux of nitrate to within a specified level of accuracy can be calculated using the following equation:

$$n = \left(\frac{z.SD}{x}\right)^2 \qquad (3)$$

where n = number of samples, z = critical value at α = 0.05, SD = standard deviation, and x = level of required precision. The standard deviations for the nitrate concentrations and fluxes were taken from Tables 2 and 4 for the suction cups at the different depths, and the results were calculated for precision levels of

Table 5 – Costs, benefits, and limitations of different installation methods in year 2000. The spike and auger costs are based on six cups and the air rotary costs are based on four cups.

	Spike 1.3m	**Auger 1.3m**	**Auger 2.5m**	**Air Rotary Drill 5m**
Costs (ex GST)				
Suction cup†	$155	$155	$170	$207
Meter box	$36	$36	$36	$36
Silica Sand#		$13	$13	$2
Spike	$28 (170)*			
Driving/drilling	$20	$56	$66	$300
Labour – installation	$50	$100	$125	$75
Total cost per suction cup installed	$289	$360	$410	$620
Sampling depth	< 1.5 m	< 2.5 m	<2.5 m	not restricted
Sample volume	moderate	high	high	high
Sand volume	low			
Angle	0°	up to 20°	up to 20°	up to 15°
Ease of installation	easy	moderate	moderate	moderate

Note * The spike is a one-off cost, divided by the six cups.
\# Assume 40 L and 5 L of sand for the auger and air rotary drill, respectively.
† The cost difference is mainly due to the different lengths of PVC required.

25% and 50% of the mean (Table 6). This estimation is a 'best approximation' only, as the above equation assumes a normal distribution, which is not satisfied for these data. The results demonstrate that significantly fewer suction cups are required at greater depths to estimate mean nitrate concentrations and fluxes at similar levels of precision. As there is only about a factor of two difference between the costs of suction cups at 5 m compared to those at 1.3 m (Table 5), it is cost-effective to install suction cups deeper in the vadose zone and take advantage of the reduced variability at greater depth.

An obvious difference among the installation methods is the maximum installation depth. The maximum depth for the spike installation was assessed at 1.5 m, based on the difficulty of extracting the spike using a hydraulic ram (from the pile driver), whereas the installation depth for the auger was based on the stability of the subsoil and its tendency to cave in at greater depths. These maximum depths are based on the Te Pirita site and are given as a guide, and would be expected to vary according to local conditions.

The volumes of soil water collected was usually sufficient for analytical purposes, with 90% of samples from the spike installations and about 98% of the other installation methods providing sample volumes greater than 40 mls. If the required volume was 100 mls, then the number of samples with sufficient volume dropped to about 65% for the spike installations, 92–95% for the auger installations and 95% for the 5 m drilled

Table 6 – Required number of samples to estimate the mean nitrate-N concentration and flux at a given level of precision. Mean nitrate-N concentration assumed to be 10 g m^{-3} and mean nitrate-N flux assumed to be 50 kg ha^{-1}; z taken as 1.96; standard deviations taken from Tables 2 and 4. Note that this is a "best approximation" only as the equation assumes a normal distribution, which is not satisfied for these data.

Cup installation method	Precision level (%)	Standard deviation	n
A: Nitrate concentration			
Spike, 1.3 m	25	15	138
Auger, 1.3 m	25	20	246
Auger, 2.5 m	25	11	74
Drill, 5 m	25	8	39
Spike, 1.3 m	50	15	35
Auger, 1.3 m	50	20	61
Auger, 2.5 m	50	11	19
Drill, 5 m	50	8	10
B: Nitrate flux			
Spike, 1.3 m	25	50	61
Auger, 1.3 m	25	50	61
Auger, 2.5 m	25	30	22
Drill, 5 m	25	20	10
Spike, 1.3 m	50	50	15
Auger, 1.3 m	50	50	15
Auger, 2.5 m	50	30	6
Drill, 5 m	50	20	2

installations. The lower volumes for the spike installations might be overcome by having the suction cup installed at a slightly shallower depth, with the extra volume created being filled with silica sand.

A significant limitation for the auger installation was the disturbance of the profile by the large diameter of hole that was excavated. Although the hole was backfilled using the excavated gravels after placement of the sand, it was difficult to ensure that the packing density matched the original density. The large hole also required much more time and effort to backfill and this added to the cost of this method of installation.

Our recommendation for the installation of suction cups in stony alluvial sub-soils is to use spike installation for depths less than 1.5 m and to use air rotary drilling for depths greater than 1.5 m.

Conclusions

All of the suction cups collected sufficient volumes of soil water for sample analysis and the volumes increased with the amounts of fine sand used and the volume of the suction cup. Silica sand volumes greater than 5 L stored excessive amounts of water and would have resulted in lags in sampled solute concentrations. The nitrate and chloride concentrations collected from the suction cups showed significant variation consistent with leaching from random urine patches. The nitrate and chloride concentrations measured in the suction cup samples were similar to those measured from the linear lysimeter. The variability of solute concentrations decreased as sampling depth increased, indicating that fewer suction cups would be required at greater depths to estimate mean concentrations of solutes leaching to groundwater. Recharge was estimated using SOILMOD and combined with the concentration data to give fluxes or leaching losses. As with the concentration data, significantly less variation occurred in the estimated fluxes in the deeper suction cups in comparison with the suction cups at 1.3 m. When the fluxes from all the suction cups were averaged, there was a fairly constant annual leaching loss of around 50 kg $ha^{-1}yr^{-1}$ for nitrate-N (range = 38–58 kg $ha^{-1}yr^{-1}$) and around 80 kg $ha^{-1}yr^{-1}$ for chloride (range = 79–89 kg $ha^{-1}yr^{-1}$) over the three-year period.

The major differences in price among the three installation methods relates to the depth limitations of each technique and the higher cost of equipment capable of installing suction cups at greater depths. A significant limitation for the auger installation was the disturbance of the profile by the large diameter of hole that was excavated. Our recommendation for the installation of suction cups in stony alluvial sub-soils would be to use spike installation for depths less than 1.5 m and to use air rotary drilling for depths greater than 1.5 m.

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