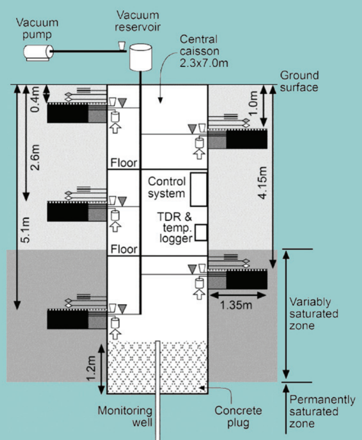
Technical Notes

G.F. Barkle*
Th. Wöhling
R. Stenger
J. Mertens
B. Moorhead
A. Wall
J. Clague

Automated Equilibrium Tension Lysimeters for Measuring Water Fluxes through a Layered, Volcanic Vadose Profile in New Zealand



The design, installation, and evaluation of a vadose zone flux monitoring system is described. This system has 15 automated equilibrium tension lysimeters at five depths, installed down to 5.2 m. These samplers have large porous sampling plates under which the vacuum is controlled to be equivalent to the surrounding vadose zone tension.

In this technical note we present the design, installation, and evaluation of a field monitoring system to directly measure water fluxes through a vadose zone. The system is based on use of relatively new measurement technology—automated equilibrium tension lysimeters (AETLs). An AETL uses a porous sintered stainless-steel plate to provide a comparatively large sampling area (0.20 m^2) with a continuously controlled vacuum applied under the plate. This vacuum is in "equilibrium" with the surrounding vadose zone tension to ensure measured fluxes represent those under undisturbed conditions. Fifteen of these AETLs have been installed at five depths through a layered volcanic vadose zone to study the impact of land use changes on water quality in Lake Taupo, New Zealand. We describe the development and testing of the AETLs, the methods used for installing these devices, a condensed data set of the measured physical properties of the vadose zone, and the initial results from the in situ operation of the AETLs, including the preliminary results from a bromide tracer test. For an AETL installed at the 0.4-m depth, where soil pressure heads are most dynamic, the average deviation between the target reference pressure head, as measured in the undisturbed vadose zone and the pressure head measured above the sampling plate was only 5.4 hPa over a 180-d period. The bromide recovered in an AETL at the same depth was equivalent to 96% of the bromide pulse applied onto the surface area directly above the AETL. We conclude that this measurement technique provides an accurate and robust method of measuring vadose zone fluxes. These measurements can ultimately contribute to better understanding of the water transport and contaminant transformation processes through vadose zones.

Abbreviations: AETL, automated equilibrium tension lysimeter; ETL, equilibrium tension lysimeter; HDS, heat–dissipation sensor; OI, Oruanui ignimbrite; P1, Paleosol 1; P2, Paleosol 2; PID, proportional-integral-derivative; TI, Taupo ignimbrite; TDR, time domain reflectometry.

G.F. Barkle, Aqualinc Research Limited, P.O. Box 14-041, Enderley, Hamilton, New Zealand; Th. Wöhling, R. Stenger, B. Moorhead, A. Wall, and J. Clague, Lincoln Environmental Research, Lincoln Ventures Ltd., Private Bag 3062, Hamilton, New Zealand; J. Mertens, LABORELEC, Rodestraat 125, 1630 Linkebeek, Belgium. *Corresponding author (G.Barkle@Aqualinc.co.nz).

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The vadose zone–groundwater continuum is acknowledged as the conduit for the majority of dissolved contaminants traveling from the land to Lake Taupo in New Zealand. This occurs either via direct groundwater seepage through the lake bed or by streams fed from groundwater (Morgenstern, 2007). Little is known, however, about the water fluxes moving through the highly porous, volcanic vadose zone in the catchment because of the absence of fundamental and reliable data on the physical properties of the porous media and the inherent difficulty of measuring water fluxes in the vadose (or unsaturated) zone (Kowall, 2001; Holt and Nicholl, 2004). Without fundamental data sets of fluxes and physical properties, the development and validation of simulation tools for the modeling of fluxes in the vadose zone–groundwater continuum will continue to be afflicted with rather large uncertainty (Bredehoeft, 2003; Halford, 2004).

Mechanistic models are the preferred choice to describe water flow in the vadose zone, especially when future states of the natural system or the effect of changes in the system are to be predicted. The reliability of the predictions of a mechanistic model is crucially dependent on the accuracy of the data sets available for calibration and evaluation of the models. Since direct measurements of water fluxes through the vadose zone under naturally occurring flow and boundary conditions are technically challenging, the accepted norm is that mathematical flow models are fitted to state variables such as pressure head or water content instead. The fluxes between computational points are inferred so that the governing equations, in either pressure head or water content form, are satisfied. However, the accuracy of simulated water and contaminant fluxes by state-variable calibrated models often cannot be evaluated directly. The instrumentation described here allows highly dynamic flux measurements to be made directly through the vadose zone and thereby allows a more accurate calibration and evaluation of flow models.

First we review techniques for measuring vadose zone water fluxes; then we describe our filed site, followed by a detailed description of our monitoring facility, the essential AETL design features, and the associated installation techniques. In the final section we evaluate our methodology and demonstrate the in situ operation of our experiment with initial results of lysimeter tension control, water fluxes and cumulative drainage measurements, and bromide recovery results from a surface applied tracer test.

Measuring Water Fluxes through the Vadose Zone

To continuously measure water fluxes through a vadose zone there are three sampling techniques that can be conceptually used: zero tension lysimeters (Jemison and Fox, 1992; Weihermüller et al., 2007; Peters and Durner, 2009), fixed tension lysimeters (Holder et al., 1991; Boll et al., 1992; Weihermüller et al., 2007), and equilibrium tension lysimeters (Brye et al., 1999, 2001; Siemens et al., 2001; Foley et al., 2003; Kosugi and Katsuyama, 2004; Masarik et al., 2004). It was found that weighing lysimeters (Owens, 1987) were not a viable option for sequentially measuring fluxes down to a depth greater than 5.0 m due to constraints on the collection of intact material and the necessary control on the bottom boundary for accurate flux measurements. The smaller suction cup samplers, typically made of ceramic and stainless-steel materials, are designed to operate on a batch mode, only subsampling pore water in the unsaturated zone, and are not capable of continuously measuring or sampling the water flux in the vadose zone.

Two types of zero tension lysimeters are distinguished. First there is the pan lysimeter, which is typically a plate the shape of a pan, without sidewalls, installed horizontally into an undisturbed profile. The second type is the barrel lysimeter, where an undisturbed soil column is collected inside a steel, PVC, or polyethylene cylinder (typically 40–80 cm diam.). Both have a solid base or pan from which the drainage flux is collected (Cameron et al., 1992; Weihermüller et al., 2007). The tension at the bottom drainage face is atmospheric; hence, for drainage to occur the tension in the soil must overcome the air-entry potential of the soil. This requirement results in the soil being wetter during and after a precipitation event than what would occur in the undisturbed profile, where the naturally occurring tensions are exerted at the equivalent depth on to the drainage face. (Alternatively, the soil column may become drier for time periods where evapotranspiration is dominant but these cases are neglected herein.) The wetter zone created in these lysimeters has three potentially detrimental effects; the importance of each of these errors depends on the soil types and hydrology at the measurement site.

1. In pan lysimeters, without sides, the flux can bypass around the wetter pan during unsaturated flow. Collection efficiencies of <10% have been reported for pan lysimeters (Jemison and Fox, 1992; Zhu et al., 2002). Barrel lysimeters are not susceptible to this bypass error, as lateral flow is contained by side walls. However, walls extending to the surface can be problematic for arable type farming operations (Moyer et al., 1996).
2. Because soil water contents are higher at the drainage face than the naturally occurring conditions (Abdou and Flury, 2004), when rainfall occurs, the volume of drainage flux collected will be greater for near-saturated flow conditions than that moving in the adjacent undisturbed profile. However, compensating for this effect is that fluxes will also stop at a higher tension (i.e., at the air entry potential of the soil), so that the soil will again remain wetter. This method has a tendency of underestimating fluxes (Gee et al., 2009), with measurement errors likely to be greater where larger variability in climate exists with more wetting and drying cycles (Flury et al., 1999)
3. Significant zones of saturation can exist above the drainage face, and hence potentially anaerobic conditions can develop and influence the composition of measured soluble contaminants. Flury et al. (1999) demonstrated this effect in a simulation study.

To overcome the potential problems with zero tension samplers, fixed tension samplers or capillary wick samplers have been developed (Wilson et al., 1995; Weihermüller et al., 2007; Mertens et al., 2007). These samplers utilize hanging wicks made from fiberglass (Holder et al., 1991) or rock wool (Ben-Gal and Shani, 2002) to maintain a fixed tension at the drainage face. This tension is less than atmospheric pressure, and consequently the soil at the drainage face remains unsaturated. The wicks can be installed in both pan and barrel lysimeters, and the technology has recently been applied in flux meters developed by Gee et al. (2002, 2009). The level of the tension exerted on the drainage face is a function of wick material, length, and diameter, all which must be carefully selected for a given soil and site conditions (Boll et al., 1992). If drainage in the undisturbed profile occurs at a higher tension than the set tension by the wick, then flow can diverge around the sampler if unconstrained, resulting in under sampling. Conversely, if drainage occurs at a lower tension than the imposed tension, the samplers can create converging flow and oversample the natural drainage fluxes. Consequently the fluxes measured by fixed tension lysimeters are not necessarily the same as that occurring in the undisturbed profile, and this may lead to rather large measurement errors (Gee et al., 2002; Kosugi, 2000). In comparative studies, the wick lysimeters have generally performed better than the zero tension lysimeters (Zhu et al., 2002), though not always (Boll et al., 1992).

To overcome the serious limitations in the existing sampling techniques for accurately measuring water and contaminant fluxes, recent developments in lysimeter technology have been based on using porous plate samplers (Brye et al., 1999, 2001; Siemens et al., 2001; Foley et al., 2003; Kosugi and Katsuyama, 2004; Masarik et al., 2004; Kasteel et al., 2007). The modus operandi of the porous plates is that a vacuum is controlled under the porous collection plate and the water drawn through the plate represents the vertical flux occurring over the plan area of the plate. Brye et al. (1999) manually adjusted the vacuum level by measuring the soil pressure head with heat–dissipation sensor (HDS) and adjusting the target vacuum two or more times a week. He coined the term equilibrium tension lysimeters (ETLs), where the term *equilibrium tension* refers to the vacuum being applied under the porous plate being in "equilibrium" with the pressure head in the material surrounding the ETL.

The size of the lysimeter plate (or combination of plates) can vary from two adjacent glass plates of 9-cm-diameter (area of 0.013 m^2; Siemens et al., 2001), to >26.9-cm-diameter (area of 0.057 m^2) ceramic plates (Kosugi and Katsuyama, 2004; Morari, 2006), to larger rectangular porous sintered stainless-steel sampling plates 0.25 wide by 0.76 to 0.90 m long (~0.2-m^2 area) (Brye et al., 1999; Foley et al., 2003; Pelger et al., 2003).

Masarik et al. (2004) added the control feature to the ETLs so that the vacuum under the sampling plate was automatically controlled and thus named them *automated equilibrium tension lysimeters* (AETL). They controlled the vacuum level by interrogating HDS to measure the pressure head in the soil adjacent to the AETL every 10 min. The target vacuum inside the lysimeter was adjusted to be 20 hPa greater than the measured soil pressure head to "overcome the resistance of the porous plate." This tension offset appears to be rather arbitrary and could potentially lead to preferential flow toward the lysimeter and thus oversampling, especially for near-saturated conditions. Kosugi and Katsuyama (2004) proposed a different control system in which a high level of vacuum (450 hPa) is applied under the plate for a short control period (3 s) with the aim to match pressure heads above the plate and in the adjacent undisturbed profile. This control system used tensiometers to measure the pressure heads in the soil. A potential risk with this control system is that with some vadose zone materials, high vacuum levels may result in thin dry zones close to the plate with very low hydraulic conductivities (Wierenga, 1995). This may cause the plate tensiometer to become hydraulically isolated from the plate (vacuum source).

To date ETLs and AETLs have only been installed at single depths to measure drainage fluxes at the bottom of the root zone. They have not been used to measure water and solute fluxes propagating through different depths of a layered vadose zone down to the permanently saturated zone or to investigate the effects of the fluctuations in the water table on the vertical fluxes and contaminant transport through the vadose zone.

In this technical note we describe a method and ongoing field experiment to accurately measure water fluxes at different depths of a highly porous, layered volcanic vadose zone in the Lake Taupo catchment. We installed AETLs at five depths (0.4, 1.0, 2.6, 4.2, and 5.1 m), with three AETLs at each sampling depth. This experimental facility is referred to as the "Spydia".

Field Site

In New Zealand, Lake Taupo (622 km^2), which in its current form was created by a volcanic eruption in 186 CE, is exhibiting early indications of deteriorating water quality, including reduced water clarity (NIWA, 2005) and increasing loads of nitrogen entering the lake (Vant and Smith, 2004). Land use changes over the last 50 yr from tussock, shrub-land, and indigenous forests to plantation forests and particularly to grazed pastoral agriculture is being suggested as the likely reason for these early signs of deterioration in lake water quality.

To respond to the specific needs for measuring the inputs and temporal dynamics of water and contaminant fluxes within the Taupo catchment, and to build comprehensive data sets for the development of modeling tools that describe the fate of contaminants in the vadose zone–groundwater continuum, a vadose zone monitoring and experimental facility known as the "Spydia" has been developed and installed within the Lake Taupo Catchment.

The Spydia field site was established on a sheep and beef station within the Tutaeuaua subcatchment (Fig. 1; 175°74.997′ E, 38°36.863′ S) of Lake Taupo. The modern soil at the site belongs to the Oruanui loamy sand series within the Podzolic Orthic Pumice Soil subgroup (New Zealand soil classification) and is a mesic Andic Haplorthod according to U.S. soil taxonomy (Rijkse, 2005). The soil developed from the Taupo eruption approx. 1.8 ka BP and is found widespread in the Lake Taupo catchment.

Before the establishment of the monitoring site, cores of the vadose zone materials were taken down to 6.3 m, and these were logged by a volcanologist (Wilson, 2004). A summary of the vadose zone profile based on the combined soil (Rijkse, 2005) and geology (Wilson, 2004) investigations is presented in Table 1. The term *in situ* in this table and in the text with regard volcanic materials refers to it being undisturbed since its deposition by eruption.

In summary, the modern soil is underlain to a depth of approx. 4.2 m by Taupo Ignimbrite (TI). Two older buried soils (Paleosols 1 and 2 [P1 and P2], at approximately 4.2 to 5.8 m

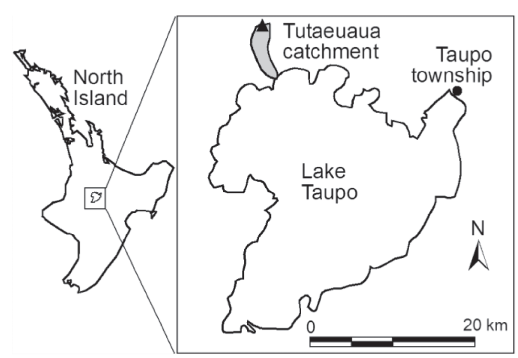

Fig. 1. Location of Lake Taupo and Tutaeuaua subcatchment in the North Island of New Zealand.

Table 1. Vadose zone profile at the field site; bracketed values are ranges in depth of the layers measured during installation of the monitoring facility.

Upper boundary	Lower boundary	Material
———— m ———		
0	0.15	Ap, gritty loamy sand; derived from Taupo ignimbrite (TI)
0.15	0.34	Bs, gritty coarse sand; derived from TI
0.34	0.69	BC, gravelly coarse sand; disturbed/redeposited material derived from TI
0.69	1.60	C1, gravelly coarse sand; disturbed/redeposited material derived from TI
1.60	2.20+	C2, stony coarse sand, in situ TI layer 2
2.20+	4.25	In situ TI, layer 2, coarse pumice clasts and fines-rich matrix
4.25	4.40 (4.10–4.55)	In situ TI, layer 1 (H), facies, lacking fine ashy matrix
4.40 (4.10–4.55)	4.41 (4.11–4.56)	Very fine Rotongaio ash
4.41 (4.11–4.56)	~5.00	Paleosol, P1, rich in clay, post-Oruanui
~5.00	5.76 (5.15–5.85)	Paleosol, P2; derived from weathered tephra or tephric loess, rich in clay post–Oruanui
5.76 (5.15–5.85)	6.45–6.80	Redeposited material derived from Oruanui ignimbrite (OI), very poorly sorted, gritty feel, clay-rich matrix
6.45–6.80	7.10+	Presumably in situ OI

depth) are followed by Oruanui ignimbrite (OI) material derived from an eruption approximately 26.5 ka BP. During the installation phase of the facility, the depths of the three horizon boundaries (TI/P1, P2/disturbed OI, and disturbed OI/in situ OI) were found to vary spatially around the caisson (Fig. 2). Water table monitoring over a 6-mo period combined with a hydrodynamic modeling approach using long-term local climate data indicated that the depth to the water table can vary at the site through time between a minimum of 3.8 m and a maximum of 6.5 m below the ground surface. Correspondingly, the in situ OI material appears to be permanently saturated, while the disturbed OI, paleosols, and the bottom of the TI are only temporarily saturated.

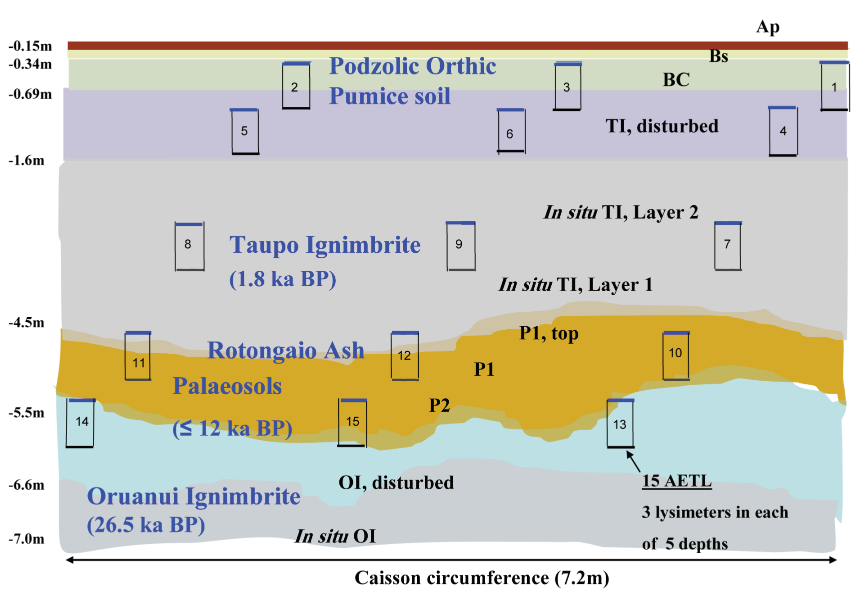

Fig. 2. Schematic of the materials in the vadose zone profile and automated equilibrium tension lysimeters (AETLs) around the circumference of the installed caisson.

Hydraulic Properties of the Vadose Zone Layers

A total of 100 undisturbed vadose zone samples (10-cm diameter, 7.5-cm height) were collected from 10 depths during the installation of the access caisson used for operation of the 15 AETLs. The nominal depths of the top of the cores were: 0, 0.10, 0.60, 1.80, 3.50, 4.00, 4.45, 5.10, 6.10, and 7.00 m below ground surface. To account for spatially variable horizon boundaries around the outside of the caisson wall (Fig. 2), the "4.00-m" samples were taken in the range from 3.72 to 4.32 m and the "4.45-m" samples between 4.15 and 4.81 m. Five vertical and five horizontal replicates from each depth were taken.

Saturated (K_{sat}) and near-saturated hydraulic conductivity ($K_{-0.4}$) were estimated from these cores with laboratory methods described by Klute (1986) and Cook et al. (1993), respectively. Near-saturated hydraulic conductivity is defined as the hydraulic conductivity at a pressure head of −0.4 kPa. While the horizontally collected cores tended to have a greater K_{sat} than the vertically collected cores, due to the high variability between replicates, the median saturated hydraulic conductivity ($\hat{K}_{sat}$) of all 10 cores at one depth is presented in Fig. 3a. Median $\hat{K}_{sat}$ values are largest (5.83×10^{-5} m s^{-1}) in the transition zone of the A and Bs horizons, and then drop consistently down to 8.40×10^{-6} m s^{-1} in the lower part of Layer 2 of the in situ TI. A second relative maximum (4.37×10^{-5} m s^{-1}) was found in Layer 1 of the in situ TI, before conductivity dropped gradually down to the 8.33×10^{-7} m s^{-1} in the deepest horizon (in situ OI). Median near-saturated hydraulic conductivity ($\hat{K}_{-0.4}$) showed a similar pattern, but less pronounced (Fig. 3a).

Table 2 presents the dry bulk density and porosity of the various materials sampled. The bulk densities were generally low with the highest measured values being in the bottom OI layers (1.04 and 1.10 g cm^{-3}). These horizons had correspondingly the lowest total porosities of 59 and 57%, respectively. The

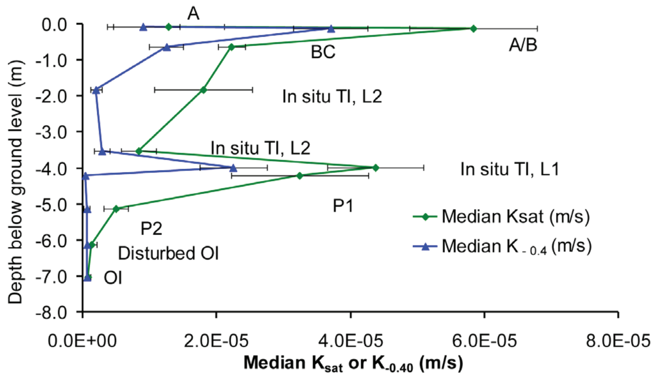

Fig. 3. Vadose zone profile hydraulic properties Median saturated ($\hat{K}_{sat}$) and near-saturated ($\hat{K}_{-0.40}$) hydraulic conductivity (m s^{-1}, $n = 7$ to 10, ± standard error of the median).

average total porosity of the profile was 65%. The two paleosols had the highest total porosity (70 and 74%), which reflects their low bulk density (0.74 and 0.65 g cm^{-3}). The OI samples had very small macroporosities, (total porosity minus water content at −0.5 kPa; McQueen, 1993) at 3 and 2%, while the highest macroporosities were measured in the transition zone of the A and B horizons (22%) and in the BC horizon (24%). These samples were also characterized by the lowest volumetric water contents (34 and 35%) at the pressure head considered close to "field capacity" (–1.0 kPa), while the maxima were found in the paleosols (62% and 66%). In the paleosols, approximately one-half of the total pore space remained filled with water at pressure heads greater than −150 kPa (30 and 36%). This indicates that a significant portion of water in these layers is considered relatively immobile.

Spydia Monitoring Facility

In contrast to the installation of barrel and weighing lysimeters, AETLs at the Spydia facility are installed horizontally outward and sequentially step downward around a central access caisson into the undisturbed vadose zone material. The caisson is a 2.3-m-diameter, 6.0-mm-thick, 7.0-m-long steel pipe installed vertically through the vadose zone down into the permanently saturated zone (Fig. 4 and 5). In this section we describe important AETL placement and design features, the installation of the facility, and our strategy for the control of the individual AETLs.

AETL Dimensions and Placement in the Vadose Zone

The optimal placement of the AETLs around the caisson at the various depths is an important design feature of the facility and to some extent dependent on the hydraulic characteristics of the vadose zone stratigraphy. In particular, lateral and vertical separation distances between AETLs need to be designed in an optimal way that the locations remain unaffected by the removal of water by the operation of the other AETLs (especially at greater depths).

A HYDRUS-2D model of the site was developed before the Spydia installation to investigate the effects of creating a dry zone beneath the sampling AETLs (Mertens et al., 2005). The modeling work showed that the distance to the dry zone under a sampling lysimeter was critical to ensure that the flux measurements made by the AETLs were unaffected. The study recommended that for our vadose zone materials the initiation of the dry "umbrella zone," where vadose zone pressure heads would be smaller than pressure

Table 2. Average physical properties and volumetric water content at pressure heads of 1, 10, and 150 kPa at various depths in the Spydia vadose zone profile.

Horizon name and sampling depth	Dry bulk density	Total porosity	Macroporosity†	Volumetric water content @ 1.0 kPa	@ 10.0 kPa	@ 150.0 kPa	Readily available water‡	Total available water§
m	g cm^{-3}	% (v/v)						
Ap horizon 0.0	0.75	67.6	9.3	51.4	38.1	13.9	13.3	37.5
A/B horizon 0.10	0.78	67.3	21.9	34.0	19.3	7.6	14.8	26.5
BC horizon 0.60	0.80	65.6	23.8	35.4	15.4	6.9	20.0	28.4
C2 in situ TI¶ 1.80	0.81	66.1	15.8	45.9	19.3	5.2	26.6	40.7
In situ TI layer 2 3.50	0.85	63.5	13.6	46.5	19.1	5.3	27.4	41.2
In situ TI layer 2 3.72–4.32	0.92	61.4	11.6	44.8	16.8	4.6	28.0	40.2
Paleosol P1 4.15–4.81	0.74	69.6	6.1	62.0	54.2	29.5	7.7	32.5
Paleosol P2 5.10	0.65	74.3	7.0	66.3	59.8	36.2	6.4	30.1
Redeposited OI# 6.10	1.04	59.1	3.1	52.2	31.4	12.0	20.8	40.1
In situ OI 7.00	1.10	56.8	1.8	53.9	27.5	8.9	26.4	45.0

† Macroporosity is total porosity − water content at −0.5 kPa.
‡ Readily available water is the water drained between −1.0 and −10 kPa pressure heads.
§ Total available water is water drained between −1 and −150 kPa pressure heads (McQueen, 1993).
¶ Taupo ignimbrite.
# OI, Oruanui ignimbrite.

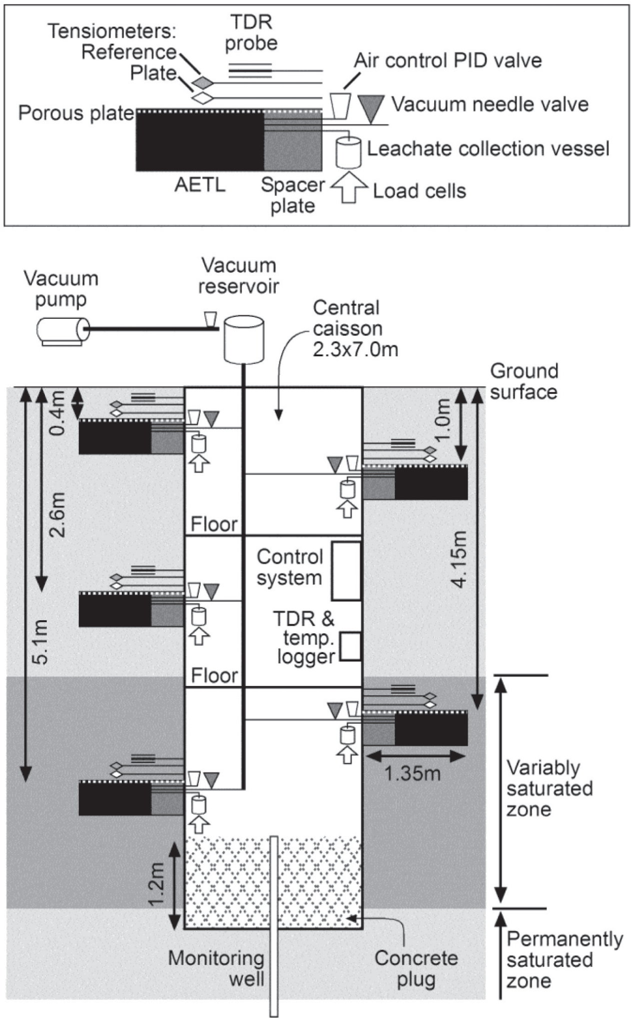

Fig. 4. Schematic cross-section through the Spydia facility.

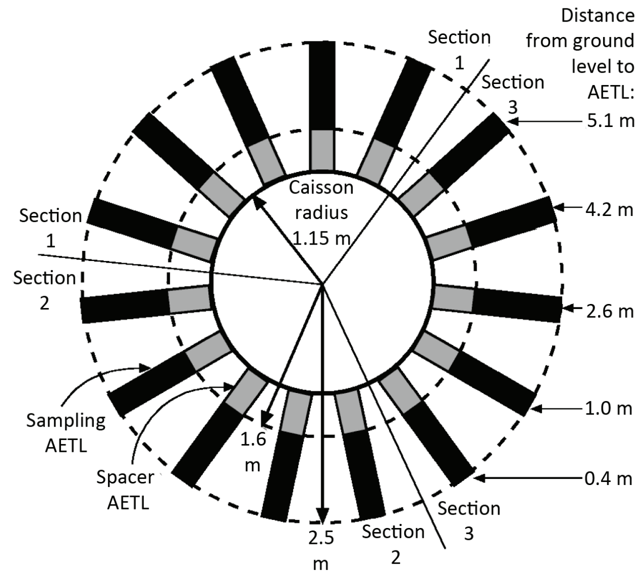

Fig. 5. Plan view of the Spydia showing the automated equilibrium tension lysimeter (AETL) positioned around central access caisson.

heads above the sampling plate, needed to be vertically separated by at least 0.50 m from the sampling plate.

Additionally, the analysis also showed that the horizontal separation distance between adjacent AETLs needed to be at least 0.50 m to ensure that the dry zone did not significantly interfere with the flux being measured in adjacent AETL installed at a lower depth. To fulfil this minimum separation distance a spacer AETL (Fig. 4, 5, and 6) of 0.45-m length was used to increase the radial distance out from the central caisson. Additionally, the spacer AETL also reduces possible boundary effects that may occur close to the caisson walls and influence the accuracy of the sampling AETL. The spacer AETL is operated and managed in an identical manner to the corresponding sampling AETL.

Since the two-dimensional analysis of the flow regime could not address in full the complex three-dimensional flow patterns at the site (Mertens et al., 2005), the numerical analysis for between AETL interference was recently revised by Wöhling et al. (2009) using a three-dimensional flow model. This study suggests that under the investigated flow regimes the minimum and mean sampling efficiencies of the AETLs attain values greater than 0.90 and 0.96, respectively.

AETL Construction

The porous sampling plates were constructed from 1.0-mm nominal thickness, 0.2 media grade sintered 316L stainless-steel plate (Mott Corporation, Farmington, CT, USA) similar to that used by Brye et al. (1999) and Foley et al. (2003). The air entry pressure for this plate material, using water as the fluid, is nominally 57.5 kPa. The porous sampling plate is fixed to the top of a reservoir box (Fig. 6). This reservoir box fulfils three functions: (i) to hold the porous plate in position against the undisturbed vadose zone material, (ii) to act as a reservoir where the vacuum is maintained at the desired target, and (iii) to collect leachate sampled through the porous plate.

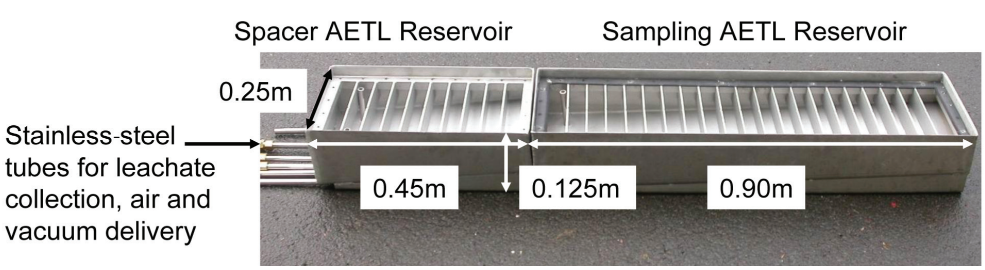

Fig. 6. Spacer and sampling reservoir boxes of the automated equilibrium tension lysimeter (AETL) without porous plates fitted.

As the AETLs were installed up to a depth of 5.1 m (Fig. 4), structural cross members (Fig. 6) are required to support the porous plate. After fabrication of the reservoir boxes, they were checked for air tightness before the porous sampling plates were fixed in place. The fitted plates were cleaned by repeatedly flushing them with 30% hydrogen peroxide, water, and isopropanol. Subsequently, the plates were water saturated, and their hydraulic conductivity was checked. A bubble point test was then conducted by applying water on top of the plate and increasing the positive air pressure under the porous plate until the first occurrence of any air bubbles was recorded. If the bubble point test was satisfactory (i.e., $\geq$35 kPa), the plate was resaturated and the hydraulic conductivity of the plate rechecked (i.e., $\geq$0.20 mm h^{-1}) before the AETL was considered ready for installation.

Following Brye et al. (1999) two sheets of filter material (in our case polypropylene needlepoint filter media) were used on the top of each porous plate to prevent possible clogging of the porous plate by mobile fine particles in the vadose zone.

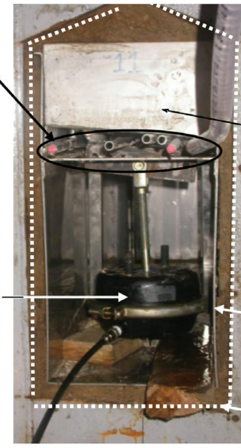

Fig. 7. Window cut through caisson with shoring box installed, pneumatic jacks in place, and spacer automated equilibrium tension lysimeter (AETL) lifted into place in the undisturbed vadose zone material.

Caisson and AETL Installation

To ensure that the vadose zone material around the outside of the caisson remained undisturbed, the 2.3-m-diameter caisson was placed upright on the ground surface, and the material within the caisson manually dug out. During that process, the caisson was secured by strops with winches, which allowed the caisson to be pulled down into the ground in small increments as the digging proceeded. Dewatering of the site was required as the bottom of the caisson needed to be placed below the water table location. Once the required depth was reached, a 1.2-m-thick concrete plug was poured into the base of the caisson to provide the bottom floor and the necessary ballast protection against floatation. Two galvanized steel-grid floors were installed within the caisson at 2.1 m and 4.0 m below ground level with vertical ladders providing access between the levels (Fig. 4). Rainfall is collected on the roof of the caisson and discharged off-site.

To install the AETLs hollow stainless-steel shoring boxes with removable top lids were used. The shoring boxes were designed to remain permanently in place to provide the necessary separation distance between the dry zone under the plate and the sampling plate itself. At each of the 15 sampling locations (Fig. 2 and 4) access windows were cut through the caisson wall (Fig. 7), and a 10-t hydraulic ram was used to install the shoring boxes. Before installation, the assembled AETLs were again cleaned and flushed. Thick slurry, made from sieved (2 mm) vadose zone material excavated from within the shoring box, was poured onto the top of the filter-covered plate to ensure good contact was established between the AETL and the undisturbed face of vadose zone material. To install the AETL the shoring box lid was pulled back just far enough to allow the sampling AETL access so that with pneumatic jacks it could be carefully raised into place against the face of the undisturbed vadose zone (Fig. 7). The load in pneumatic jacks and the upward distance traveled by the AETL during installation were carefully monitored. Once sufficient contact was made between the undisturbed vadose zone material and the AETL, determined from the distance moved and the load applied, the AETLs were locked into place within the shoring box.

The same procedure was repeated for the spacer AETLs, and the front hatch cover with a sealing gasket was bolted around the access window. The leachate collection tubes were connected using flexible food-grade silicon tubing to the collection vessels, which are monitored continuously with load cells (Fig. 8).

By May 2005 (late autumn) 15 large sampling and 15 spacer AETLs with associated monitoring equipment were installed within the vadose zone.

Control of the AETLs

Matrix potential in the vadose zone materials are measured with tensiometers (Type T4e, UMS-GmbH, Munich, Germany). The reference tensiometers, were installed 60 cm away from the center line of the AETL in the surrounding undisturbed vadose zone material. The corresponding plate tensiometers were installed 4 cm above each sampling AETL mid-distance along the center line.

The control system originally implemented was a modification of the Kosugi and Katsuyama (2004) method, in which the vacuum applied under each plate is controlled to minimize the difference between the reference and plate tensiometers. Unlike the Kosugi and Katsuyama method, the vacuum was not allowed to fluctuate rapidly between high (close to bubble point of plate material) and zero vacuum levels; rather, the vacuum was applied for as long as necessary to minimize the difference between the two tensiometers. As was to be subsequently discovered, the disadvantage of

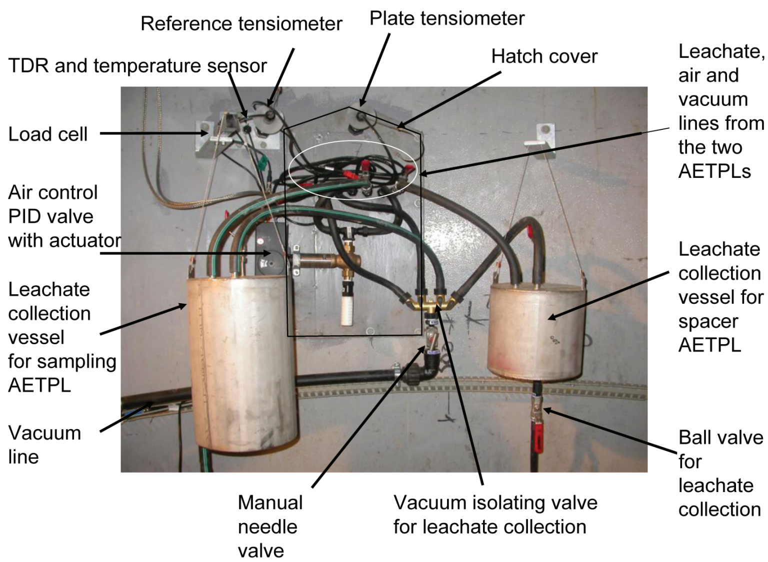

Fig. 8. Sampling site showing the two leachate collection vessels from the spacer and sampling automated equilibrium tension lysimeters (AETLs), the piping through the hatch cover, the proportional-integral-derivative (PID) control valve, the manual needle valve, a four-way splitter valve for the vacuum supply, load cell for the leachate measurement from the sampler AETL, time domain reflectometry (TDR) and temperature sensors, the reference and plate tensiometers and manual valves to allow plate isolation for leachate collection.

this strategy is that the high vacuums may dry out the relatively coarse-textured vadose zone material close to the plate (Wierenga, 1995). This could then cause the hydraulic conductivity to drop to such an extent that water could not be transported through the dry zone created (van Genuchten, 1980).

With soil pressure heads changing rapidly at the upper AETLs locations during infiltration, the matrix potential is monitored every second, and plate vacuums are controlled at the same time step. The control of the vacuum applied under the AETL uses a constant vacuum source of −500 hPa, supplied by a vacuum pump, and individual proportional-integral-derivative (PID; Samson EB 5824, Frankfurt Germany) air control valves to bleed in air accurately to maintain the vacuum under the AETLs within its target range. The vacuum level within the AETL is monitored continuously with a pressure transducer (Gems Sensors and Control, Hampshire, England). Manual needle valves are used to restrict the vacuum to keep the PID valves, which were precalibrated in the laboratory, operating within their optimum control range. Manual isolation valves allow an uninterrupted vacuum to be maintained in the AETLs when leachate vessels are emptied. Leachates are being analyzed for a wide suite of ions and metals so that we can understand the fate of contaminants moving through this vadose zone.

The system is continuously controlled and the data logged using a National Instrument Compact FieldPoint unit (cFP-2010) programmed in LabView 8.0 and connected to a GSM/GPRS modem for remote data access.

Additional Monitoring Equipment Installed at the Field Site

To aid with the understanding of the water flow and fate of contaminants moving through the vadose zone we installed time domain reflectometry (TDR) probes, gas samplers, and temperature sensors alongside the AETLs and tensiometers at the experimental facility. In-house manufactured TDR probes to measure volumetric water content were installed at each AETL location adjacent to the reference tensiometers. Details on the construction and calibration of these TDR probes are reported in Stenger et al. (2007). The TDR probes are connected to a TDR 100 unit (Campbell Scientific Inc., Logan, UT) and a CR10X (Campbell Scientific) unit for logging the data. One-meter-long passive gas samplers made from 12.8-mm-diameter peroxide silicon tubing (Cole Palmer, Vernon Hills, IL) are installed at each AETL site and additionally at the 10-cm depth (also three replicates) to investigate the composition of gas through the vadose zone. This can help in revealing the presence of contaminant transformation processes such as denitrification. Temperature sensors were installed 60 cm out from the caisson at the five sampling depths. A vented pressure transducer in a groundwater monitoring well installed through the concrete caisson floor monitors groundwater levels beneath the Spydia.

In addition, the site is equipped with a meteorological station at about 500 m distance from the Spydia, where rainfall, solar radiation, air temperature, relative humidity, and wind speed and direction are measured. Rainfall is also measured directly on site with a 0.2-mm tipping bucket rain gauge.

Initial Field Results

During the winter period of 2005 concerns were raised because water fluxes were only being measured when soil pressure heads were less than approximately −30 hPa and the volumes measured were only between 10 and 40% of those expected. Subsequent field testing showed that the level of vacuum being applied to the AETL could not influence the plate tensiometers as expected. As a result we removed one set of AETLs (spacer and sampling AETL) for further laboratory testing.

Laboratory Results

To investigate the system behavior under controlled laboratory conditions, a 60-cm-high wooden box was fitted above the AETL and filled with Taupo ignimbrite material collected from the 1.0-m depth from the Spydia site and compacted to a bulk density similar to field conditions. A T4e tensiometer was installed horizontally through the wall of the wooden box and located centrally 4 cm above the plate as in the field. The vadose zone material was wetted to obtain a pressure head of −5 hPa in the plate tensiometer before the start of each individual experiment. Different levels of vacuum were applied to the AETL, and the response in the plate tensiometer monitored. Figure 9a shows the response in pressure head in the plate tensiometer was less than 5 hPa to vacuum levels applied of −60, −150, and −50 hPa in the AETL. This behavior was consistent with what was being observed in the field.

The two sheets of polypropylene needlepoint filter media were then removed and the experiment repeated (Fig. 9b). In this case, the pressure head in the plate tensiometer responded rapidly to the vacuum applied to the AETL and asymptotically approached the applied vacuum level. We concluded that the polypropylene needlepoint filter media was acting as a hydraulic barrier disconnecting the pore water in the sequence of: porous plate, filter 1, filter 2, slurry, vadose zone material. On the basis of these results, all the AETLs were removed from installation in the Spydia and the filter media removed. After thorough retesting, the AETLs were reinstalled without filter media. To date no signs of blockage of the plates and associated reduced hydraulic performance has been observed.

Revised Control Strategy

Upon reinstallation of the AETLs we adopted a variation of the Masarik et al. (2004) control system where the vacuum level applied to the AETL is targeted to match the pressure head measured in the reference tensiometer. Masarik et al. (2004) aimed for a target vacuum level applied to the AETL to be 20 hPa lower than the surrounding soil pressure head to overcome the hydraulic resistance of the porous plate. However, using this relatively high offset, they reported the soil pressure head measured above the AETL was consistently lower than that of the surrounding soil. Morari (2006) reported that even slight overapplication of suction, typically applied to overcome plate resistance, can produce marked overestimation of water drainage (>30%). Since it is considered that the hydraulic resistance in the thin (1 mm) porous steel plates is very low, we aim for an exact match between the reference pressure head and the vacuum applied under the sampling AETL with a tolerance of ±0.2 hPa.

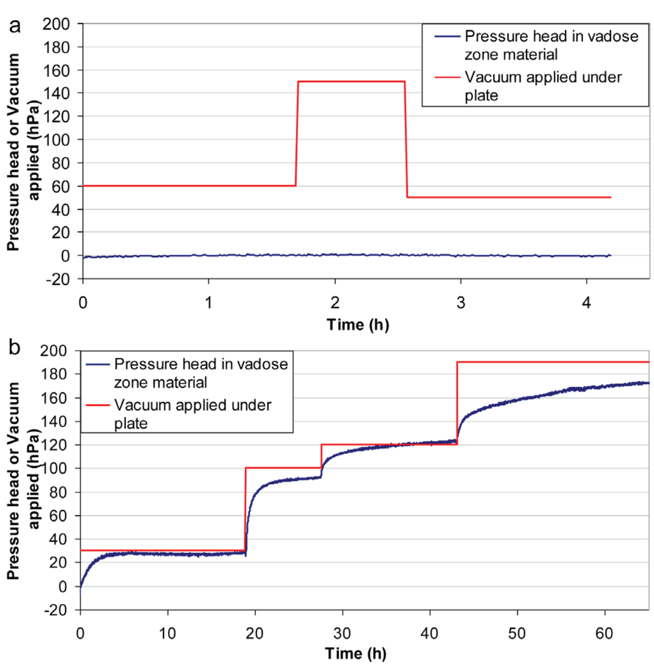

Fig. 9. Vacuum level (hPa) applied under the plate, (a) with and (b) without filters, and response in tensiometer installed directly over the plate.

The operation of individuals AETLs is stopped when pressure heads lower than 200 hPa are measured in its associated reference tensiometer. This helps to ensure the porous steel plates remain saturated. This cut-off threshold was determined from field data that have shown that the hydraulic conductivity was very low (ranges between 1×10^{-7} and 1×10^{-12} m s^{-1}) at these tensions for our vadose zone materials and unlikely to contribute significant flux volumes. As the vacuum exerted on the AETLs never exceeds −200 hPa, the setting of the main vacuum supply to the facility was reduced from originally −500 to now −250 hPa.

Evaluation of the Spydia Monitoring Facility

The Spydia facility became fully recommissioned in February 2008 (late summer). To demonstrate the performance and reliability of the Spydia flux monitoring system the following data are presented and discussed:

- Representative pressure head and water content data through the vadose zone from mid-winter (August) to mid-summer (December).
- An example of the fully functioning control system from late summer to late spring (May–November).
- Fluxes measured through the vadose zone profile following a 58-mm rainfall event over 30 h.
- The cumulative drainage recorded in AETL at each depth through the vadose zone from late summer to late spring (May–November).
- Preliminary results from an ongoing bromide tracer experiment for an AETL at the 0.4-m depth.

Field Pressure Heads

For the period between August and December, daily rainfall, pressure heads, and water contents through the vadose zone are presented in Fig. 10. The pressure heads measured at the 0.4- and 1.0-m depths show more dynamic time series, corresponding to the frequent rainfall events, as compared to the pressure heads measured at lager depths in the vadose zone (Fig. 10b). The 1.0-m pressure heads are somewhat damped as compared to the 0.4-m pressure heads, as there were some smaller rainfall events to which the pressure heads at this depth did not respond. The 0.4-m pressure heads dropped faster and further than those of the 1.0-m depth. During this saturated period the measured volumetric water content is gradually increasing with time; this effect is due to gradual dissolution of the entrapped air (Faybishenko, 1995) and its replacement by water.

The amplitude of responses decreases with depth, and the 5.1-m depth is influenced by the fluctuations of the groundwater table. Pressure heads at this depth became positive in late September when the water table rose above the 5.1-m depth. The amplitude in the pressure heads is lowest in the mid-depths (2.6 and 4.2 m) of the vadose zone, with the upper plates responding to downward directed drainage fluxes and the lower plate to the water table dynamics. The concurrently measured volumetric water contents (Fig. 10c) as expected, have a similar response to rainfall and rising water table as the pressure head data. Naturally, there is a difference between the amplitude of water content and pressure head data that is defined by the water retention characteristics of the vadose zone materials. As the rising water table passes the 5.1-m depth, the water content reaches saturation and stays relatively constant while the tensiometer reading records depth of water above this level.

The concurrent measurements of both pressure heads and water contents through the vadose zone enables the water retention characteristics at different depths to be derived from the field data using inverse fitting techniques and the derived functions to be compared to laboratory measurements (Wöhling, 2009). Additionally, the effect of using pressure head and/or water content in the calibration of flow models on the accuracy of the model simulations can be thoroughly investigated using these data sets (Wöhling and Vrugt, 2011).

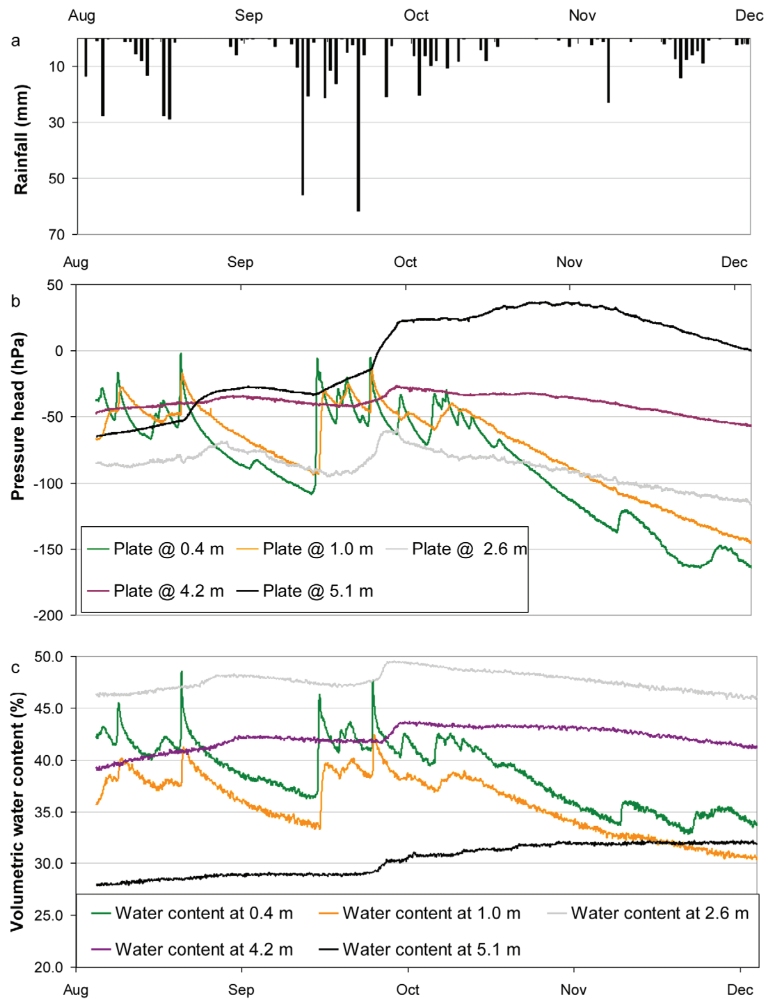

Fig. 10. (a) Daily rainfall, (b) pressure heads (hPa) of the reference tensiometers, and (c) volumetric water content, at the 0.4-, 1.0-, 2.6-, 4.2-, and 5.1-m depths of the vadose zone profile during a representative 180-d time period.

Example of AETL Control

The average 15-min vacuum level applied under the plate is within the target 0.02-hPa tolerance of the reference pressure head. The AETL control strategy is demonstrated in Fig. 11 where the reference pressure head and plate pressure head are shown for an AETL at the 0.4-m depth for a 180-d period from May to November. The average difference between the reference and the plate pressure heads is −5.4 hPa (Fig. 11c).

As shown in Fig. 11c the largest deviation between the reference and plate pressure heads occurs during the wetting up phase after an extended dry period in early September. At this time the pressure heads have dropped to relatively low values of −150 hPa, and a large wetting up event occurred, returning the pressure head values close to zero. During this process the largest deviation of 58 hPa occurs between the reference and the plate pressure heads. This deviation is due to the differences in timing of the wetting front arriving at each measurement location. After the dry period, the wetting front arrived at the reference location approximately 2 h before the plate pressure head sampling point. The vacuum applied under the plate was correctly lowered in response to the wetting front reaching the reference location. However, the plate pressure head cannot drop until the wetting front physically arrives at this location. This difference in timing of when the wetting front reaches each location leads to deviation in pressure head between the two locations. However, as this occurs relatively infrequently and only over a short duration the impact on measured fluxes is likely to be low. This behavior is attributed to variability in transport and wetting front movement throughout the vadose zone. In addition, preliminary dye studies conducted at this site (not reported here) indicate some nonuniform infiltration patterns after extended dry periods that are probably related to water repellence patches and possibly to preferential flow paths developing particularly in the thin (0.1–0.2 m) but organic matter rich A horizon. These repellence conditions break down relatively quickly after precipitation events, when the upper vadose zones get wetter and consequently flow conditions tend to become more uniform.

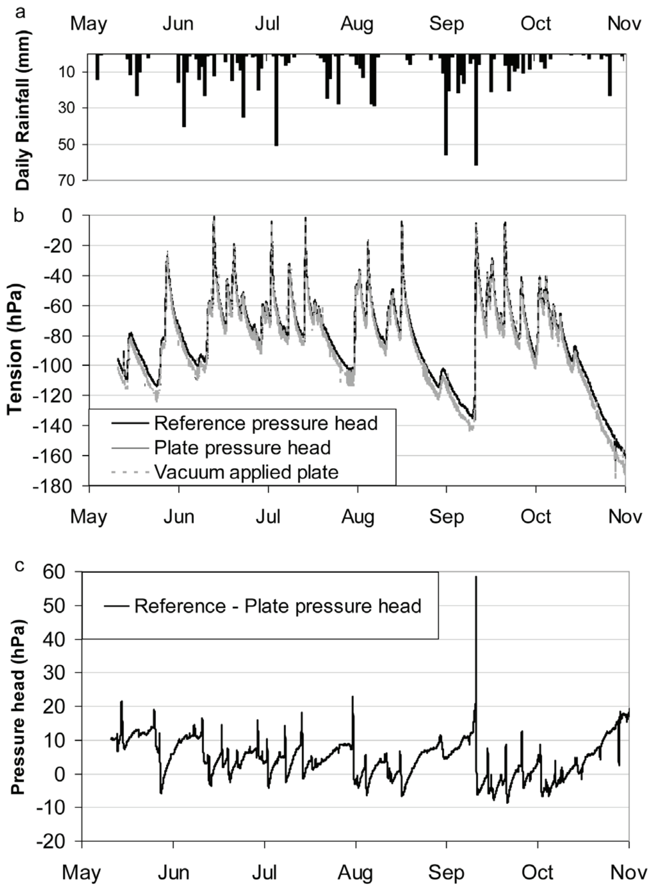

Fig. 11. Control strategy in a 0.4-m automated equilibrium tension lysimeter (AETL) showing (a) rainfall over a 6-mo period May to November, (b) pressure heads measured in the reference and plate tensiometers, and (c) deviations between the reference and plate pressure heads (hPa).

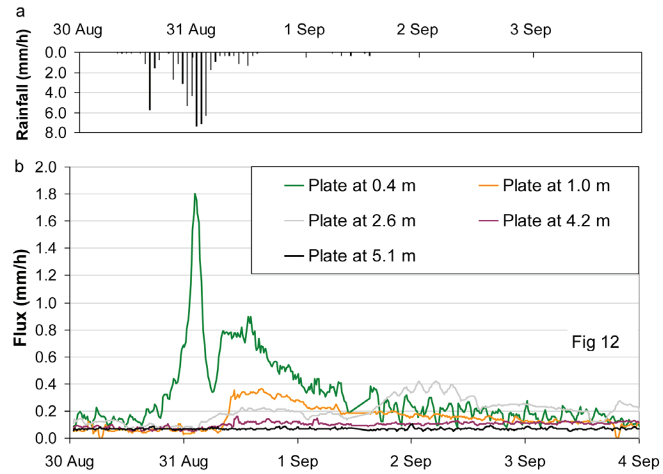

Fig. 12. (a) Rainfall (mm h^{-1}) and (b) drainage flux measured (mm h^{-1}) at 15-min increments in automated equilibrium tension lysimeters (AETLs) through the vadose zone over a 5-d period with a 57-mm rainfall event.

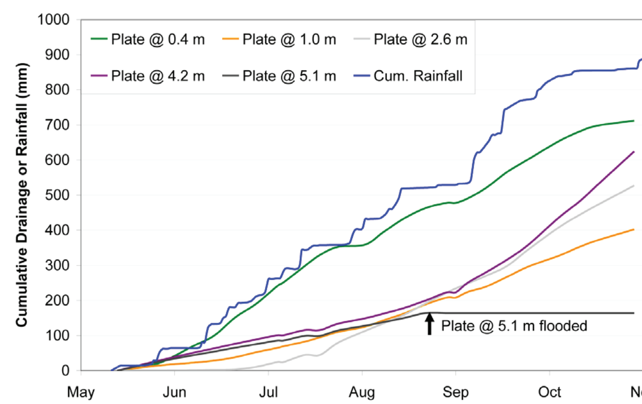

Fig. 13. Cumulative drainage measured (mm) in plates through the vadose zone profile over a 6-month period, May to November (winter to spring) and cumulative rainfall (mm) over same period.

Flux Measurements

Figure 12 shows the fluxes measured by selected AETLs, one from each of the five sampling depths, following a rainfall event of 58 mm over a 30-h period. The peak rainfall intensity of 7.4 mm h^{-1} resulted in an equivalent peak flux of 1.8 mm h^{-1} measured over 15-min intervals at the 0.4-m depth. The peak in the flux measurements at the 0.4-m depth occurred quickly: 1 to 2 h after the peak rainfall. The cumulative volume collected in the 0.4-m AETL was 37.7 mm during the 3-d time period following the event, which represents 65% of the rainfall volume of the event. As expected the peak fluxes decreased and occurred later with depth through the vadose zone. Cumulative drainage collected over this time period also decreased with depth. The flux at the 5.1-m depth remained relatively constant at 0.7 mm h^{-1} with a cumulative volume of 9.3 mm over the period representing 16% of the rainfall volume.

Figure 13 shows the cumulative water flux measured by selected plates through the vadose zone and rainfall for the 6-mo period between May and November (winter to spring). The cumulative flux is largest and exhibits the most dynamic response to rainfall at the 0.4-m depth. During the early stages of winter, with no plant water uptake, the drainage is nearly the same as the rainfall, but with warmer temperatures in spring and plant water uptake increasing concomitantly with greater soil evaporation, the difference between rainfall and flux accumulates to 170 mm over the 6-mo measurement period. When the AETL at 5.1 m becomes nearly submerged at the end of September, as observed by the location of the rising groundwater table, its operation is automatically shut off, and consequently fluxes are no longer measured at this depth. Similar to the results obtained above for the event based data (Fig. 12), the responses to rainfall of the AETLs at the 1.0-, 2.6-, and 4.2-m depths are increasingly lagged compared to the response of the AETL at the 0.4-m depth with higher drainage fluxes occurring from the end of September onward and continuing through at a higher rate to the end of the data in November. This is due to the wetting front(s) moving slowly down the vadose zone profile.

Bromide Recovery

A bromide tracer pulse of 726 Kg ha^{-1} Br (as KBr) was applied at the site in June to further investigate the movement of water through the vadose zone. This work is still on-going and will be reported in a separate study once completed. However, to provide confidence in the AETL measurement methodology, consider Fig. 14 that depicts the measured bromide breakthrough curve and cumulative bromide recovery recorded at one AETL installed at the 0.4-m depth. Bromide concentrations are derived from laboratory analysis of the leachate collected by the AETL during a 90-d period after tracer application. The analysis revealed a unimodal breakthrough curve with a relatively long tail. The measured bromide recovery of the bromide applied on the surface plan area was 96% for the data depicted in Fig. 14b. These results show that the near-surface flow during and after the trace application is mainly driven by vertical infiltration and that the AETLs reliably capture the vertical flux draining from below the root zone.

Summary and Conclusions

This technical note reports on a novel monitoring system that accurately measures water and contaminant fluxes at five different depths through a vadose zone under pastoral land use. The essential design and installation requirements to ensure that the fluxes measured are equivalent to those occurring in the undisturbed vadose zone profile are discussed.

In this AETL flux monitoring system it is designed to control, on a continuous basis, the vacuum under a relatively large porous sampling plate to match the transient pressure head in the adjacent undisturbed vadose zone. We suggest that by mirroring the transient states in the undisturbed zone, the fluxes captured on a continuous basis through the plate will accurately represent those in the undisturbed zone. The precise control strategy together with the specific design criteria of the AETLs allows an adequate measure of the highly variable flows that occur, particularly in the well-drained volcanic vadose zone materials close to the soil surface at the field site.

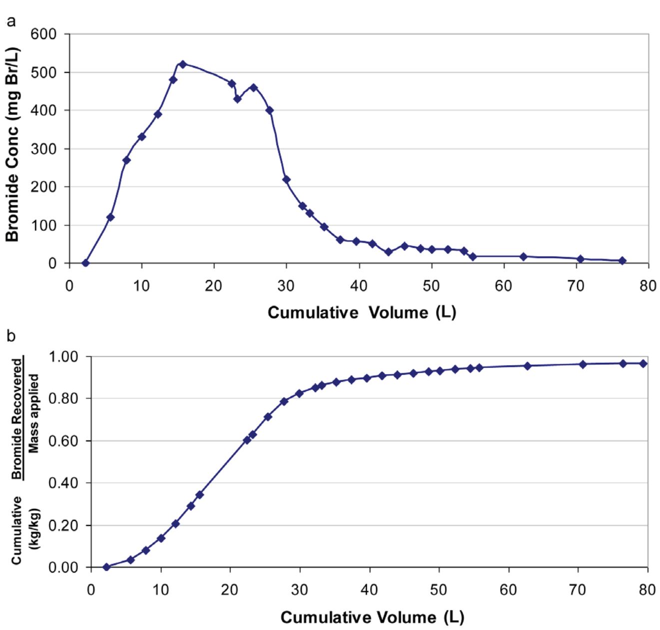

Fig. 14. (a) Concentration of bromide (mg Br L^{-1}) breakthrough in one of the AETLs installed at the 0.4-depth and (b) cumulative recovery of the mass bromide/mass bromide applied.

The initial results show exceptionally good agreement between the pressure heads in the undisturbed zone and those in the AETLs. This, combined with preliminary results from a bromide tracer experiment, provides confidence that the fluxes being measured are more accurate than those that may be measured with fixed tension lysimeters. Fixed tension lysimeters are limited to some extent by the fixed boundary conditions imposed so that the "true" flux dynamics are not captured. Additionally, the accuracy of the measured flux volumes depends on the choice of the "appropriate" tension for the bottom boundary, which is a difficult, but also a limiting choice that must be made.

This monitoring facility provides the unique opportunity to reliably measure water fluxes and contaminant concentrations through the vadose zone. For the first time, by installing sampling lysimeters at multiple depths through a vadose zone, the trajectory of water and contaminants moving from the soil surface down to the permanently saturated zone can be measured.

The acquired data are of great value for calibration and evaluation of water flow and contaminant transport models, which quite often rely on limited information from state variables of water content or pressure head; parameters derived from laboratory analysis of small-scale soil samples, which are rarely representative for the scale of interest; or flux estimates limited by controlled boundary conditions.

Data from the first months of operation of the facility have improved our understanding of the water and contaminant transport dynamics in the well-drained layered vadose zone in the Lake Taupo catchment. Long-term reliability and accuracy of the system will be assessed as further data become available. We are currently conducting a bromide tracer experiment and are planning a second experiment at the site with a nitrate-bromide tracer. Future research will also focus on nutrient transformation and variability of contaminates fluxes under grazed agriculture.

Acknowledgments

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