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Zero-Tension Lysimeter for Use in Greywater Irrigation Monitoring

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Abstract: The main purpose of the study was to develop a new zero-tension lysimeter (ZTL) as a leachate sampler in a greywater irrigation plot. Greywater is known as a wastewater that is generated from baths, showers, washing machines, laundry troughs, dishwashers and kitchen sinks; but excludes toilet wastes. The use of greywater is becoming increasingly acceptable to supply non-potable irrigation needs. However, some questions have been raised about the pollution risk of soil and receiving waters due to the content of different pollutants from the household washing activities. In this study, the new ZTLNs were trialled to compare the quantity and quality of leachate collected with the conventional pan lysimeter (ZTLP) in the pilot scale study. The calculated leachate volume incorporated a water balance using the Penman-Monteigh model. The results indicate that the new lysimeter designated as ZTL (N1), produced the lowest mean percentage deviation from the calculated volume (CV), 3.90 %. ZTL (N1) was also cost effective and required limited effort to install using an auger, which also minimises soil disturbance to install at household sites. Consequently, the lysimeter was established to facilitate the monitoring of greywater irrigation.

Keywords: Greywater, zero-tension lysimeter, leachate, monitoring

1. Introduction

Lysimeters are the common tool in soil solution or leachate collection equipment and are normally designed and adjusted to accommodate individual research requirements. Numerous in situ devices have been employed over the years to collect leachate. However, most of them are difficult to use and expensive. The simplest method of leachate collection is through using a zero-tension lysimeters (ZTLs) or pan lysimeter, where there is no capacity to exert a tension on the plates. However, installation of a pan lysimeter becomes a major obligation in many household gardens due to its physical constraints.

Conventionally, ZTLs consist of shallow pans or troughs that are inserted laterally into the soil from an access pit or trench. However, the conventional design and installation of ZTLs provides a number of problems. First, digging access pits or trenches to depths appropriate for sampling subsurface materials may be impractical or prohibitively costly. Second, the digging process during ZTL installation may alter physical conditions and limit interpretations and predictions, leading to questionable data.

The common definition of greywater is wastewater derived from bathrooms and laundry but excluding toilet. Household greywater reuse is becoming increasingly acceptable to overcome domestic irrigation needs, especially for the garden irrigation for non-edible plants. Although studies have shown greywater is a potentially reusable water resource for irrigation edible crops; tomato [1, 2]; lettuce, carrots, peppers [3] and silverbeet [4], and for household lawns and gardens [5], studies on its interaction with the environment is limited. Still, the leaching of salts and other chemicals from greywater sourced from the laundry has been examined [6]. Moreover, the pollution risk of soil and receiving waters due to the content of different pollutants are some questions that have been raised.

With these limitations in mind, an appropriate zero-tension lysimeter (ZTL) was developed as a tool that can be used to collect leachate from greywater irrigation in household gardens. The feasibility of two newly designed zero-tension lysimeters, ZTL (N1) and ZTL (N2), were compared to the conventional pan lysimeter (ZTLP). The aim of this study was to develop a lysimeter as reliable drainage monitors in assessing greywater flows within the root zone with surface application. Furthermore, it acts as a sample collector to determine the chemical composition of the leachate. The material cost of an individual lysimeter (ZTL) is approximately AUD $20 excluding labour.

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2. Materials and Method

Site description

The study was conducted at the Environmental Technology Centre (ETC), Murdoch University, Western Australia, from March to September 2008. To be representative of local conditions, the local landscape soil was used which corresponds to the type of soil commonly represent in household gardens and landscapes in Perth, Western Australia. The soil characteristics presented in **Table 1** were analyzed by a National Association of Testing Authorities, Australia (NATA) accredited soil and plant laboratory.

Table 1: Result of soil analysis

Parameter	Concentration
pH	6.2
EC (dS/m)	1.021
Nitrate N (mg/kg)	1
Ammonium (mg/kg)	14
Phosphorus (mg/kg)	110
Sulphur (mg/kg)	463
Boron (mg/kg)	1.1
Total P (mg/kg)	420
Carbon %	8.13
Total N (%)	0.18
Moisture (%)	5

Three irrigation drip lines were fitted to each cell at a spacing of 25 cm and irrigated with tap water at a rate of 10 mm/day; this is a maximum allowable application rate for greywater irrigation based on free draining sands typical of the Swan Coastal Plain [7]. This is sufficient to meet the peak water requirement at high water consumption, assuming a crop factor of 0.8, multiplied by a maximum summer daily evaporation rate of 10 mm, which produces a peak irrigation requirement of 8 mm per day. Eight lysimeters; four zero-tension lysimeter pan (ZTLP) and four zero-tension lysimeters new, designated as ZTL (N1) and ZTL (N2) were attached to each duplicate block as shown in **Fig. 1**.

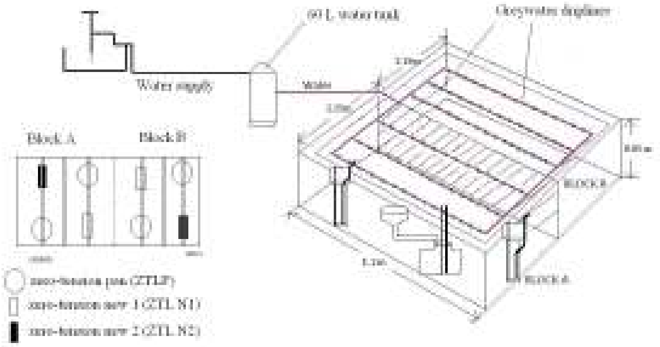
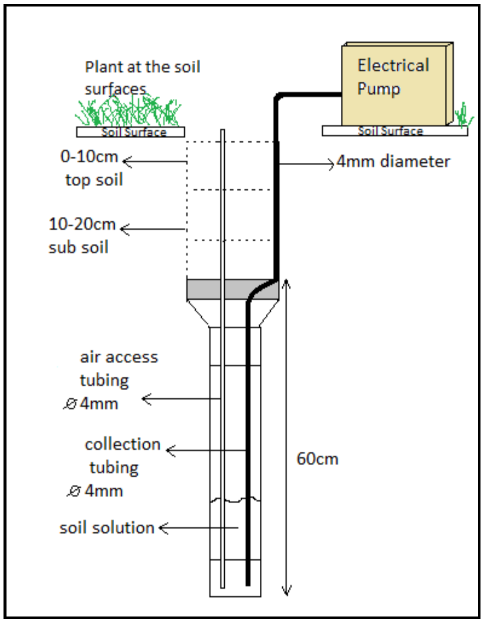


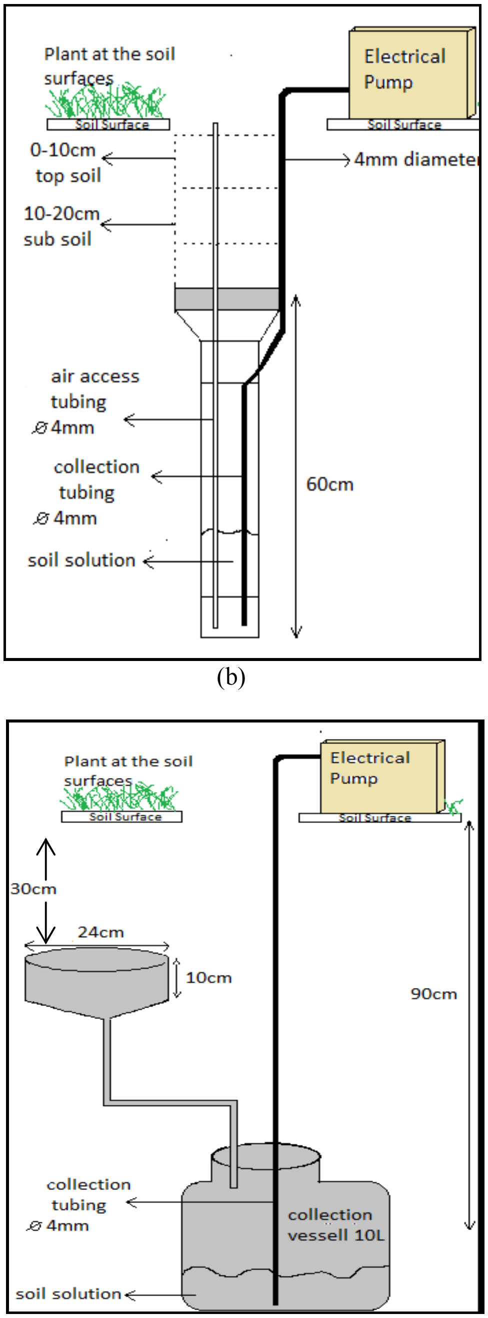
Fig. 1 shows the ZTL locations within the 1.15 m x 1.2 m block.

Zero-Tension Lysimeter Design

A ZTLP monitoring unit consists of a pan with a 240 mm inner diameter funnel connected to a tube, a 10 L collection tank and outlet tubes from these tanks that will be directed to the surface where the inspection tube is located as in **Fig. 2 (c)**. Lysimeters ZTL (N1) and ZTL (N2) were constructed from: PVC pipes, 110 mm inner diameter by 0.6 m long, pipe sewer adaptor, flexible tubing and collection plate fitted with a mesh filter. **Fig. 2 (a and b)**. The flexible tubing provides access to the inside of the lysimeter once it is buried.



(a)



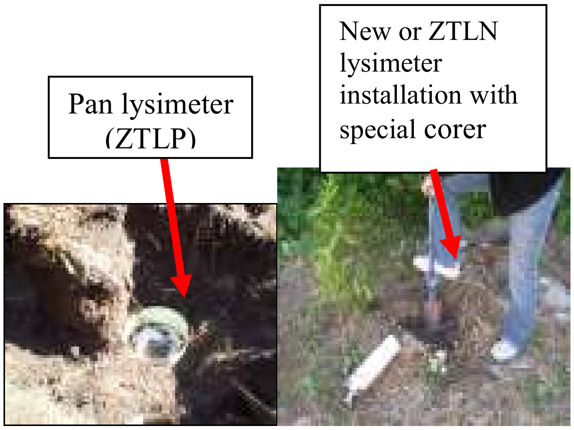
(b)

(c)

Fig. 2 Schematic diagram of the lysimeters: (a) ZTL (N1) and (b) ZTL (N2) with different tubing location; compared with (c) ZTLP (or pan lysimeter)

All the ZTLs were installed 300 mm below the surface, a depth considered the microbially active surface layer, where most of the nutrients are utilised. ZTLs should be buried deep enough so they do not interfere with surface soil operations and prevent root intrusion. However, Gazula (2006) [8] suggested that if the depth is too great the lysimeter may fail to intercept some of the vertical water flow below the root zone.

A ZTLP or pan lysimeter installation involved (i) excavating a volume of soil (1 m depth, 500 mm wide) (ii) preparing a tunnel between the conical base (pan) with plastic tubing to transfer soil solution to a collection container. The major excavation process is shown in **Fig. 3 (a)**, compared to more simple installation for ZTLN in **Fig. 3 (b).**



(a) (b)

Fig. 3 (a) Major soil excavation process in the zero-tension lysimeter pan (ZTLP) installation compared to; (b) zero-tension lysimeter new (ZTLN) installation using a corer.

Leachate Sampling and Analysis

All the samples from the ZTLs were collected on a weekly basis. Leachate was collected from the collection chambers of each ZTL using a pump powered by a 12 V rechargeable battery. According to [9], leachate should be drawn from the lysimeter reservoirs on a regular sampling schedule typically weekly, biweekly, or monthly [8]. The monitoring should avoid having solutions left in the reservoir for a long time, where chemical change from decomposition of dissolved organic carbon or the dissolution of suspended colloidal materials can occur. [10] noted that chemical transformations of certain forms (e.g., NO_3^- and NH_4^+) can be very labile; other forms (e.g., SO_4^{2-}, Ca^{2+}) are more inert. However, according to [11], changes of NH_4^+, NO_2^- and NO_3^- concentration after storage for 10 days are small (≤ 1 mg L^{-1}).

A tensiometer, HANA model HI 83900 (Rootzone, Australia) was selected to use as a tension lysimeter (TL) to compare with the ZTLs. The tensiometer was a porous ceramic cap connected to a transparent tube for leachate extraction. Such comparison was made to give an insight into the effects of applied tension on leachate chemical composition. Leachate was collected and analyzed for the following parameters: total suspended solids (TSS) by the gravimetric method; nitrate (NO_3) by the cadmium reduction method; ammonium (NH_4) by the Nesslerization method; total nitrogen (TN) and total phosphorus (TP) by the persulfate digestion method; reactive phosphorus (PO_4) using ascorbic acid method; chloride (Cl) by mercuric thiocyanate method and boron (B) by the azomethine method. All were measured using HACH 2010, an USEPA approved method. In-situ measurement of pH and Electroconductivity (EC) were obtained with an AQUA meter (TPS, Australia).

Water Balance of Leachate

Lysimeters collect leachate, and thus are not, *per se*, a flux measurement of ecosystem losses. The variation of quantity of leachate collected between ZTLs varied even with similar conditions. Quantification of leachate in the ZTLs therefore must be coupled with a water-balance model to estimate fluxes below the rooting zone. Coupled ecosystem and hydrologic models should be customized to each site, and require significant knowledge about the climatology. The water balance method is based on the principle of mass balance;

$$\text{Input} = \text{Output} + \text{Change in storage} \tag{1}$$

Equation 1

Using water-balance terminology, the simplified mass balance is:

$$PI = E_t + RO + \Delta SM \tag{2}$$

Equation 2

Where PI (precipitation + irrigation) is the total input; E_t is the evapotranspiration, RO is the runoff and ΔSM is the change in soil moisture storage.

The evapotranspiration values were obtained from the Bureau of Meteorological (BOM) of Western Australia using the Penman-Monteith equation, as recommended by the United Nations Food and Agriculture Organisation in their Irrigation and Drainage paper 56 (FAO56). The FAO56 method is an approved standard for the UN World Meteorological Organization, of which the BOM is a member agency. The climate and weather data information was obtained from the Murdoch weather station located 1.7 km from the block study area (32.07°S, 115.83°E).

Statistical analysis

Differences in leachate quantity of ZTLs collection between the two blocks and chemical composition of ZTLs compared to TL were analyzed statistically using one-way analysis of variance (ANOVA) test to determine significant differences, and were performed using *Sigmastat 3.5* (SPSS Inc.). A result was considered 'significant' if the probability of the null hypothesis was equal to or less than 0.05 or ($P \leq 0.05$). The collection efficiencies of the ZTLs between block A and B were tested for correlation using Pearson's Method.

3. Results

Collection efficiency of the ZTLs

The calculated leachate volume incorporated a water balance using the Penman-Monteigh model. The weather observations were taken between the months of April and September 2008. The percentage recovery values were converted into % absolute deviation from the mean calculated leachate volume (**Table 2**).

Table 2 Percentage of deviation from calculated volume (using the water balance method) of measured leachate volumes among ZTLs.

			Measured Mean Volume (mm)			**% |Deviation from CV|**		
Month	**Week**	**CV*, (mm)**	**ZTPL**	**ZTL (N1)**	**ZTL (N2)**	**ZTPL**	**ZTL (N1)**	**ZTL (N2)**
Without grass								
Apr-08								
	1+2	58.6	24.47	8.88	0	58.24	63.71	100.00
	3+4	28.6	26.2	13.67	15.95	8.39	47.82	16.68
May-08								
	1+2	15.2	30.79	13.67	2.51	102.57	55.60	81.64
	3+4	60.4	22.02	29.05	6.83	63.54	31.93	76.49
Jun-08								
	1+2	77.1	22.02	29.62	3.42	71.44	34.51	88.45
	3+4	169.3	34.46	36.45	10.82	79.65	5.77	70.32
With grass								
Jul-08								
	1+2	44.2	34.17	31.89	5.7	22.69	6.67	82.13
	3+4	170.9	32.63	36.45	5.47	80.91	11.71	84.99
Aug-08								
	1+2	32.8	33.12	33.94	7.46	0.98	2.48	78.02
	3+4	15.7	33.49	36.45	5.58	113.31	8.84	84.69
Sep-08								
	1+2	20	30.19	34.74	6.83	50.95	15.07	80.34
	3+4	99.4	30.75	35.88	6.26	69.06	16.68	82.55
Mean volume without grass						**29.78**	**15.82**	**66.70**
Mean volume with grass						**1.24**	**8.02**	**82.12**
Overall mean						**15.51**	**3.90**	**74.41**

* CV= Calculated volume

The results show how ZTL (N1) performed in comparison to other ZTLs. The ZTL (N1) produced the lowest mean percentage deviation from the calculated volume (CV), 3.90 %. The ZTLP and ZTL (N2) achieved 15.51 % and 74.41 %, respectively. However, the ZTLP seems to perform better than the ZTL (N1) during the months of July until September where the mean percentage ZTLP and ZTL (N1) were 1.24 % and 8.02 %, respectively. The ZTL (N2) produced inconsistent results with high variances.

Leachate volumes to ZTLs location below the driplines

Table 3 shows leachate capture within the ZTLs located in the driplines. An estimation of the percentage effective capture can be found by moving the locus of the circular opening of the ZTLs between the lines of two dripline points, 40 cm apart**.** It is clearly illustrated that the pan or ZTLP is more effective compared to the smaller opening of the new ZTLNs. However, it is possible though to optimise the most effective opening if other factors such as proper installation procedure and hydraulic gradients were well maintained.

Table 3 Efficiency of percentage leachate capture by ZTLs

	Distance from the centre dripline hole				
	0 mm	**5 mm**	**10 mm**	**15 mm**	**20 mm**
ZTLP (Φ 240 mm)	100	78	57	34	13
ZTLN (Φ 110 mm)	100	47	9	0	0

Leachate chemistry

The chemical composition of the leachate is listed in **Table 4a** and **4b.** There was no statistically significant difference in the chemical composition of leachate between the TL and ZTLs installed in both blocks for most major chemical constituents; B, H_2PO_4, and NO_3, NH_4. However, there were some significant differences for TSS, TP, TN and Cl in TL where the compositions were found to be lower than in the ZTLs. The exception was H_2PO_4, which was found to be slightly greater in the TL than ZTLs**.**

The monthly chemical composition is displayed in **Fig. 4.** Among the ZTLs, a general pattern of seasonal variation during high and low rainfall was apparent. The leachate had higher composition; Cl, NO_3 and H_2PO_4 and NH_4 during the high rainfall that occurred in June and July in the all ZTLs. No fertilizer was added in the soil; the nutrient deficiency in latter months was clear.

Table 4 a Mean composition of leachate (± S.E.) collected with the tension lysimeter (TL) and zero-tension lysimeters (ZTLs). Results are based on 3 replicates.

	pH	**EC**	**TSS**	**TP**	**TN**	**B**
		µS/cm	**Concentration (mg/L)**			
Tension lysimeter						
TL	7.3 (0.4)	560 (10)	46 (1)	1.25 (0.15)	4.75 (3.15)	0.21 (0.50)
Zero- Tension lysimeter						
ZTLP	7.8 (0.8)	650 (8.5)	67 (2.57)	4.9 (0.60)	13 (0.4)	0.27 (0.16)
ZTL (N1)	7.6 (1.2)	585 (15)	63.90 (5.90)	3.86 (1.16)	12.12 (2.12)	0.23 (0.10)
ZTL (N2)	7.5 (0.5)	600 (5)	65.11 (1.12)	5.5 (0.6)	11.26 (2.86)	0.17 (0.09)

Table 4 b Mean composition of leachate (± S.E.) collected with the tension lysimeter (TL) and zero-tension lysimeters (ZTLs). Results are based on 3 replicates.

	NH_4	**Cl**	**H_2PO_4**	**NO_3**
Tension lysimeter				
TL	1.49 (0.08)	21 (1)	0.90 (0.15)	0.14 (0.41)
Zero- Tension lysimeter				
ZTLP	1.52 (0.26)	27 (1.50)	0.85 (0.50)	0.13 (0.32)
ZTL (N1)	1.46 (0.15)	24 (1)	0.83 (0.61)	0.11 (0.03)
ZTL (N2)	1.49 (0.15)	22 (2)	0.83 (0.93)	0.10 (0.11)

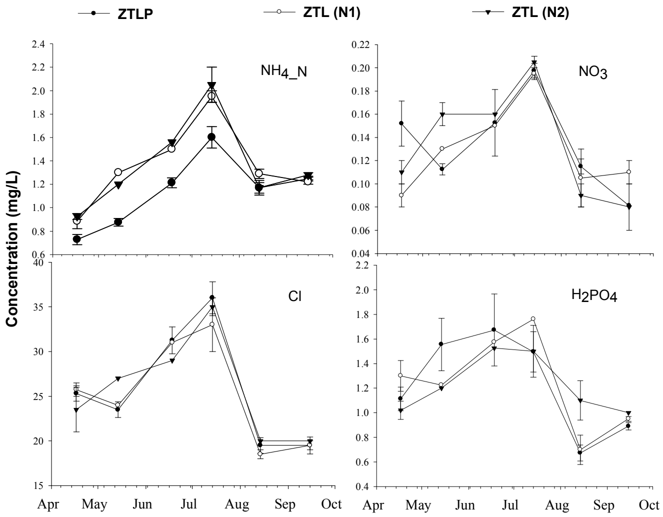


Fig.4 Leachate chemistry among ZTLs

4. DISCUSSION

ZTLs volumes and collection efficiency

The effectiveness of the pan lysimeter (ZTLP) when used to collecting soil solution or leachate is questionable. It appears that the volume of leachate collected by ZTLP has a high variance (**Table 2**). Here, a water balance approach using weather data is used as an indicator of variability and complexity in the pattern of the constituents leaching in the soil profile. The estimation of the amount of leachate indicated that the extraction domain is related to the precipitation occurring for natural soils under atmospheric boundary conditions. This implies that the calculation of mass balance by utilizing the climatic conditions of the study area assisted in recognizing the actual volumes of leachate collected.

The performance of the ZTL (N1) is relatively good compared to other ZTLs. The ZTL (N1) has produced the lowest mean percentage deviation from the calculated volume (CV) of 3.90 %. It seems that ZTL (N1) is a promising tool for use in future monitoring of greywater irrigation.

It is shown that the larger surface area of the ZTLP is able to collect more leachate by being centrally located between the two driplines which are 40 cm apart. The estimate of water capture by both ZTLs can be verified. However, as shown by the difference in leachate collection of ZTLP and ZTL (N1), the amount of leachate collected does not correspond to the surface area of the system but instead depends on its design efficiency (**Table 3**). It is apparent that efficient design when collecting leachate in the new ZTL (N1) compared to ZTL (N2) comes from the location of the tubes (4 mm diameter) in the lysimeter. The lower volumes of the new ZTL (N2) most probably relate to the reticulation system and the bending of the tubes can result in clogging and hence prevent smooth suction by the pump.

The installation procedure for the ZTL (N1) minimized soil disturbance making it a preferable and reliable tool for monitoring. Mitchell (2001) [10] stated that the inappropriate installation technique of burying the lysimeters can result in substantial disturbance to the soil. This disturbance can have a marked effect on soil water chemistry. For instance, such disturbance is associated with the stimulation of nitrification. Therefore, installation procedure is the primary concern in lysimeter works and it is paramount to ascertain any disturbances that are affecting the results.

Chemical composition of leachate

Chemical composition analyses is effective in describing element fluxes, plant nutrient availability and, chemical processes in the soil [13]. Leachate is a good source of most nutrients used by plants, and the composition and dynamics of the leachate depend on interactions with the solid phases of the soil, as well as on the overall ecosystem.

Leachate collected by TL and ZTLs

In comparative studies, leachate collected from the TL showed fewer signs of chemical interaction (TSS, TP, TN and Cl) with the soil and the solution were less concentrated than solutions collected with ZTLs (**Table 4a** and **4b**). Indeed, the TL held under suction was unable to collect representative samples from the soil matrix sample. One problem with the suction controlled lysimeters is that water and solutes can interact with the porous material used for the suction devices. Another problem is that the natural matric potential and water flow streamlines can be altered, ultimately to alter the composition of the leachate [14]. Using ZTLs to obtain chemical composition in leachate is more moderate. Shepherd, (1998) [15] claim that ZTLs are ideal for measuring a wide range of nutrients or contaminants in sandy agricultural soils in the UK.

High and low rainfall influence the leachate

Studies of the leachate with ZTLs show that the concentrations of nutrients were of the same order of magnitude during the sampling campaign. The chloride ion (Cl^-) can be used as a tracer for soil water movement. White (2001) [16] shows little adsorption of Cl^- to soil components and, unlike NO_3 and SO_4, Cl^- is not chemically altered by soil organisms. During the early part of the experiment, evaporation exceeded rainfall, and an upward movement of Cl^- was observed. After heavier rainfall, the soil water reached field capacity and a downward movement of Cl^- occurred. In the latter part of the experiment, precipitation and evapotranspiration were equal, and Cl^- redistribution was small.

Generally, nutrients are present in the leachate in ionic form; the major nutrients as NO_3^-, NH_4^+, $H_2PO_4^-$, HPO_4^{2-}, K^+, Mg^{2+} and SO_4^{2-} [17]. The 1-2 % of N that is in inorganic or mineral form as NH_4 and NO_3, are most available for plants but also cause most environmental problems [18]. In this study, the significant concentration of TP, TP and PO_4 were influenced by the landscape soil type used in the blocks, which was prepared using organic nutrient-rich compost.

Nitrate is produced in the soil through mineralization or organic matter. Microbes release NH_4 and NO_3, which will contribute to leaching if not used by plants [18]. The increase in leachate nutrients levels (NO_3 and NH_4) starting in June was the result of heavy rainfall during the month of June and July. This is supported by Sánchez Pérez (2003) [19], who through their study on lysimeters found an increased NO_3^- in leachate during high rainfall events. According to Wild (2003) [17], in cool seasons, soil temperature is usually higher than air temperature. Increased water flow and increased mineralization of soil organic matter during warm weather conditions greatly increase the potential of NO_3 and NH_4 leaching.

Most of the P in soils occurs in inorganic forms as reactive P as H_2PO_4 or phosphate. Here the concentration of H_2PO_4 declined over time. The availability of phosphate in soil is strongly controlled by pH, and different forms of phosphate occur with increasing pH. The presence of soluble Fe or Al in acid conditions, and Ca at high pH, greatly reduces the availability of H_2PO_4

[15]. In addition, soil microbes release immobile forms of P to the leachate and are also responsible for the immobilization of P [20]. Also, the transport of P through the soil profile with texture-contrast is greatly enhanced by high rainfall rates.

5. CONCLUSION

This pilot study was designed to devise a method that could be utilised for monitoring of greywater, and particularly, show how a zero tension lysimeters can affect the movement and chemical composition leaching through soil. It is clear that monitoring using zero-tension lysimeters requires (i) a lysimeter that can be installed with a minimum of soil disturbance, (ii) a lysimeter that is convenient or small enough to install in a house garden but large enough to be representative, (iii) a system that consistently integrates leachate sample collection over time. Evaluation of quantity and quality among the ZTLs found that the newly designed ZTL (N1) meets these requirements.

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