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Discussions

Spatial and temporal distribution of drainage and solute leaching in heterogeneous urban vegetation environments

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Abstract

Deep percolation enhancement from recycled wastewater irrigation may contribute to salt accumulation and water table elevation that can ultimately cause soil and ground water degradation. The spatial and temporal variation of drainage rate and solute leaching were investigated in an urban park containing heterogeneous landscape plants that were irrigated with recycled wastewater. Field monitoring was undertaken at Veale Gardens in the Adelaide Parklands, Australia. Based on the landscape variation in Veale Gardens, two landscape zones were defined: one being largely covered with turf grasses with few trees and shrubs (MG) with the second zone being mostly trees and shrubs with intermittent turf grasses (MT). Experiments were performed using two zero-tension lysimeters placed horizontally 100 cm below ground to monitor the spatio-temporal behaviour of drained water and nutrient loadings for four seasons. The outcomes showed a large spatial and temporal variation of drainage quantity and quality in the MT and MG zones. The low vegetation cover in the MG zone resulted in more drained water than in the high vegetation cover (MT zone). In both zones, more drainage water was collected in winter than in other seasons. This is in spite of the input water showing a maximum rate in summer. The seasonal salinities measured in the two lysimeters showed very similar trends with the lowest salinity rate in autumn with the levels increasing through winter and spring. Chemical analyses of the leachate solute indicated no detrimental impact from using recycled wastewater during the study period.

1 Introduction

Most soils in urban green spaces have lost their natural horizons and morphological features, and quite often top soils have been removed and refilled (Jim and Chen, 2008; De Kimpe and Morel, 2000). As a result, the spatial heterogeneity of soil physical, chemical, and biological characteristics is generally higher than for native soils.

Insufficiencies and obstacles in understanding soil conditions undermine a sound judgement of urban soils (Jim, 1998). Improving the knowledge of soil biochemical properties assists in understanding nutrient cycling in urban soils (Lorenz and Kandeler, 2005) and subsequently prevents either inadequate or excessive input applications e.g. fertilization (Rosen et al., 2008). Lassaletta et al. (2012) concluded reducing surplus N fertilization as the most promising management system.

It is of interest to study drainage rates and solute transfers beyond the effective plant root zone since this can help in understanding the soil water balance status, availability of nutrients in the leachate as well as the risk of nutrient loading to the ground water. Appropriate interpretation of water and soil test results is subject to collecting representative water and soil samples. The choice of sampling method of drained water is of great importance. Several studies have been conducted in agriculture and forestry that may provide useful information for urban soil studies (Jim, 1998). The impact of available soil water sampling systems on vadose zone behaviour increases the uncertainty in selecting a representative sample (Peters and Durner, 2009). This is even more problematic in mixed vegetation urban green spaces (Nouri et al., 2012). High spatial and temporal variability of vegetation species, canopy covers and microclimates in urban landscape vegetation leads to a high variability of soil water characteristics and soil water accessibility. This introduces more complexity and uncertainty in quantification of drained water and nutrient leachate. Soil water sampling from undisturbed soil in a heterogeneous landscape environs with the purpose of systematic investigation of quantity and quality of drainage can be achieved by in-situ soil water collectors. However, it should be noted that in-situ sampling may not be spatially representative of a large area so the results are often restricted to small observation sites such as plots or small fields.

Investigation of nutrients in drained water has been undertaken since around 1850. A number of techniques and geometries of leachate collection devices have been tested and reviewed over recent decades (Hangen et al., 2005; Moreno-Jiménez et al., 2011; Parizek and Lane, 1970; Yoo, 2001; Weihermuller et al., 2007). The most common inexpensive approaches are soil coring, suction cup (Hagedorn et al., 1999), suction plate (Kosugi and Katsuyama, 2004), wick lysimeter (Jabro et al., 2008), and zero-tension plate lysimeter (Peters and Durner, 2009; Robison et al., 2004). These studies have demonstrated the importance of soil profile characteristics in determining the infiltration rate of irrigation and/or precipitation as well as nutrient mobilization. An undisturbed soil profile can retain the natural soil structure (Goss et al., 2010) but disturbed soil can introduce artificial soil properties and changes in some natural conditions such as water paths and solute movements (Cameron et al., 1992). Of some concern is nutrient leaching beyond the root zone into ground water, which can potentially lead to ground water pollution (Goss et al., 2010). This is even more critical when recycled wastewater is used for irrigation (Tanji et al., 2007). There are numerous benefits in using recycled water for irrigation, including the low cost (when compared to other sources, particularly in an urban area), consistency of supply (regardless of season, climatic conditions and associated water restrictions), and general consistency of quality. Irrigation of recycled wastewater is also considered as a means for plant fertilization and particularly nutrient supplementation. This approach carries with it a risk of soil and water pollution through excessive wastewater application (Pandey and Srivastava, 2010). Hence, a detailed understanding of soil water conditions is essential for effective utilization of wastewater for irrigation.

This paper describes a field investigation using zero-tension pan (also known as equilibrium-tension) lysimeters. This was due to the advantages of pan lysimeters compared to other methods, including low complexity of design, reduced disturbance of the soil during installation, and simple and cheap operation (Zhu et al., 2002). The zero-tension lysimeter is a passive sampler in a pan shape, without large side walls, that freely collects the drained water, measuring drainage volume and solute leaching simultaneously below an undisturbed soil column (Weihermuller et al., 2007; Robison et al., 2004; Zhu et al., 2002). It minimizes the surrounding matric potential fluctuations and potential bypass flow resulting in the conservancy of natural and regular

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percolation patterns if sprinkler irrigation is uniformly applied in an area larger than the lysimeter area (Lehr et al., 2005).

Different materials such as stainless steel, glass or ceramic can be used for the collection tray. The lysimeter is typically placed under the ground either at a shallow or deep depth, depending on the effective root zone of the plant (Donn and Barron, 2012; Barron and Donn, 2010). The fill material in the tray has a substantial impact on the water potential gradient and water bypass (Weihermuller et al., 2007). The main sources of errors in pan lysimeters derive from diversion in water flow around the lysimeter as well as the complexity of installation.

This research is focused on the seasonal variation of drainage and solute leaching in a public park containing heterogeneous urban landscape vegetation that was irrigated with recycled wastewater. Two pan lysimeters were designed and installed in two different landscape zones. The field monitoring was undertaken for four seasons from December 2011 to November 2012. The outcomes were compared to study the effect of landscape vegetation changes on the spatio-temporal behaviour of drained water and nutrient availability in the leachate. Moreover, the volume of drainage was measured for the purpose of developing a detailed soil water budget for the study site. The rate of nutrient removal by leaching was investigated in order to propose an effective urban landscape management regime.

2 Materials and methods

2.1 Study area

The study was carried out in Veale Gardens within the Adelaide Parklands, South Australia (Fig. 1). Veale Gardens has an area of 9.6 hectares irrigated by treated (recycled) wastewater from the Glenelg wastewater treatment plant that is delivered to the Adelaide Parklands through the Glenelg to Adelaide Parklands (GAP) scheme. GAP

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recycled water is subject to strict quality standards and has been assessed as class A recycled wastewater (Martin et al., 2008).

Adelaide has a mean annual rainfall of 549 and 1600 mm of pan evaporation per annum (BOM, 2010). It experiences warm summers (December–February) with a mean maximum temperature of 29.5 °C in February and fairly cold winters (June–August) with a mean minimum temperature of 7.5 °C in July.

Veale Gardens contains more than 60 different species, size, and type of landscape trees and shrubs and a broad coverage of Kikuyu turf grasses. Kikuyu is a dominant species in most Australian parks due to its adaptability and invasiveness (Tanji et al., 2007). There were two types of vegetation cover on the site consisting of areas dominated by grasses and areas dominated by a mixture of different species of trees and shrubs accompanied by grasses.

A preliminary soil survey was conducted using EM38 soil mapping that provided rapid field measurement of apparent electrical conductivity (Hossain et al., 2010; Padhi and Misra, 2011). This enables development of an Electrical Conductivity (EC) soil map through geostatistical analysis in ArcGIS (Rodríguez Martín et al., 2006; Sarangi et al., 2006; Huang et al., 2013; Li et al., 2012). In October 2011, adjacent to each lysimeter, two bores were drilled down to 2 m and two intact core samples (50 mm internal diameter) were extracted for soil physical and chemical analysis. Standard methods were followed for sample preparation, packaging, labelling and storage (Handreck and Black, 2002). Based on the soil EC map, soil sample analysis and landscape variation in Veale Gardens, two different zones of low and high EC and two landscape zones of mostly grasses with few trees and shrubs (MG) and mostly trees and shrubs covered with intermittent grasses (MT) were defined. The experiments were performed on two zero tension lysimeters containing undisturbed soils placed horizontally 100 cm below ground to study the volume and quality of drainage as a function of time and space in two zones of MT and MG. In this study, in order to minimize the effect of spatial heterogeneity of soil salinity on the outputs in the initial stage of field work, the experiment was run in the low EC zone (less than 1.2 dS m^{-1}).

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2.2 Zero-tension lysimeter design and installation

The method of installation of the zero-tension lysimeter involved the excavation of a trench with a backhoe down to a depth of 150 cm which is mostly below the effective root zone of the plants (Fig. 2a). A small cavity of dimensions 120 cm × 55 cm × 30 cm was excavated in the long side wall of the trench at a horizontal distance of 100 cm from the edge of the trench (Fig. 2b). The cavity was precisely levelled in all five walls to prevent adding tension to the system (Fig. 2c). A galvanized metal tray of size 120 cm × 55 cm with geotextile on top (Fig. 2d) was precisely jacked up and fitted to the upper wall of the cavity in order to adequately maintain the capillary connection of the tray and above lying soil (Fig. 2e). The drainage collection bucket was placed at the base of the trench at a depth of 150 cm and a rigid PVC pipe connected the lysimeter tray to the collection bucket (Fig. 2f). The drained water was collected in the buried bucket through a rigid PVC pipe and two access tubes (Fig. 2g). To complete installation of the lysimeter, a plastic sheet was placed on the long side wall of the trench to protect the cavity from damage and to ensure separation of the undisturbed and disturbed soil (Fig. 2h). The backfilled soil was compacted by a leg rammer in layers to prevent soil subsidence (Fig. 2i).

The leachate was collected in buckets below the drainage compartments and was regularly extracted from the buckets to the flask by a vacuum hand pump (Fig. 3). The volume and salinity of collected water in each bucket was measured monthly during the period December 2011 to November 2012.

3 Results and discussion

3.1 Field and laboratory measurement of soil properties

EM38 soil mapping and spatial analysis produced a soil zoning map for Veale Gardens. Two different zones of low and high EC are illustrated in Fig. 4. Two positions in the low

EC zone (less than 1.2 $dS m^{-1}$) were marked in the field and later tested by a service locator company to ensure there was no conflict with existing assets and underground services, particularly irrigation pipes. Soil samples were taken from four bores immediately adjacent to the pan lysimeters. The results showed a texture of silty loam from the ground to 100 cm with a pH range of 8.0 to 8.5 and EC less than 1.2 $dS m^{-1}$ for lysimeter MG. For lysimeter MT, a texture of sandy loam was recorded from the ground to 100 cm with a pH range of 8.0 to 8.8 and EC less than 0.6 $dS m^{-1}$. These results are consistent with a previous SA Water Corporation report (Martin et al., 2008). Goatley (2011) indicated that loamy texture is the most ideal soil for most turf grasses and landscapes to ensure adequate water accessibility and aeration. Moreover, moderate soil pH (6.5–7.5) provides a suitable environment for optimum biological activity and nutrient availability, particularly for potassium and phosphorus. It is anticipated that the alkalinity of the soil may result in lower availability of nitrogen and phosphorus but should have no effect on potassium availability (Goatley, 2011).

3.2 Water drainage

Substantial amounts of drainage from two vegetation cover zones were observed monthly and analysed seasonally. Table 1 illustrates the seasonal volume of drained water in the MG zone from December 2011 to November 2012. Irrigation data were provided by Adelaide City Council (ACC), who manages Veale Gardens. Rainfall data for the nearest station (Kent Town, Station 023090) were downloaded from the Australian Bureau of Meteorology (BOM). Station 023090 is located on the east side of the city, 2.92 km from Veale Gardens (http://www.bom.gov.au/climate/data/). Table 2 shows the seasonal volume of drained water in the MT zone from December 2011 to November 2012 compared with the total irrigation and rainfall received. It should be noted that the irrigation rate in the MT zone was approximately 20 % higher than in MG zone, except in winter when the irrigation rate was zero in the MG zone but small volumes of irrigation occurred in the MT zone.

A high spatial variation in drainage rate was noted over the monitoring period in both MG and MT. The differences in lysimeter performance mainly could be related to the heterogeneity of vegetation or/and soil characteristics. The variation in landscape plants will have led to differences in evapotranspiration, canopy interception rates and root distribution. Root distributions in the MT zone were denser and deeper due to its mix of trees, shrubs and turf grasses and this will have led to higher moisture uptake rates. These results are in line with those of Cattan et al. (2007) and Naeth et al. (2011) who investigated the spatial variability of percolation fluxes in heterogeneous vegetation covers. In terms of soil characteristics, a higher percolation rate and lower available water capacity was expected in the sandy loam soil (MT) compared to the silty loam soil (MG). However, the results indicated a minimal effect on drainage variations from the different soil properties compared to the much stronger influence of vegetation heterogeneity.

A strong positive correlation coefficient of 0.90 was found between drainage rate collected from MG and MT. This confirms that they had a similar trend of drainage volume within the four seasons of the study period (Fig. 5).

Remarkably, the minimum drained water was collected in summer in both lysimeters. Also, the maximum input water, aggregated from irrigation and rainfall, was observed in summer which means that plant uptake of water was very high in this season particularly in the MT zone. This indicates that in summer most input water fulfils plant water needs through evapotranspiration while in winter as a consequence of the dormancy in most plant species, the evapotranspiration rate decreases significantly which results in an increased leachate fraction in winter.

3.3 Water quality of solute leaching

The differences in drainage rates associated with variation in vegetation landscape zones lead to differences in leachate solute quality. The electrical conductivity of each water sample was measured using an EC meter to quantify the salinity of solute

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leaching within the study period. The salinities were tested monthly and the seasonally, and averaged values are reported in Table 3.

A comparison of seasonal salinity for zones MG and MT indicated a strong positive correlation ($R = 0.97$) with the lowest salinity in autumn for both lysimeters. No correlation was found between seasonal drainage volume and seasonal salinity in either lysimeter.

Drained water quality and nutrient availability was analysed for each season for certain chemical characteristics including pH, EC, Sodium Adsorption Ratio (SAR), Total Dissolved Solids (TDS), potassium, nitrite, nitrate, total nitrogen, total phosphorus, and ionic balance. Soil pH was monitored with an automated system (PC Titrate) using pH 4.5 for indicating the total alkalinity end-point. Soil salinity and TDS were determined in an aqueous extract of a 1 : 5 soil-water suspension at 25 °C using an EC meter. Total phosphorus was measured using a Discrete Analyser. Nitrate was reduced to nitrite by way of a cadmium reduction column followed by quantification by the Discrete Analyser. Nitrite was determined separately by direct colorimetry. Total N was analysed using a traditional Kjeldahl digestion followed by determination by Discrete Analyser. The Ionic Balance was calculated based on the major Anions and Cations. The major anions were determined using the PC Titrate and Discrete Analyser. Major cations were measured using an inductively coupled plasma atomic emission spectroscopy (National Environment Protection, NEPM – Assessment of Site Contamination, 1999).

The importance of macronutrients (N, P, and K) is due to their fundamental role in plant functionality. Nitrogen is a component of protein and enzymes and controls almost all biological processes (Arauzo et al., 2010; Rafizul and Alamgir, 2012). Phosphorus is responsible for energy transfer in the plant, plant development, and photosynthesis (Djodjic et al., 2000). Potassium regulates the water usage of plants and their resistance to diseases (Kolahchi and Jalali, 2007). The SAR measures the ratio of sodium to calcium and magnesium ions and can be used to evaluate the effect of irrigation on soil structure (Goatley, 2011). Ionic balance represents the characteristics of the water in terms of principal dissolved salts. The required nutrients for landscape plants vary widely due to the broad numbers of species of trees, shrubs and turf grasses. For instance, turf grasses need a large amount of nitrogen for green growth while most flowering plants need more potassium and phosphorus (Tanji et al., 2007).

The drained water samples were sent to a NATA accredited laboratory (National Association of Testing Authorities, Australia) for water quality analysis. The results of the laboratory tests are shown in Fig. 6 with each column representing the average of two samples. For zone MT, the amount of collected leachate was too small to allow an accurate nutrient analysis. However, water salinity was measured in a diluted sample in the MT zone (Fig. 3). Figure 6 shows the water quality analysis for the MG zone. Hence investigation of the temporal variation of all water quality parameters apart from salinity was not possible in MT zone.

The recommended practical long-term trigger concentration levels for Adelaide Parklands irrigation (ANZECC and ARMCANZ, 2000) are 54.5 $mg L^{-1}$ for Total N, 6.8 $mg L^{-1}$ for Total P and 29.5 $mg L^{-1}$ for K. From a comparison of the results in Fig. 6 with these trigger values, it can be concluded that there is little risk of nutrient (N, P and K) build up or nutrient contamination of ground or surface waters. These results are consistent with findings of a previous SA Water Corporation study (Martin et al., 2008).

3.4 Cumulative nutrient leaching

The distribution variation of drained water creates fertigation variability. Precision irrigation and fertigation management necessitates considering the spatio-temporal variability of leachate volume and characteristics that are associated with variation of nutrient loading. The seasonal nutrient leaching in zone MG is illustrated in Fig. 7.

The cumulative nutrient loadings (g) were calculated using nutrient loading rates ($mg L^{-1}$) in a total volume of drained water in a season (L). The results showed the highest nutrient loadings were in either winter or spring. The sources of drained water were rainfall in all four seasons and recycled wastewater in spring, summer and autumn. Therefore irrigation should not have influenced nutrient loading to the ground water during the winter season. For the rest of the year, the main source of the total input

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water was recycled wastewater applied by irrigation. However, the measured loading rates were less than long-term safe trigger levels for nutrients. The seasonal variation of leached nutrients through drainage in Veale Gardens is presented in Table 4. These results will be useful for park management, particularly for formulating fertilization schedules.

4 Conclusions

This study has examined the spatial and temporal variation of drainage quantity and quality in a heterogeneous urban vegetation environment. Differences in vegetation landscape cover lead to variations in evapotranspiration and canopy interception rates as well as differences in depth, density and distribution of vegetation roots. This is likely to be the cause of the higher drainage collection rates in the low vegetation cover (MG) zone compared to the high vegetation cover in the MT zone, which contained dense trees and shrubs and intermittent turf grasses. The results of the soil physical analysis indicated a minimal effect from differences of soil properties compared to the much stronger influence of vegetation heterogeneity on drainage variations. This is in contrast with the finding of Wohlfart et al. (2012) that found that soil properties are the strongest factors explaining heterogeneity of nutrient loading.

However, investigation of the seasonal variation in drained water quantity showed similar trends in both lysimeters with the highest drainage rate in winter time. This trend is despite the maximum rate of input water which was collected in summer. As expected, in summer most input water fulfils plant water needs through evapotranspiration while in winter as a consequence of dormancy in most plants, the evapotranspiration rate decreases markedly, which results in a higher leachate fraction in winter. Interestingly, there was no relation between seasonal drained water volume and seasonal salinity rates in either of the lysimeters.

The input water from irrigation and rainfall not used by plants and passed through the root zone may carry some nutrients into the ground water. This could potentially be

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a matter of concern when recycled wastewater is a main source of irrigation. In Veale Gardens, irrigation with wastewater did not occur in the winter season in the MG zone while the highest concentrations of most analysed nutrients were also recorded during winter. Even so, the recommended Australian nutrient trigger level for solute leaching confirmed that using recycled wastewater presented no increased risk of nutrient (N, P and K) build up or contamination of ground or surface waters compared to using conventional water sources for irrigation.

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Table 1. Records of drained water from lysimeter MG and input water (mm).

Lys MG	Summer	Autumn	Winter	Spring
Seasonal drainage (mm)	1.33	24.75	206	95.51
Seasonal irrigation (mm)	331.11	123.8	0	177.28
Seasonal rainfall (mm)	78.8	160	262.7	53.7

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Table 2. Records of drained water from lysimeter MT and input water (mm).

Lys MT	Summer	Autumn	Winter	Spring
Seasonal drainage (mm)	0	0.022	25	0.025
Seasonal irrigation (mm)	403.27	150.82	20	215.91
Seasonal rainfall (mm)	78.8	160	262.7	53.7

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Table 3. Seasonal salinity of drained water from two lysimeters.

Salinity ($dS\,m^{-1}$)	Summer	Autumn	Winter	Spring
Lys MG	4.82	1.33	2.1	2.96
Lys MT	NA*	0.85	1.14	1.91

* NA: not available.

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Table 4. Total drained (lost) nutrients in Veale Gardens through drainage ($kg\,ha^{-1}$).

Drained water characteristics	Summer	Autumn	Winter	Spring
TDS	41.7	213.8	3605.0	1833.6
Potassium	0.2533	2.7225	24.7197	9.5499
Nitrite	0.0002	0.0025	0.0207	0.0095
Nitrate	0.0008	0.0247	0.0207	0.0286
Total N	0.0147	0.0742	0.2067	0.5730
Total P	0.0035	0.0223	0.0618	0.1241

Fig. 1. Veale Gardens in the Adelaide Parklands.

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Fig. 2. Pan lysimeter installation, **(a)** trench excavation, **(b)** cavity digging, **(c)** cavity levelling, **(d)** lysimeter tray, **(e)** placing the tray, **(f)** placing the collecting bucket and connect the tray and bucket by a PVC pipe, **(g)** PVC pipe and access tubes, **(h)** plastic sheet for protecting the cavity, **(i)** compacting the backfilled soil.

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Fig. 3. Extracting water samples from a buried lysimeter.

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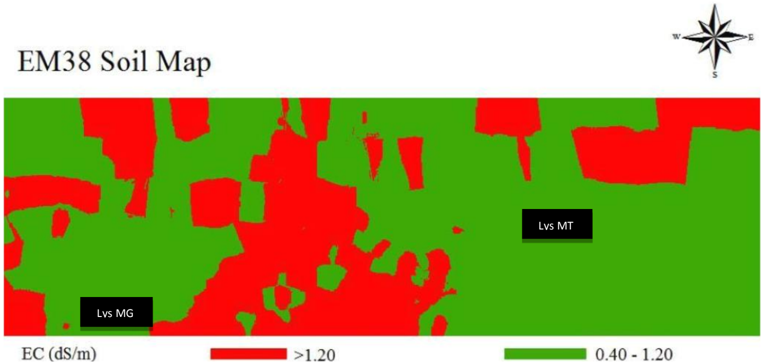

Fig. 4. EM 38 soil map of Veale Gardens showing lysimeter positions.

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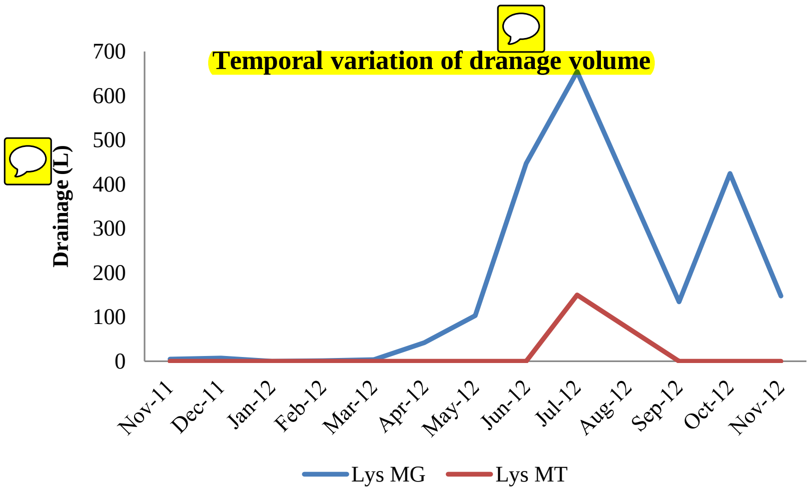

Fig. 5. Monthly variation of drainage in MG and MT zones.

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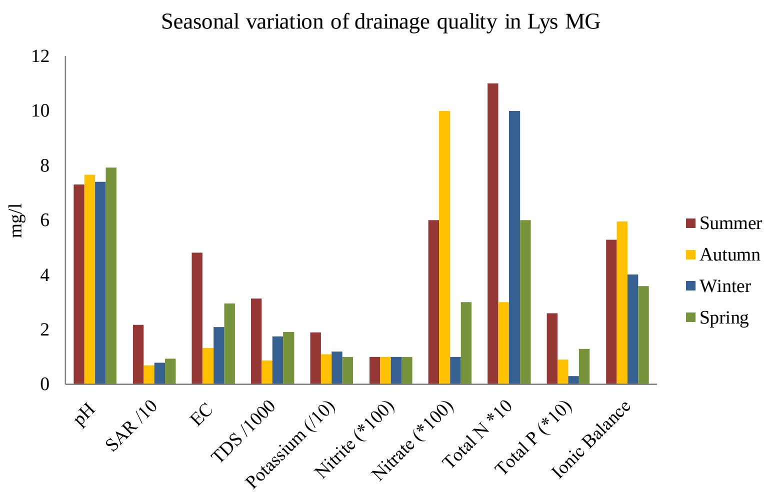

Fig. 6. Seasonal variation of solute leaching in zone MG.

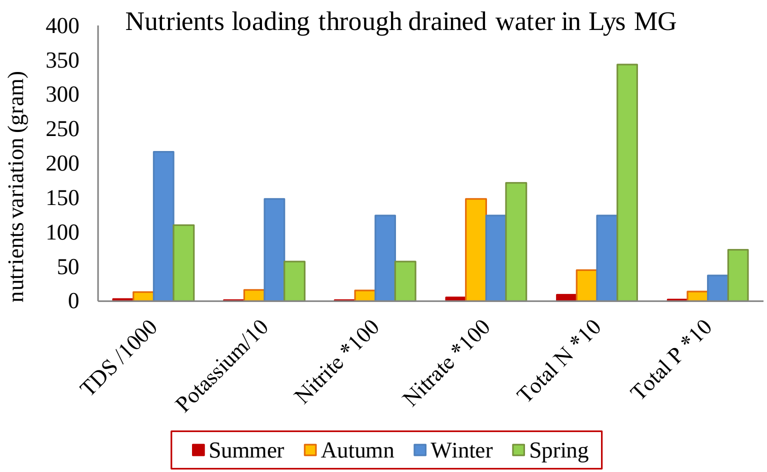

Fig. 7. Seasonal nutrient leaching through cumulative drainage.

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