

A mathematical model for estimating the extent of solute- and water-flux heterogeneity in multiple sample percolation experiments

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Abstract

Multiple sampling is widely used in vadose zone percolation experiments to investigate the extent in which soil structure heterogeneities influence the spatial and temporal distributions of water and solutes. In this note, a simple, robust, mathematical model, based on the β -statistical distribution, is proposed as a method of quantifying the magnitude of heterogeneity in such experiments. The model relies on fitting two parameters, α and ζ to the cumulative elution curves generated in multiple-sample percolation experiments. The model does not require knowledge of the soil structure. A homogeneous or uniform distribution of a solute and/or soil–water is indicated by $\alpha = \zeta = 1$. Using these parameters, a heterogeneity index (HI) is defined as $\sqrt{3}$ times the ratio of the standard deviation and mean. Uniform or homogeneous flow of water or solutes is indicated by $HI = 1$ and heterogeneity is indicated by $HI > 1$. A large value for this index may indicate preferential flow. The heterogeneity index relies only on knowledge of the elution curves generated from multiple sample percolation experiments and is, therefore, easily calculated. The index may also be used to describe and compare the differences in solute and soil–water percolation from different experiments. The use of this index is discussed for several different leaching experiments. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Modelling and monitoring transport of soil–water, solutes, contaminants and micro-organisms in soil is

complicated by the non-random spatial and temporal variability of physical, chemical and biological components of soils. Spatial variability in the physical structure of soils may result from soil-forming processes giving rise to geological fractures and cracks. The presence of subsurface layers funnels and lenses act to concentrate flow in a prescribed

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direction and consequently contribute not only to soil structural heterogeneity but also chemical and water flux heterogeneity. Spatial variability may also result from biological activity arising from animal burrows and wormholes, and from anthropogenic activity such as tillage. Modelling and monitoring transport of water and solutes is further complicated owing to temporal variation resulting from chemical non-equilibrium and the population dynamics of soil microfauna and flora.

Scientific investigations of transport involving repacked, sterile, homogenised soil cores often bear little resemblance to physical reality. Consequently many scientists are now using multiple sampling percolation systems with free draining, undisturbed soil cores to investigate the impact of soil structural heterogeneity on the distribution of solutes and water in the vadose zone (e.g. Bergstrom and Jarvis, 1993; Boll et al., 1991; Boll and Selker, 1992; Bergstrom and Jarvis, 1993; Bowman et al., 1994; Cameron et al., 1990; de Rooij, 1996; Evans et al., 1995; Evans et al., 1996; Germann et al., 1984; Jardine et al., 1990; Jardine et al., 1993; Luxmoore and Sharma, 1980; Quisenberry and Phillips, 1976, and Quisenberry and Phillips, 1978; Quisenberry et al., 1991, Quisenberry et al., 1994; Poletika et al., 1995; Roth et al., 1991; Rimmer et al., 1995; Sharma and Luxmoore, 1979; Stagnitti et al., 1998ab; Steenhuis et al., 1991, Steenhuis et al., 1995; Villholth, 1994; Wildenschild et al., 1994; White et al., 1986). Ignoring soil structure heterogeneity may lead to serious under-estimation of solute leaching and the risk of surface- and groundwater contamination (de Rooij, 1995; Edwards et al., 1988, Edwards et al., 1993a, Edwards et al., 1993b; Luxmoore, 1981; Shipitalo et al., 1990; Stagnitti et al., 1995, Suter et al., 1992; Tindall et al., 1986; Wilson and Luxmoore, 1988; Wilson et al., 1993). There have been many previous attempts to model the complex behaviour of non-uniform solute transport based on a conceptualisation of the soil as two-region flow domains (Chen et al., 1993, Gerke and van Genuchten, 1993a, Gerke and van Genuchten, 1993b; Simunek et al., 1994; Skopp et al., 1981; Zimmerman et al., 1993) or even multiple-region flow domains (Durner and Fluhler, 1994; Gwo et al., 1995, Gwo et al., 1996; Parlange et al., 1996; Wilson et al., 1992).

This paper, however, does not address the issue of modelling solute transport. Rather the paper presents a

mathematical model for a simple index of spatial and/or temporal heterogeneity that can be applied to leaching experiments involving multiple sampling techniques. A heterogeneity index is invaluable in comparing and contrasting the behaviour of soil-water and solute distributions in single soil column experiments or across several experiments. The index of heterogeneity may also be used as a decision support tool to assess the potential risk of groundwater contamination by surface-applied chemicals. For example, low values for the heterogeneity index imply near uniform flow of soil-water and/or solutes and consequently the potential risk of groundwater contamination by preferential flow is small. However, a high value for the heterogeneity index may indicate significant preferential flow with the consequent danger of groundwater contamination. Unlike other attempts to construct a similar description of heterogeneity, which rely on knowledge of soil hydraulic properties (e.g. Germann and DiPietro, 1996), our index requires only a knowledge of the soil-water percolation or solute elution curve as derived from in situ field samplers or laboratory tests on undisturbed soil cores. Thus it is easy to calculate. In this note, we do not attempt to correlate the heterogeneity index to soil-physical properties owing to incomplete information presented in the literature. However, in time and with the publication of further experimental studies employing multiple-sampling percolation methods, the relationship between the heterogeneity index and biomechanical and chemical properties of the soil may be established.

2. Theory

The standard beta function is defined by Bronshtein and Semendyayev (1979) as

$$p(x; \alpha, \zeta) = \frac{\Gamma(\alpha + \zeta)}{\Gamma(\alpha)\Gamma(\zeta)} x^{\alpha-1} (1-x)^{\zeta-1}; \quad (1)$$

for $\alpha \geq 0, \zeta \geq 0, 0 \leq x \leq 1$

where Γ is the gamma function (or Euler's integral of the second kind) and α and ζ are free parameters. Eq. (1) is often used in Statistics to model the variation in the proportions of a quantity occurring in different samples (e.g., Devore, 1987). Unlike other functions

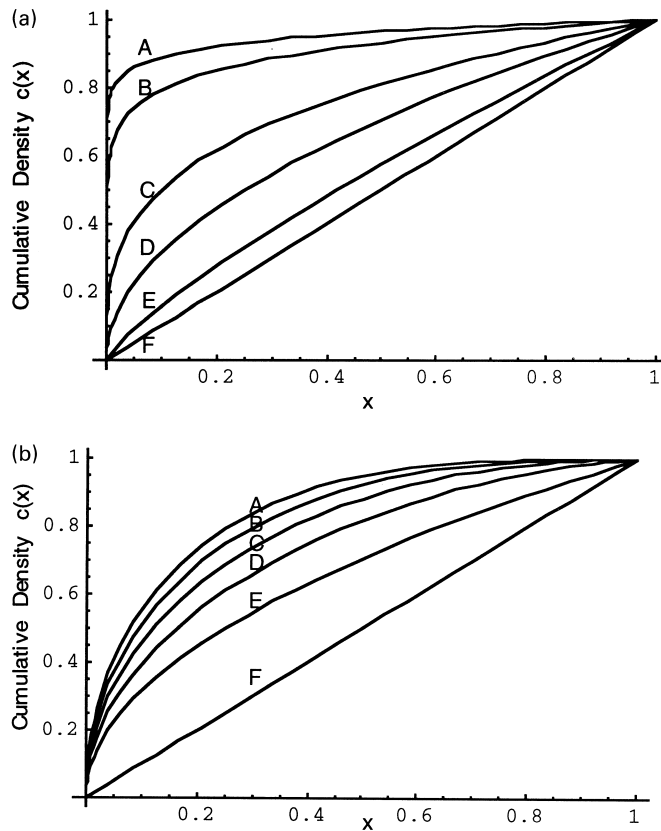


Fig. 1. The cumulative density function defined by Eq. 5 plotted as a function of x , for (i) various values for α , holding ζ constant (Fig. 1a) and (ii) various values for α holding ζ constant (Fig. 1b). The values for α and ζ corresponding to the curve labels (A to F) in each figure are listed in Table 1.

commonly used in Statistics, the beta function is bounded in the interval $[0,1]$. The next section illustrates how this property is useful in developing a heterogeneity index for water percolation and solute elution. Note that if α and ζ are both equal to one, then Eq. (1) reduces to the uniform density function,

$$p(x; 1, 1) = 1, \quad \text{for } 0 \leq x \leq 1 \quad (2)$$

The expectation (or mean) of Eq. (1) is defined by

$$\mu_x = \frac{\alpha}{(\alpha + \zeta)} \quad (3)$$

and the variance of Eq. (1) is

$$\sigma_x^2 = \frac{\alpha \zeta}{(\alpha + \zeta)^2 (\alpha + \zeta + 1)} \quad (4)$$

The cumulative density of Eq. (1) is defined by

$$c(x; \alpha, \zeta) = \int_0^x p(t; \alpha, \zeta) dt, \quad \text{for } 0 \leq x \leq 1 \quad (5)$$

where t is a variable of integration.

The standard deviation to mean ratio is often used as a measure to compare dispersion between populations with different means. In a similar manner, we can define a (scaled) heterogeneity index (HI) as

$$HI(\alpha, \zeta) = \frac{\sqrt{3}\sigma_x}{\mu_x} = \sqrt{\frac{3\zeta}{\alpha(\alpha + \zeta + 1)}} \quad (6)$$

where $\sqrt{3}$ is a factor that results from scaling HI to one when both α and ζ equal one. Thus a uniform distribution will result in $HI = 1$ and a non-uniform distribution is indicated when $HI > 1$. For our

Table 1
Values for α , ζ and HI for different cumulative densities displayed in Fig. 1a and 1b.

Curve Label	Figure 1a			Figure 1b		
	α	ζ	HI	α	ζ	HI
A	0.05	1	5.41	0.5	3.0	2.00
B	0.1	1	3.78	0.5	2.5	1.94
C	0.3	1	2.09	0.5	2.0	1.85
D	0.5	1	1.55	0.5	1.5	1.73
E	0.8	1	1.16	0.5	1.0	1.55
F	1	1	1.00	1	1.0	1.00

purposes, Eq. (6) is valid for $HI(\alpha, \zeta) \geq 1$. The magnitude of HI greater than one indicates the magnitude of non-uniformity in the distribution. Fig. 1a and Fig. 1b present examples of the cumulative density function $c(x)$ defined by Eq. (5) for different values of the free parameters α and ζ . The corresponding values for the heterogeneity index given by Eq. (6) is summarised in Table 1. The heterogeneity index (Eq. 6) may be used to quantify apparent spatial or temporal heterogeneity in water and solute distribution patterns in percolation experiments. This is illustrated in the next section.

3. Application of theory to experiments

The model for heterogeneity may be applied to any experiment in which multiple samples of the solute and water flux are determined within a defined spatial or temporal segment. The model is independent of the actual experimental technique used to determine the soil–water or solute elution. However, to illustrate the theory, we shall apply the HI to a series of percolation experiments recently conducted in Australia using a multiple wick lysimetry system. A multisegment percolation system (MSPS) has been developed to study the solute and water transport through the vadose zone. A full description of the MSPS used in our studies is found in Stagnitti et al. (1995) and Stagnitti et al. (1998). The MSPS were engineered at the Department of Agricultural and Biological Engineering at Cornell University, U.S.A. (Boll et al., 1991; Steenhuis et al., 1991). Each MSPS consists of 25 wick lysimeters (6 cm x 6 cm) arranged on a square grid.

Several investigations of solute and water leaching

from undisturbed soil cores with intact soil structure have been conducted on different soil types from various regions in Australia. The field sites were located in Tower Hill State Game Reserve, Grassmere, Rutherglen and Redland Bay. Grassmere is situated approximately 40 km north of Warrnambool, 300 km west of Melbourne in the Western District of Victoria. The Grassmere site lies in a highly productive beef and dairy farming area. The area is situated on gently undulating basalt plains. Bedrock consists of olivine and iddingsite basalt, limburgite, minor scoria and tuff (Evans et al., 1995; Evans et al., 1996). Soil above the bedrock consists of fine soil particles through to clay with buckshot inclusions (up to 1 cm diameter) and randomly distributed rocks varying in diameter from a few millimetres to approximately 20 cm. The soil is a dark balsaltic soil with high organic content (approximately 10%). Soil sampling and core extractions were conducted on a farm near Grassmere. The farm is used for cattle grazing and is covered with pasture grass. No superphosphate had been applied for 25 years. The top soil is compacted by beasts trampling. Two large intact soil cores, referred to as Grassmere-1 and Grassmere-2, with dimensions of 40 cm \times 40 cm wide and 40 cm deep, were taken from this farm. On the Grassmere-2 soil core, drainage of water and solute elution of surface-applied chloride, nitrate and phosphate were investigated (Stagnitti et al., 1998). For all other experiments described in this note including Grassmere-1, only drainage of water was investigated. A rain simulator using an x-y scanning drip irrigation system was used to apply surface water to the cores. The application rate controlled by a peristaltic pump was set to approximately 0.1 mL/cm²/h for the Grassmere experiments. This rate is comparable to average winter rain for the region. The Grassmere-1 core was irrigated continuously for 66 days commencing in August 1996. The Grassmere-2 core was irrigated continuously for 18 days commencing in October 1996.

Rutherglen is located near the Murray River about 350 km north of Melbourne. The region is noted for cattle grazing and viticulture. The summers are hot with low humidity and moderate rainfall. Plants commonly experience water stress during the summer months. The experimental site is approximately

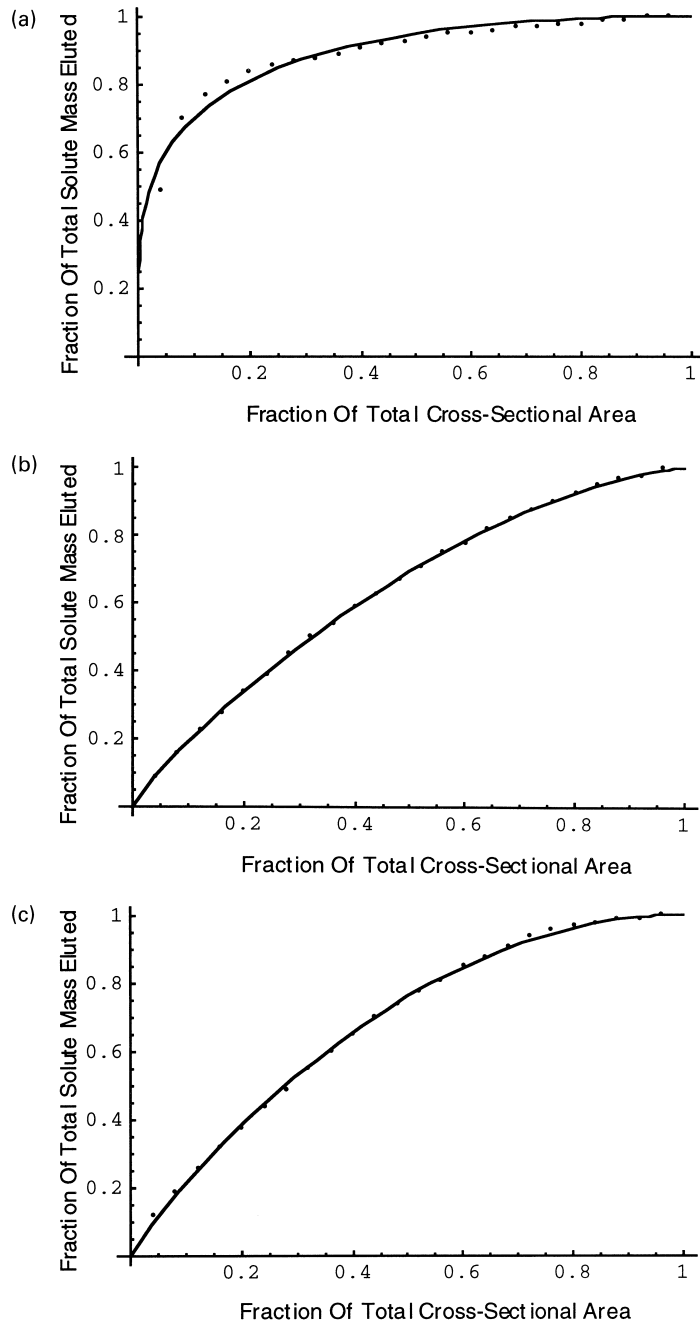


Fig. 2. Observed and predicted fractions of phosphate (Fig. 2a), nitrate (Fig. 2b) and chloride (Fig. 2c) collected from the Grassmere-2 site plotted with the fraction of the cross-sectional area of the base of the soil core. The solid line represents the fitted theoretical model given by Eq. (5) and the dots represent the experimental values. HI values for these curves are presented in Table 2.

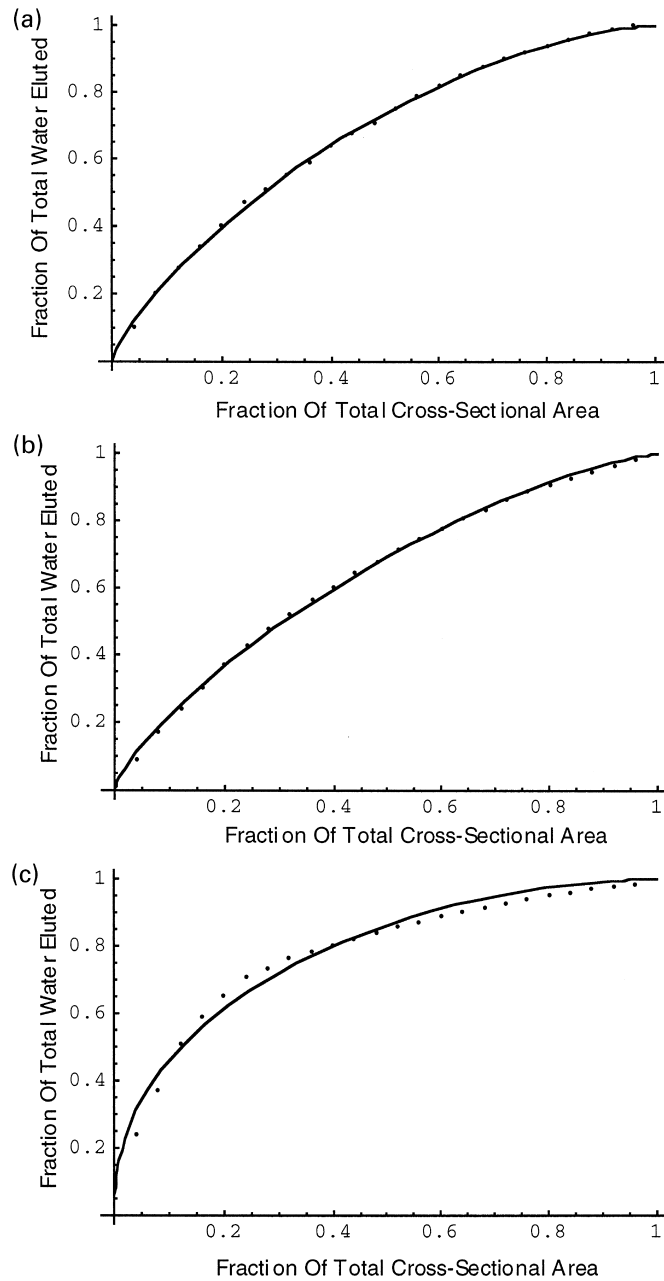


Fig. 3. Observed and predicted fractions for drained soil–water plotted with the fraction of the cross-sectional area for soil cores extracted from the Grassmere-2 (Fig. 3a), Grassmere-1 (Fig. 3b), Tower Hill (Fig. 3c), Rutherglen-2 (Fig. 3d), Rutherglen-1 (Fig. 3e) and Redland Bay (Fig. 3f) sites. The solid line represents the fitted theoretical model given by Eq. (5) and the dots represent the experimental values. HI values for these curves are presented in Table 2.

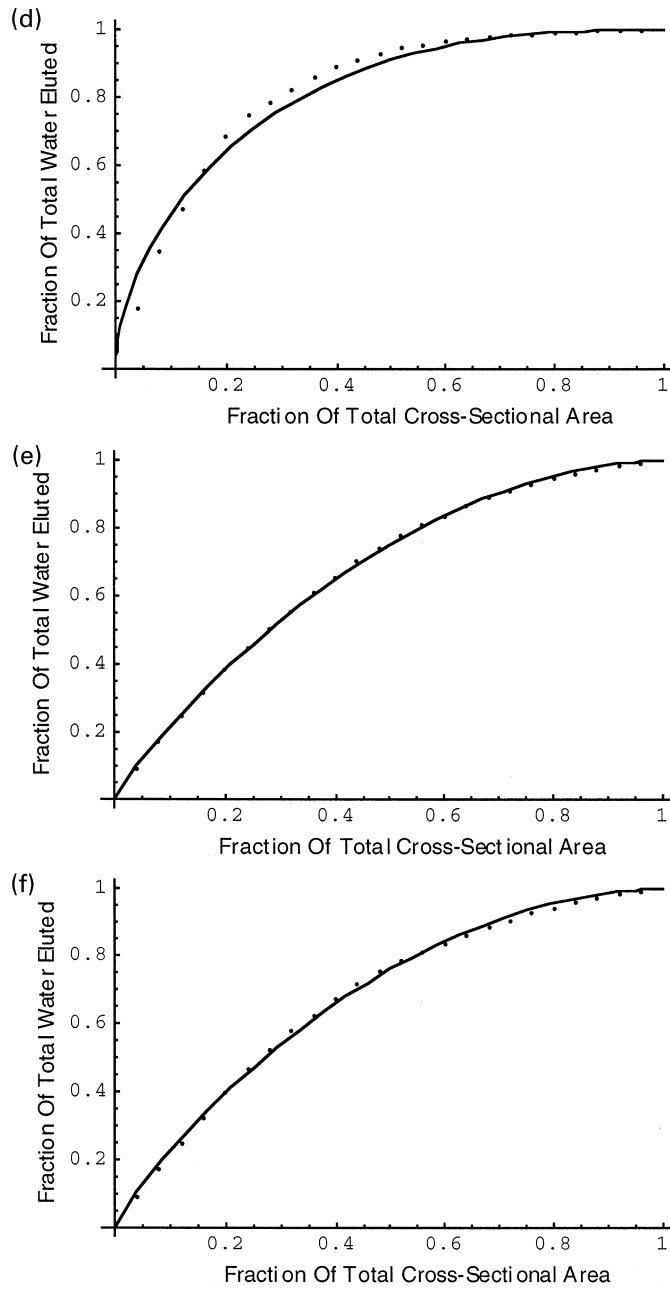


Fig. 3. Continued.

10 km south-east of Rutherglen, located in the Rutherglen Experimental Farm operated by Agriculture Victoria. The experimental farm is trialing a large-scale, intensive beef feedlot with the purpose of

developing management guidelines for the disposal of manure and urine on surrounding agricultural land. The soil is a red/black clay-loam mix. The topsoil, about 20 cm thick, is acidic with a moderate organic

Table 2
Fitted parameters (α , ζ) and descriptive statistics (μ_x , σ_x^2 , HI) for a range of experiments.

Experiment	Figure	α	ζ	μ_x	σ_x^2	HI
Uniform		1	1	1/2	1/12	1.0
<i>Nutrients</i>						
Grassmere2-P	2a	0.2411	2.034	0.1060	0.02892	2.78
Grassmere2-N	2b	0.8755	1.524	0.3647	0.06817	1.24
Grassmere2-Cl	2c	0.9199	1.935	0.3222	0.05665	1.28
<i>Soil-Water</i>						
Grassmere2	3a	0.7775	1.582	0.3295	0.06576	1.35
Grassmere1	3b	0.7639	1.366	0.3586	0.07348	1.31
Tower Hill	3c	0.4527	1.699	0.2105	0.05275	1.89
Rutherglen-2	3d	0.8477	3.993	0.1865	0.03725	1.56
Rutherglen-1	3e	0.8885	1.835	0.3262	0.05900	1.29
Redland Bay	3f	0.8651	1.842	0.3196	0.05867	1.31

content (about 1.5%). In between the topsoil and the bedrock lies a layer of bleached clay containing substantial amounts of buckshot (iron rich nodules 3–8 mm diameter) (Ueoka et al., 1997). Two large structurally stable, undisturbed soil cores, referred to as Rutherglen-1 and Rutherglen-2, with dimensions of 40 cm \times 40 cm wide by 40 cm deep, were taken from the Rutherglen site. The Rutherglen-1 core was irrigated for 7 days commencing in October 1996 and the Rutherglen-2 core was irrigated for 27 days in September 1996. The irrigation was applied uniformly and continuously to the surface of the soil cores and at a rate approximately equivalent to average winter rainfall and irrigation for the region.

The Tower Hill site is located in a State Game reserve in the Western District of Victoria, 12 km west of Warrnambool. This site is located within a crater of a dormant volcano. The reserve is surrounded by market gardens growing predominantly potatoes, carrots and onions. An underlying Upper Tertiary Limestone aquifer, used for both domestic and stock purposes, has a large number of fractures, which makes preferential flow highly likely. One soil core (30 cm \times 30 cm \times 30 cm) was taken from a ridge on the crater's tuff. The soil is described as a grey, clay loam with a nearly uniform distribution of particle sizes and moderate organic content (about 3–5% by dry-weight). A percolation experiment was conducted for a three-week period in September 1995. A uniform application of water was applied continu-

ously to the soil surface at a rate of approximately 0.8–0.9 mL/cm²/h, which simulates a high winter rainfall rate for this region.

Redland Bay is located on the coastal fringe of Moreton Bay, approximately 30 km south-east of Brisbane, Queensland. The Redland Bay region consists of extensive market gardens supplying vegetables and fruit to local markets in Brisbane. The region experiences frequent tropical storms in summer with high intensity, heavy rainfall. In contrast, the winter months experience infrequent, low-volume and low-intensity rainfall. The soil of this region is described as a Redland Bay Krasnosem, a clay and organic rich, red-earth soil. A single core (30 cm \times 30 cm \times 30 cm) was taken from a site about 50 m from a road. The soil column had noticeably large pebbles ranging from 5–10 mm randomly distributed throughout the soil profile. High volume rainfall, typical of tropical summer rainfall was applied to the Redland Bay soil column. The soil was uniformly and continuously irrigated at a rate of approximately 0.8 mL/cm²/h for 25 days commencing on November 14, 1994.

Following a procedure outlined in Quisenberry et al., 1994, Fig. 2 and Fig. 3, present patterns of soil-water percolation and solute elution. Fig. 2a, Fig. 2b and Fig. 2c present the results of a solute leaching experiment conducted on the Grassmere-2 experiment. The observed fraction of total phosphate (dots) eluted by the Grassmere-2 soil core plotted with the fraction of total sampling area of the base of the MSPS is shown in Fig. 2a. Similarly, Fig. 2b and Fig. 2c present the observed (dots) fractions for nitrates and chlorides. These figures were constructed by calculating the fraction of the total mass collected by each 6 cm \times 6 cm well (wick-lysimeter), ranking these values in descending order and plotted them with the cumulative cross-sectional area of the soil core's base. If the soil core was eluting solute mass at a uniform rate, then there would be no spatial variation in the amount of solute collected by each well, i.e. each collection well would contribute an equal mass of solute to the total. In other words, if the soil core leached solutes equally everywhere, then the fraction of the total mass plotted with the cumulative cross-sectional area of the base would fall on a 1 to 1 line. Departures from a 1 to 1 line indicate heterogeneity or potentially preferential flow.

On each figure, the fitted cumulative beta distribution $c(x)$, given by Eq. (5), is also plotted. It is represented by a continuous line. For each solute, the cumulative beta distribution fits the experimental data very well. The optimal values for the fitted ‘‘shape’’ or free parameters, α , ζ are presented in Table 2 along with the calculated descriptive statistics for the mean, variance and heterogeneity index. The optimisation of the free parameters was achieved very efficiently and simply using the BetaDistribution, CDF and NonLinear Regress functions in Mathematica (Wolfram, 1996). The calculated heterogeneity indices for phosphate, nitrate and chloride were 2.78, 1.24 and 1.28 respectively. All HI’s were larger than one, indicating heterogeneity in solute leaching patterns. Not surprisingly phosphate exhibited the highest heterogeneity with just 20% of the soil core leaching 80% of total leached phosphate. Stagnitti et al. (1998) reported that phosphate was very strongly adsorbed to the top soil (~ 2 cm) with less than 1% of the total applied phosphate actually leached from the core. In contrast 70% of the total surface-applied chloride and 100% of nitrate was recovered, the latter indicating significant nitrification.

Fig. 3a, Fig. 3b, Fig. 3c, Fig. 3d, Fig. 3e, Fig. 3f, Fig. 3g illustrate the spatial variation in soil–water percolation patterns for all experiments. The observed experimental values (dots) for the fraction of soil water drained by each well is plotted with the fraction of the base area of the MSPS. As in prior figures, the solid line represents the fitted cumulative beta distribution. In all cases the beta distribution fit the experimental data very well. The values for the free parameters and descriptive statistics are also presented in Table 2. The Tower Hill site exhibited the strongest heterogeneity in soil–water percolation with $HI = 1.89$. For this soil, about 60% of the drained soil–water was collected from about 20% of the base area. The Rutherglen-2 experiment also exhibited considerable heterogeneity, $HI = 1.56$. All other sites also showed heterogeneity (HI’s from 1.31–1.35). In the field prior to extraction, the Grassmere cores were separated by about 1 m. The distance separating the Rutherglen cores was also about 1 m. The two Grassmere cores exhibited comparable heterogeneity ($HI = 1.31$ and 1.35), whilst the two Rutherglen cores differed considerably ($HI = 1.29$ and 1.56). The latter result illustrates that considerable

heterogeneity was not only evident within the cores but also between them, an important confirmation of the difficulty of scaling small-scale transport phenomena to forecast field-scale effects. However, the level of heterogeneity in the soil–water percolation of the Grassmere-2 experiment was comparable to the level of heterogeneity exhibited in the Grassmere-1 experiment and with the Grassmere-2 chloride and nitrate elution. In this case one might be tempted to conclude that the ‘‘field-scale’’ heterogeneity in soil–water percolation and chloride and nitrate elution for the Grassmere soil might be of the order of 1.25–1.35. More experimentation, however, will lead to greater confidence in this estimate.

4. Conclusion

A simple, efficient and effective method of quantifying the level of heterogeneity in soil–water percolation and solute elution patterns generated from multiple sample percolation experiments has been developed. The method relies on calculating a heterogeneity index based on estimating two free parameters of the beta-distribution. Using this index, the elution patterns for a number of experiments was compared and contrasted. The index may be a valuable tool in estimating the potential risk of groundwater contamination by the preferential transport of chemicals through the vadose zone.

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