Prediction of steady-state flux through variably saturated zones within a septic absorption trench

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Abstract

This paper describes effluent flow dynamics within a septic absorption system and the prediction of flow through the biomat and sub-biomat zone. Using soil hydraulic properties in a one dimensional model we demonstrate how soil hydraulic properties interact with biomat resistances to determine long-term acceptance rate (LTAR). The LTAR is a key parameter used in the Australian and New Zealand Standard AS1547:2000 to calculate the area of trench required to ensure trenches are not overloaded. Results show that several orders of magnitude variation in saturated hydraulic conductivity (Ks) collapse to a one order of magnitude variation in LTAR. These results are calculated from a model using basic flow theory, allowing LTAR to be estimated for any combination of biomat resistance and soil hydraulic properties. To increase the reliability of prediction of septic trench hydrology, HYDRUS 2D was used to model two dimensional flow. For more permeable soils, the exfiltration zone above sidewall biomat growth is shown to be a key pathway for excess effluent flow.

Key Words

Clogging, biomat resistance, soil absorption system, modelling, on-site, unsaturated flow, LTAR.

Introduction

Approximately 20% of Australian households use on-site wastewater treatment and disposal systems to treat and dispose of household wastewater (O'Keefe 2001). The most common on-site system in Australia is the septic tank–soil absorption system (SAS) with over 80% of the 170,000 non-sewered properties in south-east Queensland alone using this technology (Beal *et al.* 2003). A SAS operates by primary treatment of effluent in a septic tank followed by infiltration into the subsoil via trenches. The mechanisms governing purification and hydraulic performance of a SAS are complex and have been shown to be highly influenced by the biological mat or 'clogging' layer (biomat zone) which develops on surfaces within the trench (Bouma 1975; Kristiansen 1981). Hydraulic failure, or surcharge, occurs when the inflow into the trench exceeds the ability of the biomat/soil interface to discharge the inflow into the unsaturated subsoil.

There is a lack of substantiated knowledge of the key processes of SAS in Australian soils. Groundwater and surface water contamination, and potential health hazards, have all been linked to soil absorption systems in Australia (Geary and Whitehead 2001; Hoxley and Dudding 1994). Circumstantial evidence, rather than a thorough scientific evaluation, has, in many cases, led to these conclusions of water pollution. Therefore, information on the long-term behaviour of SAS in Australian soils is necessary to determine the true sustainability of these systems. Effluent flow mechanisms in SAS, particularly in American soils, have been studied extensively in the past under laboratory and field conditions (Bouma *et al.* 1972; Van Cuyk *et al.* 2001). Despite a diversity of literature available, hydraulic processes within a SAS still remain poorly understood. This is particularly true for the relationships between soil hydraulic properties and the development and resistance of the saturated biological zone within the trench. Often there are difficulties, both practical and economic, associated with obtaining field measurements and soil samples of operating trench systems. For this reason, modelling the unsaturated flow within trenches, using measured soil hydraulic properties, can be a useful guide to predicting some of the key pathways in SAS under a range of scenarios (e.g. effluent loading rates, soil types, ponded water depths within the trench).

Effluent entering a trench can infiltrate into the soil either through the bottom or sidewalls. The area of sidewall that has no impedance from a biomat zone is referred to in this paper as the **exfiltration zone** (Figure 1) and is hypothesised to be an important absorption pathway for effluent, in permeable soils particularly, under situations of peak loading (e.g. extended rainfall, high household water use). There are a limited number of studies modelling unsaturated flow in SAS (e.g Janni *et al.* 1980; Hansen and Mansell 1986; Huntzinger Beach and McCray 2003), but the specific partitioning of biomat zone and non-biomat zone flow in SAS is not widely reported. A study by Brouwer *et al.* (1979) found flow through the sidewall to be greater than bottom flow in some duplex soils in Victoria. This conclusion was drawn from field measurement of matric potentials below and adjacent to trenches and ponded height in the trenches. The infiltration rate through the sidewalls was calculated at 35mm/day, however it is not clear if sidewall flow was through the biomat zone. McGauhney and Winneberger (1964) reported greater sidewall water flow in sands compared with finer-grained soils. Huntzinger Beach and McCray (2003) used HYDRUS-2D to predict unsaturated flow within SAS, and described a strong relationship between the biomat zone hydraulic properties, and the steady-state (long-term) infiltration rates within the unsaturated zone. However, the model assumed that all flow occurred through either the trench bottom or trench sidewall biomat layer, thus precluding the opportunity to predict flow dynamics for the remainder of the trench sidewall. The main objectives in this paper are to: briefly review the theory of effluent flow in SAS; predict steady-state one-dimensional flow through the bottom biomat zone; and model steady-state two-dimensional flow of effluent through the biomat zones (bottom and sidewall) and exfiltration zones of a SAS.

Summarised theory of flow within SAS

Suspended solids and organic matter from septic tank effluent accumulate over time on the bottom and, to a lesser extent, lower sidewalls of a SAS. There is no discrete layering where the biomat stops and soil begins and therefore it is better described as a zone rather than a distinct mat or layer. The hydraulic conductivity of the biomat zone (K_b) is generally low, particularly along the trench bottom. Bouma (1975) calculated K_b values of approximately 0.6 mm/day for clay soils and 2 mm/day for sandy soils. A crust-capped soil, as occurs in a mature SAS, has been shown to behave as a “self-adjusting” system, where a steady-state infiltration rate and soil moisture profile develops over time (Hillel 1980). The hydraulic properties of both the saturated biomat zone and underlying unsaturated soil zone interact to establish an moisture profile that allows a state of equal flux through both zones (Hillel 1980). This condition can be expressed as:

$$Q_b = Q_u = K_b\left(dH / dZ\right)_b = K_u\left(dH / dZ\right)_u \qquad [1]$$

where Q_b is the steady-state flux through the biomat (m/day), Q_u is the steady-state flow through the unsaturated zone below the biomat (m/day), K_b is the biomat hydraulic conductivity (m/d), $(dH/dZ)_b$ the biomat hydraulic gradient, K_u the unsaturated hydraulic conductivity (m/day) and $(dH/dZ)_u$ the hydraulic gradient of the unsaturated sub-biomat zone. The resultant flow rate is the long-term steady-state flux (m/day) at which, theoretically, a SAS can continue to accept effluent without hydraulic failure occurring. This flux value is also known as the long-term acceptance rate (LTAR), with units of m/day or L/m^2/day.

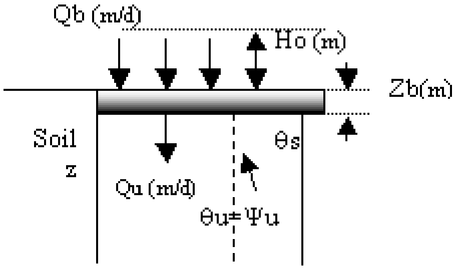
The hydraulic effects of a biomat on long-term effluent flow rates can be predicted if the resistance of the biomat (R_b) and the unsaturated hydraulic conductivity characteristics of the underlying soil are known. Bouma (1975) showed that the hydraulic conductivity of the biomat is a function of both R_b and the matric potential (Ψ) of the soil immediately below the biomat. Biomat resistance is the product of the inverse of K_b and the effective thickness of the biomat (Z_b). Taking $K_b(dH/dZ)_b$ from Equation [1], and assuming a steady infiltrating soil profile where the hydraulic gradient approximates unity, we can write:

$$Q_u = K_u = K_b \left(dH/dZ \right)_b$$

$$= K_b \left(\frac{Ho + \Psi + Zb}{Zb} \right) \qquad [2]$$

By rearranging this we can determine the hydraulic resistance of the biomat:

$$\frac{K(\psi)}{Ho + \psi + Zb} = \frac{Kb}{Zb} \equiv \frac{1}{Rb} \qquad [3]$$



where K(Ψ) is the unsaturated hydraulic conductivity of the sub-biomat zone as a function of soil matric potential, and H_o is the positive hydraulic head on top of the biomat.

Methods

Soils

Hydraulic properties measured on undisturbed cores from four soils; Red Dermosol (red podzolic), Red Kandosol (red earth), Semiaquic Podosol (podsol) (Verburg *et al* 2001) and Yellow Kurosol (yellow podzolic) (Talsma 1983), were taken from the literature. The first three of these soils were chosen as they generally represent the type of permeable, well-structured soils that are suitable for SAS. The final soil was chosen to represent an ‘unsuitable’ soil type for SAS, based on the high clay content and low permeability.

One-dimensional modelling

Measured moisture retention characteristics of the four soils (Talsma 1983; Verburg *et al.* 2001) were used to predict one-dimensional steady-state fluxes for various biomat resistances. The steady-state flux through the biomat zone was calculated using Equation 2. Campbell’s (1974) model, using the measured saturated hydraulic conductivity (K_s) values as the matching K factor, was used to calculate the unsaturated hydraulic conductivity of the sub biomat zone. The Campbell model is represented as:

$$K = K_S \left(\frac{\psi_e}{\psi} \right)^{2+3/b} \qquad [4]$$

where Ψ_e is the air-entry potential of the soil (m), and *b* is the slope of the Ψ(θ) relationship. The value Q*b*= Q*u* (Equation 2) was solved as a simultaneous equation for a range of biomat resistances. This was performed by using “Flux for Septic Trenches” (FLUX), a spreadsheet model developed by the authors (Beal *et al*. 2004). Results were checked by running the same input parameters in SWIM v1.0 (Ross 1990). Biomat resistances used in the model encompassed a range of values reported in the literature (Huntzinger Beach and McCray 2003; Magdoff and Bouma 1974). The model assumed that all flow was steady-state with a unit gradient, and flow occurred in a one-directional manner, vertically through the biomat zone only. A relatively deep and homogenous soil profile is assumed. Ponded water height was set at 0.25m and the biomat thickness was assumed to be 0.02m.

Two-dimensional modelling

HYDRUS-2D, a two-dimensional variably saturated flow model (Simunek *et al.* 1996), was used to model flow through the bottom and sidewall areas of a SAS. HYDRUS-2D uses the Richard’s (1938) equation as the governing equation for water flow. The soil water retention curve, θ(Ψ), is described using the closed-form equation of van Genuchten (1980):

$$\theta(\psi) = \theta_r + \left[\left(\theta_s - \theta_r \right) \Big/ \left(1 + \left(\alpha |\psi| \right)^n \right)^{(m)} \right] \qquad [5]$$

The unsaturated soil hydraulic conductivity function, K(Ψ), is described by combining the van Genuchten equation with the pore-size distribution model of Mualem (1976):

$$K(\psi) = K_S S_e^l \left[1 - \left(1 - S_e^{1/m} \right)^m \right]^2 \qquad [6]$$

where θ is the volumetric water content (m^3/m^3), Ψ is the pressure head (m), □, *n*, *m* (=1-1/*n*) and *l* (= 0.5) are empirical parameters, $S_e = (\theta\text{-}\theta_r)/\theta_s\text{-}\theta_r)$ is the degree of saturation, θ_r is the residual water content, and θ_s is the saturated water content.

The input parameters used in HYDRUS-2D are presented in Table 1.

Table 1. Input parameters used in SAS modelling

Soil type	θr	θs	Alpha	n	Ksat (m/d)	Sources / references
Red Kandasol (RK)	0.0741	.346	0.0416	2.37	0.744	Verburg *et al* (2001), ROSETTA (Schaap 2001)
Red Dermosol (RD)	0.0318	.330	0.0443	2.57	0.98	Verburg *et al* (2001), ROSETTA (Schaap 2001)
Semiaquic Podosol (SP)	0.0365	.324	0.0277	2.57	0.504	Verburg *et al* (2001). ROSETTA (Schaap 2001)
Yellow Kurosol (YK)	0	.485	0.0013	1.33	0.014	Talsma (1983)
Biomat zone	0.07	.36	0.0033	1.5	0.02 - 0.0033	Huntzinger Beach and McCray (2003) Magdoff and Bouma (1974), Bouma (1975)

The input parameters for the Verburg *et al.* (2001) soils were derived from the soil hydraulic properties reported in the literature and by the pedotransfer function model ROSETTA (Schaap 2001). Optimisation of input parameters for the Talsma (1983) soil was done by minimising the squared differences between the measured moisture retention data reported (Talsma 1983) and the water contents and K values which were estimated using equations 5 and 6. There are few specifically measured biomat zone saturated hydraulic conductivities in the literature; they are usually estimated or derived from equations 1 and 2. The saturated hydraulic conductivities for the biomat zone fall within the range reported by previous researchers (Bouma 1975; Huntzinger Beach and McCray 2003). As there are no reported values for biomat water retention characteristics, the parameters θ_r, θ_s, and *n* were assumed to be similar to a silty clay soil as discussed by Huntzinger Beach and McCray (2003) and based on observations of biomat development in current soil column experiments by the author (Beal unpublished data).

Conceptual model

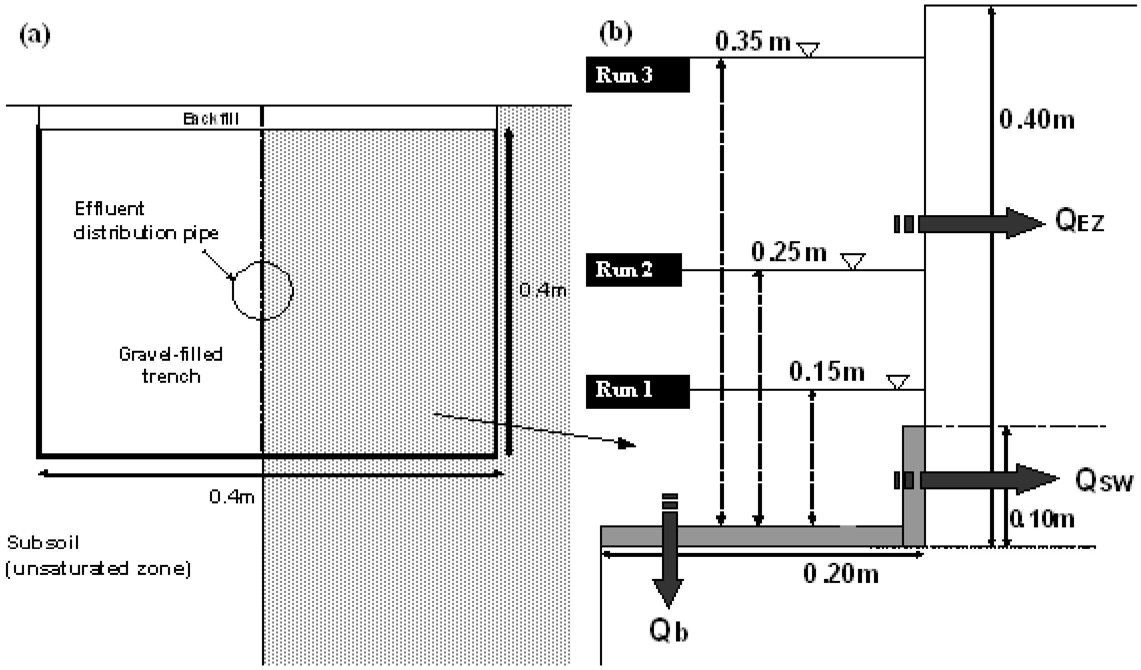


Figure 1. (a) Schematic cross-section of a typical of septic trench system where the shaded area is the model domain for all Scenarios (b) Example of trench domain modelled in HYDRUS-2D (Scenario 1)

Table 2. Biomat properties and ponded trench conditions used in Scenarios 1-3

Scenario	Rb (days)	Kb (m/d)	SW biomat ht. (m)	Water ht. (m)
1 Increasing ponded water height (WH)	25	0.0008	0.10	0.15, 0.25, 0.35
2 Increasing biomat resistance (Rb)	0, 10, 30, 60	0, 0.002, 0.00067, 0.00033	0.10	0.25
3 Increasing sidewall (SW) biomat	25	0.0008	0, 0.10, 0.20, 0.30	0.35

The geometry of the SAS modelled is shown in Figure 1. Only half the system was modelled with an assumption of soil homogeneity and symmetry in the hydraulic behaviour of the trench. In Figure 1, Q_b is vertical flow through the bottom biomat zone, Q_{SW} the horizontal flow through sidewall biomat zone, Q_{EZ} is horizontal flow through exfiltration zone (biomat-free sidewalls) of the trench. An initial condition of field capacity (approximately -0.2m to -0.3m for sandy soils and approximately -2.0 to -3.0m for light clays / clays) was used. As the steady-state flow regimes were being examined, the initial conditions were not a critical consideration as they have no influence on the final modelling outcomes. A constant pressure head (m) boundary condition was assigned for all runs for each of the three scenarios. The pressure head (m) was maintained at hydrostatic equilibrium for all scenario runs. The value of the pressure head varied depending on which scenario was being modelled (Table 2).

Results and Discussion

One-dimensional modelling

The predicted effect on flow rates from increasing R_b is shown in Figure 2. As these results are calculated from a one-dimensional model, LTAR can be estimated for any combination of biomat resistance and soil hydraulic properties. As the R_b of the biomat zone increases, the infiltration rate through the biomat zone decreases and soil moisture tensions immediately below the biomat zone increase (ie. the soil becomes “drier”). Our findings (Figure 2) are similar to other studies (Bouma 1975; Kristiansen 1981; Siegrist 1987) in that a 2–3 order of magnitude variation in saturated hydraulic conductivity between the soils collapsed to a one order of magnitude variation in LTAR. Biomat zones of low resistance (e.g. R_b = 10 days) can have a marked effect on flow rates in sandy soils, but not in clay soils (Figure 2). This was clearly apparent in the suitable soils. This can be directly attributed to the moisture retention characteristics of sandy soils as they undergo substantial pore water draining at high matric potentials (i.e. low soil tensions) and consequently the conductance of water through the soil will be reduced as the larger pores drain (as flow is proportional to the fourth power of the pore radius).

Therefore, as the sub-biomat soil becomes more unsaturated due to increasing biomat resistance, flow rates in this unsaturated zone will be substantially reduced. Conversely, in soils of low saturated hydraulic conductivities (e.g. <0.01m/day), biomats of low resistance will not markedly affect the underlying soil hydraulic properties. For example, flow rates in the Yellow Kurosol of low hydraulic conductivity (0.02 m/day) only began to be noticeably impeded by a biomat of R_b 60 days (Figure 2). Huntzinger Beach and McCray (2003) also found that (modelled) water flow through a biomat was influenced to a greater extent in sandy soils compared with silt soils. They reported that a decrease in K_b by a factor of 2 to 3 resulted in a corresponding increase in trench pond height up to a factor of five in sandy soils. The same degree of increase in pond height was not observed for the silt soils under the same K_b increases (Huntzinger Beach and McCray 2003).

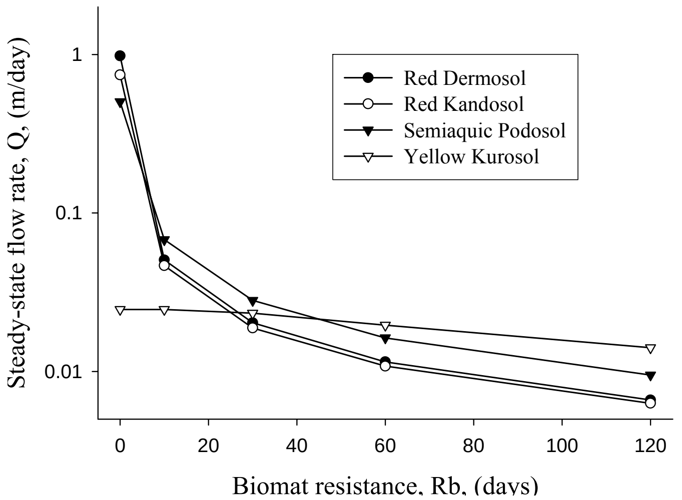


Figure 2. Influence of biomat resistance on steady-state flux using FLUX

Two-dimensional modelling

The partitioning of flow between the biomat zones (sidewall and bottom) and exfiltration zone for each scenario is shown in Figure 3. Flow in the Yellow Kurosol is much more evenly partitioned between the biomat zones and exfiltration zone compared with the more permeable Red Dermosol. With the exception of run 1 for scenario 3 (sidewall biomat height = 0m, Table 2), the biomat zones were as important as the exfiltration zone in infiltrating the ponded water in the Kurosol (Figure 3).

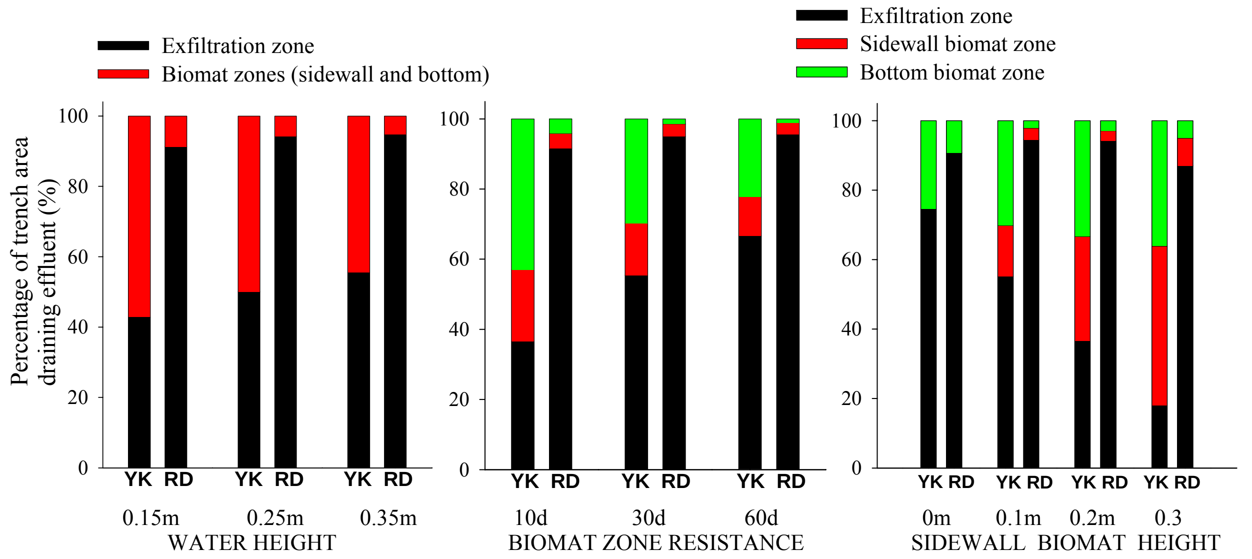


Figure 3. Percentage of trench area (exfiltration zone and biomat zones) contributing to effluent drainage into surrounding soil for Yellow Kurosol (YK) and Red Dermosol (RD)

Conversely, flow through the exfiltration zone in the suitable soils (Red Dermosol shown only here) was predominant, ranging from 82-96% of overall flow. In permeable soils, the hydraulic conductivity of the near-saturated exfiltration zone is likely to be higher than the saturated hydraulic conductivity of the sidewall biomat zone, therefore effluent will preferentially flow through the exfiltration zone during periods when ponded effluent rises above the sidewall biomat zone. Huntzinger Beach and McCray (2003) reported two-dimensional flow through biomat sidewalls was greater in a sandy media than in a silt media. In their study, water content distribution in sandy soils were uneven across the modelled domain, with a preferential flow through the sidewall biomat. This was concluded to be result of the higher saturated hydraulic conductivity of the sidewall. Conversely, the water distribution was much more uniform in the silt soil, suggesting a more even distribution of water flow through the bottom and sidewall biomats than occurred in the sand (Huntzinger Beach and McCray 2003).

The total flux of effluent (L/m/day) infiltrating through the trench area (biomat + exfiltration zone) is shown in Figure 4. Volumes of up to 400L/m/day of effluent were predicted to flow through the trench (bottom and sidewalls) in the Red Dermosol (Ks 0.98 m/day) with a ponded water height of 0.35 m. Figure 3 indicates that about 90% of this will be through the exfiltration zone. In comparison, total flux of effluent predicted to flow through the trench in the Yellow Kurosol (Ks 0.014 m/day) is 9 L/m/day for the same water height (0.35 m) with only about 50% flow through the exfiltration zone Figure 3). This data further suggests that the exfiltration zone in permeable soils appears an important flow pathway for water during peak loading periods such as heavy rainfall and high water use.

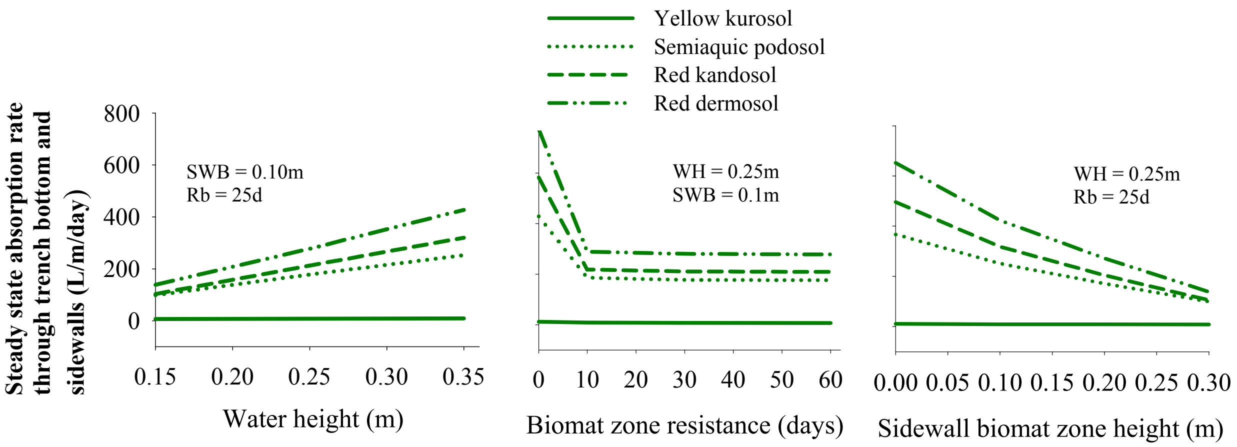


Figure 4. Total volume of effluent infiltrating through trench with increasing water height (WH), biomat zone resistance (Rb) and sidewall biomat zone height (SWB) (identical y-axis scale for all plots)

Increasing biomat resistance (bottom zone) did not appreciably influence effluent flows within the trench (Figure 4). This is not consistent with results from FLUX (Figure 2) or with other published data (Hansen and Mansell 1986; Huntzinger Beach and McCray 2003; Janni *et al.* 1980) and may be explained by the absence of an exfiltration zone pathway in these models. Total volumes did decline sharply from R_b 0 to R_b 10 days for the suitable soils, as shown in Figure 4. However, there was no further reduction in total volume at R_b >10d, suggesting a steady-state had been reached, (which was not the case as the R_b continued to increase with each run), or there was some other mechanism responsible for discharging the effluent through the trench, such as the exfiltration zone. The exfiltration zone was not considered as a flow pathway in the FLUX model as it was one-dimensional, which would explain why resistance directly reduced flows (Figure 2). As previously discussed, the modelling reported by Huntzinger Beach and McCray (2003) did not consider the trench walls above their sidewall biomat zone as an effluent flow pathway. Again, this would “force” all effluent to travel through a biomat zone of increasing resistance, thereby having a direct effect on flow rates through the biomat zones. This was not observed in our modelling as the total sidewall length was being considered, therefore providing an alternative (less resistant) pathway for effluent flow.

As sidewall biomat zone increased there was a concomitant decrease in total effluent flows through the system (Figure 4). This is expected as the area of exfiltration zone availability becomes considerably reduced as sidewall biomat increases up the trench walls. Increasing sidewall biomat occurs as the equilibrium level of effluent in the trench gradually rises over time, thus exposing more and more of the sidewall to “clogging agents” (organic matter and suspended solids) contained in the ponded effluent (Siegrist and Boyle 1987). Rising trench water levels is usually as a result of changes (increases) in bottom biomat zone resistance. Changes to equilibrium bottom biomat resistance may be triggered by several factors including a deterioration in effluent quality (more clogging agents contained in effluent), and episodes of solids carry-over from septic tank (USEPA 2002). As the sidewall biomat zone rises up the trench sides, the ratio of permeable (native soil) to low-permeable (biomat) sidewall decreases with a consequent decrease in total effluent flow through the system. Under field conditions this situation would be likely to cause surface surcharging of effluent.

Although the exfiltration zone appears to provide an effective hydraulic pathway during high trench loading, effluent treatment efficiency may be compromised in these conditions. Effluent treatment processes are associated with long hydraulic retention times in soil (Van Cuyk *et al.*, 2001), and therefore in situations of rapid discharge through the exfiltration zone, an adequate level of treatment (i.e BOD, suspended solids, pathogens and phosphorous reduction) may not be attained, particularly when a shallow water table exists.

Conclusion

The data from the modelling suggests that the exfiltration zone in SAS located in permeable soils plays a major role in hydraulic performance. This conclusion is drawn from the following observations from the modelled data:

i) water heights (scenario 1) and sidewall biomat height (scenario 3) influenced infiltration rates and total volume of effluent more markedly than biomat resistance (scenario 2);

ii) the common factor in both scenarios 1 and 3 was the *availability of exfiltration zone able to be utilised* – the data demonstrates that an increase in effluent infiltration corresponded with a greater availability of exfiltration zone, rather than a lower resistance of biomat (although the early stages of biomat development did result in a reduction in flows); and

iii) during significant ponding of water within the trench (e.g >75% of trench ponding), hydraulic gradients across the exfiltration zone are generally such that flows through the exfiltration zone are close to the soil Ks. This can result in large volumes of water exfiltrating the trench during peak loading.

The critical role of the exfiltration zone can help explain why failure of SAS in permeable soils are reported rarely, despite widespread evidence that the biomat zone reduces flows in permeable soils to a greater extent than less permeable soils. Further, the hydraulic functioning of SAS in soils of lower hydraulic conductivity are theoretically easier to predict. This is due to the fact that they are largely governed by the $K(\Psi)$ characteristics of underlying soil, rather than trench design and sidewall biomat development which is an additional consideration in sandier soils.

Field experiments, measuring bottom and sidewall trench flow under ‘normal’ and peak loadings, are currently in progress to validate the modelling.

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