Predicting the failure of septic tank – soil absorption systems: A step closer to managing water quality in non-sewered catchments

C. D. Beal*, T. A. Gardner**, N. W. Menzies***

* School of Land & Food Sciences, University of Queensland, St. Lucia, Qld 4073 and Coastal CRC, Indooroopilly, Qld. (E-mail: *c.beal@uq.edu.au*)
** Queensland Department of Natural Resources & Mines, Indooroopilly and Coastal CRC, Indooroopilly, Qld. (E-mail: *Ted.Gardner@nrm.qld.gov.au*)
*** School of Land & Food Sciences, University of Queensland, St. Lucia, Qld 4073 (E-mail: *n.menzies@uq.edu.au*)

Abstract

The number of non-sewered developments are increasing rather than declining in many peri-urban areas of the world, including Australia and the United States. The most common (>85%) on-site system in Australia is the septic tank – soil absorption system (SAS). Studies have shown that localised contamination of groundwater from SAS can occur. Soil columns, field studies and modelling were used to investigate the effects of biomat development on long term infiltration rates and provide insight into the key hydraulic pathways of septic absorption trenches. Column results demonstrated clearly that the resistance of the biomat zone controls water flow through a trench, regardless of whether the soil is a sand or a clay, challenging previous conceptions of trench design. Modelling indicated that during episodic peak loading, exfiltration of excess effluent above the sidewall biomat zone occurs to a greater extent in permeable soils than previously thought. Field data substantiated the modelling, indicating that during high trench loading a majority of water "escapes" through the exfiltration zone in permeable soils. Effluent treatment efficiency may be compromised in these situations of high sidewall flow because of low hydraulic retention time in the soil matrix. The research has provided useful data on biomat hydraulic properties which can be used as key model input parameters for on-site system risk assessment models. Results demonstrate the importance of considering alternative hydraulic pathways when predicting off-site impacts from septic systems.

Keywords*:* sidewall, biomat, Hydrus 2D, clogging, modelling, on-site systems

INTRODUCTION

There are over 1 million households (>2,600,000 people) in Australia that rely on on-site wastewater treatment and disposal systems. In the United States, over 60 million people use on-site systems and in developing countries up to 100% of households in townships rely on this technology to treat and disperse household wastewater. The coastal regions and hinterlands of major cities in Australia have become "boom" areas of development and many will remain non-sewered. The most common (>85%) on-site system in Australia, indeed universally, is the septic tank – soil absorption system (SAS). An effective SAS relies on a range of interactive processes, many of which remain poorly understood. Without knowledge of the SAS process, there can be no meaningful progress towards achieving sustainable management of these systems (e.g. design and allotment density).

Concern is growing that poorly functioning SAS affect stream and groundwater quality in non-sewered catchments (Charles *et al.* 2003). The key pollutants of concern are nitrates and pathogens (i.e. bacteria, viruses). For example, around 700ML of effluent may be generated daily in Australia (Beal *et al.* 2005a); resulting in the discharge of 31,500 kg of nitrogen, 8,400 kg of phosphorus and 70 x 10^{10} faecal coliform organisms (assuming daily water use of 200L per person). Although the evidence remains ambiguous as to the extent of contamination from on-site systems, there is some conclusive research demonstrating impacts to water quality in non-sewered areas. Tracer experiments have revealed that nitrate originating from SAS can travel in aquifers in relatively well-defined, narrow plumes which have been recorded to be up to 130 m in length (Robertson *et al.* 1991). There have also been reports of SAS-related waterborne disease outbreaks, although these have usually been localised and associated with a single poorly performing system (Cliver 2000). Eutrophication of waterbodies in non-sewered catchments have also been related to poorly functioning SAS (Dillon *et al.* 2000).

A detailed review of the hydrology of septic trenches is given in Beal *et al.* (2005b). Correct design and maintenance of SAS can substantially reduce the potential for off-site impacts (Siegrist *et al.* 2000; van Cuyk *et al.* 2001). Appropriate SAS design is difficult when the interactions between treatment and hydraulic mechanisms in these systems are inadequately understood. The limiting factor in the long term performance of the absorption system is the low permeability biomat zone that develops along the bottom and lower sidewalls of a trench (Siegrist and Boyle 1987). The biomat zone is a heterogenous layer believed to be comprised of accumulated suspended solids and organic matter in the septic tank effluent and the by-products of microbial activity (e.g. polysaccharide residues) (Baveye *et al.* 1998; Siegrist and Boyle 1987). The hydraulic and purification processes that occur when effluent passes through the biomat and underlying unsaturated zone are closely linked. The relatively long hydraulic retention time in the unsaturated soil provides opportunity for treatment processes such as oxidation, adsorption, pathogen die-off, and ion exchange. Although unsaturated flow characteristics vary between soils, studies have indicated that the biomat zone acts to regulate the long term acceptance rate (LTAR) to within a narrow range, regardless of soil type (Bouma 1975; Huntzinger Beach and McCray 2003). LTAR for trench design is based on the saturated hydraulic conductivity of soils (Standards Australia and Standards New Zealand 2000). There is some scepticism as to the scientific basis underpinning these recommended values (e.g. Charles *et al.* 2001).

There are a limited number of studies modelling unsaturated flow in SAS (e.g 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. 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.

A three-pronged approach of soil columns, field studies and modelling was used in this research. The main objectives of the soil column experiment were to investigate the effects of biomat development on long term infiltration rates and to provide some experimental data on the hydraulic properties of biomats to be used as input parameters in subsequent modelling work. The objective of the modelling was to investigate the main hydraulic pathways in SAS and the flow rates under different hydraulic loading rates and biomat resistances. Finally, field studies were conducted to provide some experimental data on flow rates and hydraulic pathways in two permeable soils and to validate the two-dimensional modelling.

MATERIALS AND METHODS

Soil column experiment

Three soils with varying textures and mineralogy were chosen for the soil column experiment; a coarse river sand, a Red Ferrosol (medium clay) and a Grey Vertosol (heavy clay). Soil samples were air-dried and ground to pass through a 2mm sieve. Twelve PVC columns (diameter 15cm, length 105cm) were packed with the air-dried soils at a uniform bulk density. There were 3 replicates plus a control for each soil type. The columns were located in a dark, temperature-controlled laboratory where a temperature range of 15-20° C was maintained. Fresh septic tank effluent was applied daily to each of the treatment columns. Soil moisture potentials were measured using pencil ceramic tensiometers inserted horizontally into columns at depths of 2.5cm, 5cm and 10cm below the biomat zone (i.e. below soil surface). All statistical analyses were performed using a one-way analyses of variance in Minitab Student Release v 14 for Windows® (Minitab Inc. 2003).

Modelling

Measured moisture retention characteristics of four soils (Verburg *et al.* 2001) were used to predict one-dimensional steady-state fluxes for various biomat resistances. This was performed by using "Flux for Septic Trenches", a spreadsheet model described in Beal *et al*. (2004). Ponded water height was set at 0.25m and the biomat thickness was assumed to be 0.02m.

To develop a better understanding of flow partitioning in trenches, two-dimensional hydraulic modelling was conducted on some Australian soils. Hydraulic properties measured on undisturbed cores from four soils were used (Verburg *et al.* 2001). 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. Only half the system was modelled, because of the generally accepted assumption of symmetry in the hydraulic behaviour of the trench. Further details on the soils and modelling methodology are presented in Beal *et al*. (2004).

Field experiments

Two trenches on household allotments were instrumented at Mango Hill and Maleny, Qld. Trenches were located on a Tenosol (loamy sand) at Mango Hill and a Red Ferrosol (clay loam) at Maleny. The trenches were in good condition (>10 years old) and received blackwater only. Jet-fill tensiometers were used to measure soil moisture potentials. The tensiometers were positioned under and adjacent to the trenches at depths between 25cm and 70cm below the surface(Figure 1).
Trenches were inundated gradually by placing a hose (with a water meter attached) in the septic tank.

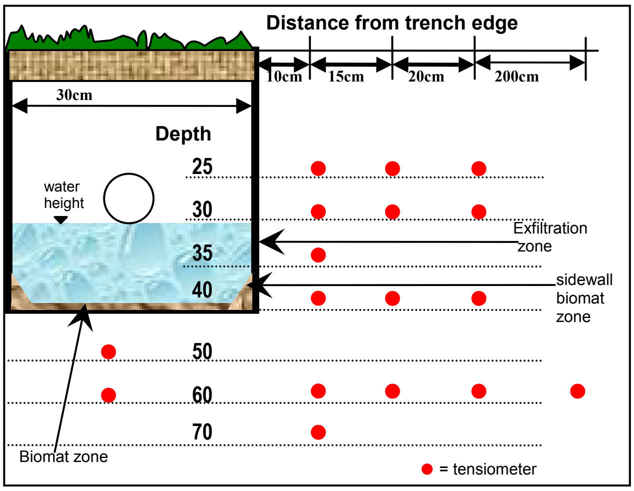

Figure 1 positioning of tensiometers under and adjacent to trench at field site in Mango Hill

An outlet filter was fitted to prevent any solids carry-over from the septic tank during the experiment. The trenches were inundated to a ponded height of 10cm up to 30cm over 5cm increments (i.e. 5 different ponded heights). Each height increment was maintained for a minimum of one hour, or until the tensiometer readings indicated an equilibrium soil moisture.

RESULTS AND DISCUSSION

Soil column experiments

A summary of some physical characteristics of the biomat zone from each soil treatment is presented in Table 1. Biomat zones developed on the soil surface of all treatment columns over the 15 month (470 day) period of STE application. The key parameter influencing flow through the biomat zone is the biomat resistance (R_b) (Bouma 1975). The greater the resistance, the lower the flow through the biomat.

Table 1. Summary of data taken over an average of the last month (442-470 days) of the experiment (standard deviations). Averages with different letters (a, b) are significantly different (P<0.05) from each other.

Soil (treatment averages)	Biomat thickness (Zb) (cm)	Biomat Ksat (Kb) (cm/day)	Biomat resistance (R_b) (days)	Infiltration rate (LTAR) (cm/day)	Initial saturated hydraulic conductivity (cm/day)	Total STE loading (L)
Sand	^{a}**2.0** (±0.3)	^{a}**0.22** (±0.25)	^{a}**34** (±24)	^{a}**0.52** (±0.44)	2470 (±242)	**134** (±11)
Ferrosol	^{a}**2.0** (±0.2)	^{a}**0.22** (±0.15)	^{a}**32** (±25)	^{a}**0.53** (±0.28)	835 (±32)	**110** (±11)
Vertosol	^{b}**0.77** (±0.25)	^{a}**0.15** (±0.06)	^{a}**16** (±5.7)	^{a}**0.38** (±0.08)	23 (±1.2)	**34** (±1.8)

Data in Table 1 suggest that although there were no significant differences (P>0.05) in R_b between soils, the more permeable soils had higher R_b than the Vertosol. The lack of significant difference is likely to be due to the high within soil variability observed in the sand and Ferrosol. However, the thickness of the Vertosol biomat zone (Z_b) was significantly less (P<0.05) than the other soils. This was likely to be a result of the larger volumes of STE, and hence suspended solids and biochemical oxygen demand, applied onto the more permeable soils. The biomat zone has been shown to be a function of cumulative biochemical oxygen demand (BOD) and suspended solid loading (Siegrist and Boyle 1987).

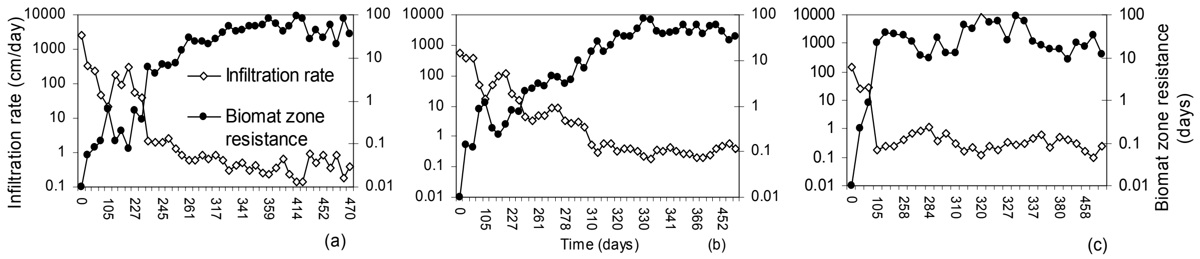

Figure 2. Decrease in infiltration rate over time and subsequent increase in biomat zone resistance for sand (*a*), Ferrosol (*b*), Vertosol (*c*)

Infiltration rates (or LTAR) through the biomat zone reduced over time with a concomitant increase in biomat resistance (Fig. 2). Patterns of reduced infiltration rate over time is in agreement with other similar studies (van Cuyk *et al.* 2001). The observed 3-log reduction from initial saturated hydraulic conductivity in the Ferrosol and Vertosol and a 4-log reduction in the sands demonstrated the influence of the biomat zone on LTAR. Further, the greater reduction in LTAR in the sand and Ferrosols shows that the biomat zone has much greater effect on flow in permeable soils compared to low permeable soils e.g. the Vertosol. This can be directly attributed to the moisture retention characteristics of the sand and Ferrosol soils, as they undergo substantial pore water draining at high matric potentials (ie. low soil tensions) and consequently the conductance of water through the soil will be reduced as the larger pores drain.

Modelling

One-dimensional modelling was used to demonstrate how the interaction of biomat resistance with soil hydraulic properties can be used to predict LTAR. The LTAR for some Australian soils are shown in Figure 3. Results were similar to other studies (eg. Huntzinger Beach and McCray 2003) 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 long term flow rates. These results also supported the soil column data.

Two dimension flow was then modelled to predict the relative partitioning of effluent volume through the sidewalls and bottom zones of a trench. This is somewhat poorly understood area, yet it is an important factor in the treatment process. Modelling results from Hydrus 2D (Figure 4) showed that a substantial volume of water is lost through the exfiltration zone (non-biomat sidewall) of the trench. For example, the partitioning of flow between biomat zones (bottom and sidewall) and the exfiltration zone as trench water height is increased, is shown in Figure 4(a). Flow in the Yellow Kurosol (YK) is much more evenly partitioned between the biomat zones and exfiltration zone compared with the more permeable soils.

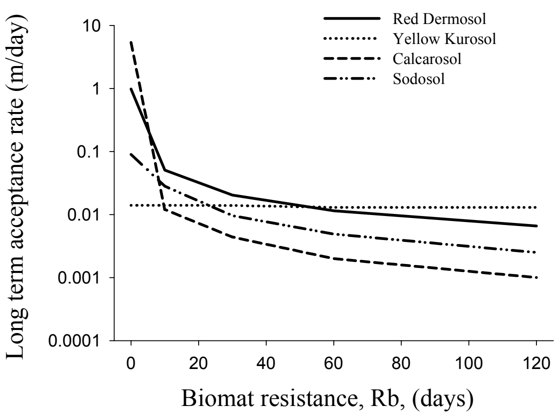

Figure 3. Predicted effect of increasing biomat resistance on steady state flow rates for a range of Australian soils

Flow through the exfiltration zone in the Red Dermosol (RD) was predominant, ranging from 82 - 96% of overall flow. Huntzinger Beach and McCray (2003) also reported two-dimensional flow through biomat sidewalls was greater in a sandy media than in a silt media.

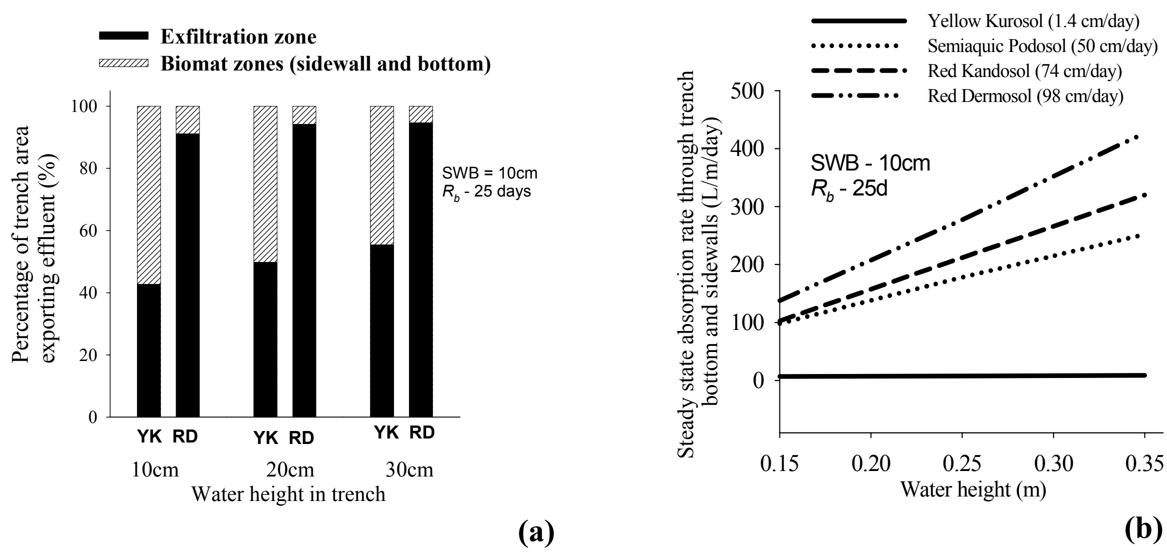

Figure 4 **(a)** Relative fractions of trench area (exfiltration vs biomat zones) contributing to effluent drainage into surrounding soil as water height increases for a range of soil textures (SWB = sidewall biomat height); and **(b)** total volume of effluent infiltrating through absorption trench with increasing water height (saturated hydraulic conductivity, K_{sat}, shown in brackets)

The total flux of effluent (L/m/day) infiltrating through the trench area (biomat + exfiltration zone) is shown in Figure 4b. Volumes of up to 400L/m/day of effluent were predicted to flow through the trench (bottom and sidewalls) in the Red Dermosol (Ks 98 cm/day) with a ponded water height of 0.35 m. Figure 4a 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 1.4 cm/day) is 9 L/m/day for the same water height (0.35 m) with only about 50% flow through the exfiltration zone (Figure 4a). This data further suggests that the exfiltration zone in permeable soils appears an important flow pathway for water during episodic peak loading periods such as heavy rainfall and high water use.

Field experiment

Soil matric potentials at varying ponded water depths in the field absorption trench from the Mango Hill site are shown in Figure 5. The darker the shading, the wetter the soil. During low flow (3.5cm ponded height) flow appeared to occur through the bottom and lower sides of the trench. As ponding height increased, water is shown to preferentially flow through the sidewalls. The lower matric potentials (drier) under the trench can be explained by the hydraulically resistant biomat zone observed along the bottom and the lower sidewalls of the trench. The biomat zone extended up the trench sidewalls to heights ranging from 7 - 10 cm. The thickness of the biomat zone also varied along the bottom and sides. Whilst it was difficult to measure, we estimated thicknesses of 5 – 15 mm (bottom) and 1 – 5 mm (sides). Field results support our modelling predictions whereby preferential flow is occurring through the less resistant sidewall exfiltration zone. As shown in Figure 5, the sidewall exfiltration of water was observed during the high trench loadings (>10cm ponding height).

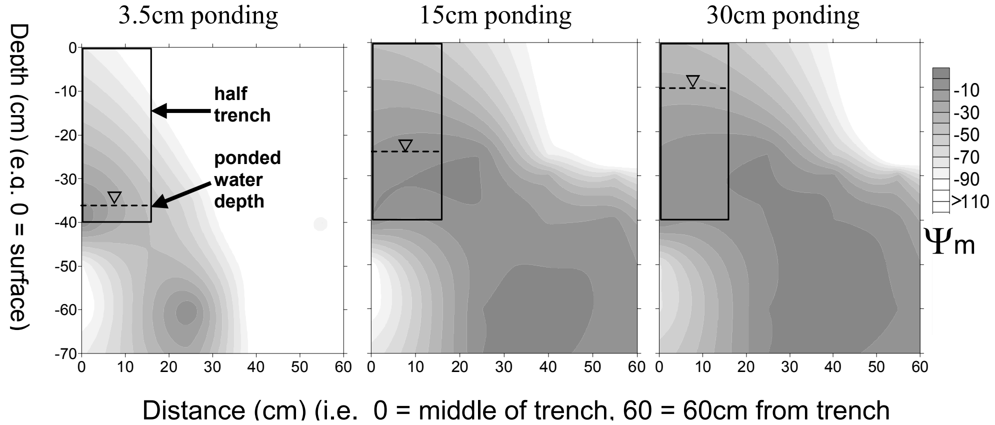

Figure 5. Soil matric potentials (cm) with increasing height of water in the absorption trench of the Mango Hill field experiment

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. Hence effluent will preferentially flow through the exfiltration zone during episodic periods when ponded effluent rises above the sidewall biomat zone. Several other studies have also reported high flows through the trench sidewalls (Brouwer *et al.* 1979; Siegrist *et al.* 2000) and modelling work has also indicated this area to be a key pathway for excess water (Huntzinger Beach and McCray 2003).

GENERAL DISCUSSION

The results of the research demonstrate that the fundamental assumptions used to size absorption trenches in the Australian and New Zealand Standard 1547:2000 are without robust scientific foundation. Results from soil column, field and modelling studies strongly suggest that vertical flow through trenches is restricted due to the low permeability biomat zone. Further to this, LTAR in permeable soils are substantially more affected by the biomat than in less permeable soils. However, the Standard assumes a positive curvilinear relationship between permeability and LTAR, whereby the more permeable the soil, the higher the LTAR (Standards Australia and Standards New Zealand 2000). Results from this research suggest that this relationship may be overestimating the vertical long term flow rates in permeable soils.

Another key assumption in the AS/NZS 1547 Standard (Standards Australia and Standards New Zealand 2000) is that in "*permeable and freely draining soils, absorption through the bottom area of trenches and beds is the significant absorption mechanism*". Data provided here show that this is not the case. Field studies and modelling work suggest that during episodic peak loading, the significant absorption mechanism appears to occur through the upper sidewalls in permeable soils. The capacity for sidewall flow is included in the design loading rates recommended in the AS/NZS Standard. However, it is not known how these values were calculated, nor how they are related to the LTAR recommended in the earlier Standard (Standards Australia 1994).

The high flows through the sidewalls of SAS raises the question of treatment efficacy during these near-saturated soil conditions. Effluent treatment processes are associated with long hydraulic retention times in soil (van Cuyk *et al.* 2001). The aerobic environment required for secondary treatment of the effluent is provided by the underlying unsaturated soil zone created by the hydraulically resistant biomat zone. The relatively long hydraulic retention time in the unsaturated soil provides opportunity for treatment processes. If, in the case of sidewall exfiltration during high flows, effluent flow is largely saturated and hence has a short contact time in the soil matrix, adequate treatment may not occur before entering groundwater. In this instance, off-site exports of contaminants such as pathogens can occur. Drawing from the results of this research, the use of wider and shallower trenches would help to reduce the volume of water flowing through the sidewalls. Therefore effluent would be forced to flow under more unsaturated conditions thus improving treatment efficiencies. Additionally, in shallower trenches, evapo-transpiration would play a greater role in helping to reduce water levels.

CONCLUSIONS

Soil column results show that there were no significant differences in infiltration rates between soil types and that the biomat zone was the governing factor of vertical flow, irrespective of soil type. Two-dimensional modelling demonstrated that the sidewall areas of a trench that are not impeded by the biomat zone, are key pathways for excess effluent during episodic peak loadings. Flow in less permeable soils were shown to be more evenly partitioned between the biomat zones and the exfiltration (non-biomat) zones as ponded height temporarily increased. Field work supported the modelling results by demonstrating that effluent preferentially flowed through the sidewalls rather than vertically during high trench loading into permeable soils. Although sidewall flow occurring in peak loading conditions (rainfall, increased water use) would provide an effective export hydraulic pathway, effluent treatment efficiency may be compromised in these conditions.

The research has provided useful data on biomat hydraulic properties (e.g. thickness, height, resistance). This data can be used as key model input parameters for on-site system risk assessment models. Additionally, this work has illustrated the importance of considering alternative hydraulic pathway scenarios when predicting off-site impacts from septic systems. For example, different hydraulic pathways (sidewall vs vertical flow) result in different degrees of treatment and therefore different risks to water quality. Finally, results reported here may be incorporated into future AS/NZS Standards design loading recommendations, e.g. the relationship between LTAR, biomat zone resistance and sidewall flow.

ACKNOWLEDGEMENTS

The authors would like to thank Alison Vieritz for her work in developing the Flux model and David Rassam for his invaluable advice on Hydrus 2D modelling. Thank you also to the Chamberlain, Cregan and Kreft families for allowing us access into their properties. The authors also acknowledge the support of the Coastal CRC.

REFERENCES

Baveye P, Vandevivere P, Hoyle BL, DeLeo PC, de Lozada DS (1998) Environmental impact and mechanisms of the biological clogging of saturated soils and aquifer materials. *Critical Reviews in Environmental Science and Technology* **28**, 123-191.

Beal CD, Gardner EA, Menzies NW (2005a) Septic absorption trenches: are they sustainable? *Water (Australia)* **32 (1)**, 22-26.

Beal CD, Gardner EA, Menzies NW (2005b) Process, performance and pollution potential: A review of septic tank - soil absorption systems. *Australian Journal of Soil Research (in press).*

Beal CD, Gardner EA, Menzies NW, Rassam DW, Vieritz AM (2004) Prediction of steady-state flux through variably saturated zones within a septic absorption trench. In 'Proceedings of the International Soil Science Conference 2004, 5 - 9 December 2004, Sydney, Australia.'

Bouma J (1975) Unsaturated flow during soil treatment of septic tank effluent. *Journal of Environmental Engineering*, 967-981.

Brouwer J, Willatt ST, van der Graaff R (1979) The hydrology of on-site septic tank effluent disposal on a yellow duplex soil. In 'Hydrology and Water Resources Symposium, 10-12 Sept 1979, Perth'. (IEAust, ACT)

Charles K, Ashbolt N, Roser D, Deere D, McGuinness R (2001) Australasian standards for on-site sewage management: Implications for nutrient and pathogen pollution in the Sydney drinking water catchments. *Water (Australia)* **28**, 58-64.

Charles K, Roser D, Ashbolt N, Deere D, McGuinness R (2003) Buffer distances for on-site sewage systems in Sydney's drinking water catchments. *Water Science and Technology* **47**, 183-189.

Cliver DO (2000) Research needs in decentralized wastewater treatment and management: Fate and transport of pathogens. *National Research Needs Conference Proceedings: Risk Based Decision Making for Onsite Wastewater Treatment.* EPRI Palo Alto, CA, U.S. Environmental Protection Agency and National Decentralized Water Resources Capacity Development Project: 2001 1101446 p. 31

Dillon KS, Corbett DR, Chanton JP, Burnett WC, Kump L (2000) Bimodal transport of a waste water plume injected into saline ground water of the Florida Keys. *Ground Water* **38**, 624-634.

Hansen EC, Mansell RS (1986) Simulated unsaturated-saturated water flow from a septic tank drain to groundwater. *Soil and Crop Science Society of Florida* **45**, 21-29.

Huntzinger Beach DN, McCray JE (2003) Numerical modeling of unsaturated flow in wastewater soil absorption systems. *Ground Water Monitoring and Remediation* **23**, 64-72.

Minitab Inc. (2003) MINITAB Statistical Software, Release 14 for Windows, State College, Pennsylvania. MINITAB® is a registered trademark of Minitab Inc. In.

Robertson WD, Cherry JA, Sudicky EA (1991) Ground-water contamination from two small septic systems on sand aquifers. *Ground Water* **29**, 82-92.

Siegrist R, Boyle WC (1987) Wastewater-induced soil clogging development. *Journal of Environmental Engineering* **113**, 550-566.

Siegrist R, Tyler EJ, Jenssen PD (2000) Design and performance of onsite wastewater soil absorption systems. *National Research Needs Conference Proceedings: Risk Based Decision Making for Onsite Wastewater Treatment.* EPRI Palo Alto, CA, U.S. EPA and National Decentralized Water Resources Capacity Development Project: 2001 1101446 p. 48

Standards Australia (1994) 'Australian Standard - 1547: Disposal systems for effluent from domestic premises.' Standards Association of Australia, NSW.

Standards Australia, Standards New Zealand (2000) 'AS/NZS 1547:2000 On-site domestic wastewater management.' (Jointly published by Standards Australia International Ltd, NSW and Standards New Zealand, Wellington)

van Cuyk S, Siegrist R, Logan A, Masson S, Fischer E, Figueroa L (2001) Hydraulic and purification behaviours and their interactions during wastewater treatment in soil infiltration systems. *Water Research* **35**, 953-964.

Verburg K, Bridge BJ, Bristow KL, Keating BA (2001) 'Properties of selected soils in the Gooburrum - Moore Park area of Bundaberg.' CSIRO Land and Water, Canberra. Technical Report 9/01, April 2001.