Effluent tracing and the transport of contaminants from a domestic septic system

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Abstract A domestic soil absorption system in a coastal location was instrumented with suction lysimeters and piezometers and monitored between August and December 2002. Using the sandy soils from the site, column leaching experiments were also undertaken and these suggested that bromide would be a suitable conservative tracer which could be added to the wastewater system to determine the direction and rate of groundwater flow. The septic system plume boundaries were identified from the monitoring results and the subsurface fate of the inorganic nutrients determines using ion ratios. The tracing results indicated that groundwater was moving at 0.4 m/day towards a nearby drain. The ion ratios indicated that total inorganic nitrogen and orthophosphate were not substantially lost or diluted in the sandy soils downgradient from the soil absorption system, and that without riparian vegetation lining the drain, these nutrients would have been largely unattenuated in transport. In the absence of adequate vertical and horizontal setback distances, riparian vegetation is regarded as very important in limiting the subsurface transport of inorganic nutrients from domestic septic systems.

Keywords Bromide; contamination; nitrate phosphorus; riparian zone; septic system; tracers

Introduction
This research project was undertaken within the Port Stephen area of new South Wales (NSW) and involved an investigation of the use of different chemical tracers (lithium, fluorescein and bromide) to determine if hydrologic links and pathways existed between on-site wastewater systems, drainage channels and groundwaters in the community of Salt Ash, adjacent to Tilligerry Creek. Three unsewered domestic properties were instrumented and the movement of added tracers monitored from the soil absorption system at each property (Geary, 2003). The migration and transformation of various domestic wastewater contaminants, including nitrogen and phosphorus, in the vadose zone and groundwater, were also monitored. In this paper, the results from part of the research work from one of the unsewered properties (Property G) are discussed.

The Port Stephens area contains 4200 on-site sewage management systems, a significant number of which are in close proximity to the waterfront and along drainage channels that feed into the estuary. Port Stephens is a major shellfish producing area and a sensitive breeding ground for marine life. Recent surveys of drainage channels detected high numbers of faecal coliforms, particularly following rainfall, and the contamination has been attributed to urban runoff, animal wastes and large numbers of failing on-site systems. A recent bacterial source tracking study by Geary and Davies (2003) using bacterial antibiotic resistance pattern analysis founds that no one single source of faecal material was more significant than another in the contamination of the estuary or Tilligerry Creek. While bacteria from cattle and chicken faeces were all found to be contributing to faecal contamination of the drainage channels and estuary, human bacteria were also present.

This particular investigation was partly funded by the Department of Local Government’s SepticSafe Program which was introduced into NSW following a viral outbreak of waterborne Hepatitis A in nearby Wallis Lake in 1997 which affected approximately
444 people throughout Australia. Consumed shellfish which had been contaminated by human faecal waste were considered to be responsible, and failing on-site wastewater systems were seen as the likely source due to high rates of system failure in the area which, like Salt Ash, is characterised by coarse sandy soils and high groundwater tables. A subsequent sanitary survey of the Wallis Lake catchment (Brooker, 1999) was not able to identify the faecal source, although other human activities, including waste from boating were also considered possible sources of the faecal pollution responsible for the oyster contamination.

The fate and transport of contaminants in different environments, either from individual systems or from the cumulative impacts of large numbers of systems have been researched by many authors. Using either a network of suction lysimeters or groundwater monitoring bores, the distribution of septic effluent in the vadose zone and groundwater may be determined. In general, plume boundaries in groundwater can be usually identified by geochemical analysis and/or various tracers (dyes or conservative compounds) may be added to identify hydraulic pathways, monitor the velocity and direction of subsurface effluent movement and determine the hydrodynamic characteristics of the groundwater. In Australia a number of studies have been undertaken where there are sandy soils on unconfined shallow coastal aquifers (Whelan and Barrow, 1984a,b; Gerritse et al., 1995; Cromer, 2001; Geary, 2003) which show that effluent from septic systems can produce contaminant plumes in shallow, unconfined aquifers and these can impact on groundwater systems. There studies have reported high rates of nitrification usually within metres of the soil absorption system (and acidity due to depressed levels of pH due to the oxidation of organic carbon and ammonium) and that the nitrate in groundwater is highly mobile. Nitrate in groundwater however may be partly attenuated and removed particularly where groundwater encounters riparian zones and discharges into streams. The primary processes of subsurface nitrate removal within riparian zones are generally considered to be dilution, denitrification and vegetative uptake.

Phosphorus transport from septic tank effluent has also been extensively studied, and although the potential mobility of phosphate through soil is high due to its solubility, it is usually attenuated in soil by sorption and precipitation reactions in the vadose zone. In general terms, most Australian soils have high capacities to immobilise phosphate from septic tank effluent and therefore the subsurface transport of this nutrient tends to be limited compared to the fate of nitrate. The phosphate adsorption capacity of soils may be significantly lower in coarser grained sandy soils and under these conditions phosphate may be more mobile. Whelan and Barrow (1984b) examined phosphorus concentrations in sandy soils in Western Australia and found elevated phosphorus concentrations at more than 8 m below the soil surface and as far as 4 m away. Lateral phosphorus movement in sandy soils at distances greater than 30 m has been reported, as has the persistence of phosphorus for a number of years even after decommissioning of septic systems (Robertson and Harman, 1999). Generally, phosphorus contamination in groundwater from individual on-site systems can occur in cases where the water table is near the surface, the site soil is coarse textured, the flow rate and loading rates are high, and if the site soil has a low phosphorus adsorption capacity (or when this capacity of the soil has been met).

**Materials and methods**

Property G which was instrumented as part of this study is located within the small community of Salt Ash (Geary, 2003). Two older adults occupied the large 3–4 bedroom house which is located on approximately one hectare. Household fixtures included a dishwasher; two toilets and two showers; a rainwater tank was used for potable use and a spear point for garden watering. The wastewater system consisted of a 2300L septic
tank with 9 m tunnel trench located approximately 9–10 m from an open drain. The results of water use monitoring at the property indicated that the residents’ average water use was 301 L/day during the study period (August–December 2002) with an effluent loading to the wastewater disposal trench of approximately 55 L/m²/day (55 mm/day).

**Laboratory columns**

Soils in the area are part of the Pleistocene Tomago Sand Beds and are comprised of coarse-grained freely draining sandy soils. Soil samples from Property G were analysed in the laboratory for a number of physical and chemical properties, and in order to further examine the usefulness of several tracers, a number of simple laboratory column studies were conducted. Two 35 cm long PVC columns with an internal diameter of 5 cm were used in parallel for this experimental work. Both columns were repacked with sieved – 2 mm Tomago sands from Property G and run in parallel for each of the tracer experiments. A Gilson Minipuls 3 peristaltic pump was utilised to establish a constant flow rate of tracer solutions through the columns at approximately 1 mL/minute for a period of 8 hours. The tracers used and their concentration were: 50 mg/L nitrate from potassium nitrate (KNO₃), 20 mg/L bromide from potassium bromide (KBr), 20 mg/L lithium from lithium chloride (LiCl) and 20 mg/L fluorescein from sodium fluorescein (C₂₀H₁₀O₅Na₂). During each experiment, the volume of filtrate was recorded and samples were collected for analysis from each column every half hour. The runs were principally undertaken to determine the breakthrough curves for each tracer and to establish which of the tracers might be most useful in determining effluent pathways from the soil absorption system.

**Site instrumentation**

A detailed investigation of the movement and fate of the septic system contaminants from the soil absorption system was undertaken at the property using suction lysimeters installed to the vadose zone/groundwater boundary as shown in Figure 1. This type of sampler was chosen for use because sands have high hydraulic conductivities and at low suctions, it was expected that sufficient sample volumes would be collected for

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*Figure 1* Site instrumentation – property G

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chemical analysis. The single chamber vacuum-operated samplers (Soil Moisture Equipment Corporation Model 1900L ceramic cup sampler 4.8 cm o.d.) were installed down-gradient from the soil absorption system outside the property boundary and adjacent to a nearby drain. The distribution and boundaries of the effluent plume in the vicinity of the drain and riparian zone were initially identified by soil water sampling. Two piezometers (P1 and P2) made from slotted 20 cm diameter PVC pipe were also inserted into the groundwater and depth to groundwater was regularly monitored using an electronic Yamayo Million Water Level Measure.

Tracer additions and monitoring
After an initial period of monitoring to determine background concentrations and the effluent plume boundaries, both lithium chloride and potassium bromide solutions (20 L at a concentration of 20 g/L) were introduced into the system via an access port after the septic tank. These tracers were added on the 18 September 2002 to confirm groundwater flow direction towards the nearby drain and obtain groundwater flow velocities. Monitoring continued for both tracers as well as the following analytes: pH, electrical conductivity, dissolved oxygen, ammonium, nitrite, nitrate, orthophosphate, sodium, chloride and sulphate. Samples which were collected either weekly or biweekly were analysed using field meters or by laboratory instruments (atomic absorption spectrophotometry or ion chromatography) using standard methods. The septic tank was also regularly monitored (additional analytes included total Kjeldahl nitrogen, ammonia, total phosphorus, biochemical oxygen demand and faecal coliform bacteria) and sample sites both upstream (Creek 1) and downstream (Creek 2) were established. Later in the monitoring period, as it became clear that effluent was entering the adjacent drain, three additional samplers were installed (in November) into the nearby creek bed (suction lysimeters at CS, CL and another piezometer at CH), and a similar range of analytical testing was undertaken on these samples.

Results and discussion
The typical Tomago Sands consist of a surface sand layer darkened by organic material which is then underlain by a deep coarse white crystalline sand. The results of the physical and chemical testing of soils at the monitoring site are reported by Geary (2004). In summary the soil is typical of the freely draining sandy soils found along the NSW coastline and is acidic with low electrical conductivity and very low cation exchange capability. It is also low in total and organic carbon, nitrogen and phosphorus indicating leached and nutrient deficient soils. The phosphorus sorption of the soil is low (15 mg/kg) suggesting there is little possibility that phosphorus from effluent disposal would be bound on site in sub-surface soils.

Laboratory columns
The results from the addition of different tracers to the laboratory columns are shown in Figure 2. The basic plot of the tracer concentration as a function of time passing through each of the sand column (columns A and B) is shown as a single solute breakthrough curve for the tracers used. The normalised concentration is shown as $C/C_o$, which is the ratio of the measured tracer concentration ($C$) to the input tracer concentration ($C_o$). The nitrate, lithium and bromide moved rapidly through the sand columns with the initial breakthrough times being similar. The median time of travel of nitrate and bromide ($C/C_o = 0.5$) indicates a moderate yet similar amount of dispersion. While it has been reported that nitrate may lag behind bromide as a tracer, it appears in these columns as though there is some minor loss of bromide relative to nitrate. The displacement shown in the lithium tracer plot does indicate that the ion has moved more slowly through the
sand columns and is more hydrodynamically dispersed than the bromide or nitrate ions. Cation exchange may be responsible for the retardation of the lithium ion in the columns, although the soil laboratory analyses indicated that the capacity of the soil in this regard is low. The fluorescein tracer does not appear to breakthrough during the time of the experiment which is to be expected given the reported adsorptive properties of fluorescein. On the basis of this column testing, the anionic tracer, bromide, would appear a preferable tracer to use in field testing to determine the fate of contaminants from failing on-site wastewater systems given that the relative concentrations are higher than lithium and that its dispersive characteristics are similar to nitrate.

**Tracer additions and monitoring**

The two piezometers (P1 and P2) which were located along the transect of maximum hydraulic gradient and plume centre line (A–A’ shown on Figure 1) were used to monitor groundwater level variations during the monitoring period. Very little rainfall was recorded for a large proportion of the monitoring time and, as a consequence, groundwater levels dropped rapidly and the adjacent drain ceased to receive upstream flow. The sole contribution of flow to the drain was the subsurface movement of effluent from the property. The result of the bromide tracer addition for three samplers along the A–A’ section which is shown in Figure 3 indicates a clear hydraulic connection between the septic system and the suction lysimeters. Over the short horizontal distance between suction lysimeters and, using the peak-to-peak travel times, the tracer velocity...
was estimated at 0.4 m/day. Using a form of the Darcy equation and the groundwater hydraulic gradient, the saturated hydraulic conductivity of the soil was calculated as 14 m/day, which is typical for a medium of coarse-grained sand.

The summarized analytical results from monitoring the septic tank and the suction lysimeters located along the plume centerline (Section A–A’ Figure 1) are shown in Table 1.

Samples of septic tank effluent are generally reflective of the typical domestic household waste stream. The effluent pH is neutral with the electrical conductivity, and hence dissolved solids, also relatively consistent around 900–950 mg/L. Almost all of the nitrogen in the tank is present as ammonium and organic nitrogen (total Kjeldahl nitrogen) with little free oxygen being available. As a result nitrite and nitrate nitrogen concentrations are negligible. After the effluent is discharged to the infiltrative surface of the absorption system, the ammonium is rapidly oxidized in the vadose zone. The movement of nitrate away from the absorption system is dependent on the hydraulics of the groundwater, however, it remains in the system unless it is removed or transformed by microbial processes. Samplers L7, L6 S4 and S7, which all have high mean nitrate nitrogen concentrations, suggest the source of the contamination is clearly the septic tank effluent. Total phosphorus results from the septic tank are high (arithmetic mean 18.5 mg/L) with most of the phosphorus being present as the inorganic orthophosphate. High orthophosphate concentrations are also found in the suction lysimeter samples downgradient from the disposal area.

Nitrogen and phosphorus
To examine the effect of nitrogen removal from dilution processes, nitrogen loss has traditionally been studied by evaluating concurrent nitrate and conservative ion concentration patterns. Robertson and Blowes (1995) for example found that attenuation of nitrogen along the plume core flowpath was indicated by a decrease in the nitrogen/chloride ratio from an effluent value of 1.7 to a plume value of only 0.5 after four metres of subsurface flow. Sodium has also been found to be a good indicator of an impact of

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(Mean, Standard Deviation and Number of Samples for pH; EC – electrical conductivity; DO – dissolved oxygen; PO₄-P – orthophosphate; NO₃-N – nitrate nitrogen; NH₄-N – ammonium nitrogen; TIN – total inorganic nitrogen (NO₂-N + NO₃-N + NH₄-N); Na – sodium)
septic systems because it occurs in the plume at 10–20 times the background levels and it, along with chloride, can be used because it is conservative. Other studies have added conservative tracers such as bromide to estimate the losses of nitrogen from a decrease in the nitrogen/bromide ratio in groundwater downgradient from the septic tank. For example, Gerritse et al. (1995) using bromide found that at least 80% of inorganic nitrogen leaching into soil appeared to be lost within 10 m from a disposal field, while others typically report negligible nitrate removal in often long and narrow septic plumes. In conditions associated with shallow riparian water tables however, nitrate removal may be generated by denitrification as the plume passes through a riparian zone of organic, anaerobic sediments just before entering a drain or watercourse.

In this study, ion ratios using sodium rather than chloride have been used to examine the movement of nitrogen and phosphorus through the soil absorption system to the nearby drain. Sodium was used in preference to chloride due to the possible confounding effects of lithium chloride which was also added as a tracer in the study. Using the collected data over the monitoring period, the ratios of total inorganic nitrogen (ammonium, nitrite and nitrate) to sodium (TIN/Na) and the ratios of orthophosphate to sodium have been calculated for the samplers along or near the centerline of the plume. The mean TIN/Na ration (circular dot) and the sampled distribution at each sampler location relative to its distance from the septic tank are plotted in Figure 4. In conjunction with the data in Table 1, it would appear that the septic effluent is rapidly nitrified and as a result pH is depressed. The ion ratios however do not substantially decrease downgradient from the soil absorption system suggesting that nitrogen does not appear to be lost or attenuated through the sandy soil. In contrast however, there a significant reduction in the ratio between samplers S4 and S7 through the riparian zone to sampler CS which is in the subsurface of the drain. At this site in the drain there are still elevated levels of ammonium but nitrate nitrogen is substantially reduced suggesting that the riparian zone consisting of a line of large paperbark trees (Melaleuca quinquernervia) is responsible for nitrate removal. It is difficult to assess whether denitrification is also contributing to this observed nitrogen removal. A similar plot of the orthophosphate sodium ratio, which is shown in Figure 5, demonstrates that the orthophosphate is highly mobile and is also not attenuated in groundwater transport from the soil absorption system. It too however is substantially reduced relative to sodium after passing through the riparian zone located between samplers S4, S7 and CS.

Figure 4 TIN/Na ratios with distance from the septic tank
Conclusions

The results from this study suggest that septic effluent boundaries may be clearly defined by monitoring work and that the transport of inorganic nitrogen and orthophosphate from a soil absorption system may be substantially unattenuated in sandy soils. Effluent tracing to determine hydrologic links and pathways from domestic septic systems may also be undertaken successfully using bromide as a conservative tracer. The presence of riparian vegetation is regarded as very important in limiting the subsurface transport of inorganic nutrients from wastewater systems in sandy coastal locations, particularly where there are shallow groundwater tables and inadequate vertical and horizontal set-back distances in place.

References


![Figure 5 OrthoP/Na ratios with distance from the septic tank](https://iwaponline.com/wst/article-pdf/51/10/283/433281/283.pdf)