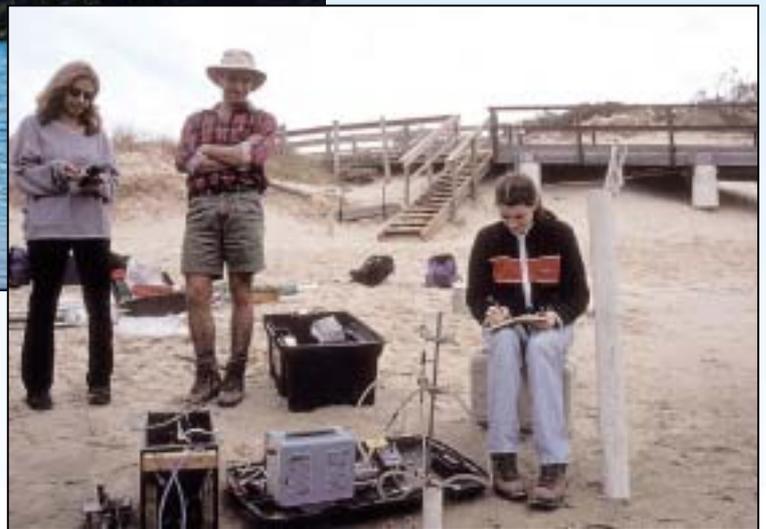


Estimation of groundwater velocity in riparian zones using point dilution tests

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Estimation of groundwater velocity in riparian zones using point dilution tests

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Summary – The point dilution test is a simple method to estimate the velocity of groundwater in the riparian zone of streams, lakes, and estuaries. The method involves following the loss by groundwater advection of a tracer added to a single well. Here, a simple apparatus used to perform the point dilution test in shallow alluvial aquifers is described together with a graphical method to estimate groundwater velocities from the dilution curves. During field trials, groundwater velocities measured with the point dilution test varied from 0.5 to 3 cm per hour in the riparian zone of Australian semi-arid and sub-tropical sand bed rivers at baseflow. Groundwater velocities up to 40 cm per hour were measured during ebbing tides in the intertidal zone of an estuary. Research opportunities to improve the accuracy of the point dilution test are recommended.

Introduction – The riparian zone forms an important ecotone between terrestrial and aquatic ecosystems (Junk et al. 1989). One of the roles played by the riparian zone in the landscape is the regulation of nutrient inputs from groundwater to surface waters (Cirimo and McDonnell 1997; Findlay et al. 2001). Riparian zones are active sites for biogeochemical processes because the availability of labile carbon and variable water tables result in a complex mosaic of reactive redox environments. The pathways and the velocity of groundwater flow are strong controls on biogeochemical cycles within the riparian zone (Hill 1996).

Several approaches have been used to estimate the input of groundwater at the stream-riparian zone interface but all have limitations. The use of Darcy's law requires that both the hydraulic conductivity (K) of the porous medium and the hydraulic gradient are accurately measured (Lee and Cherry 1978; Landon et al. 2001). However, both parameters have large spatial variability and, if K is large, hydraulic gradients may be small in the riparian zone and difficult to measure accurately. Seepage meters have been used to directly measure groundwater input rates at the groundwater-surface water interface (Lee 1977; Boyle 1994). However, seepage meters are impractical to use at higher stream flows and the measured seepage may have artifacts associated with the instrument's perturbation of the natural flow regime along the stream bed. The input of tracers in the subsurface and their detection downgradient can provide accurate information about groundwater flow rate and direction in riparian zones (Simmons et al. 1992; Tobias et al. 2001). However, tracer injections require elaborate experimental designs and significant delays may occur before the tracer reaches downstream monitoring wells.

A complementary and inexpensive alternative to hydraulics, seepage meters, and tracer injection methods is the use of point dilution tests, which estimate groundwater velocity using the rate of dilution of a tracer added to a single well (Freeze and Cherry 1979; Gaspar 1987). The theory behind point dilution tests is well known (Halevy et al. 1967; Drost et al. 1968; Gaspar 1987), the equipment required to perform such tests in riparian zones is inexpensive, and the analysis of the results is straightforward. The purpose of this report is to describe how to perform the point dilution test in riparian zones. Applications and potential pitfalls of the test will be illustrated using examples from sand bed rivers and estuaries in semiarid and subtropical regions of Australia.

Apparatus and Installation – Any well or piezometer can be used to perform the point dilution test providing the screened area is below the water table. A standard removable well and recirculation system (Fig. 1) was used at our study sites. Because of the non-cohesive sands present, the well was installed by first excavating the sand within a larger casing (90-mm O.D. PVC) using an auger (Dormer Engineering, Murwillumbah NSW, model SA7510) and a bailer (model SLW 6210). Following excavation to the desired depth, the standard well was inserted within the casing and was kept in place for a few minutes, during which time loose sand generally filled the space between the well and the casing. The casing was then removed while the standard well was held in place with a pole. This method was used for water tables ranging in depth from 0.1 to 1.5 m below ground surface and at distances from the river varying between 30 cm to several tens of meters.

Following the installation, water was recirculated within the well for 20 minutes to allow the water table surrounding the well to recover from potential mounding or drawdown induced by well installation. The recirculation system consisted of a peristaltic pump (Cole-Parmer model 7533-20), an in-line electrical conductivity (EC) cell (TPS Engineering, Springwood Qld, LC81 EC meter and in-line cell No. 122240), and a small reservoir for the injection of the tracer (Fig. 1b). The system was designed for the well water to be recirculated from the bottom to the top of the well at a rate of approximately 1 L min^{-1} (or ~ 0.9 well volumes min^{-1}). This corresponded to a vertical recirculation velocity of $2500 - 3000 \text{ cm h}^{-1}$, several orders of magnitude greater than typical groundwater velocities in sands ($0.1 - 40 \text{ cm h}^{-1}$). A beach umbrella was used to maintain the system in the shade at all times to limit changes in temperature and bubble formation within the tubing. The background EC was recorded at the end of the equilibration period.

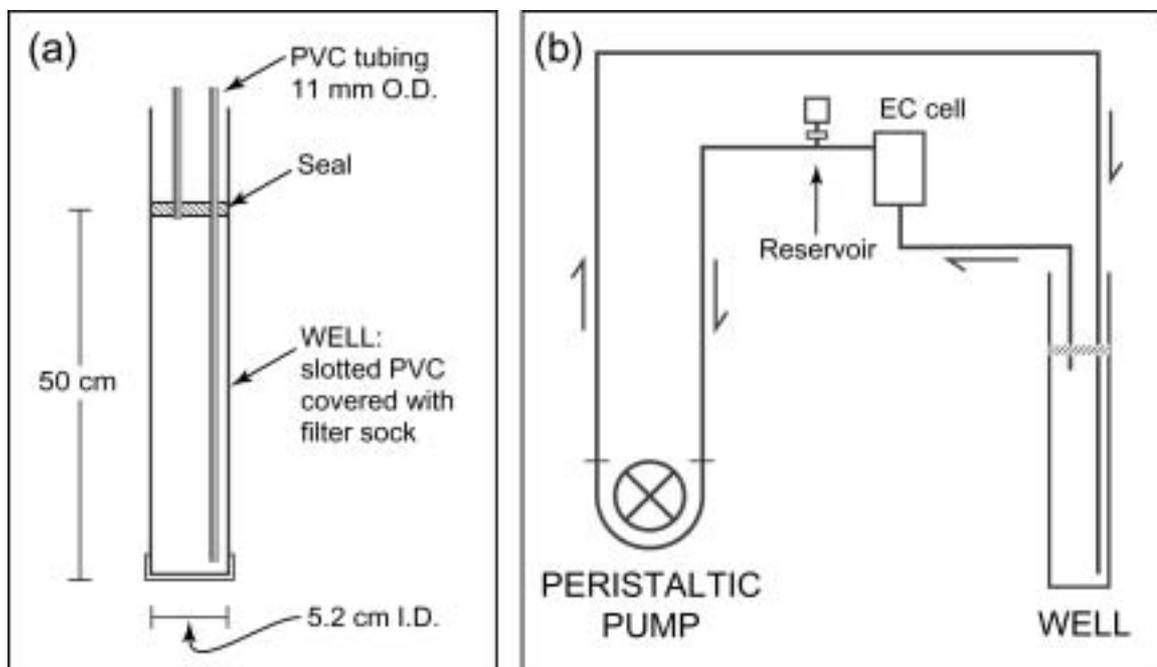


Figure 1. Diagram of **a)** the standard well and **b)** the recirculation system used for the point dilution test. The screen for the well was made of 60 mm x 4 mm helicoidal slots covered with a coarse netting material.

The release of the tracer in the well is a critical step in the point dilution test (artifacts associated with imperfect tracer release are described in the *Assumptions* section). The release mechanism consisted of a PVC T-junction connecting the recirculation system to a small reservoir containing the tracer. In fresh groundwater, 1 to 3 mL of 3M KCl was added to the reservoir, which was generally sufficient to increase EC in the well by 50% to 200%. In saline groundwater, a larger volume of a stronger brine (20 – 60 mL of 5M KBr) was necessary. To initiate the point dilution test, a clamp at the T-junction end of the reservoir was opened. We found it useful to dye the tracer solution to follow its release from the reservoir, which generally occurred within one or two minutes. When most of the tracer had left the reservoir,

the clamp was closed again. This release system is simple but was found to be robust and easy to use under field conditions.

Ideally, it would be preferable for the tracer to mix instantaneously within the well volume following release. In practice, this is difficult to achieve with most designs. With our experimental set-up, several recirculation volumes were required before a stable initial EC reading was obtained (Fig. 2). The appropriate initial time (t_0) and initial EC (EC_m) for the dilution test are arbitrary. In theory, any point along the curve could be used as t_0 (Gaspar 1987). However, it is preferable to choose t_0 as early as possible during the test because the departures of the test curves relative to theoretical curves can be used to diagnose potential artifacts during the test (see *Assumptions*). Tests were usually terminated when EC readings were within 20–25% of the background EC, with the time required to complete the test varying between <2 hours in clean sands during flow recession (i.e., when a pronounced hydraulic gradient occurred) and >18 hours in silty sand at baseflow.

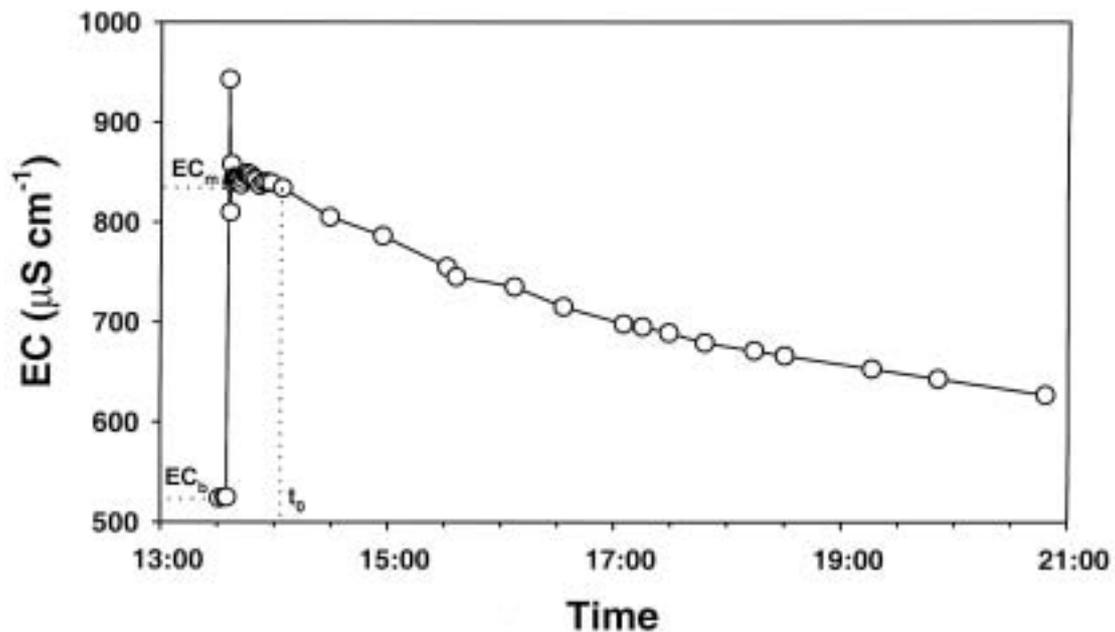


Figure 2. Change in EC during a point dilution test at the Wollombi Brook, New South Wales. EC_b represent the background EC of groundwater prior to the tracer injection and EC_m is the EC at an arbitrary initial time (t_0).

Data analysis – A graphical approach was used to estimate groundwater velocity from point dilution tests. Firstly, a calibration curve for the EC cell was used to convert EC units into equivalent concentrations (C). However, the increase in EC during the tests was generally small and using EC units or equivalent concentrations yielded similar results. Secondly, C was standardized so that $C = 1$ at t_0 and $C = 0$ at $EC = EC_b$:

$$C_{(t)}^* = \frac{C_{(t)} - C_b}{C_o - C_b} \quad (1)$$

where $C_{(t)}^*$ is the standardized concentration at time t , $C_{(t)}$ is the equivalent concentration at different times following the injection of the tracer, C_b the background concentration in groundwater, and C_o the concentration in the well at t_0 .

To estimate groundwater velocity, a series of characteristic curves are plotted along with the standardized curve from the point dilution test. These characteristic curves provide an estimate for the *apparent groundwater velocity* (v^* ; Freeze and Cherry 1979). Characteristic curves are defined by using the following equation:

$$C_{(t)}^* = e^{-\frac{v^* A t}{V}} \quad (2)$$

(modified from Halevy et al. 1967) where v^* is an arbitrary apparent velocity, A is the cross-section area of the well perpendicular to groundwater flow, and V is the volume of water in the test well and recirculation system. Several such curves are plotted for different values of v^* until a few reasonable matches are available to compare with the experimental data (Fig. 3).

The apparent groundwater velocity is the velocity of the groundwater *when travelling through the well*. This will differ from the “true” velocity of groundwater in the porous medium because of two factors. Firstly, the hydraulic conductivity of the well is usually much greater than the one of the surrounding porous medium, resulting in the well acting as a preferential flowpath (Fig. 4). Secondly, a correction must be included to account for the porosity of the porous medium (n). Thus, the groundwater flux or *specific discharge* (q) can be estimated using:

$$q = \frac{v^*}{\alpha} \quad (3)$$

where α is the groundwater focussing or *well-shape factor* (modified from Freeze and Cherry 1979). The *groundwater velocity* (v) can be estimated using:

$$v = \frac{v^*}{\alpha n} \quad (\text{Freeze and Cherry 1979; 4}).$$

While the porosity of the porous medium can be measured (Freeze and Cherry 1979), α is more difficult to estimate. For cases where no gravel packs are used, α can be estimated from Ogilvi's formula (cited in Halevy et al. 1967):

$$\alpha = \frac{4}{\left[1 + \left(\frac{r_1}{r_2}\right)^2\right] + \frac{K_2}{K_1} \left[1 - \left(\frac{r_1}{r_2}\right)^2\right]} \quad (5)$$

where r_1 and r_2 are the inner and outer well radius, K_2 the hydraulic conductivity of the porous medium, and K_1 the hydraulic conductivity of the well screen. Ideally, K_1 should be estimated in the laboratory under controlled conditions (Halevy et al. 1967; Drost et al. 1968). Alternatively, K_1 can also be estimated by theory from the configuration of the well (Halevy et al. 1967). However, it can be seen from (4) that when $r_1 \sim r_2$ and $K_1 \gg K_2$ that $\alpha \cong 2$. Using the theoretical approach suggested by Drost et al. (1968), $\alpha \cong 2.1$ for our well design in sandy porous media.

The above set of equations is valid for groundwater velocities in the range of 0.01 to 15 m d⁻¹. Below 0.01 m d⁻¹, an additional term must be included for the diffusion of the tracer out of the well (see Gaspar 1987). Above 15 m d⁻¹, flow may not be laminar within the well and a correction to the well-shape factor may be required (Gaspar 1987).

Assumptions – Several assumptions must be made or tested when interpreting dilution curves from point dilution tests. These include: *i*) steady groundwater flow during the test, *ii*) an homogeneous mixing of the tracer within the well, *iii*) a known distortion of the flow field around the well (i.e., well-shape factor), *iv*) no density gradients induced by the tracer, and *v*) that the well-mixing mechanism does not increase the rate at which the tracer moves out of the well (Halevy et al. 1967; Drost et al. 1968; Gaspar 1987).

Some of the assumptions of the point dilution test will be more difficult to meet than others in riparian environments. The assumption of steady groundwater flow may be difficult to maintain under some circumstances, such as during flow recession in rivers with flashy hydrographs or tidal cycles in estuaries. However, the point dilution test can be use in conjunction with measurements of the hydraulic gradient to verify that groundwater velocities remain constant in the vicinity of the well during the test. Homogeneous mixing of the tracer within the well was tested using a transparent model well in the laboratory. Injections of dyed KCl solutions showed that the tracer initially moves as a plug in the well but eventually completely mixes after several recirculation volumes. No “dead spaces”, where mixing occurs more slowly than the average, were detected.

The generation of density gradients in the well and adjacent aquifer by the addition of salt solutions is of concern but can be minimized by limiting the increase in solute concentration. No such artifact was found when EC was increased by different amounts (1.5 to 5-fold) at the same location over successive days (Figs. 3a & 3b). If density gradients would have been a significant factor, the dilution curves would have been steeper initially at higher tracer concentrations. Thus, for the small changes in solute concentration proposed here, density effects are probably negligible.

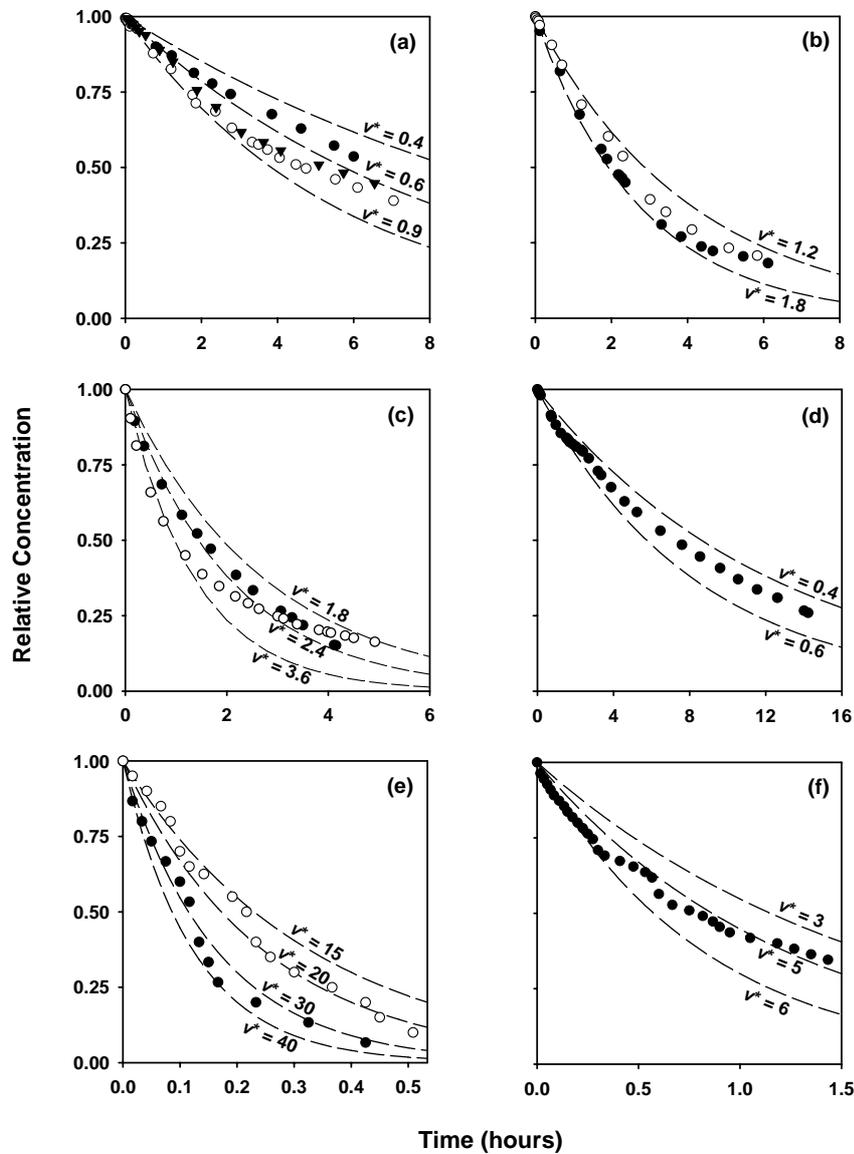
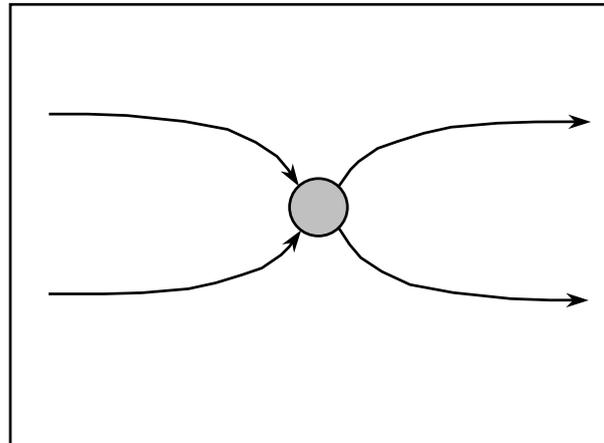


Figure 3. Field (symbols) and theoretical (lines) dilution curves for a series of point dilution tests at several locations in Australia (v^* in cm h^{-1}). *Wollombi Brook, NSW:* **a)** Broke Site 1 (2 - 4 November 2001): (\blacktriangledown) $EC_m = 2 \cdot EC_b$; (\bullet) $EC_m = 3 \cdot EC_b$; (\circ) $EC_m = 5 \cdot EC_b$. **b)** Broke Site 2 (5 - 6 November 2001): (\bullet) $EC_m = 1.5 \cdot EC_b$; (\circ) $EC_m = 2 \cdot EC_b$. *c)* Warkworth (\circ) 29 March 01; (\bullet) 4 April 2001. *River Murray at Hattah-Kulkine Park, VIC:* **d)** Loosing stream section through a clay bank. *Onkaparinga Estuary:* **e)** Ebbling tide (7 December 2001) (\bullet) hydraulic gradient (i) decreasing from 0.032 to 0.028 m/m during the test; (\circ) i decreasing from 0.028 to 0.021 during the test. **f)** Ebbling tide (17 December 2001), with i decreasing from 0.029 to 0.026 during the test.

Figure 4. Conceptual diagram of the disturbance in a groundwater flowfield induced by a well with a screen K larger than the one of the porous medium (adapted from Drost et al. 1968).



Based on our experience, displacement of tracer into the subsurface by an improper release or by the well mixing mechanism are the two most significant technical difficulties associated with the point dilution test. Improper release of the tracer can result in an initial “plateau” in tracer concentration at early times during the test (Fig. 5a). This could occur if a change in pressure within the recirculation system at the time of tracer release (by suddenly stopping and starting the pump, for example) result in some of the tracer being mixed with groundwater adjacent to the well. Thus, at early times, tracer concentration would not decrease because some of the advected groundwater would contain tracer. However, at later times, the dilution curves should still match the shape of theoretical ones.

A more insidious artifact is the potential for the well-mixing mechanism to increase the rate at which tracer moves out of the well (hereafter referred to as “dispersion”). The recirculation system proposed here is less likely to push tracer out of the well relative to the mechanical mixing devices used in deep borehole dilution test studies (Drost et al. 1968). However, there is some evidence that dispersion of the tracer still occurred with our system (Fig. 5b). Tracer dispersion should result in dilution curves that initially decline faster but eventually plateau relative to characteristic curves. This would occur because some of the tracer initially displaced upstream by dispersion would later re-enter the well by advection. Vibration from the pump, accidental compression of tubing, and a number of similar artifacts could contribute to tracer dispersion during the test. In part, dispersion may have been promoted in our early tests by the large recirculation velocities used ($2500 - 3000 \text{ cm h}^{-1}$) relative to groundwater velocities ($0.1 - 40 \text{ cm h}^{-1}$). Assuming that tracer dispersion is proportional to the recirculation velocity, the optimal recirculation velocity may be a compromise between greater mixing and less dispersion. At the present, we suggest to adjust the recirculation velocity to be approximately 500 times the one of groundwater. Further work is underway to evaluate the cause of tracer dispersion and to improve the design of the recirculation system.

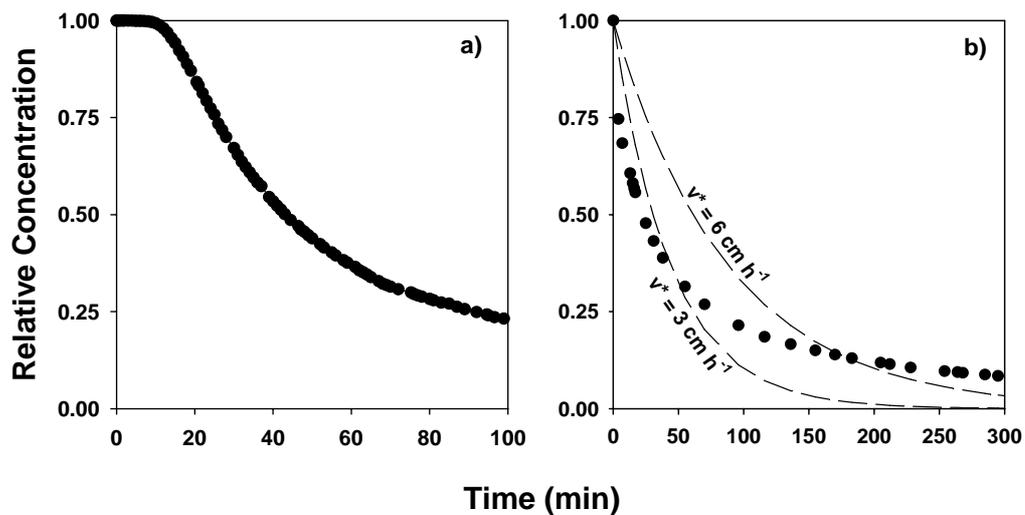
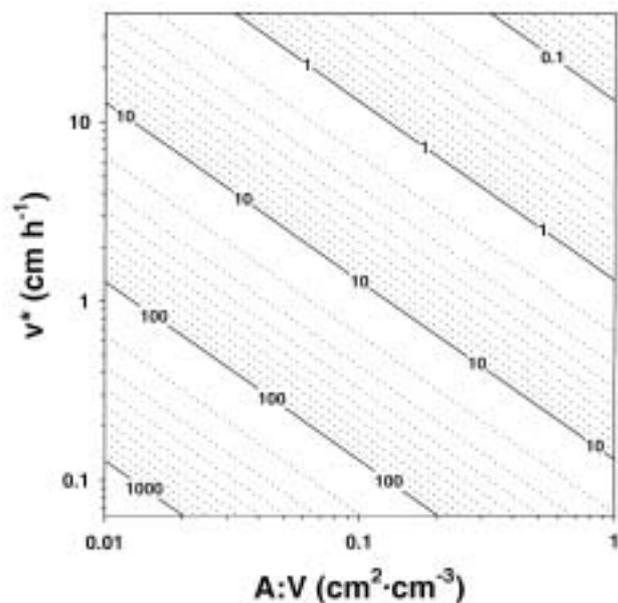


Figure 5. Examples of potential artifacts related to tracer release and mixing during the point dilution test. **a)** Tracer pushed out of the well at the time of tracer release (Onkaparinga Estuary, 18 September 2001). **b)** Tracer dispersion induced by well-mixing (Hattah-Kulkine, 6 March 2001).

There are practical limitations to the application of the point dilution test. While the test can be applied to piezometers in theory (i.e., wells with a low $A:V$ ratio), the time required to perform the test may become prohibitive at low groundwater velocities (Fig. 6). For example, for our test well ($A:V = 0.2$) about 7 hours are required to complete the test at $v^* = 1 \text{ cm h}^{-1}$. The same test would require between 30 to 100 hours with a typical piezometer ($A:V = 0.01 - 0.05$). Thus, small diameter wells should be used for point dilution tests at low groundwater velocities.

Figure 6. Expected time (in hours) required for the relative concentration to reach 0.25 during a point dilution test as a function of the apparent groundwater velocity (v^*) and the ratio of the effective area (the cross-sectional area of the well perpendicular to groundwater flow) to the combined volume of the well and recirculation system ($A:V$).



Field trials – Point dilution tests were performed at three sites with contrasting hydrogeological features. Wollombi Brook (NSW) is an unregulated subtropical sand bed stream with an extremely variable flow regime. The brook flows through a massive amount of erosional sands (“sand slugs”) that form an alluvial aquifer. The site on the River Murray (Hattah-Kulkine Park, VIC) is more representative of a semiarid lowland river setting. At Hattah, the river gently meanders through a floodplain covered with a mature river red gum (*Eucalyptus camaldulensis* Dehnh.) woodland. The banks of the river are a mixture of gently sloping sand bars inside river meanders alternating with steeper clay banks. The Onkaparinga Estuary is a coastal embayment located near Adelaide, South Australia. At the study site, the substrate was fine sand derived from local sand dunes. Because the point dilution test does not indicate the direction of groundwater flow, the shape of the water table was determined independently at each site using piezometer networks and potentiometer measurements (Winter et al. 1988).

At Wollombi Brook, v^* at baseflow was fairly constant across several sites at different times of the year, usually ranging between 0.5 to 1.5 cm h⁻¹ (Figs. 3a & 3b and *unpublished data*). However, because of very small hydraulic gradients at the scale of the riparian zone ($i < 0.001$), the direction of groundwater flow was often difficult to determine accurately (probably parallel or oblique relative to river flow; Woessner 2000). For one sampling period during the tailing end of a storm hydrograph, v^* was higher (2.0 to 3.6 cm h⁻¹; Fig. 3c) and groundwater flow was perpendicular to the river. Similar v^* were also measured at baseflow along the banks of the River Murray (~0.5 cm h⁻¹; Fig. 3d). However, in this case the direction of groundwater flow was away from the river (possibly induced by the respiration of groundwater by the riparian forest).

The largest groundwater velocities measured were during ebbing tides at the Onkaparinga Estuary (5 – 40 cm h⁻¹; Figs. 3e & 3f), when large hydraulic gradients towards the estuary occurred (0.020 – 0.032). In an estuarine context, the assumption that groundwater velocity remains constant during the test may be difficult to maintain because hydraulic gradients may decline during the ebbing tide. However, the shorter duration of the test at high groundwater velocities, the installation of the well in the upper part of the intertidal zone, and proper timing of the test during the tide cycle can minimize this artifact. Lowering of the hydraulic gradient during the test results in a “tailing” dilution curve relative to the theoretical ones (Fig. 3f). Another complication of the test in an estuarine environment is that baseline EC may vary if parcels of groundwater with different salinities occur. The use of Br⁻ salts as tracer in combination with Br⁻-specific electrodes may be a better alternative to EC electrodes in estuaries. With some limitations, the point dilution test appears a promising tool for groundwater – surface water interaction studies in estuaries.

Potential applications – The estimation of groundwater discharge to a stream using the q obtained from the point dilution test requires similar assumptions as when using the Dupuit-Forchheimer approximation with flow nets (Freeze and Cherry 1979). These assumptions are 1) that flowlines are horizontal and equipotentials vertical and 2) that the hydraulic gradient is equal to the slope of the free surface and invariant with depth (i.e., q is constant). In practice, these assumptions can be met in shallow unconfined aquifers with small hydraulic gradients (Freeze and Cherry 1979). In addition, the q determined from the point dilution test must be perpendicular to the

stream (or the component of q towards the stream estimated). If these assumptions are met, then the groundwater discharge (Q) from the riparian zone can be estimated using:

$$Q = q \cdot b \quad (6)$$

where Q is the groundwater discharge ($\text{m}^3 \text{s}^{-1}$) per meter of stream and b the thickness of the unconfined aquifer. The groundwater flux for a given solute can also be estimated using:

$$F_s = Q \cdot \bar{s} \quad (7)$$

where F_s is the solute flux per meter of stream (in unit mass s^{-1}) and \bar{s} the average solute concentration in groundwater. Because of the prevalence of redox gradients in the vicinity of stream beds (Jones and Mullholland 2000), the estimated F_s should be considered a *potential* input rate for redox-sensitive species. For example, part of the groundwater NO_3^- discharge can be assimilated, denitrified, or converted to NH_4^+ during its passage through stream sediments (Duff and Triska 2000).

Determining the hydraulic conductivity of sands is problematic because of the difficulty in collecting undisturbed samples for laboratory measurements and a large spatial variability (Landon et al. 2001). The groundwater flux measured with the point dilution test may be used to estimate hydraulic conductivity *in-situ* if an estimate of the hydraulic gradient (i) is available. Following Darcy's law,

$$q = -K_H i \quad (8)$$

where q is the specific discharge, i is the slope of the water table in the direction of groundwater flow, and K_H the saturated horizontal hydraulic conductivity of the porous medium. An estimate of the hydraulic conductivity can be obtained by rearranging and solving (8) for K_H . Using q and i values measured at the Onkaparinga estuary (Figs. 3e & 3f), K_H was found to range between 0.02 and 0.2 cm s^{-1} . These values are consistent with a clean sand porous medium (Freeze and Cherry 1979).

Conclusion – The point dilution test is a simple tool to obtain information about groundwater velocity in riparian zones. The theory behind the point dilution test is well known and the method can be adapted for a variety of purposes or conditions (Gaspar 1987). However, the test requires careful field measurement and interpretation of results. Because the point dilution test measures the groundwater flux or velocity in the direction of groundwater flow, the shape of the water table must be determined independently because groundwater flow can be towards, away or parallel to a surface water body. While more sophisticated apparatus could be used to perform the test, the one presented here was designed so that it could be easily assembled at a minimal cost using equipment commonly available in laboratories. While we have mostly used the point dilution test in the riparian zone of semi-arid and sub-tropical sand bed rivers, the method should be applicable in similar riparian environments adjacent to lakes and estuaries. The potential for the well-mixing mechanism to increase the rate at which tracer moves out of the well is the main technical difficulty associated with our test design at the present. Future research on the point dilution test should quantify this problem and seek to develop instrumentation that would limit this potential bias.

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