The trigger-tube: A new apparatus and method for mixing solutes for injection tests in boreholes

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Abstract The trigger-tube apparatus and method has been developed for rapid introduction of homogenously mixed solutes in boreholes. Tests gave a Darcy velocity 4.06 m/d, seepage velocity 122.89 m/d and effective porosity 0.33 using NaCl as conservative tracer. The apparatus and method enables comparatively shorter test-time than is possible using traditional tracer tests by pump mixing method. The trigger-tube apparatus and method is useful for any borehole test that requires introduction of homogenous tracer at specific depths.

Key Words Field tracer test apparatus, Single-well test method, Point dilution test apparatus, Homogeneous solute mixer

Introduction

Borehole dilution is a well-established method for analysing groundwater velocity in hydrology and the oil industry. It is a tracer technique performed in a section of a well isolated by inflatable packers. Tracer is injected into isolated test section from a reservoir and subjected to continual mixing in/out of borehole by a submerged/surface pump. As groundwater gradually replaces the tracer solution in the well, a log normalised concentration-versus-time curve is plotted and the magnitude of the horizontal velocity of the groundwater flow calculated. Testing vertically distinct sections of the well, a picture of the vertical groundwater velocity variation in the aquifer (near the well) can be obtained. The measurement of lateral variability of flow system depends on number and distribution of monitoring wells. This method endeavours to account for flow system distortions through well screen. However, this accounting requires a calibration test for each well. The groundwater through-flow gradually removes tracer introduced into well, to produce a time-concentration relationship from which groundwater velocity is computed.

Natural gradient tests (Devlin, 2002), point dilution tests (Labaky *et al.*, 2007), tracer tests, single well injection withdrawal tests (SWIWT; push-pull tests; Freeze and Cherry, 1979; Drost *et al.*, 1968) and forced gradient tests (Lamontagne *et al.*, 2002) are carried out based on assumptions. The most important of these are that:

- Solutes are injected as well mixed slugs
- Well mixing mechanism does not increase rate at which tracer moves out of the well
- Injection time is short compared to the overall time required to carry out the experiment (Neretnieks, 2007; Lamontagne *et al.*, 2002)

However, researchers who have carried out these tests in the field attest that one of the major problems in the use of these tests in hydrogeological investigations is the field procedure which requires a homogeneous mix of solute to be created in tested well using pumps. The importance of homogeneity of solute in the test well can never be overemphasised, and presents the greatest challenge to generating good data, irrespective of which type of tracer or test method is being applied. In fractured rock aquifers, where tests are carried out with the fracture in a continuous flow field with the pump mixing method, it is exceedingly difficult to completely eliminate the influence of pumping on the rate at which the tracer moves into the fracture. This gives higher or lower velocities than would otherwise have been recorded.

Wolkersdorfer (2008) observed that many tracer tests results are not reported in literature because they were unsuccessful due to lack of suitable method to inject tracer into mine water at predetermined depths or without contaminating mine water above injection point.

Neretneiks (2007) noted that the notion of Taylor dispersion is valid for the case when the traced solution is collected and mixed at the 'outlet' of the fracture, and that if there has not been time to even-out the concentration between the streamlines, the 'dispersion' will not be seen when the fluid is rapidly pulled back, as in a SWIW test.

Lamontagne *et al.* (2002), in their very instructive paper, came to one major conclusion: the potential for the well-mixing mechanism (by pump circulation) to increase rate at which tracer mixes and moves out of the well is the main technical difficulty associated with point dilution test designs at present. They further concluded that future research on point dilution tests should quantify this problem and seek to develop instrumentation that would limit this potential bias.

Devlin (2002) affirmed that the chief disadvantage of the borehole dilution method by pump-mixing is the need for mixing in the well; that down-hole mixers have not proven reliable and that recirculation of the tracer solution from the well to the surface and back limits the depth at which the measurements can be made. The difficulties associated with calibration for an in-ground well screen are also non-trivial, though necessary for calculations for groundwater velocity from pump-mixing point dilution tests.

Aim

After many failed tests and ambiguous results from field tests, due to the above assumptions not being met, we undertook to develop a new apparatus and method aimed at:

- Mixing the solute inside the borehole homogeneously on injection
- Instantaneously introducing solute inside the borehole (within seconds)
- Introducing the solute inside the borehole without perturbations

Field test site

The Campus Test Site at the University of the Free State (UFS) is a test site for research covering an area of approximately 180 x 192 m. To date 30 percussion and 7 core-boreholes have been drilled. The site has been used a number of research projects, e.g. on Karoo aquifers (Botha *et al.*, 1998) and on tracer tests in fractured aquifers (Van Wyk *et al.*, 2001; Van Tonder *et al.* (2000).

Apparatus

The trigger-tube apparatus

The trigger-tube was designed and built after laboratory experimentation. It is made up of a 500 mm length of polyvinylchloride (PCV) piping with a lid and trigger mechanism at one end and a threaded coupling joint at the other. The trigger mechanism consists of a lid, a larger retractor spring, a trigger disc, a smaller retractor spring and a circular rubber seal (Fig. 1). The circular rubber seal is glued all round the lid to make the assembly leak-proof. The lid, which is hinged at one end of the tube, is opened by the larger retractor spring attached to it. At the opposite end to the hinge is the lock, which is L-shaped with a small bearing at the tip. To close the lid, the cord (blue) attached to the trigger disc is pulled, to align the slit to the bearing, while the cord (yellow) attached to the lid is pulled simultaneously, bringing the lid's lock bearing into the trigger discs through the slit. Releasing the disc cord (blue) allows the small retractor spring to rotate the trigger disc anti-clockwise, locking the lid in place. The lid cord (yellow) is then released. This trigger-tube was tested to pressures equivalent to down-hole pressures of up to one hundred meters (100 m) below the water table, it opened and closed smoothly. The trigger-tube is coupled with segments of PVC tubes of the same diameter to make up the trigger-tube assembly. Fourteen PVC tubes of 2 m lengths were used for the field tests to a depth of 28m.

Figure 1 *Trigger-tube apparatus*

Method

Solute (homogeneous mixing)

Determination of the test solute concentration is calculated by taking into consideration the concentration of the borehole water (background EC), the total volume of water in the borehole (the volume of water outside the trigger-tube and its concentration), the volume of the trigger-tube and the solute concentration in the trigger-tube, using the formulae below.

From laboratory experimentation, the concentrations for various trigger-tube sizes and EC values were calculated using the following:

$$EC_T V_T = EC_b V_b + EC_t V_t \tag{1}$$

$$V_T = \pi r^2{}_T h \tag{2}$$

$$V_t = \pi r^2{}_t h \tag{3}$$

$$V_b = \pi (r^2{}_b - r_t^{\,2}) h \tag{4}$$

Where: EC_T = solute EC required for carrying out test in the whole borehole (test EC), r_b = radius of borehole, r_t = radius of trigger-tube, EC_t = trigger-tube EC (pre-mixed solute EC in trigger-tube), V_t = trigger-tube volume (includes volume due to thickness of tubes), EC_b = borehole background EC, V_T = total borehole volume, V_b = borehole volume outside trigger-tube, h = length of test segment.

Laboratory tests were carried out using trigger-tubes of 30 mm, 63 mm, 100 mm, 110 mm and 120 mm in diameter, to determine the input solute concentrations and required volumes of fluid for any desired initial solute concentration. The calculated values are given in Fig2.

EC meters

Two types of EC meter were used to measure water levels and profile the borehole, and to measure EC and temperature:

- Solinst Temperature/Level/Conductivity (TLC) meter
- A multi-parameter probe

Winch

A winch was used to lower/ raise the trigger-tube assembly into/out-of the borehole. It was made up of a solid tripod, pulley, gear and sprocket and a stainless steel cable of 5 mm diameter.

Clamps

A set of 3 clamps is used to attach the trigger-tube assembly to the borehole casing and to couple and decouple the PVC tubes during insertion and withdrawal from the borehole. It is very important to clamp the trigger-tube assembly firmly to the borehole casing, in order to counter the enormous buoyancy forces that come into play; these push upward when the tube assembly becomes empty, once all the water has been pumped out of the trigger-tube assembly before the introduction of the solute. This may present a hazard if the trigger-tube assembly is not firmly attached.

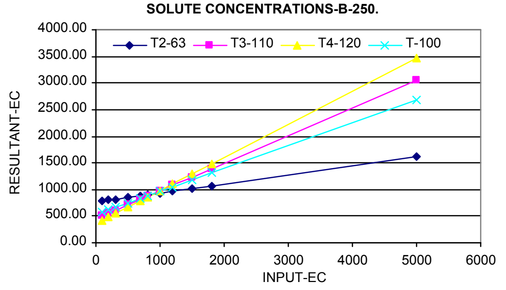

Figure 2 *EC calculator for various trigger-tube sizesT, T_2, T_3,T_4; Each input gives a resultant EC mixture value in the borehole.*

Test procedure

The procedure used to carry out the test using the trigger-tube assembly was as follows (Fig3).

The multi-parameter EC probe is placed inside test-well UO5, below the water table at required test depth for investigation (21 m) (point dilution test). The probe is activated to start taking readings. At observation borehole UO7, another TLC probe is lowered simultaneously to the fracture at a depth of 21 m, and readings are taken at 1 min intervals (passive test). The combined readings from the 2 probes make up the natural gradient tracer test.

Results and Discussion

Darcy velocity

The Darcy velocity q, for point dilution tests is given by;

$$q = -\frac{V}{\alpha A t}\log\left(\frac{C}{C_0}\right) \quad \text{Van Wyk et al. (2001)} \qquad (5)$$

Where: V = volume of fluid contained in the test section, A = cross sectional area normal to the direction of flow, C_0 = Tracer concentration at t = 0, C = tracer concentration at time = t, $q\alpha = \nu$ where ν = apparent velocity inside well, α = borehole distortion factor (between 0.5 and 4; = 2 for an open well), t = time when the concentration is equal to C.

In practice either the radial flow solution or the parallel plate model is used to estimate the cross-sectional area A (Novakowski *et al.*, 1998): For the radial flow model:

$$A = \pi r_w b \qquad (6)$$

Where: r_W = well radius, b = the length of the tested section in the borehole.

For the parallel plate model:

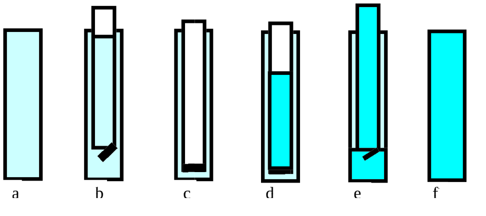

Figure 3 *Steps in carrying out the solute injection; (a) Borehole with water, (b) Insertion of trigger tube with valve open, (c) Trigger tube assembly with valve closed and water pumped out. (d) Solute filled into trigger tube assembly with valve closed. (e) Trigger tube assembly with valve opened, being withdrawn. (f) Borehole now filled with homogeneously premixed solute (trigger tube withdrawn). Only the saturated section of borehole is shown.*

$$A = \pi r_w (2b) \quad (7)$$

Where: 2b = equivalent aperture of the fracture rock.

Natural flow velocity

The natural flow velocity is given by:

$$V = x/t \quad (8)$$

Where: x = distance of observation well UO7 from test well UO5, t = is the time taken for the tracer to travel from test well to observation well.

$$V = q\alpha \quad (9)$$

Where: q is the Darcy velocity which is equal to V when α =1 (parallel plate model for fracture has porosity as 1 at the fracture).

The results for a point dilution test on borehole UO5 and a natural gradient test on borehole UO5/UO7 showed that the solute was mixed to the desired EC within a minute of withdrawal of the trigger tube assembly from the borehole. The data from the TLC probe in the passive natural gradient test were plotted on an x-y scatter diagram (Fig4); this shows the arrival of the peak pulse of EC 82 min after the release of the tracer (solute) in UO5. Using Eq. (8), a natural flow velocity of 123 m/d was determined. The data from the multi-parameter probe for the point dilution test in borehole UO5 was analysed using Eq. (5) in excel SOLVER, from which effective porosity 0.033 (3.3%); Darcy velocity 4.06 m/d and seepage velocity 122.89 m/d were calculated. From these results, the natural flow velocity calculated from the natural gradient test (123 m/d) and the seepage velocity of calculated from the point dilution test (122.89 m/d) were found to be equal, which shows that the trigger-tube test results are accurate. In comparison, results obtained for the same fracture at 21 m, from tests carried out by Van Tonder *et al.* (2000) using the effective porosity but different values for Pump-mixing mechanism, give the same value (0.03) for seepage velocity and Darcy velocity using radial convergence tests and injection withdrawal tests.

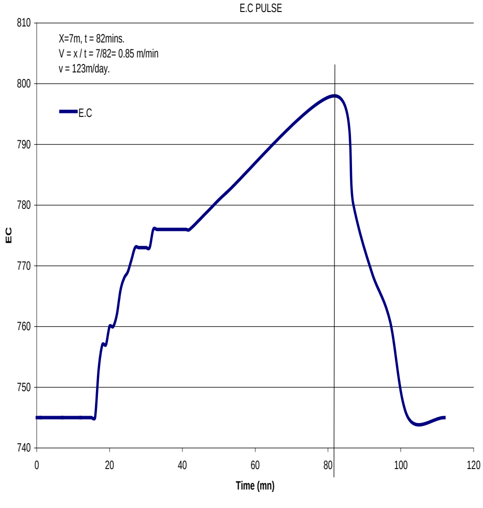

Figure 4 *EC pulse of natural gradient test using triggers tube; Note arrival time of 82 minutes at UO7.*

Comparing the results from tests carried out on the UFS campus test site using the trigger-tube to those gathered over a number of years by other researchers using the pump-mixing mechanism, it is evident that the total time for set-up and introduction of tracer is shorter when using the trigger-tube than when using the other methods. When using the trigger-tube the smoothness of the plotted data is better (Fig. 5). The calculated seepage velocity and natural velocity are equal when using the trigger-tube but not when using other methods.

At the test site, groundwater velocities in the larger fractures are high (hundreds of meters per day) and overall time taken for test is relatively short (tens of minutes). When using the method of pumping and mixing at the surface (Lamontagne *et al.*, 2002), the injection time is long compared to the overall time needed for the experiments. Thus it is difficult to get good data and accurate results from the pump-mixing method.

Conclusion

- From the results of the field tests it was concluded that the trigger-tube apparatus and test method for the mixing of solutes for injection tests in wells was successful in satisfying the 3 most important assumptions on which the point dilution test, single well injection withdrawal test, natural gradient test and forced gradient test are based, namely:
- Solutes were injected as well mixed slugs
- Introduction of solute by the trigger-tube does not increase the rate at which the tracer moves out of the well
- The injection time is short compared to the overall length of time required to carry out the whole experiment

Thus, a very useful apparatus and method for carrying out field tests that involve the injection of homogeneously mixed tracers/solutes in tests wells has been developed, which is user-friendly, cost-effective and accurate.

Use of the trigger-tuber apparatus has the following advantages over use of the pump-mixing mechanism:

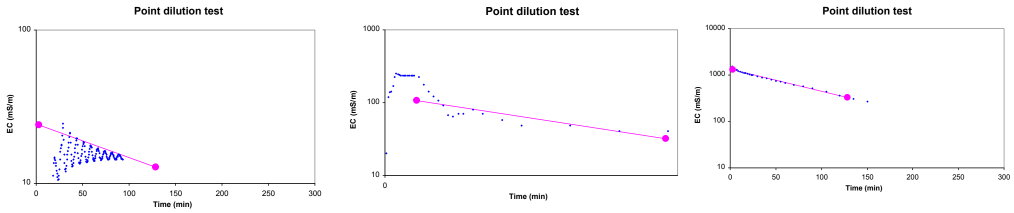

Figure 5 *Results of tracer tests from: Trigger tube (c) pump mixing methods (a) Van Wyk (1998) & (b) Van der Merwe (2008). Note the linear data points in (c) and oscillating data points in (a & b) due to the effect of pumping mixing.*

- No perturbation of well since there is no pumping in the well
- A specialised pump (peristaltic, etc.) is not required
- Isolation of test section or use of packers is not necessary
- No recirculation of borehole water which can affect the rate of tracer entry into the test well
- Better control of solute concentration (predetermined)
- No mechanism for mixing of solute down hole since the solute is more homogenously premixed
- The whole length of the borehole can be tested at once
- This test method uses few instruments and as such is quicker to set up and carry out
- The solute is released at once (instantaneously)
- Simple equipment to transport and handle
- Economical, as the trigger-tube is inexpensive to construct
- Accurate data acquisition

Disadvantages of the trigger-tube apparatus are as follows: The pipes for the trigger-tube assembly are bulky to carry for very deep boreholes. Also, there is a hazard during the transition between emptying the trigger-tube and filling it with a tracer if the tube assembly is not securely attached; the empty tube becomes buoyant with a tremendous lifting force.

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References

Botha JF, Verwey JP, Van Der Voort I, Vivier JJP, Colliston WP AND Loock JC (1998) Karoo aquifers; their geology, geometry and physical behaviour. WRC report no. 487/1/98. Water research Commission, Pretoria, South Africa

Devlin JF (2002) Groundwater velocity probe US patent 6393925.

Drost W, Klotz D, Koch A, Moser H, Neumaier F and Rauert W (1968) Point dilution methods for investigating groundwater flow by means of radio isotopes, Water resour. res. 4 125—146.

Freeze RA and Cherry JA (1979) Groundwater, Prentice-hall Englewood Cliff Inc. NJ. 604 pp

Labaky W, Devlin JF AND Gilham RW (2007) Probe for measuring groundwater velocity at the centimetre scale. Environ. Sci. Technol. 41 (24) 8453—8458

Lamontagne S, Dighton J and Ullman W (2002) Estimation of groundwater velocity in riparian zones using point dilution tests. CSIRO Land and Water technical report 14/02, Adelaide CSIRO-Australia

Neretnieks I (2007) Single well injection withdrawal tests (SWIW) in fractured rock. Some aspects on interpretation

skb rapport r-07—54 Svensk Kärnbränslehanterin (Swedish Nuclear Waste Co.) Ab, Stockholm.

Novakowski KS, Lapcevic PA, Voralek J and Sudicky EA (1998) A note on a method for measuring the transport properties of a formation using a single well. water resour. res. 34 (5) 1351—1356.

Van der Merwe CJ (2008) Hydraulic assessment of low-yield boreholes in fractured rock aquifers, M.Sc. thesis, University of the Free State South Africa

Van Tonder GJ, Botha JF, Chiang W-H, Kunstmann H and Xu Y (2001) Estimation of the sustainable yields of boreholes in fractured rock formations, J. Hydrology 241 70—90

Van Wyk B, DE Lange F, Xu Y, Van Tonder GJ and Chiang W-H (2001) Utilization of tracer experiments for the development of rural water supply management strategies for secondary aquifers, WRC report no. 733/1/01. Water Research Commission, Pretoria South Africa

Van Wyk AE (1998) Tracer experiments in fractured rock aquifers. M.Sc. thesis, University of the Free State, South Africa (unpublished)

Wolkersdorfer C (2008) Water management at abandoned flooded underground mines, Springer, Heidelberg, 438pp