Technical Note: T20-2

MEASURING SOIL PERMEABILITY:
Observations in field and laboratory methods

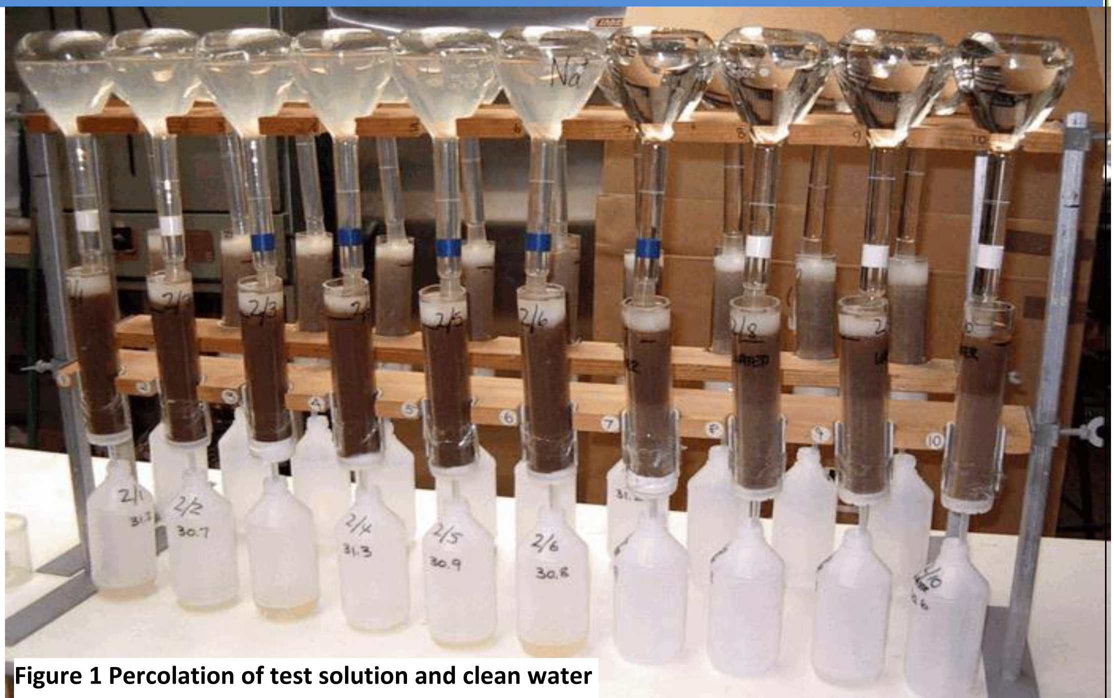

Figure 1 Percolation of test solution and clean water

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1. Introduction

Water and air move into and through soil in all directions, some gases and water vapour are emitted to the atmosphere in an environment of solids, liquids and gases – the soil profile. Water moves into and through soil, often at different rates for a variety of reasons, physical, chemical and biological. The water in soil provides the essential component of life to plants and soil fauna alike, as well as acting as a storage and drainage mechanism. The complexities of water storage and movement are often misunderstood and even difficult to measure, but of what we do know, there are some components we can measure and make informed decisions about their application to on-site wastewater issues.

The reasons for attempting to measure the movement of water through soil may be many and varied. Simply throwing a bucket of water over a patch of soil and recording the time for all the water to disappear off the surface may give a measurable rate of *infiltration* – the rate of movement of water into the soil. A more scientific approach may be to construct a 1 m x 1 m area edged with something like plastic garden edging, to confine the water to that 1 m^2 area. The carefully, but quickly, pour 10 L water into that space, equivalent to 10 mm depth of water. Using a stop watch, accurately record the time taken for all the water to disappear, that is infiltrate the soil. Now repeat the process and compare the times. Can you explain the difference? Was the first rate faster than the second, or vice versa? We can keep repeating this routine and observe the differences. That's exactly what the following methods were developed to measure, although some measurements were under-estimating the movement of water into and though the soil. Let's keep open the possibility that what we measure is not what we think we have measured.

2. Measuring techniques

Various methods have been developed to measure the rate at which water enters or passes through the soil. In-field methods are assumed to better represent, are more 'accurate' approach to the task, while laboratory measurements may be more 'precise'. Can we have both accuracy and precision when the soil landscape changes so significantly from one location to another in relation to the soil profile, or pathways for water movement in the soil?

2.1 Percolation Test Calculations

A simple test was developed by Henry Ryon in Chicago (van de Graaff et al., 2007) in about 1926 to estimate the 'percolation' of water in soil in relation to the movement of wastewater. Initially Ryon used a 1 foot x 1 foot (305 mm x 305 mm) square hole hand dug into the soil to the depth proposed for the bottom of the trench (drainfield). Water was poured into the soil and allowed to equilibrate overnight. The following day, water was poured into the hole to a depth of about 6 in. (150 mm) and the time taken for the water level to drop one inch (25 mm) was measured. Over the years, the square hole became a 1 foot (305 mm) diameter round hole, excavated with a post hole digger. Then a four inch (100 mm) hand auger was used or perhaps a three inch (75 mm) auger. All the time relating to a drop in water level of one inch, irrespective of the size of the hole or the soil moisture after equilibration, although assuming saturation. It was assumed that water only flowed down through the bottom of the hole – we'll get to this 'belief' later. After the 1950's some changes were made in USA to Ryon's original calculation because of differences in domestic wastewater chemistry and soils different to Ryon's test soil. The 'percolation test' became the acceptable method, as was required by NSW Health until about 1990. What changed over this period was the relationship of the bottom area to the area of the wetted sidewalls. The wastewater chemistry has also changed over the period, particularly with respect to production rate (litres per person per day (L/p.day)) and use of automatic washing machines and modern laundry detergents. Read interesting developments of Ryon's percolation test by conducting an internet search – most fascinating.

For a depth of six inches (150 mm) the ratio of the wetted sidewall to the area of the bottom changes significantly with a decrease in the hole's diameter, as shown in Table 1. The wetted sidewall area, to a depth of 150 mm, in the 100 mm diameter hole is six times the bottom area. To state that the sidewall area is ignored in calculation of soil permeability (AS/NZS 1547:2012, Cl 4.1 page 143) disputes these simple calculations of surfaces exposed to the water. The combined wetted sidewalls and the bottom area are seven times larger in the original test than in a 75 mm auger hole. The 'percolation test' as it is known cannot be used to derive a bottom area only relationship to soil permeability.

Table 1. Relationship of bottom area to sidewall area for 150 mm depth changes with hole dimensions.

Dimensions of test hole	Bottom area (m^2)	Wetted sidewall area (m^2)	Ratio sidewall to bottom areas	Combined bottom and sidewall area(m^2)
1 foot x 1 foot	0.093	0.183	2:1	0.276
1foot (305 mm) diameter	0.073	0.144	2:1	0.213
4 in (100 mm) diameter	0.0079	0.047	6:1	0.055
3 in (75 mm) diameter	0.0044	0.035	8:1	0.039

That the 'percolation test' was performed with clean water raised other issues about interaction of effluent with difference sodium adsorption ratios (SAR), soils with different exchangeable sodium percentages (ESP) leading to soil dispersion, or even the formation of clogging layers from the build-up of a biological ooze at the soil/effluent interface. An effectively loaded trench has only minimal clogging layer as when the water level falls, the build-up of ooze dries and sloths off.

A further question arises as to the depth of testing for the ‘percolation test’. As shown in Figure 2, the different coloured horizons suggest different soil horizons with possible different rates of permeability related to bulk density, soil structure, stability of the soil peds, or large or small pores or spaces. Do we only investigate the soil horizon into which the water will be discharge, as at 450 mm deep for a trench, or 100 mm deep for sub-surface irrigation? Or, do we need to understand any limitation that underlying horizons may play in moving water deeper into the profile.

Figure 2 shows the profile excavated to 600 mm using a 100 mm Jarrett type auger, revealing several horizons. Which part of that profile do we expect will become the pathway for effluent into the soil? Do we only investigate the soil horizon into which the water will be discharge, as at 450 mm deep for a trench, or 100 mm deep for sub-surface irrigation? Or, do we need to understand any limitation that underlying horizons may play in moving water deeper into the profile? The same question keeps repeating – why do we need to know?

Two terms we need to understand:

Falling head permeameter – during the operation the head (depth) of water varies and may need to be topped up at various intervals, so that it is difficult to put a precise value to the operating head – it varies up and down.

Constant head permeameter operates by controlling the depth (head) of water impinging upon the sides and bottom of the hole by using a breathing tube to accurately level the depth of water, hence control the pressure head.

Of the two variants, the latter is more easily defined by an equation, such as Darcy’s Principle.

Figure 2 Soil exposed during excavation of auger hole, left to right

2.2 Double ring infiltrometer

From a simple single ring infiltrometer, where there is no control over the lateral spread of the percolating water, the double ring system, shown in Figures 3 and 4, offers some control over the lateral spread. The outer ring (B) accounts for the outward movement (D), assuming that the movement of water from the inner ring will be directly down (C). The fall in depth in the inner ring (A) over time can be used to calculate the ‘percolation rate’ in a surface soil. Only water movement in the inner ring (A) is monitored, while the outer ring (B) is ‘topped-up’ to maintain an equivalent depth with the inner during the measuring period to theoretically negate the bulge (D) in the water cone. The decrease in water depth is read off the rule placed in the inner ring. The fall of water is based upon a ‘falling head’ principle, where the time for a constant fall is measured. The device measures the ‘falling head’ of water over the soil.

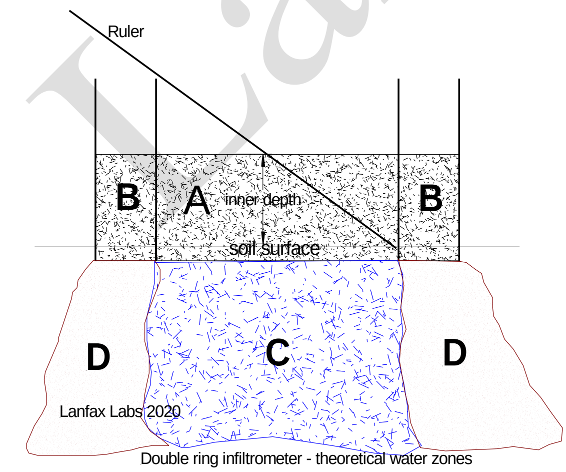

Figure 3 Side elevation of double ring

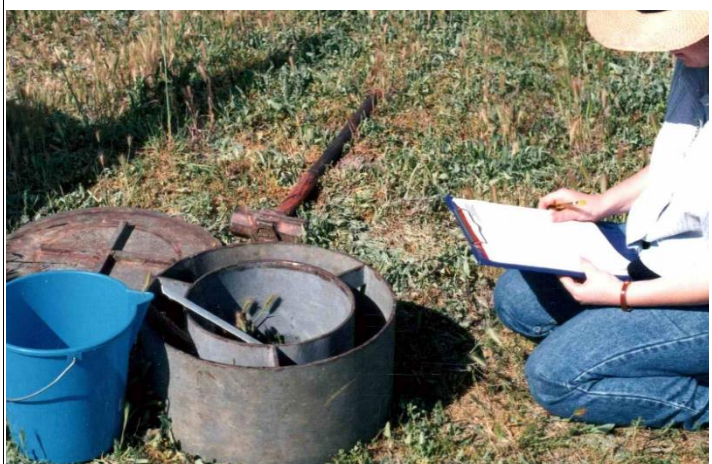

Figure 4 Double ring infiltrometer in field test

Grasses and weeds on the surface need to be trimmed with a pair of scissors as their shoots may be pathways for the water to enter the soil. Other litter needs to be carefully removed from the surface. When a uniform fall in the inner water level is reached, the measuring ceases. A soil sample is taken, from the inner ring, for estimating moisture content and void ratio. The purpose of this soil moisture measurement is unclear as the soil will be near saturation.

2.2 Constant head permeameters

The aim of any constant head permeameter is to allow the measurement of the 'steady state' of movement of water from the test hole into the soil body, both through the sidewalls and the bottom area, as shown in Figure 10.

An expensive Geulph permeameter (after University of Guelph, Canada) is a device that maintains a constant head of water in a hole at depth in the soil profile. A benefit over this permeameter is that the device can be used to measure the hydraulic conductivity at depths up to 750 mm within the soil profile. In practice, it takes up to two hours per measurement. If you are measuring two horizons, allow another two hours.

Other consultants have manufactured their own versions that simply replicate the 'constant head' based upon Darcy's Principle – which simply states that the discharge rate is proportional to the hydraulic head (depth of water) and the hydraulic conductivity (permeability) of the soil. The aim is to keep a constant depth of water in the excavation and measure the volume that enters the soil over time – a simple task with simple home-made equipment. The algorithms will vary with the unique dimensions of each system, but water leave the hole through the sidewalls and base.

The Cromer Permeameter, developed in Tasmania by Bill Cromer, is shown in Figures 5 and 6. The advantage of this device is that its large volume is more suited to soils that exhibit high rates of permeability, such as sands and sandy loams.

Figure 5 Cromer's permeameter

Figure 6 Cromer's permeameter in action

A hole is augered into the field site to a depth required for the task at hand. If required for the particular soil conditions the walls of the hole need to be lightly scarified with a wire brush to remove any smooth surface. Where domestic effluent is being discharged into the soil, the ideal depth would be to the bottom of the trench (450 mm).

But is testing with clean water the same as testing with septic tank effluent where the chemistry of the effluent interacts with the soil physical properties and a biological film develops on the soil interface over time? Perhaps you need to consider using a synthetic effluent, one without the bacteriological properties, to at least replicate the chemistry of the domestic effluent and any immediate influence the effluent would have on the soil.

In New Zealand, agricultural engineer Andrew Dakers of Christchurch has a similar device that permits the measurement of the loss of water into the auger hole using a 'constant head' device. The depth of the water level in the hole is adjustable, as shown by the adjustable base in Figure 7.

The constant head permeameter has many variants that use a breather tube to maintain water at a pre-determined height.

In Figure 7, a vacuum pump is being used to remove excess water in the hole so the measurement can commence at the depth set by the device. The fall in water level in the clear plastic tube is monitored against time and used to calculate the hydraulic conductivity.

As with similar devices, the depth of water in the hole is maintained at a constant depth, hence a 'constant head permeameter' that can be equated to Darcy's formula.

The three wings and screws maintain the tube in a vertical orientation.

Figure 7 Andrew Dakers with home-made permeameter

The Australian Standard (AS/NZS 1547:2012) provides details of a constant head permeameter developed by Dr Robert van de Graaff, a professional soil scientist of Melbourne.

Figure 8 Dr Robert van de Graaff with home-made permeameter

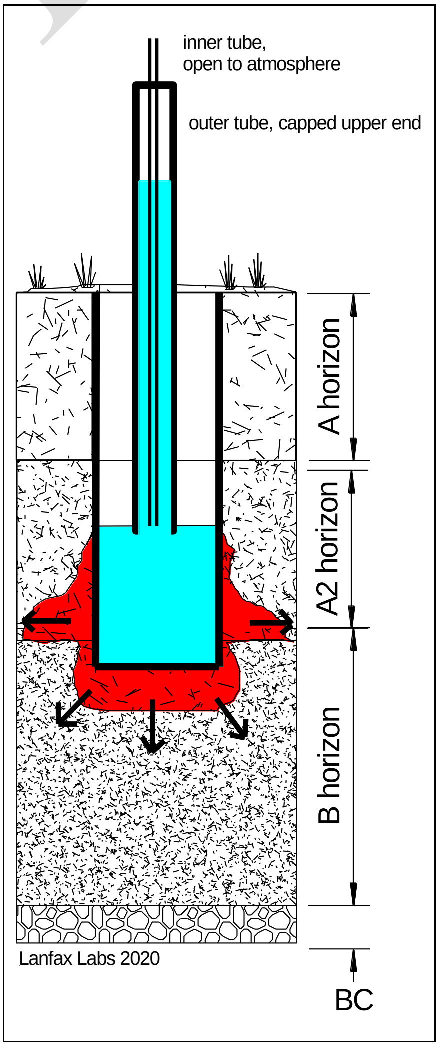

Figure 9 Diagram of permeameter in operation

Note that in Figure 9, the discontinuity in the water permeating into the soil (red) is caused by the textural difference between the A2 horizon and the finer textured B horizon (more clayey).

The Standard (AS/NZS 1547:2012, Appendix G, page 112) provides details to construct and operate the device with an equation to calculate the permeability.

Dr van de Graaff runs six of these at a time to account for in-field variability. The device in his hand (Figure 8) is used to remove excess water from the hole so that the bubbling starts immediately, noting that the bubbles in the tube indicate the loss of water as it enters the surrounding soil. The benefit of operating more than one device is that the results can be statistically analysed, rather than having only one set of results and not knowing site variability.

It is recommended that the water being use as the test solution has a small amount of calcium chloride, or sodium chloride (common salt) to increase the electrical conductivity (EC) to mimic domestic wastewater. Refer to http://lanfaxlabs.com.au/sodium_adsorption_ratio.htm for a discussion about threshold electrolyte concentration with respect to a more suitable cocktail of calcium, magnesium, potassium and sodium ions to better mimic an artificial domestic effluent with respect to EC and SAR.

The whole process to measure the permeability in the field may take at least two hours with regular recording of the fall in water level in the above ground plastic tube. It is only after the soil equilibrates to the water that a more uniform ‘steady state’ permeability will be measured. Figure 10 shows how the permeability decreases to a constant state after time as all the capillaries and void spaces are filled and saturated hydraulic conductivity is the operative function.

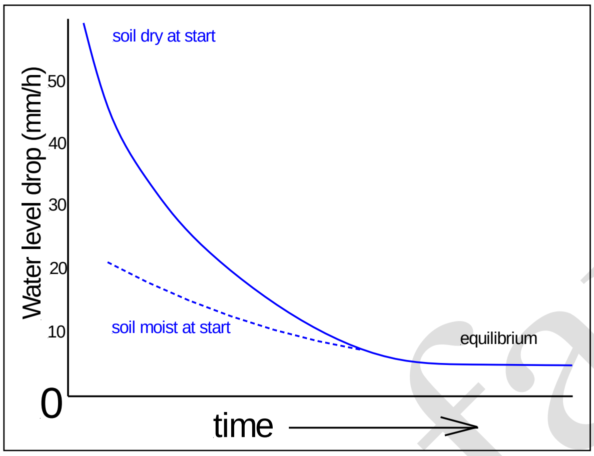

Figure 10 Drop in water level over test period

Depending upon the soil moisture at the start of the test, the initial period of ‘wetting up’ the soil macropores and capillaries is in response to forces of attraction. It may take some time and the rate of water movement may seem large.

These early values are not really important so that accurate recording over the first half hour may be less intense unless one is interested in the early part of the graph in Figure 10.

Towards the end of the test it may be easier to record the time for a uniform fall interval rather one based on time. One requirement for an accurate assessment is that the water is not allowed to run out. There must be a tried and proven method for topping-up the reservoir without disturbing the water level in the hole.

2.4 Disc permeameter

The Australian CSIRO (1988) developed a disc permeameter based upon Darcy’s principle that utilises a large area for percolation of the test solution, as shown in Figure 9. A stainless steel ring is hammered into the soil (see hammer plate and hammer to left in photo) to a depth of about 20 mm, and set level. Three wing nuts on the edge of the plastic plate support the device and are set so that the underneath of the disc is about 10-15 mm above the soil. The two upright tubes are filled to capacity by placing in plastic dish filled with the testing solution and using a vacuum pump extracting the air at the stop cock atop the tube. A very fine mesh in the base plate hold the columns full for sufficient time to move the device from the dish to the disc. The smaller tube is released for the water to fill the space, without air pockets, between the soil and the bottom of the plastic plate. Cohesive forces will pull the water from the longer tube and with the aid of the tape measure on the side of the tube, the fall in water level can be accurately measured over time. Equations provided by CSIRO are used to convert the fall of water into a saturated hydraulic conductivity (Ksat) rate.

Where the water measurement is required for a lower horizon, an excavation at least 400 mm square, to the desired depth needs to be made to set the device up in the same manner as for the surface. A stepped trench provides a suitable excavation to undertake measurements at selected depths. The disc permeameter is not as easy to use for sub-surface horizons as the constant head devices mentioned above.

Figure 11 Disc permeameter in action

The permeameter consists of two erect tube, each with a ball valve at the top to be used when filling the tube under suction.

The steel ring is hammered into the ground, about 20 mm, using the disc and hammer shown in the lower right in Figure 11. The permeameter is set up so that a gap of about 10-15 mm exists between the bottom of the permeameter plate and the surface of the soil. Three screws assist with adjusting the depth and the vertical plane of the tube.

Water in the smaller column is released to fill the void between the plate and the soil and form a common surface with the water in the larger column. As the water percolates into the soil, water is drawn from the larger tube, observed as bubbles rising through the column.

Over time the rate of bubbling will reduce as the saturated hydraulic conductivity (Ksat) of the soil is reached. Recording the fall in the water column against time permits calculations of the Ksat value.

The procedure is replicated as required, with not less than six readings per soil location. The process can then be repeated using solutions of differing SAR and EC as required.

2.5 Percolation testing

The set-up shown in Figure 1 is used to determine the permeability of various soil textures with respect to clean water and wastewater from a sewage treatment works, typical of domestic wastewater. The six tubes, numbered from the left, were treated with the wastewater while tubes 7-10 were treated with clean water (rainwater in this instance). The difference in the water was mostly related to SAR, EC and pH. The soil in each column was from the same sample batch, sieved to minus 2 mm and compacted to approximately the same bulk density.

The aim of the trial was to relate any difference in percolation rate with water quality with respect to clean water (rain) or simulated effluent or other industrial/agricultural waters. The trial was repeated for other soil types, as required, and the variation in total volume of leachate collected and the colour and/or turbidity of the leachate assessed.

For the particular soil used in Figure 1, it can be seen that the 'dirty water' percolate varied within the six bottles as small variations in the soil – compaction, void spaces as drainage pathways – alter the percolation rate. In all cases the first six columns had become saturated and leaked into the bottles. For the clean water, dispersion and blocking of soil voids slowed the rate of percolation quite significantly. At the time the photo was taken, about six hours after the start, the wetting front for the clean water was less than half way down the soil column. Clearly, one immediate observation suggests that the soil drains relatively freely with 'dirty water' but becomes very slowly permeable to clean water. When run over several days to a week, the differences may become more obvious.

Other soils, with different chemical characteristics, may behave completely opposite to Figure 1 as the water quality produces different effects within the soil column. Note, however, that because the soil is packed in a column, the performance of the column is by gravity flow only, there is no opportunity for sideways movement as would occur in a natural soil body. The measurement is strictly in accordance with Darcy's Principle.

2.6 Undisturbed cores

As part of my Ph.D. (Patterson, 1994) I took undisturbed cores using an hydraulic push rod soil sampler mounted to a vehicle. Soil cores of 38 mm diameter were extracted from several depths as, appropriate. Sections about 100 mm long were broken from longer core sections. Each core was individually placed in a plastic sheath (heat shrink plastic tube), as shown in Figure 12, sitting on a metal tube around which to shrink a drainage funnel (bottom) and a wooden peg around which to form the upper reservoir. The length of each undisturbed core varied to avoid fracture lines in the core.

Using aqueous solutions of various EC and SAR ratings, each tube was subjected to the constant head, the upturned bottle, feeding the upper reservoir and each equilibration ran for about a week.

Figure 12 Heat-shrink wrap with reservoir and funnel

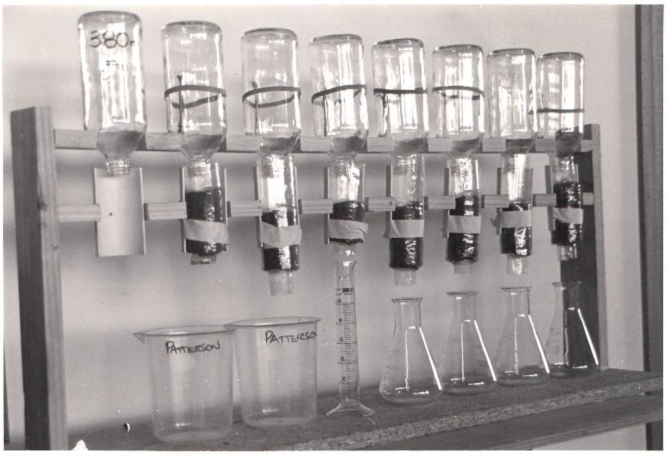

Figure 13 Individual undisturbed cores with constant head devices

Statistical analysis was performed on the results to determine the saturated hydraulic conductivity for each soil texture set measured as part of the project. The benefit of this arrangement is that long equilibrating periods can be employed in a laboratory environment. The downside is that obtaining the soil cores is dependent on the ideal soil moisture at time of sampling and being able to obtain a suitable core for wrapping. The percolation rate (Ksat) is calculated using Darcy's formula.

When the experiment is run on various textured soil, for surface and B-horizon samples and several SAR equilibrating solutions, the interactions of effluent chemistry and soil properties is likely to become evident. Figure 14 shows the outcome of a heavy black clay (Vertosol) with 10 replicates for each of five treatments. Notice that as the SAR increases the saturated hydraulic conductivity decreases. As each soil behaves differently, it is not possible to simply relate soil texture to Ksat for increasing SAR. Thus, much of the tabulated data in the Standard (AS/NZS 1547:2012, Tables L1 and M1) would be difficult to validate with behaviour under various domestic effluent quality, even for similar soil textures from different landscape. The 'smoothing' of the data ignores the in-field and landscape variabilities.

2.7 Percolation demonstration

Figure 14 was used to demonstrate that depending upon the soil texture and other soil properties, the percolation rate may vary unpredictably. The demonstration set up five soils of different texture, each paired for treatment with a clean water and sodium rich water (marked with red Na^+). The soils were prepared by air-drying, crushing and sieving to minus 2 mm, then repacking in the plastic tubes (50 mL syringes) at similar bulk densities. A full 250 mL bottle was upended into the tube to provide a 'constant head' over the soil column of about 40 mm. Refer to previous discussion about constant head versus falling head permeameters.

The demonstration was allowed to continue over about two hours before assessing the outcomes. While this demonstration mimics the set up for the undisturbed cores, it is extremely difficult to replicate actual soil pore configuration as the soil has been dried and sieved prior to column packing.

Firstly, notice that some of the collection vessels (250 mL containers) are almost full. These columns have passed all the 250 mL through the sample – columns 1,2,3,4,7 and 10. Column 6 and 9 passed very little through the soil. Notice also the difference in volume for the paired 5 & 6, 7 & 8 and 9 & 10 – same soil different equilibrating chemistry.

Secondly, notice the colour/turbidity difference between the paired columns and with each paired column.

In assessing the demonstration, the leachates for columns 1 & 2 are clear and of similar volume suggesting very little difference between the different solutions. Columns 3 & 4 indicate that both the clean water and the sodium rich solution flushed organic colloids from the soil. These colloids are most likely plant nutrients and organics. Columns 5 & 6 also flushed colour but column 6 had a very slow rate. Columns 7 was slightly tinged with soil colloids (turbidity) that was not obvious in column 8, but the latter had passed less than a third of the percolate. Columns 9 & 10 were clear, but very little water passed through column 9, whereas the sodium rich solution passed quickly.

This demonstration provides some insight into the complexities of measuring percolation rate in water compared to using a synthetic wastewater, and not all soils performed the same way with respect to percolation rate. The values used in such a demonstration are simply to guide one's understanding of the different and sometime opposite behaviour of re-packed soils. Do not attempt to transfer these outcomes to behaviour in the field.

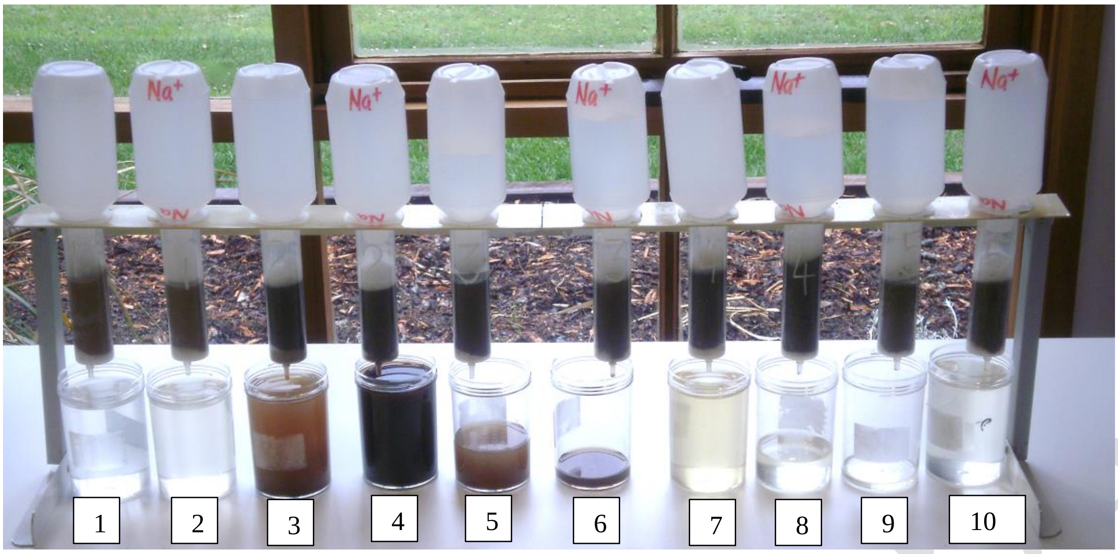

Figure 14 Comparison of percolation rate for sodium rich water to clean water for five soils

3. Comparisons of Field Permeability Rates

What has been discussed so far is that some field methods can be used to evaluate a saturated hydraulic conductivity (Ksat) of soil in the field. The 'percolation test' offers no such practical application as there is almost no control over the ratio of wetted perimeter to the diameter of the hole and the depth of the 'falling head'. Time has come for all current use of this test to be permanently rejected.

Similarly, the double ring does not provide any confidence that the calculated hydraulic conductivity bears any relationship to the movement of water, over the longer test period, to watching paint dry on pickets. The equipment is heavy, the measurements tedious and the mathematical calculations dubious.

The real 'in-field' assessment of saturated hydraulic conductivity using constant head permeameters, as shown by the three simple devices, provides a reliable method. The use of a water more closely resembling domestic wastewater, a simulated effluent, can be used to better replicate what will happens in on-site systems. Each of the three systems works on Darcy's principle of maintaining a constant head in a hole of known dimensions, over sufficient time that the 'steady state' saturated condition is being measured.

The CSIRO's disc permeameter, measuring saturated hydraulic conductivity, can we thwarted by ant holes, decayed root channels and void spaces between soil aggregates that are not recognized until the end of the two hour operation. Where these annoyances are avoided, the results from the use of the disc permeameter has reasonable replication, Again, the measurements can be used with synthetic effluent to better reflect the influence of SAR and EC in the soil.

Obtaining undisturbed cores for laboratory measurement of Darcy's principle is time consuming in field work as site conditions make obtaining an ideal core difficult to predict, and impossible in soils with low moisture. The small diameter of the cores lead to significant errors when extrapolating to large area estimates. The distinct advantage is that the testing regime can be run over many days or weeks as required in the comfort of the laboratory.

Figure 15 shows the type of results obtained from the laboratory study (Patterson, 1994) where the 10 replicates have been re-arranged to make observed differences easier to understand. It is clear from Figure 15 that as the SAR and EC of the percolating solution increases, there is an overall loss of Ksat permeability. Other soil textures responded in different ways, with low Ksat under clean water (SAR 0) and an increase with SAR 3. In other words, not all soils of the same texture responded in the same manner, dismissing the premise that long term acceptance rates simply decrease with increasing clay content, the inference behind AS/NZS 1547:2012.

Demonstrations provide valuable teaching tools, where the interactions of clean water and simulated effluent present similar and opposing outcomes in a short time, in the classroom situation. That all soils perform the same under a constant head over the same time can be dismissed quite quickly. That all soils perform in a predictable manner under simulated effluent compared to clean water often draws great interest and suggests that what is professed to be fact about soil permeability may not be so easily demonstrated.

A range of statistical methods can be employed to determine the number of replicates required to achieve an outcome with a 50% or 90% confidence limit. However, such discussions are beyond the scope of this paper. Suffice to say that even the in-field constant head devices need at least six replicates to have even a 75% confidence level, other methods may require several tens of replicates to even match a 'guess'.

One fact is clear, that testing with 'clean water' is a useless exercise compared with using a synthetic effluent to better mimic the effects of effluent chemistry on soil properties.

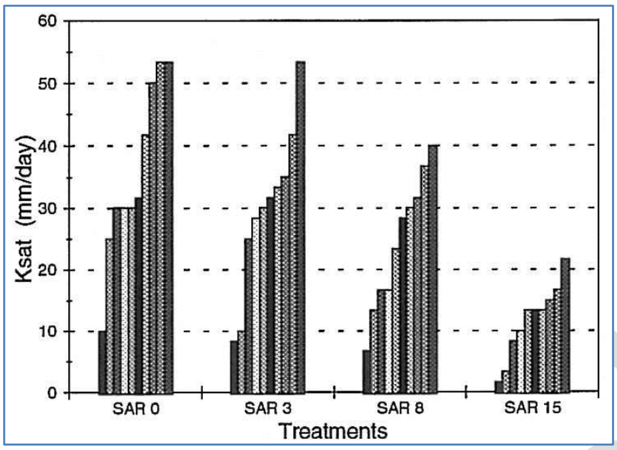

Figure 15 Ranked Ksat measurement for Vertosol (Patterson, 1994)

4. Conclusion

The measurement of soil permeability, whether unsaturated or saturated hydraulic conductivity, as has been outlined in the sections above, is not as easy as some regulators have come to believe. If we were to believe in statistics then we would only ever measure anything once, then we would know all there was to be known and no fear of any contrary outcome. Fortunately, science teaches that to test an hypothesis allows us to sort out fact from fiction. The 'percolation test' following Ryon's example never really sorted out the fact, but it did give us a 'number' that could be manipulated to give what looked like a scientific outcome. That premise has since been discredited, even though some regulators follow this simplistic past.

Methods that employ repetition of measurement provide some statistically valid 'estimate' of permeability. The word 'estimate' is used because for any number of measurements on a soil profile, significant in-field variability may compromise a rational outcome. Take for example the ant hole under the disc permeameter, one I experienced on many occasions. Or the cracks in sub-soil that consumed much of the percolating water that was being so carefully monitored over a two hour period. We need to question outliers in the data we generate and ask the hard questions about the accuracy and precision of our own work. We need to understand the tools that we use and their shortcomings or positive attributes.

The methods outlined above provide a range of simple tools, many can be home-made, to better understand the complexities of water movement into and through the soil. We can use some of these tools to demonstrate the influence of wastewater chemistry, soil bulk density, soil texture, soil structure, sodicity and other valid variables in the pursuit of a reliable numerical value. But that's all it is; a reliable numerical value, not the definitive must-be-believed absolute proven value. We can also use the experience of in-field measurements to test the validity of using the association between soil texture and permeability to validate or modify the values proffered by government guidelines or national standards. One size fits all is not the way of the soil landscape.

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