1991

Manual of field techniques in hydrology

Department of Agriculture, Western Australia. Division of Resource Management

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MANUAL OF FIELD TECHNIQUES IN HYDROLOGY

Compiled by officers of the Division of Resource Management, Department of Agriculture, Western Australia

November 1991

DEPARTMENT OF AGRICULTURE
WESTERN AUSTRALIA
MANUAL OF FIELD TECHNIQUES IN HYDROLOGY

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First compiled in 1990
PREFACE

This manual was compiled by officers of the Division of Resource Management for the following reasons:

1. Many of the field techniques we use come from publications which are scattered throughout the literature. Often the techniques are only described briefly and there are no worked examples. Some techniques (notably geophysical techniques) have been developed within the Division but are not well documented.

2. We need detailed explanations of techniques to ensure uniformity across the Division and to encourage the collection of quantitative data.

3. The rapid turnover in staff means that individuals who have acquired skills in certain areas sometimes leave before their skills are passed on to new workers.

4. Some techniques have been adapted to account for special conditions which occur in Western Australia. We need to continually review and communicate these adaptions.

The manual will be updated whenever new techniques are developed, when adaptations are made to old techniques and when inaccuracies or unclear areas are identified.

If you have only suggested changes, contact:

The Manager
Catchment Hydrology Group
Division of Resource Management
Western Australian Department of Agriculture
ALBANY 6330

ACKNOWLEDGEMENTS

The followings people are gratefully acknowledged for their helpful comments and assistance in compiling this manual, Richard George, M. Howes, D.J. McFarlane, J. McFarlane and A.T. Ryder.

The contribution of many officers in the Division of resource management and Dave Tenant from Division of Plant Industries is also gratefully acknowledged.
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SECTION 1: RAINFALL AND EVAPORATION

1.1 STORAGE RAINGAUGES

1. WHAT IS MEASURED?
Amount of rainfall between visits.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:
Pluviometers (Section 1.2).

3. PREVIOUS USES OF THE METHOD:
Used in all catchment hydrology studies (particularly water balance studies) as well as trials where estimates of rainfall are needed.

The Bureau of Meteorology have standard raingauges at all their stations and recording sites throughout Australia.

4. COST/AVAILABILITY OF EQUIPMENT:
The standard raingauge has a 203 mm diameter rim (8 inch). A galvanized iron gauge with a plastic measuring cylinder costs $150 (1987). Available from:

Selby Scientific  
21 Glassford Road  
KEWDALE WA 6105  
Phone: (09) 353 3577

Hinco Engineering  
309 Hay Street  
SÜBIACO WA 6008  
Phone: (09) 381 4477

Other raingauges include a 127 mm (5 inch) plastic raingauge, made by Nylex for $30 (1987). Available from hardware stores such as Bunnings.

5. PRINCIPLES OF METHOD:
The funnel of the gauge collects a representative sample of rainfall which is stored in the measuring cylinder. It is essential that the funnel has a deep and sharp rim to limit rain splashing out.

6. FIELD PROCEDURE:
The number of gauges required depends upon how accurately rainfall needs to be measured. In a water balance study on a catchment, a minimum of two but preferably three or more gauges are required. One raingauge per hectare is a sampling density of $3 \times 10^{-6} \text{ m}^2/\text{m}^2$.

Installing gauges is simple. The gauge can be left on the ground surface and fixed in a vertical position or dug into the soil so that its rim is level with the ground surface. The gauge may need to be protected from stock.

Site the gauge to take account of rim exposure, topography, rim height and wind effects.
If the rim is 0.3 m above ground level rainfall can be underestimated by up to 3.2% compared with a raingauge at ground level (Green 1970). The following percentage errors were estimated by Kurtyka (1953):

<table>
<thead>
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<th>Percentage</th>
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<tr>
<td>Evaporation</td>
<td>-1.0%</td>
</tr>
<tr>
<td>Adhesion</td>
<td>-0.5%</td>
</tr>
<tr>
<td>Colour</td>
<td>-0.5%</td>
</tr>
<tr>
<td>Inclination</td>
<td>-0.5%</td>
</tr>
<tr>
<td>Splash</td>
<td>+1.0%</td>
</tr>
</tbody>
</table>

Subtotal: -1.5%

Wind: -5.0 to -80.0%

The greatest errors are caused by wind. A gauge with a rim height of 0.3 m may be deficient by 10% with a wind speed of 11 km/h, rising to 50% with a wind speed of 80 km/h (Wilson 1954).

7. SPECIAL PRECAUTIONS:

Gauges with their rim at ground level reduce the effects of wind dramatically. When installing a gauge at ground level, a splash guard is required to avoid rain splashing into the gauge from the ground. Guards are generally made from thin sheet metal. Figure 1 shows the dimensions needed for a 203 mm raingauge. It is a circular design and consists of 12 m x 50 x 0.4 mm strips wound and pushed into slots. The slots are cut into four equal lengths of 355 x 100 x 1.2 mm galvanized iron. A suitable size hole is dug and the rigid strip is pushed down to ground level so that the top of the raingauge and splashguard is flush with the ground. A drain is needed to remove water from the hole so that the raingauge does not float and cause errors.

If the raingauges are not read regularly, then light oil or another evaporation suppressant should be added to the measuring cylinder.

8. ANALYSIS OF RESULTS:

The measuring cylinders in the raingauges are calibrated in millimetres so no analyses are required.

9. ADDITIONAL COMMENTS:

Raingauges can be bought with smaller rim diameters; their size does not appear to affect accuracy. Raingauges are made from various materials. A plastic gauge may last 3 to 5 years, while a metal gauge with a glass cylinder may last more than 10 years.

10. REFERENCES:


Wilson, W.T. (1954). Discussion (Precipitation at Barrow, Alaska, greater than recorded, Black R.S.) Transactions American Geophysical Union 35.

11. MAIN CONTACT PERSONS/ORGANIZATIONS:

Bureau of Meteorology

Ian Laing, South Perth

Don McFarlane, Albany
1.2 PLUVIOMETERS

1. WHAT IS MEASURED?:
The intensity, duration and volume of rainfall.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:
The intensity of rainfall may be measured by the increase in weight or depth of rain received, or the time taken to fill self-emptying tipping buckets. Distrometers measure the energy of raindrop impacts, hitting a surface.

3. PREVIOUS USES OF THE METHOD:
Rainfall-runoff studies on catchments (all WAWA gauged catchments have pluviometers), erosion studies.

4. COST/AVAILABILITY OF EQUIPMENT:
Self-siphoning "Dines" float-operated pluviometers are available from Britain at a cost of approximately $2,000. A tipping bucket raingauge (0.2 or 0.5 mm tip) costs $455 (1988) from Monitor Sensors (Queensland) which can be attached to a Wesdata logger ($220, 1990 price) for continuous operation. Other types of older instruments with weighing mechanisms are also available.

5. PRINCIPLES OF METHOD:
"Dines" pluviometers record the rise in water level by marking a chart revolving once each day, or once each week (optional). After 25 mm of rain, the float trips a self-siphoning mechanism, which empties the container and returns the pen to the base of the chart, and the process is repeated.

Tipping-bucket recorders register the time of each tip. An electrical pulse is transmitted to the recorder each time the bucket tips. The time of each pulse is recorded in the logger's memory.

6. FIELD PROCEDURE:
The spring-driven chart drive on "Dines" pluviometers must be re-wound each week. It is desirable to change the chart of one-revolution-per-day records after each rain-day, in order to avoid the need to infer the date of each rainfall event from independent daily records when the chart is left unchanged for more than a day's rainfall. Re-zeroing by pouring water in the spout until the tilting siphon operates simultaneously checks the recorder's operation. The operation of tipping buckets should also be checked in the field, in order to ensure that the mechanism is working satisfactorily and that the appropriate signal is recorded.

7. SPECIAL PRECAUTIONS:
Insects may block the funnel or internal workings of pluviometers.

8. ANALYSIS OF RESULTS:
One-day "Dines" charts allow reasonable accuracy of resolution down to one-minute time intervals and approximately 0.2 mm depth intervals. The resolution of tipping bucket raingauges is determined by the volume-per-tip,
and the accuracy of time recording. Better accuracy can be achieved with tipping buckets than float or weighing-type recorders.

9. ADDITIONAL COMMENTS:

As for all instruments at remote locations, those which allow fault diagnosis and immediate repair in the field are less likely to cause lost data. The "Dines" Pluviograph is simple to repair while the data loggers for the tipping buckets are more complex.

10. REFERENCES:

Trade brochures.

11. MAIN CONTACT PERSONS:

Kevin Bligh, Jim Prince (Resource Management Division).
Water Authority.
Bureau of Meteorology.

Figure 1. A Tipping bucket rain gauge

Figure 2. Pluviometer, staff gauge, recorder and rain gauge
1.3 CLASS 'A' PAN EVAPORIMETER

1. **WHAT IS MEASURED?:**

The potential rate of evaporation in millimetres.

2. **ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:**

Floating pans (Section 1.4), Penman equation.

3. **PREVIOUS USES OF THE METHOD:**

Only used to measure daily evaporation. The Bureau of Meterology uses these pans exclusively and they are the standard technique throughout Australia.

4. **COST/AVAILABILITY OF EQUIPMENT:**

Commercial Class A pans can be purchased for about $1,000 (1990) from:

Hinco Engineering, 309 Hay Street, Subiaco. Phone (09) 244 2777

A local sheet metal worker could make the same for around $250. A plan with exact dimensions is available from Kim Burke, South Perth or the Bureau of Meteorology.

5. **PRINCIPLES OF METHOD:**

Wind, sunshine and rainfall combine to produce an effect on the water contained within the pan. In the case of wind and sunshine a loss is recorded i.e. evaporation. Rainfall adds to the water level.

A cage made of wire netting is kept over the top of the pan to prevent birds and animals from drinking the water.

6. **FIELD PROCEDURE:**

A Class A size pan is filled with water to a known point, usually a sharp pointed rod in the middle of the pan with a stilling well around it. This enables accurate refilling or emptying of the water to a constant level. Each day at the same time (e.g. 9.00 a.m), water is added or taken out of the pan. The volume of water must be recorded. This volume is then converted to millimetres and recorded as the daily evaporation.

Evaporation is expressed as positive when water is added and negative when water is taken out of the pan. A negative result means that rainfall exceeded evaporation on that day. If a raingauge is present on the site, the evaporation can be estimated by difference.

Evaporation need not be recorded daily; it can be expressed as a total amount over any time period.

7. **SPECIAL PRECAUTIONS:**

When installing a pan, make sure it is level.

Do not let the water level in the pan fall below the bench mark by more than approximately 50 mm between readings. The shallow water level becomes shaded and the water temperature can rise due to heating of the pan bottom.
The site should be representative of the area, do not avoid shading and sheltering from the wind if this is normal for the conditions being monitored.

8. **ANALYSIS OF RESULTS:**

If a bird cage is not used, the measured evaporation needs to be reduced by 7 per cent (Hoy and Stevens 1979), to account for shading effects of a bird cage. All evaporation figures are standardised to bird cage readings.

9. **ADDITIONAL COMMENTS:**

To obtain daily evaporation figures, you need to be at the site every day at the same time. This will be a drawback for many experiments. A compromise is to take readings only when you visit the site. A company which makes data loggers is looking at ways of measuring the small changes in water levels continuously. If successful, this could be the way to get daily evaporation figures without daily attention. Also, the Water Authority have developed a method of automatically measuring the water that needs to be added to bring the pan back to a reference level.

10. **REFERENCES:**


11. **MAIN CONTACT PERSONS:**

Kim Burke, South Perth
1.4 FLOATING PAN EVAPORIMETER

1. WHAT IS MEASURED?:

The potential rate of evaporation from water bodies in millimetres.

2. ALTERNATIVE METHODS OF ESTIMATION/MESUREMENT:

Pan evaporimeter. Penman equation with lake/pan factor.

3. PREVIOUS USES OF THE METHOD:

Measuring evaporation from water held in level banks and dams.

4. COST/AVAILABILITY OF EQUIPMENT:

Floating pans are not made commercially. Those that have been used have been made in the Department workshops. They are easy to make, with cost depending on the type of materials used.

The size of the pan and floats depends upon the size of the water body being measured. In the case of level banks, a 20 L metal drum, painted white and with its lid cut off was fitted with 3 sheep trough floats. A pointed rod is fastened to the bottom and was cut so that the pan had 5 cm freeboard (Figure 1). When placed in the water wires were connected to the bank and the floats were adjusted to maintain the freeboard and prevent water splashing into the pan.

A large diameter floating pan with radial vanes (to dissipate heat from the pan) has been used to estimate evaporation from a dam.

5. PRINCIPLES OF METHOD:

A floating pan works on the same principle as the pan evaporimeter (Section 1.3). The only difference is that it floats in the water body from which you want to measure evaporation. The advantage of this technique is the ability to keep the water in the pan as close to the real conditions as those in the water body being measured. Temperature, turbidity and wind effects are similar on both water surfaces, so evaporation is similar.

6. FIELD PROCEDURE:

The pan is filled with water from the water body to the level set by the top of the pointed rod. Adjust floats so that a reasonable amount of freeboard prevents water from splashing in. It is better to have too much freeboard than not enough, otherwise the pan may fill up with rain or waves and sink. Use posts and wire to keep the pan in one position. Make sure that it can rise and fall with the changing level of the water body.

After the initial setup, any water that needs to be added or taken away, must be measured and recorded with a volumetric cylinder. This can be done daily for daily evaporation or weekly for weekly readings.

7. SPECIAL PRECAUTIONS:

Ensure adequate freeboard to enable the pan to remain afloat if rainfall exceeds evaporation.
Cover the floating pan with wire netting to prevent birds and animals drinking.

8. ANALYSIS OF RESULTS:

Calculate the area of the opening of the pan in cm$^2$. Convert this to a volume by multiplying by 0.1 cm. The result is the volume of water that is equivalent to 1 mm evaporation.

Example

Diameter of a circular pan with parallel sides: 30 cm.
Area: $15 \times 15 \times 3.1429 = 707$ cm$^2$.
Volume: $707 \times 0.1 = 70.7$ mL.

Therefore every 70.7 mL water equals 1 mm evaporation.

It is now a simple division of the volume measured in the field by 70.7 to convert to evaporation in millimetres.

9. ADDITIONAL COMMENTS:

The period between measurements dictates the time over which evaporation occurred. If you want daily evaporation figures, you need to obtain a measurement every day at the same time.

Maintain a raingauge at the site to enable rainfall to be subtracted or added to evaporation.

10. MAIN CONTACT PERSONS:

Don McFarlane, Albany District Office.
Arjen Ryder, Albany District Office.

Figure 1. Cross-section of a 20L floating pan evaporimeter.
A floating pan evaporimeter
SECTION 2: RUNOFF

2.1 WEIRS

1. WHAT IS MEASURED?:

The flow rate and volume of water flowing in a defined channel. When fitted with rising stage or pumped sediment samples, soil loss can be measured.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:

Flumes (Section 2.2), tipping buckets, natural channel gauging (Section 2.3).

Peak flows can be estimated from crest gauges and by constant head velocity devices.

3. PREVIOUS USES OF THE METHOD:

Thirty degree V Notch weirs have been used to measure seepage flows in reverse bank seepage interceptor drains. Compound 30° and 120° V Notch weirs have been used to measure overland flows in seepage interceptor drains. Ninety degree V Notch weirs have been used to measure the amount of water being drained by deep open drains constructed with an excavator.

4. COST/AVAILABILITY OF EQUIPMENT:

Weirs are usually made to the requirements of the user. They can be made in the Department's workshops or by private enterprise. The cost depends on who does the job, what type of material is used (stainless steel or galvanized) and the thickness of the material. A 3,000 mm * 900 mm * 1.6 mm galvanized sheet costs about $100 (1990). Galvanized sheet in various thicknesses and cut to your size are available from:

- Stratco Cook St (cnr Bannister Rd)
- CANNING VALE WA 6155
- Phone: (09) 455 1911

- Sandovers Sheet and Coil
- 9 Hodgson Way
- KEWDALE WA 6105
- Phone: (09) 451 1177

5. PRINCIPLES OF METHOD:

Weirs come in many shapes and sizes. The type chosen will depend upon the estimated flow rates, the accuracy required and the shape and grade of the natural channel (see USDA Handbook 224 for a method of choosing weirs). This section will deal with V Notch weirs, because they are the best for low flows and we have first hand experience with their use.

Weirs can be thought of as overflow structures built across an open channel. Water flowing in the channel builds up behind the weir. Its velocity becomes negligible and as the level rises to the bottom of the V Notch, it flows over and flow measurements begin. Critical flow occurs over the weir resulting in a unique relationship between stage heights and flow rates. Stage heights (depth of water flowing over the weir invert) are recorded using float or electronic water level recorders. The data is then converted to flow rates by a known formula or by calibrating the weir and obtaining a rating curve. Water levels downstream of the weir should be low enough to allow for an "aerated nappe" (the thin sheet of water flowing over the weir) (Figure 1).
6. **FIELD PROCEDURE:**

### Site Selection

When looking for suitable sites, consider the following:
(from ISO 1438-1975)

(i) availability of an adequate length of channel of regular cross-section;
(ii) the existing velocity distribution;
(iii) avoid a steep channel, if possible;
(iv) the effects of any increased upstream water levels due to the measuring structure;
(v) the conditions downstream such as confluences with other streams, dams or other controlling features which might cause a submerged weir;
(vi) the impermeability of the ground on which the structure is to be built and the necessity for sealing if too permeable;
(vii) the necessity for flood banks to confine the maximum discharge to the channel;
(viii) the stability of the banks;
(ix) the effect of wind, which can have a considerable effect on the flow over a weir or flume, especially when these are wide and the head is small and when the prevailing wind is in a transverse direction.

### Installation

There are three parts which make up the measuring installation:

(i) Approach channel (stilling pond).
(ii) Weir.
(iii) Downstream channel.

The approach channel should be smooth and free of obstructions. The velocity distribution should be as normal as possible over the cross-sectional area.

The weir should be rigid, watertight and capable of withstanding the required flows without distortion. A sheet metal weir is dug in at a right angle to the channel flow. Ensure that no water can seep under or around the weir plate. The weir should act as a dam and all water from the channel needs to go over the crest (the 90° cut-out of the plate). Use concrete if necessary to form a seal.

The downstream channel must remain clean and free of debris, to allow a continuous and unrestricted flow. If water is held back, a submerged weir may result (the aerated nappe is lost) and you cannot use the formula to calculate flows.

To measure stage heights, a continuous water level recorder is needed (see Section 3). The stilling well should be placed 3 to 4 times the height of the maximum flow, upstream of the weir. When collecting data from the water level recorders, also read and record the water level height from a staff gauge in the approach channel. The staff gauge zero should be set at the bottom of the V Notch. It enables a cross check between the recorder and actual height. Appendix 1 contains notes on weir installation and examples.

7. **SPECIAL PRECAUTIONS:**

If flows contain high sediment (sand) loads, use a flume (Section 2.2) or construct a sediment trap upstream of the weir.
Ensure that the water loses most of its velocity in the approach channel. This can be overcome by making a large enough stilling area. The stilling area slows down the flow to an extent and therefore the recorded flows can be slightly delayed in comparison with the catchment runoff.

Floating debris (stubble etc.) can block the V notch. Open wire guards can be used to prevent this happening.

Recorders have a habit of failing during the most extreme events (which are the most important to collect). It is worthwhile installing two level recorders in the stilling well behind the weir.

Figure 1. V notch sharp-crested weir.

Figure 2. Using break point analysis to digitize a chart.
8. ANALYSIS OF RESULTS:

A float recorder gives a chart of stage heights over time. If you have access to a digitizer which records x and y axes, then this will speed up analysing the chart. Digitized data can be put through a computer program to calculate peak flows and flow volumes. If a digitizer is not available, then use break point analysis to record the time and stage height where the record changes slope (Appendix 2), (Figure 2). The scale in which the data was collected should be known. Once recorded, the heights are used to calculate instantaneous flow. The correct formula depends on the angle of the V Notch. In Appendix 2 a 30° V Notch weir was used.

The formula for a 30° V Notch weir is:

\[ Q(\text{m}^3/\text{s}) = 0.3596H^{2.48} \]

where \( Q \) = Discharge \( \text{m}^3/\text{s} \)
\( H \) = Stage height (m)

Flow in \( \text{m}^3/\text{s} \) is calculated by multiplying the instantaneous flow by the time interval. These flows are added to determine the total flow.

An electronic water level recorder records stage height in millimetres. Time is recorded as a number, the whole number being the day of the year and the fraction is the time in hours, minutes and seconds. In this format, the data can be put directly into a computer program with the correct rating curve and instantaneous and total flow calculated. Ed Hauck (South Perth) can help with computer programs.

9. ADDITIONAL COMMENTS:

V Notch weirs are recommended for the measurement of low flows by the USGS (National Handbook of Recommended Methods of Water Data Acquisition).

Avoid using weirs in flows laden with sediment.

A copy of the book 'Discharge Measurement Structures' by Bos (1989), is held by A.T. Ryder, Albany District Office.

10. REFERENCES:


Field Manual for Research in Agricultural Hydrology. Agriculture Handbook 224, Science and Education Administration. USDA.


11. MAIN CONTACT PERSONS:

Ed Hauck, South Perth.
Don McFarlane, Albany District Office.
Hydrographers employed by WAWA (in most major country centres).
Appendix 1. Notes on installing weirs in reverse bank seepage interceptor drains

For assessing drainage performance and for drainage design it is often useful to have measurements of the amount of water flowing in existing drains. Such measurements may be made using tipping buckets (e.g. Schrale 1982), flow meters, weirs and flumes. These notes summarize the method used to install weirs in surface drains at Narrogin and Mount Barker.

V notch weirs can be used to measure seepage flow from drains, provided there is little sediment in the flow (i.e. overland flow does not enter the drain) and the drain has a sufficient grade. Where there are significant amounts of sediments, two options are available.

(i) The stilling pond in front of the weir needs to be large enough to contain the sediment between cleaning periods.

(ii) A self-cleaning flume is used (Section 2.2).

The shape of the weir can be a simple V notch, a compound V notch (30°-120°) or a compound V/rectangular (e.g. Cipoletti weirs) or several other shapes. Only simple V notch weirs are considered in this report.

The size of the weir for a drain can be estimated from a knowledge of likely maximum flows. The weir should be large enough to accommodate high flows but not so large as to be expensive and/or have low sensitivity for small flows.

Flow in a channel can be estimated using Manning's equation in conjunction with an estimate of the cross-sectional area of flow as illustrated in the example below:

Example

A weir is required for a parabolic drain on a 0.5 per cent grade. The maximum depth of flow in the drain has been 20 cm and the width of flow at this time was 50 cm.

Hydraulic radius (R) = 2/3 depth of flow = 0.13 m.
Drain gradient (S) = 0.005 m/m.
Roughness coefficient (n) = 0.02 (few pebbles, uniform cross section, little vegetation).

Average flow velocity = $R^{2/3} S^{1/2} = 0.9$ m/s.

Cross sectional area = 2/3 flow width x flow depth = 0.067 m².

Maximum flow volume (Q) = 0.06 m³/s = 60 litres/s.

For a 90° V Notch Weir

$Q = 1.342 \frac{H^{2.48}}{2}$

where $H =$ depth of flow above the invert of the weir (m).

Thus for a flow of 0.06 m³/s, $H = 0.25$ m.

For $V$ Notch Weirs Between 90° and 60°

$Q = 1.342 \tan \frac{\theta}{2} H^{2.48}$
Thus for a 60° V notch weir, $H = 0.36$ m when $Q = 0.06$ m$^3$/s which is a 45 per cent increase in sensitivity relative to a 90° V notch weir.

**For V Notch Weirs Between 28° and 60°**

$$Q = \left(1.322 + 0.522N_e\right) \tan \theta \frac{H^{2.5}}{3.281 e H^e}$$

where $N = 0.035 + 0.033 \left(\tan \theta \right)^{-0.8}$

and $e = 0.2475 \left(\tan \theta \right)^{0.09} + 0.340 \left(\tan \theta \right)^{0.035}$

For a 30° V notch weir, $N = 0.13$ and $e = 0.576$ and for a flow of 0.06 m$^3$/s, $H = 0.49$ m which is almost a 100 per cent increase in sensitivity relative to a 90° V notch weir.

In reverse bank seepage interceptors, the grade of the drain is increased towards the discharge end to enhance removal of drainage water. Placing the invert of the weir 10 cm above the bottom of a drain with a 0.75 per cent grade will produce a 13 m pond of water in front of the weir before flow commences. This pond is considered sufficient to ensure a negligible approach velocity but it will be necessary to see if bridging occurs across the drain in the stilling pond. If bridging does occur, a lining will need to be used. Below the weir the drains require deepening to ensure no ponding occurs. One pass with a grader should be sufficient to ensure this.

The weir consists of a 2 mm thick sheet of galvanized steel held in place by soil, steel posts or concrete. A continuous water level recorder is placed on the bank about three metres up stream from the weir. A length of 225 mm P.V.C. pipe is used as a stilling well for the recorder float. In reverse bank seepage interceptors, a single recorder can monitor flows on both sides of the bank. However, the period of overland flow is likely to be small so a fast chart speed is required. A slower chart speed may be required for seepage flows. Using a 100 mm diameter recorder, chart speed is over 14 mm/h for a daily revolution, but only 2 mm/h for a weekly revolution.

**Reference**

Appendix 2. An example of breakpoint analysis of a flow hydrograph.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time (h)</th>
<th>Height (m)</th>
<th>Instant. (m^3/s)</th>
<th>Average Q (m^3/s)</th>
<th>Interval time (s)</th>
<th>Flow (m^3)</th>
</tr>
</thead>
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<td>0.0000311</td>
<td>0.0000311</td>
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Total flow (m^3): 116.725
2.2 FLUMES

1. **WHAT IS MEASURED?**

The flow rate and volume of water flowing in a defined channel. When fitted with rising stage or pumped sediment samplers, soil loss can also be measured.

2. **ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:**

Weirs, tipping buckets, natural channel gauging.

Peak flows can be estimated from crest gauges and by constant head velocity devices.

3. **PREVIOUS USES OF THE METHOD:**

Parshall flumes have been used to measure flows from a V drain with a low gradient.

H flumes are commonly used to measure runoff and soil loss from agricultural land.

4. **COST/AVAILABILITY OF EQUIPMENT:**

There are many different designs and types of flumes but in this section, the Parshall flume will be used as the example.

Most flumes are made in the Department’s workshops. Costs depend upon size and the type of materials used. A 305 mm flume made with 1.6 mm galvanized sheets and angle iron had a material cost of $150 (1986).

Fiberglass Parshall flumes are made by:

Hydrological Services
18 Scrivener Street
LIVERPOOL NSW 2170

Phone: (02) 601 2022

There are 15 models each with a different throat width. A flume with a 305 mm throat width costs $4,000+ (1990).

Portable (Replogle, Bos and Clemmens) RBC flumes can be made relatively easily in a workshop. Throat widths vary from 50 mm to 200 mm and discharge rates of 0.0263 to 49.35 L/s can be measured. Design plans and ratings tables are included in Clemmens et al. (1984) or Replogle and Bos (1982).

5. **PRINCIPLES OF METHOD:**

The theory of flumes is based on energy balance between the upstream gauge location and the control section within the flume throat, where flow is critical. For critical flow, the flow rate and energy head have one known functional relationship. Thus the water level at the gauging station is related to the rate of flow (Clemmens et al. 1984).

Figure 1 shows a plan of the various sections making up a Parshall flume. A flume is rated by its throat width and accurate construction is needed for
accurate discharge rates. Appendix 1 shows a table with various throat widths and their minimum and maximum discharge capabilities.

The main advantage of the Parshall flume is its relatively low head loss. The head loss is only about a quarter of that needed to operate a weir having the same crest length (Brakensiek et al. 1979).

6. FIELD PROCEDURE:

Installation

The flume can be constructed in several ways, depending on its size. Small flumes can be made in one piece (e.g. the portable RBC flumes) or made in sections assembled on site (Figure 1). Prepare the site for installation and dig the channel to suit the flume.

The channel gradient below the flume should be sufficient to allow water to flow away. The depth of the stilling area is not critical, however the slope of the ramp should be 1:4. Ensure that no water can seep under or around the flume entrance. Wing banks or walls may be needed to control and divert flow into the flume. The floor of the converging section needs to be level so that water flows over it at an even depth. Backfill the flume to give it support and ensure the sides remain parallel and rigid.

A stilling well and take off are placed off the converging section. A float recorder or electronic water level recorder (see Section 3) is used in the stilling well to record water levels. A tape is fixed to the inside of the converging section. The level floor is the zero for the readings. The tape is read and checked with the reading from the recorder.

7. SPECIAL PRECAUTIONS:

An estimate of the flows to be measured is required to decide the size of flume necessary for the job. There is a large overlap of minimum and maximum flows that each flume can measure (Appendix 1). Note that each flume needs a critical depth (head) of water flowing through the converging section before you can begin calculating flows. For example with the 305 mm throat width flume, 30 mm is the cutoff depth for measuring flow. Appendix 1 shows the minimum head requirement for various throat widths.

8. ANALYSIS OF RESULTS:

Data is analyzed with the formula:

\[ Q = Kh_a^u \]

where \( Q \) = flow in m\(^3\)/s,
\( K \) = dimensional factor which is a function of throat width,
\( h_a \) = upstream gauge reading in metres,
\( u \) = a constant between 1.522 and 1.607 depending on throat width.

A flume with a 305 mm throat width uses the following formula to calculate discharge:

\[ Q = 0.6909 h_a^{1.522} \]

When using this formula we need to know the upstream gauge reading. This is obtained by a water level recorder in the stilling well. If a float recorder
is used then use break point analysis or a digitizer to convert the chart to a set of x and y axis readings (refer to Section 2.1, analysis of data).

For more information on discharge and formulae of various throat widths see Bos (1989).

An electronic water level recorder records the stage height in millimetres and time as a number e.g. 187.4325. The whole number is the day of the year and the fraction represents hours, minutes and seconds. In this format, with the data stored on a computer disk, a program can be run and the correct formula used to calculate instantaneous flow and total discharge. Ed Hauck can be contacted in South Perth to help with programs.

9. ADDITIONAL COMMENTS:

Flumes are generally more expensive than weirs to make and purchase. However they can handle sediment better and can be used on drains or channels with low gradients.

10. REFERENCES:


11. MAIN CONTACT PERSONS:

Arjen Ryder and Don McFarlane, Albany District Office.
Ed Hauck, South Perth.
Figure 1. Plan view and section of a Parshall flume.
## Appendix 1. Discharge characteristics of Parshall flumes

<table>
<thead>
<tr>
<th>Throat width (b)</th>
<th>Discharge range ((m^3/s \times 10^{-3}))</th>
<th>Equation (Q = Kh^n)</th>
<th>Head range (metres)</th>
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</thead>
<tbody>
<tr>
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<td>Minimum</td>
<td>Maximum</td>
<td>((\text{metric}))</td>
</tr>
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<tr>
<td>2&quot;</td>
<td>0.18</td>
<td>13.2</td>
<td>(0.1207 h^{0.55})</td>
</tr>
<tr>
<td>3&quot;</td>
<td>0.77</td>
<td>32.1</td>
<td>(0.1771 h^{0.55})</td>
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<td>6&quot;</td>
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<tr>
<td>1'</td>
<td>3.32</td>
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<td>(0.6909 h^{0.522})</td>
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<td>1'6&quot;</td>
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<td>(1.056 h^{0.538})</td>
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<td>2'</td>
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<td>3'</td>
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<td>(2.184 h^{0.566})</td>
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<td>4'</td>
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<td>1,923</td>
<td>(2.953 h^{0.578})</td>
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<td>5'</td>
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<td>(6.112 h^{0.607})</td>
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### in \(m^3/s\)

<table>
<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>Maximum</th>
<th>Equation (Q = Kh^n)</th>
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2.3 UNGAUGED STREAMS

1. WHAT DOES IT MEASURE?

This system measures the average surface velocity.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:

See Section 2.4, Current Meters.

3. PREVIOUS USES OF THE METHOD:

This quick method has been used to measure the approximate discharge of the streams of upper Denmark catchment. Water Authority uses this method wherever other more accurate methods can not be used.

4. COST/AVAILABILITY OF EQUIPMENT:

A measuring tape, stop watch and a few marker spikes.

5. PRINCIPLES OF METHOD:

Floats are means of measuring the velocity in the vicinity of the surface. Floats can be a wooden risk, or any other small floating object. Debris can be used as natural floats.

A coefficient of 0.85 is commonly used to convert surface velocity to mean velocity. This value is an average of many observations, although for a particular channel, the coefficient may be as low as 0.80 or as high as 0.95.

6. FIELD PROCEDURE:

Site Selection:

An adequate length of stream is selected to allow a 20 second travel time. This reach ideally should be straight with little variation in depth or shape.

Site Preparation:

All big stones, debris and objects that may delay the travel time of the float should be removed. Two cross-sections of the stream should be selected and marked by placing markers on both banks at each section.

Field Work:

The longitudinal distance between the two sections is measured and recorded. The width of the stream should be divided into segments (Figure 1). The average width of each segment (w), is measured and recorded. The average depth of each segment (d), is measured and recorded. A float should be dropped above the upstream section, allowing it to reach a constant velocity before timing it. The float's travel time (t), between the two cross-sections, for each segment is measured. This measurement should be repeated a few times for each segment and the shortest time recorded.

For small streams, it is difficult to measure the travel time for each segment. In this case, the float is dropped a few times and average t calculated.
7. **SPECIAL PRECAUTIONS:**

Figure 1. The streams are divided into small segments, based on the shape of the creek bed.

8. **ANALYSIS OF RESULTS:**

The surface velocity for each segment \( v \), is calculated.

\[
v = \frac{1}{t} \text{ (m/s)}
\]

The average velocity for each segment \( v_a \), is calculated.

\[
v_a = 0.85 \times v \text{ (m/s)}
\]

The cross-section area of each segment \( a \), is calculated.

\[
a = d \times w \text{ (m}^2\text{)}
\]

The discharge for each segment \( q \), is calculated.

\[
q = v_a \times a \text{ (m}^3\text{)}
\]

The discharge for the stream \( Q \), is calculated.

\[
Q = q_1 + q_2 + \ldots \text{ (m}^3\text{)}
\]

For small streams, the average surface velocity, is used for all the segments.

9. **ADDITIONAL COMMENTS:**

Under good conditions of fairly uniform flow and cross-section, no waves or wind, and with a certain amount of care, an error of less than 10 per cent is possible. Under adverse condition, the results may be as much as 25 per cent in error.
10. REFERENCES:

11. MAIN CONTACT PERSON:

Ruhi Ferdowsian, Albany District Office.
2.4 CURRENT METERS

1. WHAT IS MEASURED?:

Rotating-element current meters can be used to measure the velocity at specified depths below the surface. These specified points have been derived theoretically from the assumption that the vertical velocity curve resembles a parabola and has been checked by considerable field investigations.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:

See Section 2.3, Ungauged Streams.

3. PREVIOUS USE OF THE METHOD:

This method has been commonly used for discharge measurement of streams and rivers throughout Western Australia.

4. COST/AVAILABILITY OF EQUIPMENT:

A measuring tape, stop watch, current meter, and a few marker spikes, are required to measure small streams. To measure the velocity of large streams and rivers, a ladder, a cable and a boat may be necessary.

Survey equipment may be needed to survey the cross-section of these rivers. Preferably this survey should be done when the river is not in flood.

5. PRINCIPLES OF METHOD:

The mean of velocity measurements taken at 0.2 and 0.8 of the depth, measured from the water surface, equals the mean velocity at that verticle. The velocity measurement taken at 0.6 of the depth is also equal to the mean velocity.

The average of velocities taken at 0.2, 0.6 and 0.8 is the best representative of the mean velocity and has the advantage that any inaccuracy in a point measurement is divided by three, reducing the error.

For shallow streams, where measurement of velocity at 0.8 of the depth is impossible or difficult, the velocity measurement at 0.6 of the depth should be used as mean velocity.

6. FIELD PROCEDURE:

Site Selection

The selected site should have the following condition:

(a) Banks of the stream should be straight and the bed smooth.

(b) Flow through the section uniform, free of turbulence and 90 to the selected cross-section.

(c) The depth should be sufficient to measure the velocity at specified depths.

(d) The velocity should be within the measuring range of the current meter.
Site Preparation

All stones, debris and objects that may change or disturb the flow direction, should be removed.

The selected cross-section of the stream should be marked by placing markers on both banks of the stream.

Field Work

A cable or a measuring tape is stretched across the stream at the selected site.

The width of the stream should be divided into segments (Figure 1).

The edges of the segments should be projected nad marked on the cable or measuring tape.

The average width of each segment (w), is measured and recorded.

The average depth of each segment (d), is measured and recorded. (The depth of water can be measured by sounding with the meter cable or rod).

Set meter to 0.8 d and measure velocity by starting a stop watch on an impulse from the meter and stopping it on another impulse about 45 seconds later. The number of impulses counted (taking the first as zero) and the elapsed time permit calculation of velocity from the meter calibration.

Raise meter to 0.6 d, measure and record the velocity as above.
Raise meter to 0.2 d and repeat as above.

Some of the meters may have an electrical counting device that can count the number of impulses per preset period of time. In shallow water a single velocity determination at 0.6 d may be used.

7. SPECIAL PRECAUTIONS:

8. ANALYSIS OF RESULTS:

Refer to the calibration table of the current meter and convert all the impulse counts to velocities. Average the velocities for each segment. Calculate the area of each segment.

\[ a = w \times d \text{ (m}^2\text{)} \]

Calculate discharge for each segment.

\[ q = a \times v \text{ (m}^3\text{)} \]

Calculate the stream's discharge.

\[ Q = q_1 + q_2 + \ldots \ldots \ldots \text{ (m}^3\text{)} \]
Figure 1. The streams are divided into small segments, based on the shape of the creek bed.
SECTION 3: WATER LEVEL RECORDERS

3.1 MECHANICAL FLOAT WATER LEVEL RECORDERS

1. WHAT IS MEASURED?:

Water levels in (i) Bore holes; perched aquifers in duplex soils.
(ii) Dams, level banks, weirs, flumes and rivers.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:

Capacitance water level recorders and data loggers (Section 3.2).

3. PREVIOUS USES OF THE METHOD:

Monitoring deep and shallow groundwater; water levels in dams and level banks; flow through flumes.

4. COST/AVAILABILITY OF EQUIPMENT:

A.U.S. 1 float recorder $3,000+ (1990) (Figure 1)
Available: Hydrological Services Pty Ltd
18 Scrivener Street
LIVERPOOL NSW 2170
Telephone: (02) 601 2022

Queensland D.P.I. recorder $700 (1990) (Figure 2)
Available: Make them yourself
Buy clockwork drive from:
Bristol Babcock
Sydney Office
Telephone: (02) 529 3622

5. PRINCIPLES OF METHOD:

The A.U.S 1 recorder uses an electronic clock to wind the chart paper through at the required speed. The higher the speed the greater the resolution. An ink pen marks the chart and is moved via a float and pulley system. Beaded wire tied to the float is hung over the pulley with a counter weight. This gives a positive response to any fluctuation in water levels. Different floats and pulley diameters are used to vary the accuracy required (see Operating Instructions).

The Queensland D.P.I. recorder (Freebairn 1983) operates on a fixed 1:1 scale (i.e. 1 mm water level rise is recorded as 1 mm on the chart). A spring loaded pencil is attached to an aluminium rod and a sheep trough float is connected to the other end of the rod. The float and rod are contained within a stilling well. As the water level changes a direct line is drawn on the chart paper. A mechanical clock drives the chart at speeds of either 1 revolution per day or 1 per week. Using 100 mm P.V.C. pipe as the chart drum, 1 revolution per week will use 50 mm of chart per day.
Figure 1. A.U.S. 1 water level recorder.
A mechanical float recorder
Figure 2. Queensland D.P.I. water level recorder.
6. FIELD PROCEDURE:

Installation

Use suitable stilling wells when installing recorders. Keep recorders level and ensure the float does not touch the sides of the stilling well or become stuck to the soil at the bottom.

The A.U.S. 1 recorder needs a base plate and weather-proof cover for operating in the field. The Queensland D.P.I recorder is made for direct field installation.

Keep a spare battery, chart and ink pen with the A.U.S. 1 recorder.

Operation

Ensure charts are attached, floats run freely and pens or pencils operate.

A.U.S. 1

Connect the battery and listen for chart movement at evenly spaced intervals. Mark the time, date and height of water on the chart.

Queensland D.P.I.

Wind up the clock and listen to check that it is working. Replace the chart drum and ensure that the pencil touches and writes on the chart. Mark the time, date and water level height. Soft pencils and plastic film (e.g. Cronaflex) are recommended to ensure that the pencil leaves a trace and the sheet does not warp when moist.

7. SPECIAL PRECAUTIONS:

A.U.S. 1

Can be adapted to most situations.

To obtain a 1:1 scale, you need a float (e.g. 375 mm diameter) inside a larger diameter stilling well. This is not always available (i.e. 50 mm bore hole). In this case you need to reduce the sensitivity and use a scale of 1:5 (i.e. 5 mm water level rise equals 1 mm on the chart). This is achieved using a smaller diameter float and different size pulleys.

The instrument is large and cumbersome to move.

Queensland D.P.I.

The clock needs winding once a week, which dictates the spacing of visits.

The chart needs to be changed every week and can only record a maximum rise or fall equal to the drum length (e.g. 400 mm) between visits. If the watertable moves more than this in a week then your visits will need to be more frequent to adjust the pencil.

The depth to the watertable should not be greater than 1.5 m, as the aluminium rod is likely to bend and become stuck. Apply teflon spray to the rod to prevent sticking.
In general, the Queensland recorder is cheap to make but labour intensive to operate while the A.U.S. 1 costs more, but requires less labour once installed.

An advantage of the Queensland recorder is that it is simple and farmers feel confident to adjust it and change charts.

8. ANALYSIS OF RESULTS:

The analysis depends on what water levels have been collected and for what reason. Groundwater levels are collected to determine long term trends or to determine how fast and by how much a watertable rises after rainfall. When used on a weir or flume the water levels are converted to flows.

Both recorders give lines on a chart representing the water level. It is possible to quickly check in the field what changes have occurred since the last visit.

9. ADDITIONAL COMMENTS:

Capacitance probe water level recorders (Section 3.2) are replacing float recorders. In the past, float recorders have proved cost effective and reliable. The accuracy of capacitance recorders is equal to, and in many cases better than float recorders. The initial setup costs for capacitance recorders can be high, depending upon the availability of portable computers but collecting and processing the data is quicker and easier.

10. REFERENCES:


Operating Instructions for A.U.S. 1 Water Level Recorders.

11. MAIN CONTACT PERSONS:

A.T. Ryder, Albany District Office.
3.2 CAPACITANCE WATER LEVEL RECORDERS AND DATA LOGGERS

1. WHAT IS MEASURED?:

Continuous water levels in (i) aquifers (deep and perched) i.e. bores and wells;
(ii) channels i.e. streams, weirs and flumes;
(iii) above ground i.e. dams, level banks and tanks;
(iv) disk permeameters.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:

Mechanical float water level recorders (Section 3.1).

3. PREVIOUS USES OF THE METHOD:

Changes in water levels over time in (i) level banks;
(ii) weirs and flumes;
(iii) perched aquifers in duplex soils;
(iv) deep aquifers;
(v) disk permeameter (Section 7.2).

4. COST/AVAILABILITY OF EQUIPMENT:

The equipment is manufactured and sold by Geoff Smith of:

WESDATA
Unit 14/11 Milford St
EAST VICTORIA PARK WA 6101

Telephone: (09) 362 3980

A price list is given in Appendix 1. It includes other sensors which can be attached to the data logger for measurements. (e.g. temperature, wind speed and direction). Maintenance is also done by WESDATA.

5. PRINCIPLES OF METHOD:

The complete unit consists of two parts, a data logger and a sensor.

Logger

The logger consists of a 32 mm diameter, 30 cm long, P.V.C. pipe containing the electronics. A removable top allows access to a communication port. Silica gel is left in the top to absorb moisture. A rubber 'O' ring seals the top and prevents moisture entering the logger. The bottom end of the logger has a female plug to which the sensor is connected. A rubber 'O' ring seals the logger and sensor when screwed together. This makes the whole unit waterproof. The logger holds the batteries (4 'AA'), memory (32K) and all of the electronics necessary to record and store the readings.

Sensor (capacitance probe)

For detailed information on how the probe works, see Section 2, page 3 of "Capacitance water level probes" in the WESDATA handbook. Briefly, a rod or wire (3 mm dia.) is coated with teflon which is located centrally with in a 35 mm P.V.C. pipe. An earth wire is wrapped around the outside of the pipe (Figure 1). The TEFLOM covered measuring element forms one plate of the capacitor and the TEFLOM is the insulator or dielectric. The second plate is the water in which the probe is immersed. As the water level varies, the area
of water that is in contact with the TEFiON surface also varies. The water is like a cylinder that is moving up and down the cylindrical TEFiON lined element. Hence the variation in capacitance is directly proportional to the height variation of the water in contact with the TEFiON. The capacitance is recorded between the water and the rod in millivolts.

Figure 1. Cross-section of probe components.

Figure 2. Distance to be measured when calibrating a probe.
Each probe needs to be calibrated so that a conversion can be made from millivolts to millimetres (WESDATA handbook, Section 2, p.9-11 "Capacitance water level probe").

Probes come in various lengths, depending on the job required. For example a 0.5 m long probe is commonly used on shallow aquifers, while a 1.5 m probe is commonly used in level banks.

Probes are waterproof and become a complete unit when connected to the logger and left in the field.

6. FIELD PROCEDURE:

Installation

It is necessary to use a stilling well when recording water levels. The minimum size for this logger is 40 mm P.V.C. pipe. The probe's 'zero reading' is not at the bottom of the P.V.C. pipe but the end of the teflon-coated rod. Therefore depending on where the probe is used, a certain amount of water is needed before readings take place. This distance is measured when the probe is calibrated (Figure 2).

The water level recorder can be left in a bore hole at any depth by hanging it from stainless steel wire.

If the logger will be exposed to direct sunlight then a sunshield is necessary to protect it from high temperatures.

Probes need to stand vertical for accuracy. If they cannot, then the calibration should be carried out at the same angle as they will be installed (e.g. on a dam wall).

Operation

It is best to read the handbook and do a few trial runs to become familiar with the probes operation. You require access to an IBM compatible computer, preferably battery operated and portable but this is not essential. A portable computer allows you to set up and download the loggers in the field. WESDATA do sell a FIELD TRANSFER UNIT which will do all this but it cannot process the data. An IBM compatible computer will process the data and can be used for running other programs. Load the computer with the WESDATA program. Steps for field operation are as follows:

(i) have the computer run the WESDATA program;
(ii) plug the communications cable into the logger and into the RS232 port on the computer;
(iii) load the required SETUP program 1 (see handbook);
(iv) disconnect the cable;
(v) screw on the end cap and leave the water level recorder in its required position for recording (e.g. a certain distance down a bore hole).

The length of field operation, before retrieving the data depends upon the time interval used between readings. Usually four to six weeks between downloading is adequate. To download data, the steps taken are the same as above except in step (iii), choose the download option 'Z', give a filename and then use SETUP to restart the logger.
7. **SPECIAL PRECAUTIONS:**

Do not load or download the logger in the rain. Keep all electronics as moisture free as possible.

The charge in the batteries can be checked with a multimeter. If less than 6V they need replacing. If the logger does not run with new batteries it will need servicing at WESDATA.

8. **ANALYSIS OF RESULTS:**

Data is collected from the field logger in binary format recording the time and height of the water level.

Before the data can be analysed it needs to be converted from the binary (.DAT) format to the ASCII (.PRN) format (see Section 1, p.26 of the WESDATA handbook). If the probe has been calibrated the data will be expressed in millimetres.

An example is shown in Appendix 2. Test.dat shows Day number from 12/7/1989 (193), time in hours, minutes and seconds and the reading in millivolts. Test.prn shows Day number from 12/7/89 (193), time as a fraction of a day and the reading in millimetres.

Analyses of the data will depend upon why it was collected. Spreadsheet programs such as Lotus 123 or VP Planner are useful. If flow calculations are needed then other programs should be used.

The steps necessary for graphing from Lotus 123 are:

(i) The .DAT file should be converted to a .PRN file.
(ii) Run the Lotus 123 program.
(iii) Import the .PRN file.
(iv) Enter the graph command.
(v) Enter Type then choose the XY option.
(vi) Select the first column in the file as the X axis.
(vii) Select the second column as the Y axis.
(viii) Enter View (the graph is drawn).
(ix) If the file contains more than 500 readings then the line will appear with too many symbols. To remove the symbols from the line, enter Options, Format, A, Line, Quit, Quit and View.
(x) Further additions can be made to the graph (e.g. titles).
(xi) Future field data can be appended to this file and the graph extended.

Figure 3 shows Test.prn graphed with and without symbols, using Lotus 123. Each symbol represents actual readings. Note that when the water level is fairly constant, few readings of the level are taken. When the level changes rapidly, readings are taken every 10 minutes.

9. **ADDITIONAL COMMENTS:**

10. **REFERENCES:**


11. **MAIN CONTACT PERSONS:**

A.T. Ryder, Albany District Office.
J. Prince, South Perth.
Figure 3. Graphs of Test.Prn using Lotus 123.
Appendix 1. Wesdata price list as at March 1988.

<table>
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<tr>
<th>Part</th>
<th>Description</th>
<th>Price $A</th>
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<td>884</td>
<td>16 way multiplexer for 888</td>
<td>$65.00</td>
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<tr>
<td>890</td>
<td>Data transfer interface</td>
<td>$316.00</td>
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<td>892</td>
<td>Weather proof housing for 888 logger</td>
<td>$120.00</td>
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<td>893</td>
<td>Batteries 4*C size alkaline</td>
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<td>894</td>
<td>Play back cable</td>
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<tr>
<td>895</td>
<td>Solar panel and sealed lead batteries</td>
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<tr>
<td>896</td>
<td>Small Stevenson screen</td>
<td>$410.00</td>
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<td>900</td>
<td>Single channel 187 logger</td>
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<td>902</td>
<td>Sun shield for 187 logger</td>
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<td>906</td>
<td>Pressure sensor 0 to 10 metres</td>
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<td>907</td>
<td>Pressure sensor 0 to 20 metres</td>
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<td>Battery pack 4*AA size</td>
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<td>910</td>
<td>Chopper stabilized amplifier</td>
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<td>912</td>
<td>pH pre-amplifier</td>
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<td>916</td>
<td>Dissolved oxygen pre-amplifier</td>
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<td>Thermistor temperature probe</td>
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<td>Humidity probe</td>
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<td>Salinity measuring system</td>
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<td>Photosynthetic irradiance</td>
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<td>Cable 3 and 4 core per metre</td>
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<td>Cable screened per metre</td>
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<td>940</td>
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<td>6.0 metre water level probe</td>
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<td>889</td>
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<tr>
<td>897</td>
<td>Additional 64K data packs</td>
<td>$205.00</td>
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Prices do not include tax or freight.
Postal address P.O. Box 1064, East Victoria Park 6101.
Appendix 2. File name for data source.

LOG HEADER
Logger start time = 193:17:0:0 (Day 193, 5.00 p.m.)
Log scan time = 0:5:0 (5 minutes)
Log average time = 0:0:0 (no averages taken)
Logger sn. number = 10099 (logger identification number)
Logger prog number = 2 (water level compressed data)
Probe resolution = 10 (take a reading if the level has changed by 10 mV)

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<th>Test.prn</th>
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Log ended at 194:14:45:00
3.3 MANUAL PROBES FOR MEASURING WATER LEVELS IN BORES

1. WHAT IS MEASURED?:

Water levels in bores which vary according to recharge, groundwater flow, atmospheric pressure, tides, pumping and drainage. In unconfined aquifers, the water level is the watertable. In confined or semi-confined aquifers the water level is the piezometric surface.

Bores may be divided into two categories:

Wells - PVC tubes which are fully slotted from the bottom to just below the ground surface. They show the average hydraulic pressure over the depth of the bore.

Piezometers - PVC tubes which are only slotted at the bottom for a metre or two. They reflect the hydraulic pressure at the depth of the slotting.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:

Continuous recording methods (Sections 3.1 and 3.2).

3. PREVIOUS USES OF THE METHOD:

Widespread use in salinity and waterlogging studies.

4. COST/AVAILABILITY OF EQUIPMENT:

Low cost - $30 for a tape and plopper, and up to $500 for commercially made electrical probes. The cheapest device available from Hydraulic Services Pty Ltd is the Contact Meter Type KLL which has a range of 15-50 m and costs $430. Australian Groundwater Consultants sell a hardy electrical probe for about $500.

5. PRINCIPLES OF METHOD:

Tape and plopper - constructed from a fibreglass tape measure. The plopper can be either a plastic screw top vial or a copper tube closed at one end so that the overall weight of the plopper is approximately 100 g. These can be made for less than $30 from 20 m tapes available through Government Stores. Ideally the bottom of the plopper should be at 0.00 m when attached to the tape. However, to avoid cutting the tape measure, attach the top of the copper tube to the metal zero of the tape. Most ploppers are made with a 20 cm copper tube and so add 20 cm to the readings in the field to compensate for this.

Electric probes may be constructed from 12-gauge, multistrand, figure eight electrical flex connected to a beeper, light globe or milliammeter with a suitable battery (Appendix 1).

6. FIELD PROCEDURE:

For Tape and Plopper Measurements:

1. Select a standard reference point from which all measurements are to be taken. The best point at the top of the PVC tube. A measurement of its height above ground level should be kept in case the tube is broken.
2. Let the plopper fall down the PVC tube until a plop is heard. Then pull the tape measure up approximately 1 metre.

3. Lower the plopper at 1 cm intervals, using a rapid downward movement until a distinct plop is heard and then take the measurement. Record the level to the nearest centimetre.

**For Electric Probe Measurements:**

Lower the probe gently down the PVC tube. A previous reading is useful to indicate the expected depth.

Once the probe has been immersed, especially in salty water, a film of brine may remain on the probe which can lead to the signal not cancelling when the probe is withdrawn. If the signal continues the probe should be withdrawn and wiped.

7. **SPECIAL PRECAUTIONS:**

Correct the reading to account for the length of the plopper, if the plopper extends below 0.00 m on the tape.

Some electric tapes are sensitive to water salinity which may require special calibration.

8. **ANALYSIS OF RESULTS:**

Water levels are measured and recorded in the field. Enter data into a LOTUS 123 spreadsheet called BOREREC.WK1 (Section 3.4).

Salty water, due to its greater density, will record lower levels than fresh water.

The calculations for correcting levels for water salinity are contained in Appendix 2.

9. **ADDITIONAL COMMENTS:**

In most bores the water levels are less than 10 metres below ground level and the sound of the plopper can be heard easily. It is therefore possible to use a tape and plopper most of the time. The electric probe is generally used when the plopper cannot be heard such as deep (> 50 m) wells. An adequate level of accuracy can be achieved by making your own device as described in Appendix 1.

10. **REFERENCES:**

11. **MAIN CONTACT PERSONS:**

R. George, Bunbury.
A.T. Ryder, Albany.
Appendix 1. Materials needed for the manufacture of an electric probe.

P.V.C. pipe and sheet to manufacture the reel spindle, handles and a box to house the battery and bleeper.
A bleeper, buzzer or light for the signal.
A battery to run the signal.
Multistrand, figure eight 12-16 gauge wire.
Silastic.
P.V.C. glue, hole saw.
Appendix 2. Adjusting groundwater levels for salinity.

Piezometers measure the pressure head at the midpoint of the slotted section. The pressure head is represented by the height of water that the pressure can support. The pressure will support a shorter column of dense (saline) water than one that is less dense. Therefore where groundwaters of different salinity are encountered it is necessary to correct the pressure head. The heads can be corrected to fresh water or to sea water.

Assuming that the salts in the groundwaters are mainly NaCl, the following relationship between specific gravity (S.G.) and salinity has been determined for salinities between 0 and 100,200 mg/L (CRC Handbook of Chemistry and Physics, 1980).

\[ S.G. = 1.000 + 0.000681 \text{ salinity (g/L)} \]

\[ r^2 = 0.9999 \]

For salinities above 100,000 mg/L and for long columns of water refer to the CRC Handbook.

To correct all levels to the density of fresh water:

1. Determine the salinity of the groundwater.
2. Calculate the S.G. using equation 1.
3. Multiply the S.G. height of the water in the pipe above the midpoint of the slots.
4. Add the corrected height to the reduced level of the midpoint of the slotted section.

\[ \text{e.g. Groundwater with a salinity of 15,150 mg/L (15.15 g/L) is 15.00 m above the midpoint of the slots. The reduced level of the midpoint of the slots is 240.00 m A.H.D. What is the equivalent level of fresh water?} \]

\[ \text{S.G. of groundwater} = 1.000 + 0.000681(15.15) = 1.010 \]

\[ \text{Equivalent column of fresh water} = 15.00 \times 1.010 = 15.15 \text{ m.} \]

\[ \text{The equivalent head of fresh water} = 240.00 + 15.15 = 255.15 \text{ m.} \]

To correct all levels to the density of sea water:

1. Determine the salinity of the groundwater.
2. Calculate the S.G. using equation 1.
3. Multiply the height of the water in the pipe above the midpoint of the slotted section by the ratio of its S.G. to that of sea water (1.024).
4. Add the corrected height to the reduced level of the midpoint of the slotted section.

\[ \text{In the above example:} \]

\[ \text{S.G. of groundwater} = 1.000 + 0.000681(15.15) = 1.010 \]

\[ \text{Equivalent height of sea water} = 15.00 \times 1.010/1.024 = 14.79 \text{ m.} \]

\[ \text{The equivalent head of sea water} = 240.00 + 14.79 = 254.79 \text{ m.} \]
3.4 STORING AND GRAPHING MANUALLY READ BORE DATA

1. WHAT IS MEASURED?:

Nothing.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:

Calculators and graph paper.

3. PREVIOUS USES OF THE METHOD:

Other computer programme such as dBase.

4. COST/AVAILABILITY OF EQUIPMENT:

A floppy disk with the file BOREREC.WK1 is available from A.T. Ryder.

5. PRINCIPLES OF METHOD:

BOREREC.WK1 is a Lotus 123 file. It is loaded into a blank Lotus worksheet after which data can be entered in the appropriate columns. A set of formulas are copied, and the resulting data can be graphed as the water table depth below ground.

The way in which the file is set up enables the data to be copied directly to dBase, which is then sent to WAWA to be kept on the State Water Resource Information System (SWRIS). All of the Department of Agriculture bores will, in due time be registered on this system. This will be standardize all bore records. Registration and Bore Identification details are available from A.T. Ryder. Access to data is freely given to all Government Departments enabling you to use data from other Government bores.

6. FIELD PROCEDURE:

Record water levels with manual probes as shown in Section 3.3.

7. SPECIAL PRECAUTIONS:

Make sure you know how to save a file when using Lotus 123.

8. ANALYSIS OF RESULTS:

Have BOREREC.WK1 ready on floppy disk or on your hard-disk. Call up Lotus 123 on your computer, a blank worksheet should appear. From now on abbreviated Lotus commands will be used to guide you through. If you are unfamiliar with these commands, then read a Lotus manual.

Load BOREREC.WK1 use /fr.

Type in your filename. The screen should look like Figure 1. It is probably easiest if you use a name which reflects the bore number. NOTE if you have BOREREC.WK1 on floppy disk, then the files created will be stored on disk. When this disk is full copy the file BOREREC.WK1 to another disk and continue.
BORE RECORDS FOR MANUALLY PLOPPED BORES

This is a Master File.
Do not enter field data onto it!

Enter a new filename and a New File will be created
which will do calculations for one hole only.

Use a name which represents SITE and NUMBER.

eg. NA = Narrogin
21 = Site Number
A = First Depth

ENTER THE NEW FILENAME: NA21A

Figure 1. BOREREC.WK1 spreadsheet.

[Enter] [Esc] Enter catchment name?:

<table>
<thead>
<tr>
<th></th>
<th>CATCHMENT:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BORE NO.:</td>
</tr>
<tr>
<td>4</td>
<td>EASTING:</td>
</tr>
<tr>
<td></td>
<td>NORTHING:</td>
</tr>
<tr>
<td>6</td>
<td>TOTAL DEPTH:</td>
</tr>
<tr>
<td>7</td>
<td>A.H.D. GROUND LEVEL:</td>
</tr>
<tr>
<td>8</td>
<td>P.V.C. ABOVE GROUND:</td>
</tr>
</tbody>
</table>

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SITE TIME</th>
<th>DATE</th>
<th>SALT. (mS/m)</th>
<th>S.L. (m)</th>
<th>D.B.G. (m)</th>
<th>R.L. (m)</th>
<th>FIELD (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>0 12:00</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>0 12:00</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2. Screen display after filename is entered.
Figure 3. Screen display after data entry.

Figure 4. Bore details.
Once the filename is entered the screen will look like Figure 2.

- Enter catchment name.
- Enter bore number.
- Enter easting, metres east (Appendix 1).
- Enter northing, metres north (Appendix 1).
- Enter total depth (m) from ground level.
- Enter relative ground level or Australian Height Datum (AHD) (m).
- Enter the height of PVC tube above ground (m).

If you have not obtained all of the above numbers then enter a '0' in its place. You can always go back and correct it when you have got the correct number.

When you have finished entering all of the above data, the computer will take approximately 10 seconds and look like Figure 3. You are now ready to enter your bore reading. The box on the left hand corner contains the commands needed to enter and graph the data. Use the cursor and the Enter key to pick the command you wish to use.

To enter bore readings:

First enter DATE of the bore reading. It will ask for day, month and year (two digits). Then enter the FIELD bore level measured from the top of the PVC tube in metres (Figure 4). Continue to enter as many bore readings as you have got. The first two bore readings will have already had their relative levels calculated. If you enter more than two readings, go to UPDATE and the rest of your bore readings will be calculated.

To graph data:

Go to the GRAPH command, it will ask if you want 2 'Y' axis. Only say yes if you have entered salinity readings, otherwise always say no. The graph will appear on the screen. Press ESC to get back to the commands.

To enter salinity reading press ESC and the command box will disappear. Then move the cursor in the spreadsheet to where you want the salinity reading and type it in, press enter. Continue down the salt column for further salinities. To return to the commands hold down the ALT key and press Z.

To print data:

This command will print either your spreadsheet data or your graph. Make sure you have viewed the graph before you print it.

To save and retrieve:

This enables you to save the existing file and retrieve another. When you retrieve a file which you have already created and entered data into, the screen will look similar to Figure 3 and you continue to use the commands in the box.

9. ADDITIONAL COMMENTS:

10. REFERENCES:

Lotus 123 manual.
11. **MAIN CONTACT PERSON:**

A.T. Ryder, Albany District Office.
Appendix 1. Experimental sample data sheet (explanation notes)

**Australian Map Grid**

**Eastings**
Metres EAST to the nearest one, ten or a hundred metres (6 figures).

**Northings**
Metres NORTH to the nearest one, ten or a hundred metres (7 figures).

**Zone**
Zone of Australian Map Grid, (in Western Australia 49, 50, 51, or 52).

**Note**
Full Eastings and Northings are usually given at or near the lower left hand corner of the map and appear as small numbers combined with the larger numbers of the Grid, e.g. on a 1:100,000 scale map:

531000 mE 7768000 mN

This is written on the computer sheets as 531000, 776800.

**Officers should attempt to give the location of each site as accurately as possible.** The use of an appropriate scale will assist accuracy and lessen the chance of errors.

If AMG co-ordinates are not available, then at least latitude-longitude should be provided. Co-ordinates should be given in degrees, minutes, and seconds where possible. Again, a scale will be needed to achieve accuracy.
SECTION 4: WATER EROSION

4.1 RISING STAGE SEDIMENT SAMPLERS

1. WHAT IS MEASURED?:
Sediment suspended in flowing water.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:
Manual hand sampling.
Pumping sediment samplers (Section 4.2).
Continuous nephelometer readings in a stream.

3. PREVIOUS USES OF THE METHOD:
The Water Authority of W.A. have used rising stage sample bottles in the
agricultural areas on their stream-gauging stations since 1986.

Gauged flows in contour banks and seepage interceptor drains.

4. COST/AVAILABILITY OF EQUIPMENT:
Cost of sample bottles and mounting, with stopper, inlet and outlet tubes.
Details of construction can be found in Brakensick et al. (1979, p. 267) and

5. PRINCIPLES OF METHOD:
A bottle with two tubes (inverted U shaped with the inlet facing upstream)
through a rubber bung is placed upright in the stream bed. Flow enters the
bottle when the water level in the stream rises above the highest point in the
lower (inlet) tube Figure 1, while air that was formerly in the bottle escapes
through the higher (outlet) tube. The inlet tube extends deeper into the
bottle than the outlet tube. A series of bottles can be placed at different
levels to sample sediment as water levels rise.

6. FIELD PROCEDURE:
(i) Mount the required number of sample bottles at a point suitable for
capturing a representative sample of streamflow.

(ii) Refer to Figure 1 for symbols used. Set the highest points of the inlet
tubes of each bottle at the required height for sampling'A', and their
entry points at the required sampling depth below the surface'B'.

(iii) Set the air outflow tubes higher than the expected maximum flow depth'C'
to ensure that there is no flow through the bottles after they fill
(which could result in a diluted sample) and invert their ends to
prevent rain from entering.

(iv) Replace full bottles with empty ones after each flow in order to collect
samples from the initial, rising limbs of all hydrographs.
7. **SPECIAL PRECAUTIONS:**

Ensure that sufficiently large-bore inlet tubing is used to minimize blockages caused by solids. The tubes should be checked periodically to see that they are not blocked by insects etc.

8. **ANALYSIS OF RESULTS:**

The amount of sediment in the sample collected in the bottles can be determined by resuspension and evaporating a representative sample or by nephelometry (Section 4.4).

9. **ADDITIONAL COMMENTS:**

As rising stage samplers only sample the rising limb of hydrographs, results of comparisons between rising stage and pumped samples on contour bay catchments have been reported by Freebairn (1983). Olive and Rieger (1984), on the other hand, report complex suspended sediment patterns in Australian rivers, which therefore require automatic pumped sampling for adequate measurement.

10. **REFERENCES:**


11. **MAIN CONTACT PERSONS:**

Kevin Bligh, Hernan Ortiz.
Adrian Reed, Albany District Office.
Water Authority hydrographers.

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Figure 1. Rising stage sample bottle showing inlet and outlet tubes.
4.2 PUMPING SEDIMENT SAMPLERS

1. WHAT IS MEASURED?:

It automatically samples water in a flowing stream to determine the amount of suspended sediment.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:

Manual hand sampling.
Rising stage samplers (Section 4.1).
Continuous nephelometer readings in a stream.

3. PREVIOUS USES OF THE METHOD:

The Water Authority of W.A. have used pumped sediment samplers in the agricultural areas on their stream-gauging stations since 1986.

Gauged flows in contour banks and seepage interceptor drains.

4. COST/AVAILABILITY OF EQUIPMENT:

Available for approximately $4,000 from "Gemet" (P.O. Box 767, Armidale, N.S.W.). Operate on DC batteries.

5. PRINCIPLES OF METHOD:

One flow-depth sensor at a pre-set height in the stream, triggers initiation of sampling, which then proceeds at set or partly-variable time intervals until all sample bottles are full. Samples are then removed manually, and replaced with empty containers.

6. FIELD PROCEDURE:

Set the inlet to the pump at the required location and elevation (depending on stream approach conditions) to capture representative samples of flow. The pump-initiating sensor and variable timing sensors (if required) are pre-set at heights considered most appropriate. Check that the pump, sensors and the sampler purge cycle are working properly.

7. SPECIAL PRECAUTIONS:

All electrical connections should preferably be silver-plated to minimize corrosion, and weather-proofed to improve reliability. Pump and bushes need to be adjusted carefully and lubricated in order to avoid seizing and fuses blowing after prolonged periods between runoff events.

8. ANALYSIS OF RESULTS:

The suspended sediment concentration can be determined by evaporation or by nephelometer (Section 4.4).

9. ADDITIONAL COMMENTS:

Carry spares of major components in the field for immediate replacement to reduce data loss through breakdown.
10. REFERENCES:
Manufacturer's instructions manuals.

11. MAIN CONTACT PERSONS:
Kevin Bligh, Hernan Ortiz, South Perth.
Water Authority hydrographers and Welshpool workshop staff.

A sediment sampler
4.3 PIN PROFILOMETER

1. **WHAT IS MEASURED?**

   Topography of the soil surface. Applications include soil loss, erosion processes, soil trafficability, surface water storage and roughness.

2. **ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:**

   Techniques for measuring surface topography fall in two categories, contact and non-contact. The pin profilometer is a contact technique. Listed below are published papers on various systems. A copy of each reference is held by Dan Carter, Albany District Office.

   Stereo Photography - L. Martin (1978)
   Contour Frame - S.J. Riley (1983)
   S.G. Bervoets (1980)
   Laser Systems - M.J.M. Römkens et al. (1988)
   C. Huang et al. (1988)

3. **PREVIOUS USES OF THE METHOD:**

   Measuring soil erosion in potato furrows (McFarlane 1984, McFarlane et al. 1990). Stubble height, % ground cover and soil surface roughness.

4. **COST/AVAILABILITY OF EQUIPMENT:**

   There are many instruments available, most of which are delicate and expensive. Equipment can be made, bought from scientific suppliers or borrowed from various officers in the Division.

   Pin profilometers can be borrowed from A.T. Ryder, Albany District Office (900 mm), Dan Carter, Albany District Office (3 m) and P. Findlater, Geraldton District Office (1.5 m with electronic recorder and storage).

   Cost depends on the size of the pin profilometer and the accuracy required. A 900 mm wide manually-read meter made by the Department for use in potato erosion cost $120 (1986). A 3 m wide meter with pins spaced 20 cm apart cost $100 (1987) to construct. In general the smaller the differences to be measured, the greater the cost of the instrument.

5. **PRINCIPLES OF METHOD:**

   Lightweight pins which are attached to a board, fall freely to touch the ground surface. The board has lines drawn across it at various intervals (e.g. 1 cm). The bottom of the board is the baseline or zero. Pins of equal height rest on the ground below the baseline. The resulting pin heights are read from the board and recorded.

   Increasing the number of pins increases the accuracy of the measurements. A laser microrelief meter can measure vertical elevation to 0.25 mm accuracy with continuous measurements being taken along its 2.6 m transect. It is also able to record transects 0.5 mm apart.
6. **FIELD PROCEDURE:**

Lock pins for transport and lay the board flat. In the field the pins are freed. Lift the board vertically and place it on the site. Release the pins slowly until they touch the ground surface and their heights recorded. A system for recording speeds up data collection i.e. read the pin heights from left to right and record likewise.

7. **SPECIAL PRECAUTIONS:**

Care needs to taken to ensure that the pins sit on the ground surface and do not break the surface. Siting the profilometer on the ground also needs to be consistent. Some workers (Salaway 1981) use permanent pegs for re-siting the profilometer through time. However soil settling is then hard to separate from soil loss.

8. **ANALYSIS OF RESULTS:**

The profile of eroded and non-eroded rows can be estimated. Soil loss (or deposition) can be estimated by difference.

The analysis of results depends on the type of roughness measurements desired (Rankens and Wang 1986), and whether orientated roughness e.g. wheel tracks, need to be removed by the analysis.

Spatial statistics, e.g. semivariogram analyses, have also been advocated (Lehrsch, et al. 1988).

9. **ADDITIONAL COMMENTS:**

The sample size and accuracy necessary will usually determine what type of profilometer to use (e.g. potato furrows are approx. 900 mm wide and 45 cm deep). A meter was constructed to span 900 mm and have pins capable of measuring 0-90 cm depth.

From a simplistic point of view, the profile should be plotted on graph paper and more sophisticated analyses be made with reference to the above papers, or consultation with Biometrics Section.

10. **REFERENCES:**


11. MAIN CONTACT PERSONS:

Dan Carter, Don McFarlane, Albany District Office.
4.4 NEPHELOMETERS

1. WHAT IS MEASURED?:

Turbidity (e.g. either for direct comparison or for correlating with suspended sediment).

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:

Direct measurement of suspended sediment, by filtering, drying and weighing, or evaporating and weighing.

3. PREVIOUS USES OF THE METHOD:

Used to estimate suspended sediment in samples collected by pumping sediment samplers (Section 4.2).

It can be set up in a stream to provide continuous measurements of turbidity.

4. COST/AVAILABILITY OF EQUIPMENT:

A hand-held nephelometer (the "Analite") suitable for field use is available from Kevin Bligh. It was bought from Selby's Scientific Ltd and cost about $1,400. Laboratory nephelometers are also available.

5. PRINCIPLES OF METHOD:

In the Analite hand-held nephelometer a probe which emits light in the near infra-red is inserted into the liquid sample. The light is reflected by suspended particles at 180 degrees. Reflected light is measured as nephelometer turbidity units (NTU's). Other nephelometers use different frequencies.

6. FIELD PROCEDURE:

Check the nephelometer zero-reading in a sample of distilled water. A sample of the liquid containing the sediment is agitated and placed in a container of known depth (e.g. 20 cm). The liquid's temperature is taken and the sample is left undisturbed for the time it takes for sand-sized particles to settle (Loveday 1974, p. 190). A turbidity reading is taken in the sample.

7. SPECIAL PRECAUTIONS:

Direct sunlight should never be allowed onto the "Analite" nephelometer probe when set in the most sensitive range. This range is not normally used in the field.

Turbidity and oven-dried suspended sediment should be correlated for each soil type.

8. ANALYSIS OF RESULTS:

The correlation between NTU readings and oven-dried suspended sediment samples is usually satisfactory for suspended soil sediment. Every nephelometer needs to be calibrated. Turbidity accounted for 81% of the variance of oven-dried sediment measurements, from 22 runoff samples of small plots (Bligh 1984). This was used to calibrate the nephelometer and the resulting suspended sediment concentration (g L⁻¹) was then calculated as 0.79 NTU's + 0.04.
9. ADDITIONAL COMMENTS:

The technique enables convenient, indirect measurement of suspended sediment.

10. REFERENCES:


11. MAIN CONTACT PERSONS:

Kevin Bligh, Hernan Ortiz, South Perth.
Water Authority.
4.5 SAMPLING FOR Cs-137

1. WHAT IS MEASURED?

Erosion status - the amount of soil that has been lost (or added) from a site since 1954, when Cs-137 first labelled the soil.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:

Erosion status can be estimated when there are well defined horizons in soil profiles and eroded soil profiles can be compared with nearby uneroded soil profiles (e.g. inside an uncleared area).

3. PREVIOUS USES OF THE METHOD:

Samples have been analysed for Cs-137 from ten hillslopes in the south-west and from three stations in the Murchison to estimate soil losses since 1954.

A national survey of sheet erosion using the Cs-137 method commenced in 1990.

4. COST/AVAILABILITY OF EQUIPMENT:

The equipment to sample for Cs-137 is cheap and easy to make but the equipment to detect Cs-137 is only available at the Australian Nuclear Science and Technology Organisation (ANSTO) at Lucas Heights, N.S.W., the University of Newcastle, N.S.W. and the CSIRO Division of Water Resources, Canberra. Before using the method it is necessary to involve people from one of these organizations and to arrange for the samples to be analysed.

Equipment needed to take samples:

(i) steel cores (20 or 30 cm long);
(ii) metal plates large enough to cover the cores;
(iii) a metal frame (20 * 50 cm);
(iv) a sharp scraper blade (20 cm wide) with holes in the side every 2 cm so that steel rods can be attached with bolts. The rods enable the blade to be held and set the depth at which soil is to be removed from within the frame;
(v) a sledge hammer and wooden blocks for driving in the cores; and
(vi) a mattock for digging out the cores.

All equipment can be borrowed from Don McFarlane at Albany.

5. PRINCIPLES OF METHOD:

Cs-137, a radioisotope with a half life of 30 years, is produced in thermonuclear explosions. Rainfall washes the Cs-137 out of the atmosphere. As some Cs-137 was injected into the upper atmosphere it takes many years for it to be removed. Therefore some Cs-137 still comes with rainfall (and dryfall) despite the absence of thermonuclear testing.

When Cs-137 comes in contact with soil it is very rapidly and strongly adsorbed, even in sandy soils (Singh and Gilkes 1990). Therefore Cs-137 is a good tracer of topsoil which has been labelled with Cs-137.

To estimate soil movement since labelling commenced in 1954 it is necessary to compare the Cs-137 contents of soils from areas with little erosion since 1954.
Profile sampling of uncultivated soils is used to estimate how much of the input profile has been removed (or how much sediment has been added to the profile). For cores, a calibration between the percentage of Cs-137 removed and soil loss (determined by direct measurement) is needed for both cultivated and uncultivated soils.

6. FIELD PROCEDURE:

For water erosion

(i) Inspect the hillslope and chose a transect which water flows down (i.e. at right angles to the contour). Estimate the length of the transect and divide it into equal distances between sampling points (for uniform slopes) or select sites which are representative of the hillslope cross-section (for non-uniform slopes).

(ii) Peg the sample sites and measure their relative levels with a dumpy level. This enables a cross-section of the hillslope to be drawn showing where each sample site is located. The distance between sample sites can be measured by measuring wheel or by stadia when you are surveying the hillslope.

(iii) Coring: Select a typical soil surface and hammer in the core. Use a piece of wood on top of the core to absorb the shock of the hammer. Be careful not to jar soil out of the core while hammering. As most Cs-137 is in the top few centimetres, losing a little topsoil can greatly affect readings. It is often necessary to cover the core with a metal plate to prevent soil loss.

Hammer the core to ground level. Keep the core covered with the metal plate while you dig a hole beside the core with a mattock. Keep one foot on the plate while digging. If soil is added or spilt from the core while digging it is necessary to discard the core and start again.

Once a hole has been dug beside the core, push the metal plate under the core to prevent soil from falling out and pull the core out of the ground. Empty the soil into two plastic bags (one inside the other) and put the details of the core number and location on a piece of paper placed between the two plastic bags.

(iv) Depth profiling: Used to collect 2 cm thick sections of soil profile for determining the distribution of Cs-137 with depth.

- Lightly hammer or press a 20 * 50 cm rectangular frame into the soil, being careful not to add or lose topsoil from within the frame.
- Adjust the rod on the scraper blade so that a 2 cm thick section will be scraped from within the frame when the rod is laid upon the frame.
- Carefully scrape the soil from within the frame and put it into a plastic sample bag. Ensure that soil from below the section is not included if large aggregates are dislodged. A paint brush can be used to collect loose soil.
Adjust the rod on the scraper blade so that the next 2 cm section will be scraped and proceed down the soil profile. It is usual to take 2 cm samples between 0 and 10 cm and to then take two cores between 10 and 20 cm to provide six samples for the depth profile (i.e. 0-2, 2-4, 4-6, 6-8, 8-10 and 10-20 cm).

(v) Sample preparation. Dry the samples at 105°C for 24 hours and calculate the bulk density of the soil. Sieve the sample to separate the > 2 mm fraction. Send both samples for analysis.

For wind erosion

Instead of selecting sites along a hillslope catena, select sites along a wind direction known to be erosive. For example, where the most erosive winds are from the north-west, select a NW-SE transect across the paddock to include the erosion, transport and deposition zones within the paddock (or downwind of shelter).

7. SPECIAL PRECAUTIONS:

Problems with the use of the Cs-137 method in Western Australia are:

(i) Cs-137 is not evenly labelled in some bush areas used as input sites. It is thought that cryptogamic mats on the soil surface result in water (and Cs-137) running over the surface before entering the soil. Therefore Cs-137 concentrations at input sites have been lower than expected.

(ii) Water repellent soils may result in similar uneven labelling of soil. If the soil samples come from a repellent area, soil loss may be overestimated but underestimated from areas where the water soaks in will be.

(iii) It is possible wind erosion could blow Cs-137 rich dust into bush areas used for input sites, resulting in input levels that are too high. This problem has not yet been confirmed.

(iv) Significant amounts of Cs-137 may be attached to gravel stones, which requires the stones to be crushed.

(v) As it takes about 12 hours to measure Cs-137 in one soil sample, selecting representative sites is crucial. It is necessary to examine a number of possible sites and interview the farmer to find out the site's history since 1954 before samples are taken.

8. ANALYSIS OF RESULTS:

Cs-137 is measured as millibecquerels (mBq) per gram of soil. It is necessary to convert this measurement to mBq/cm² using:

(dry sample weight * Cs-137 concentration)/area of core of frame.

9. ADDITIONAL COMMENTS:

When working with ANSTO, pack the cores inside a box and send them (and details of their location, core diameter and length etc.) to:
10. REFERENCES:


11. MAIN CONTACT PERSONS:

Don McFarlane, Albany.
4.6 EROSION PINS

1. WHAT IS MEASURED?:
Sheet erosion, estimated by ground retreat about a fixed pin.
Sedimentation/deposition, estimated by soil accumulation about a fixed pin.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:
Sediment can be sampled (by pumped sediment sampler or rising stage samplers) in runoff gauged by weirs or flumes.
Pin profilometers.

3. PREVIOUS USES OF THE METHOD:
Used to estimate sheet erosion from potato cropland after harvesting has redistributed the soil in the rows.
Used to estimate the amount of sediment deposited at changes in slope on paddocks, and at the mouths of rills.

4. COST/AVAILABILITY OF EQUIPMENT:
It is easy to make the pins from heavy gauge wire e.g. 0.3 m lengths of fencing wire. Electrical tape is wound around the wire to provide a reference level against which ground retreat is measured.
In settling soils, wash prevention rings (cylinders) are required to estimate soil settling rates.

5. PRINCIPLES OF METHOD:
Sheet erosion: the pin (bent at the top to facilitate pushing) is pushed into the ground until the tape is at ground level. Measurements are periodically made of how much of the pin below the tape is exposed above the ground giving an indication of the amount of soil loss.

After cultivation, soil settling can be considerable and may continue for many weeks. Therefore a method is required to estimate soil settling so that erosion is not overestimated. Wash prevention rings can be placed around pins placed beside unprotected erosion pins. The rings enable soil to settle during rainfall but soil loss in runoff is avoided. In some soils, rainsplash can add more soil to the inside of the ring than it removes and soil settling may be slightly underestimated. The rings should therefore be wide and shallow to reduce this effect.

Sedimentation: Similar pins as described above can be used in conjunction with flat metal plates. Each plate has a hole in the middle through which the pin is inserted. The pin is pushed into the ground with the base of the plate resting on the soil surface. Measurements are periodically made of the depth of soil above the plate giving an indication of the amount of deposited sediment.
6. **FIELD PROCEDURE:**

At least 50 pins should be pushed into the soil at the measurement site. If soil settling is likely to be a problem when measuring erosion, install wash prevention rings around the pins. Measure both erosion and deposition after major storms.

7. **SPECIAL PRECAUTIONS:**

Soil settling.
Rain splash into wash prevention rings as explained above.

8. **ANALYSIS OF RESULTS:**

Take the soil settling measurement from the unprotected pin measurement to estimate soil loss. If pins have been placed in areas with different treatments (e.g. cover versus bare soil), pooled t-tests can be used to compare the effect of the treatment on soil loss.

9. **ADDITIONAL COMMENTS:**

10. **REFERENCES:**


11. **MAIN CONTACT PERSON:**

Don McFarlane, Albany.
5.1 GRAVIMETRIC SOIL WATER CONTENT

1. WHAT DOES IT MEASURE?

Water content expressed as a percentage of the oven dry weight of the soil.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:

Neutron moisture meter. Schmugge et al. (1980).
Soil moisture probes e.g. gypsum blocks.
Tensiometers which measure soil matric potentials and can be related to water contents through the soil moisture characteristic curve Schmugge et al. (1980).

3. PREVIOUS USES OF THE METHOD:

Used to determine the soil water content in saturated and unsaturated soils for calibrating neutron moisture meters and for determining the height of capillary rise above watertables.

4. COST/AVAILABILITY OF EQUIPMENT:

The main cost is to obtain a number of soil moisture tins. Cost varies depending upon their size. An aluminium tin and lid, 60 mm diameter by 25 mm deep costs $1.35 (1989) and is available from:

Anderson Metal Spinners
48 Owen Road
KELMSCOTT WA 6111

Telephone: (09) 399 3043

Larger tin sizes can be made to order.

A fan forced oven capable of reaching 105°C is needed to dry the soil.

5. PRINCIPLES OF METHOD:

A sample of soil is collected in the tin. To avoid water loss, the lid is sealed with electrical tape.

6. FIELD PROCEDURE:

A sample of soil, (e.g. 100 grams) is collected from areas which need to be measured. Samples can be collected from the soil surface and at various depths below ground. For good results, samples should be taken quickly after soil disturbance. The aim is to measure soil water content with minimal losses during sampling.

Many samples are collected from pits dug with a backhoe. Soil augers can also be used to collect samples at depth.

Soil surface samples are collected by scraping soil into the tin after pasture etc. has been cut away.
Soil tins and lids should be numbered and weighed before use. By keeping records of tin numbers and weights, this can be a one off operation.

When sampling, record the tin number and its sample's location. If you can take a portable weighing scale in the field, then weigh the complete sample as it is collected. Record this as the wet weight, otherwise seal the join between tin and lid with electrical tape and weigh in the laboratory. Keep the samples cool (i.e. in the shade) to reduce moisture losses.

At the laboratory, weigh and record the 'wet weight' of each tin, without the electrical tape. It is essential to record the 'wet weights' as soon as possible after collection. Weigh them on the day they are collected. Put the tins in the oven at 105°C for 24 hours. Remove tins and let them cool in a desiccator. Weigh the tins and record as 'dry weight'.

7. SPECIAL PRECAUTIONS:

Use minimal disturbance when collecting the soil sample. Weigh the complete tin, lid and soil sample as soon as possible after collection, to record 'wet weight'.

8. ANALYSIS OF RESULTS:

A worked example is shown in Appendix 1. All weights are in grams and to one decimal place.

Tin weight is recorded next to the corresponding tin number. Once the 'wet and dry weights' are known, simple calculations derive % gravimetric soil water content. To obtain soil water, subtract 'wet weight' from 'dry weight'. For oven dry soil, subtract 'dry weight' from 'tin weight'. For % gravimetric moisture:

\[
\text{soil water} = \frac{\text{oven dry soil}}{100}
\]

Express % gravimetric water as a whole number (g/g).

If you know the bulk density of the soil, then multiply it by % gravimetric water content to get % volumetric water content. This is expressed as m³/m³ or dimensionless and represents the volume of water in a known volume of soil.

9. ADDITIONAL COMMENTS:

Gravimetric moisture can be obtained in conjunction with bulk density. Use the core method to obtain bulk density, as shown in Section 6.1 of this manual. No tins are needed as the soil cores act as containers. It is essential that the cores are placed in plastic bags, sealed with an elastic band to prevent evaporation immediately after collection and stored in a cool dry place. To simplify weighing, use the same size plastic bags and elastic bands.

In the laboratory, a balance is zeroed with the same size plastic bag and elastic band. The weight of each core, complete with plastic bag and elastic band, is weighed and recorded as 'wet weight'. Record the core number. Weigh a number of small aluminium trays and record their weight. Open the plastic bag, remove the core and empty the soil into a small aluminium oven tray. Place the tray in the oven at 105°C for 24 hours. Weigh the dry weight and record it on the sheet in Appendix 1.
An Australian Laboratory Handbook is being prepared for release in 1990 which contains a chapter on soil water. A photocopy can be obtained from Terry Doney in South Perth.

10. REFERENCES:


11. MAIN CONTACT PERSONS:

T. Doney, South Perth.
### Appendix 1. % Gravimetric water content

<table>
<thead>
<tr>
<th>Tin id.</th>
<th>Tin wt. (g)</th>
<th>Wet wt. (g)</th>
<th>Oven dry wt. (g)</th>
<th>Soil water (g)</th>
<th>Oven dry soil (g)</th>
<th>% Gravimetric water content</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>32.6</td>
<td>105.7</td>
<td>95.1</td>
<td>10.6</td>
<td>62.5</td>
<td>16.96</td>
</tr>
<tr>
<td>7</td>
<td>33.2</td>
<td>112.9</td>
<td>100.2</td>
<td>12.7</td>
<td>67</td>
<td>18.95</td>
</tr>
<tr>
<td>12</td>
<td>31.6</td>
<td>135.7</td>
<td>102.6</td>
<td>33.1</td>
<td>71</td>
<td>46.61</td>
</tr>
<tr>
<td>9</td>
<td>31.9</td>
<td>150.1</td>
<td>131.9</td>
<td>18.2</td>
<td>100</td>
<td>18.2</td>
</tr>
<tr>
<td>6</td>
<td>32.1</td>
<td>145.9</td>
<td>129.6</td>
<td>16.3</td>
<td>97.5</td>
<td>16.71</td>
</tr>
</tbody>
</table>
5.2 NEUTRON MOISTURE METERS

1. WHAT IS MEASURED?

Soil water content is estimated from neutron back scattering.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:

Direct sampling of soil to determine the gravimetric water content (Section 5.1):
- gravimetric water content (g water/g dry soil);
- volumetric water content (cm$^3$ water/cm$^3$ soil) = (gravimetric water content x dry bulk density of soil).
- gypsum blocks.

3. PREVIOUS USES OF THE METHOD:

The neutron moisture meter is frequently used to measure the water content of soil profiles and their change through time. The advantages are that it provides rapid, repeatable, non-destructive measurements of soil water content. With appropriate assumptions and analyses it is possible to estimate changes in the amount of soil water stored in the soil, storage capacity of profile, the available water capacity and the soil water deficit.

4. COST/AVAILABILITY OF EQUIPMENT:

Campbell Pacific Nuclear Corp
CPN-503 Hydroprobe
4.5 diameter probe + 10 m cable
Cost: $10,000 (approximately)
Ex Neutron Probe Services
P.O. Box 486
NARRABRI N.S.W. 2390
Normally stored in "Break-up room"
Department of Agriculture
SOUTH PERTH W.A. 6151

5. PRINCIPLES OF METHOD:

The method is based on the assumption that hydrogen is the major thermalizer of fast neutrons and that hydrogen occurs predominantly in soil water. The concentration of hydrogen atoms in soil water is much higher than in living organic matter (roots) or in non-living organic compounds (humus). Neutron probes contain a radioactive source (Americium 241/Beryllium) in the end of the probe that is lowered down an access tube. The source emits fast neutrons which are slowed by collision with hydrogen atoms in soil water molecules. A detector counts the back-scattered slowed neutrons.

6. FIELD PROCEDURE:

1. Installation of Access Tubes

(a) Sandy soils

For holes up to 2 m deep, hand auger a 55 mm diameter hole, and backfill around the aluminium access tube with spoil or cement slurry. For
deeper holes, various lengths of aluminium access tubing, sharpened on
the leading edge, may be pushed into the soil. Where this may compact
the soil around the tube, power drilling is necessary for deeper holes.
Soil cores obtained may be used for calibration.

(b) Clay and gravelly soils

Drill a 65 to 75 mm diameter hole with a power rotary auger drilling
rig. A slurry consisting of 40% kaolinite, 10% portland cement and 50%
water by weight is poured into the hole. The access tube, sealed at the
bottom is inserted into the slurry to displace it up the full length of
the tube, completely filling the annular space between soil and tube.

In cropped paddocks, tubes should be cut at about 15 cm below ground
level and removable extensions fitted. The position of the buried
access tube can be located with a metal detector after the crop has been
sown.

Access tubes which may be used are Aluminium (50 mm), or P.V.C.-AS1415
(50 mm).

2. Instrument Readings

(a) Standard count

Switch the instrument on about half an hour before taking readings.
Place the container box on the ground with the neutron meter inside.
Press the START button and accumulate five readings in a series. When
monitoring is completed, accumulate another five readings in a similar
manner. Determine the average and the square root of the average. Add
and subtract the square root to the average count. Statistically, more
than seven of the ten counts should lie within the limits of ± square
root of the average. Appendix 1 shows a Field Data Sheet.

(b) Field counts

The probe is lowered down the access tube to be to the desired depth and
locked into position with the aid of a cable step. Upon completion of
the reading, the probe is lowered to the next pre-determined depth. To
take a reading, push the START button, and the gauge sends out a audible
signal at the end of the count cycle. The number on the digital display
is the number of thermal neutrons counted during the period which is
proportional to the total amount of hydrogen present in the surrounding
material. It is not necessary to take more than one reading at a depth.

7. SPECIAL PRECAUTIONS:

All users of neutron gauges must be licensed by the Radiological Council.
This involves passing a written exam and applying for a licence which is
issued for a three year period. Film badges must be worn routinely. They are
processed bi-monthly. Gauges must be anchored in position in the rear of
vehicles at a maximum practical distance from drivers and passengers. Three
radiation labels are to be attached to the vehicle on the sides and rear and
are available from the Transport Officer. Radiation safety involves
maintaining the maximum distance from the source at all times. All use of the
instrument should be performed with speed.
8. **ANALYSIS OF RESULTS:**

**Calibration**

The manufacturer's calibration curve should not be used, rather it is necessary to construct calibration curves for each soil and horizons with soils where they are very different.

(a) **Drum calibration**

Refer to Greacen (1981) p. 73. This method is recommended to aid in calibrating of deep layers, and has the advantage of higher precision and minimum site disturbance.

(b) **Field calibration**

Measure the count rate in the soil at the usual depth intervals over the depth for which calibration is required. For sandy soils and in soft clays it will be possible to hand auger three holes within a 15 cm radius of the access tube. Soil samples are bulked over the required depth range. When hand augering is not possible, a backhoe pit is excavated to the required depth. Cylindrical cores may be used to obtain samples for gravimetric moisture (Section 5.1) and dry bulk density determination (Section 6.1). Additional access tubes should always be installed for the purpose of destructive sampling, one at the wettest time of the year and the other at the end of the dry season. The field calibration method is recommended for the depth range 0-3 m, where major site disturbance is not a problem and for the inspection of soil profiles.

The recommended calibration equation is:

\[ NCR = A + B\Theta \]

where \( NCR = \text{neutron count ratio} = \frac{\text{Field count}}{\text{Standard count}} \)

\( \Theta = \text{volumetric soil water content (cm}^3/\text{cm}^3\) obtained by multiplying the gravimetric water content (g H_2O/g soil) by the bulk density of the soil.

Hence \( \Theta = (NCR - A)/B \).

A worksheet is shown in Appendix 2.

(c) **Analyses of profile data**

A computer program is available from David Tennent for analysing the field data.

9. **ADDITIONAL COMMENTS:**

In duplex (sand over clay) soils, care must be taken that water perching on the clay subsoil does not flow down the annulus around the access tube. In some cases two holes should be used, one for the topsoil and one for the subsoil with a bentonite plug being placed at the topsoil/subsoil interface which will reduce the risk of annular leakage.
Water contents near the top of the soil profile may be underestimated in dry soil if neutrons escape from the soil profile. If surface readings are important, gravimetric samples should be taken (Section 5.1).

10. REFERENCES:

11. MAIN CONTACT PERSONS:
David Tennant, Kim Burke, Ed Solin, Rob Deyl, South Perth.

A neutron moisture meter
Appendix 1.

FIELD DATA WORKSHEET

EXPERIMENT TITLE: ___________________________ NUMBER: ___________
LOCATION: ___________________________ DATE: ___________
NEUTRON METER SERIAL NUMBER: ________________
STANDARD COUNTS: ___________________________

AVERAGE: _______  \( \sqrt{\text{AVERAGE}}: \) _______
AVERAGE: \( \pm \sqrt{\text{AVERAGE}}: \) _______

ACCESS TUBE NUMBER

<table>
<thead>
<tr>
<th>DEPTH (cm)</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>

Appendix 2.

NEUTRON PROBE CALIBRATION WORKSHEET

SITE: ___________________________

<table>
<thead>
<tr>
<th>ACCESS TUBE NO.</th>
<th>DATE</th>
<th>DEPTH (cm)</th>
<th>FIELD COUNT</th>
<th>RATIO(^1)</th>
<th>GRAVIMETRIC MOISTURE</th>
<th>VOLUMETRIC(^2) MOISTURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>20/6/84</td>
<td>25</td>
<td>12,260</td>
<td>0.91</td>
<td>0.054</td>
<td>0.082</td>
</tr>
</tbody>
</table>

\(^1\) Ratio = field count/standard count.
\(^2\) Volumetric water content (\(\text{cm}^3\ \text{cm}^{-3}\)) = gravimetric water content x dry bulk density (\(\text{g cm}^{-3}\)).
5.3 Tensiometers

1. **What is Measured?**
   Soil matric potential.

2. **Alternative Methods of Estimation/Measurement:**
   Soil matric potential can be inferred from moisture retention curves determined in the laboratory using pressure plate equipment (Loveday 1974) or a filter paper technique (Fawcett and Collis - George 1967, Hamblin 1981, Greacen et al. 1987). The filter paper technique can also be used in specific field situations (Greacen et al. 1987).

3. **Previous Uses of the Method:**
   Tensiometers have been widely used to measure soil matric potential and to schedule irrigation.

4. **Cost/Availability of Equipment:**
   Available from: Irrigation Technology and Management
   53 Fitzherbert Avenue
   Wanganui
   NEW ZEALAND
   Prices at March 1990.

<table>
<thead>
<tr>
<th>Item</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monitor</td>
<td></td>
</tr>
<tr>
<td>- cbar/00 model</td>
<td>$695.00</td>
</tr>
<tr>
<td>- mbar/000 model</td>
<td>$795.00</td>
</tr>
<tr>
<td>Tensiometer tubes</td>
<td></td>
</tr>
<tr>
<td>(complete)</td>
<td></td>
</tr>
<tr>
<td>- 300 mm long</td>
<td>$24.00</td>
</tr>
<tr>
<td>- 400 mm long</td>
<td>$25.00</td>
</tr>
<tr>
<td>- 600 mm long</td>
<td>$26.00</td>
</tr>
<tr>
<td>Parts</td>
<td></td>
</tr>
<tr>
<td>- Vacuum stopper</td>
<td>$0.75</td>
</tr>
<tr>
<td>- Dust cap</td>
<td>$0.30</td>
</tr>
<tr>
<td>- Needle for monitor</td>
<td>$0.45</td>
</tr>
<tr>
<td>- Tensiometer cup</td>
<td>$11.00</td>
</tr>
</tbody>
</table>

5. **Principle of the Method:**
   As water is removed from the soil, the suction created removes water from the tensiometer through a porous ceramic cup and generates a suction within the tensiometer vacuum which is equivalent to the suction (matric potential) of the soil.

   The older tensiometers, which had a mercury manometer, were troublesome to use - leakage, de-airing and long equilibration times were areas of concern. Replacing the mercury manometers with vacuum gauges or pressure transducers has improved their efficiency, but unit costs are high, limiting widespread use. Switching devices to allow several tensiometers to be read using a single pressure transducer are described in the literature, but are not commercially available. With the development of self sealing stoppers, several manufacturers have produced systems which allow large numbers of tensiometers to be read with a portable meter. The meter gives a digital readout from a single pressure transducer which is connected to the tensiometer vacuum through a syringe needle piercing the self sealing stopper. The system allows multiple and repeated readings to be carried out easily.
6. **FIELD PROCEDURES:**

Before inserting the tensiometers into the ground, make holes of the same diameter as the tensiometer. We have used a small flighted 'Dutch' auger. The tensiometers are then carefully inserted. Good contact is needed between the soil surface and the tensiometer cup. In some cases a soil slurry has to be used. The hole should be carefully backfilled to prevent water movement between the tensiometer tube and the hole wall. One option is to insert the tensiometers at an angle or horizontally. After insertion, de-aired water is poured into the tensiometer to a predetermined height, the vacuum stopper inserted and covered with the dust cap. Range of measurement is 0 to 1 bar.

7. **SPECIAL PRECAUTIONS:**

The electronics of the monitor must be treated carefully and should be kept in a cool dry place when not in use. Contact between tensiometer cup and soil is critical. Cover the above ground portion of the tensiometer with foil to reflect heat. Removing tensiometers from the ground after use is difficult and cup breakages are likely.

8. **ANALYSIS OF RESULTS:**

Gives direct readout in mbar.

9. **ADDITIONAL COMMENTS:**

10. **REFERENCES:**


11. **CONTACT PERSONS:**

David Tennant, South Perth.
5.4 LYSIMETERS

1. WHAT IS MEASURED?:

The change in weight of a block of soil in which plants may be growing. Any change in weight is assumed to be water entering or leaving the soil.

2. ALTERNATIVE METHOD OF ESTIMATION/MEASUREMENTS:

Sections 11.1 to 11.4.

3. PREVIOUS USES OF THE METHOD:

Large lysimeters have not been used but micro-lysimeters (< 20 kg) have been used to measure soil evaporation (Dave Tennant) and dewfall (Rob Sudmeyer) on a daily basis. Monolith lysimeters have been used by CSIRO (Munna Sharma) and University of Western Australia (Ralph Sedgely).

4. COST/AVAILABILITY OF EQUIPMENT:

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Cost (AU$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>monolith weighing lysimeter</td>
<td>??? (a lot)</td>
</tr>
<tr>
<td>small lysimeter</td>
<td></td>
</tr>
<tr>
<td>balance</td>
<td>3,500</td>
</tr>
<tr>
<td>materials for block and pit</td>
<td>100</td>
</tr>
</tbody>
</table>

5. PRINCIPLES OF METHOD:

A weighing lysimeter consists of a container holding soil and perhaps growing plants. The container is sunk into a pit so that the soil surface in the container is level with that of the surrounding surface. The block of soil should be undisturbed and exhibit the same thermal capacity as the surrounding soil. The container may be mounted on a weighing device or removed from the pit and weighed on a balance. Rainfall or dewfall will be registered as a weight gain while evapotranspiration (Et) and drainage will register as a weight loss; drainage is collected and measured.

Depending on the resolution of the weighing device, weight changes can be expressed in mm/day or mm/hr.

6. FIELD PROCEDURE:

The plant species will to some extent determine the size of the lysimeter, this could range from something capable of holding a 28 m tree weighing 30 tonnes to a lysimeter with a surface area less than 0.1 m². The time over which measurements are made is also critical, container size should be large enough so that the thermal and moisture characteristics will not vary significantly from the surrounding soil.

Large lysimeters usually provide a continuous record of weight change. The small lysimeters used within the Department are removed from the pit for weighing and provide weight change over the time period.

7. SPECIAL PRECAUTIONS:

A micro-lysimeter soil core should only be used for a maximum of 48 hours before a fresh soil sample is obtained, this ensures soil properties are similar to those of the surrounding soil.
When using small lysimeters the leaf area index (LAI) of the vegetation on the lysimeter should be compared with the LAI of the surrounding vegetation and any differences accounted for when determining Et.

Careful consideration should be given to the placement of the lysimeter in terms of fetch and exposure.

A lysimeter 15 cm deep will be representative of the surrounding soil for at least 48 hours.

8. ANALYSIS OF RESULTS:

Weight loss (g of water) can be expressed in terms of volumetric water loss if the volume of the lysimeter is known or in terms of mm of water if the surface area is known.

9. ADDITIONAL COMMENTS:

I should be emphasised that monolith lysimeters are an expensive and fixed option, the cost involved in establishing the facility precludes their use in comparative trials. Micro-lysimeters can provide a cheap and simple method of measuring soil evaporation and may be of limited use in determining Et.

10. REFERENCES:


6.1 BULK DENSITY

1. WHAT IS MEASURED?
   Apparent density of field soils and aggregates.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:
   Gamma radiation method. Water content at time of measurement must be known.

3. PREVIOUS USES OF THE METHOD:
   The method is a partial expression of soil structure and can be used to
determine porosity, pore space relationships and density.

4. COST/AVAILABILITY OF EQUIPMENT:
   Readily available from Eijkelkamp (Sauze Technical Products Corp. 212 Oak St.
   Extension, Plattsburgh, New York 12901); or stainless steel pipes can be
   purchased from Stirling Metals (Perth) and cut to the appropriate length.

5. PRINCIPLES OF METHOD:
   A known volume of soil is collected from a natural site and oven dried at
   105°C for 48 hours. The bulk density is the oven-dried mass divided by the
   volume of the sample.

6. FIELD PROCEDURE:

A Core method (measures the bulk density of the soil)

1. Prepare a flat surface in a sampling pit (either vertical or horizontal).
2. Press or hammer the core sampler into one soil.
3. Remove the core with the sample from the site, cut the soil flush with a
   sharp knife at both ends, cut off roots with a pair of scissors.
4. Put the core and sample into a plastic bag and seal it. Keep the sample
   in a cool place (to prevent evaporation from the sample).
5. Transport the sample to the laboratory and keep it in a fridge at +5°C.

Laboratory Procedure

1. Transfer the soil from the core to a weighed and labelled container with
   lid.
2. Weigh the sample in the container, then dry it at 105°C until a constant
   weight is reached (at least 48 hours) then cool in desiccator and weigh.
3. Determine the volume of the core.
4. Calculate the bulk density:
   \[
   \text{Bulk density} = \frac{\text{weight oven-dried soil}}{\text{soil volume}} \quad \text{Mg/m}^3 \text{ or (g/cm}^3\text{)}
   \]

B Clod method (measures the bulk density of aggregates)

1. Collect natural clods (50 to 200 mm size).
2. Transport the clods in sealed containers.
Laboratory Procedure

1. Tie a length of thread to a clod of soil and weigh it.
2. Quickly dip the clod with the thread into molten wax.
3. Wax must be just above the melting point.
4. Wax covering must be complete (water should not be able to enter soil).
5. Weigh the wax covered block in air (mass of wax is then known).
6. Weigh a beaker of water on a top weighing balance.
7. Weigh the wax-covered clod (suspended from a fixed support) in the water when its completely submerged.
8. Determine the moisture content of the clod by peeling off the wax or with a subsample of the same layer and drying in oven for 48 hours at 105°C.
9. The volume of the clod equals the volume of the clod plus wax less the volume of the wax (density of the wax must be known).
10. Calculate the bulk density:

\[
\text{Bulk density} = \frac{S_w \cdot W_{odc}}{W_{ca} - W_{cpw} + W_{pa} - (W_{pa} \cdot S_w/S_{wax})}
\]

where
- \(S_w\) Density of water at the temperature of determination.
- \(W_{odc}\) Oven dried weight of the clod.
- \(W_{ca}\) Net weight of the soil clod in air.
- \(W_{cpw}\) Net weight of the soil clod plus wax in water.
- \(W_{pa}\) Weight of the wax coating in air.
- \(S_{wax}\) Density of wax (approximately 0.9 mg/m³).

A method using kerosene and pycnometer bottles can also be used to estimate the bulk density of aggregates.

C Excavation Method Procedure

1. Excavate a certain quantity of soil (e.g. hole 12 x 12 cm).
2. Dry and weigh the excavated soil material.
3. Determine the volume of the excavation site by:
   - filling the hole with sand with a known bulk density; or
   - inserting a balloon into the hole and filling it with water until the hole is just full.

The volume of the excavated soil sample is then equal to the volume of the added sand or water.

7. SPECIAL PRECAUTIONS:

Be careful not to cause compaction (when too wet) or fracturing (when too dry).

Both methods (core and clod method) are inappropriate in stony or gravelly soils. Bulk densities should be determined by a replacement method, e.g. the excavation method in such soils.

If sand is used to determine the volume of the excavation site, it must be dry, clean, and free-flowing. Sand sizes between 0.25 mm and 0.85 mm are recommended. Test the sand-filling procedure beforehand, especially the flowing rate and falling height of the sand that will be used in the field. In the field the same flowing rate and falling height must be maintained. More compaction may occur from a higher falling level. Calibration curves must be constructed for various sand sizes and falling heights.
Bulk density determinations become inaccurate when stone contents exceed 10% by volume or the diameter of stones exceeds 2 cm. The replacement method should then be chosen. For soils with up to 30% stones, less than 6 cm in diameter, a sample volume of 20 litres should be obtained by the replacement method.

Core samples should not be taken in very dry or wet soils. In wet soils friction along the walls of the core and in dry soils vibration due to hammering are likely to disrupt the natural structure.

Compression occurs in dry soil, even if the soil material is very loose. In clayey and/or hard soil hammering becomes the only means to push the core into the soil material. A loosening of the soil structure may result and the core obtained will not be representative.

A close examination of the sample in the core and the soil material at the excavation site will give an idea of the seriousness of the shattering effect.

The weight of the sand used should be known to the nearest 5 g and the volume of the mass of sand can be read from the calibration curve.

If a balloon is used, the volume of water used to fill the hole must be estimated to within 2 mL (use a 1,000 mL measuring cylinder).

8. ANALYSIS OF RESULTS:

The bulk density should be given to the second decimal. The units are g/cm³ and the SI-units Mg/m³.

If the soil core or clod contains a stone, the solid density of the stone and its volume must be determined in order to calculate the bulk density of the fine earth:

\[ G = \frac{\text{Weight of soil} - \text{weight of stone}}{\text{Volume of core} - \text{volume of stone}} \]

Results obtained should show: means and standard deviation for replicates, and details of sampling depths.

9. ADDITIONAL COMMENTS:

Bulk density measurements are only a partial expression of soil structure but they are a very important in estimating water holding capacity, void ratio and air capacity.

Some unexplained variation in water retained in soil layers is due to inaccuracy in measuring bulk density and is due to the heterogeneity within seemingly homogeneous soil layers.

Water retention in the topsoil is most correlated with organic matter and bulk density, and in the sub-soil layers with the particle size group 2-100 µm, the clay mineralogy and the bulk density (Hall et al. 1977).

The volume of cores should be larger than 290 cm³ (size of core diameter should be 1.5 times larger than its length; core volumes of 700 to 1,000 cm³ are common). The corer should be made of strong, non-rusting metal so it will not lose its shape.
Samples should not contain coarse fragments bigger than 10-20 mm in diameter and no large cracks.

For cracking clays, very large cores are necessary to obtain representative bulk density values. Using small cores to determine small changes of bulk density over short distances is not advisable because of an increasing error due to heterogeneities in the soil and due to experimental inaccuracies.

10. REFERENCES:


11. MAIN CONTACT PERSONS:

G. Scholz, South Perth.
6.2 PENETROMETER MEASUREMENTS OF SOIL STRENGTH

1. WHAT IS MEASURED?:
Penetrability - the ease with which a probe can be pushed into the soil.
A measure of soil strength.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:
Measurement of impact soil penetration - used on very high strength soils; bulkier equipment, slower to use, less able to detect differences between soil horizons.

3. PREVIOUS USES OF THE METHOD:
Used to detect depths and strengths of hardpans (both natural and as a result of human activities), and to measure the depth of an infiltration wetting front. It can also be used to investigate soil variability, as soil penetrability integrates a combination of other soil properties.

4. COST/AVAILABILITY OF EQUIPMENT:
(a) Bush Recording Penetrometer, with electronic digital readout of depth and force units to a maximum depth of 52.5 cm. Purchase price approx. $5,000; units available for loan from P. Blackwell or D. Carter, Soil & Vegetation Management Branch, or R. Jarvis, Plant Industries Division. A Datamyte data logger for this model of penetrometer is made, but is not currently available.

(b) Remix Cone Penetrometer, with digital readout and inbuilt data logging of depth and force values to a maximum depth of 45.0 cm. Purchase price approx. $3,500; a unit is available for loan from Tony Proffitt, Northam Regional Office.

5. PRINCIPLES OF METHOD:
The instrument records the force required to push a cone downwards through the soil. This force is determined using a pressure transducer in the instrument box, with the force reading being the average value over a pre-determined depth increment. Light sensitive cells detect the depth of the force reading from markings on the penetrometer shaft.

The force required to push the cone through the soil depends on a number of factors. These include soil density, moisture content, particle size distribution, inter-particle bonding and the depth of overburden, all of which affect soil cohesion and friction. The cone angle, its basal area, material of manufacture, rod structure and speed of penetration also affect the soil resistance measured.

The force reading is commonly converted into a pressure value by dividing it by the basal area of the cone. When used for detecting hardpans, the object is to obtain a soil resistance index that will in some way quantify the resistance to roots (or less commonly water), moving through the particular soil layer being investigated. The assessment of depth to a wetting front depends on measuring a rapid increase in soil penetration resistance as the cone moves into drier soil.
6. **FIELD PROCEDURE:**

**Instrument calibration**

The calibration should be checked at approximately weekly intervals and a confidence check carried out before and after each day's use. This may be done by using the instrument's own weight or by loading the instrument's tip while on a weighing balance with the moving main shaft supported.

The calibration procedure is:

(i) Switch on and allow one minute warm-up before calibration. With the cone tip unloaded, turn the BALANCE knob until the minus sign on the display just disappears.

(ii) Use the RESET STORE switch to record the load-cell reading in each register and on the display. This provides a convenient means of observing load-cell readings during the calibration. The load-cell will register either in "kg f" (kilograms force) or arbitrary units as specified by the customer.

(iii) A set of weights is required, covering the load range in suitable intervals. The recommended arrangement is a set of 5 kg weights suspended from the handles by a hanger. The penetrometer head weight (6 kg) is used as the first step, and the hanger weight arranged to bring this up to 10 kg for the second step.

(iv) Release the main shaft clamp. Rest the cone tip on a block of wood or plastic to avoid damage. Press RESET STORE. This should register the penetrometer head weight 6 kg (or equivalent arbitrary units).

(v) Increase the load in steps, pressing RESET STORE each time to observe the readings. Repeat the procedure as the load is reduced to zero.

(vi) The accuracy of this calibration procedure in establishing the relation between cone resistance and load reading is limited by the sensitivity of the read-out (+ 1/2 unit), and the number of independent observations on which the calculation is based.

This is a matter for orthodox statistical treatment, and a calculator program can be provided to supplement basic regression analyses with estimates of 95% confidence intervals for predictions based on the calibration data.

**Cones**

Select either the small cone (12.83 mm diameter) or the large one (20.27 mm diameter) according to the strength of the soil to be tested. It is important to record which size is used. Cone wear should not be allowed to exceed 3% of the diameter and should be checked daily. If the cone passes through the hole in the test gauge provided, the cone should be discarded and a new one fitted. The rectangular notches in the gauge may be used to remove or retighten cones and the support rod.

**Using the penetrometer with a calculator**

(i) Switch ON for one minute before use. Numbers should appear on the readout displays.
(ii) Check the zero balance, and if necessary adjust as follows:

Remove the plastic cover of the instrument and with the cone unloaded set the BALANCE knob so that the minus sign on the load readout is just off. Replace the cover.

(iii) Press the RESET STORE switch with the cone unloaded and hold it down for two seconds. This clears all the load registers and the LOAD readout will then read 00. RESET DEPTH must be pressed after RESET STORE.

(iv) Release the main shaft clamps. Push the instrument into the ground at a penetration rate of about 3 cm/s. At this rate it penetrates 52 cm in 17 seconds.

If the cone hits a stone or a hard soil layer the instrument overloads and it will bleep. This is a warning that the last reading recorded may be unacceptable. The overload signal is usually set at 50 kg. Pull the instrument out of the ground. Press the RESET DEPTH switch so that the DEPTH LEVEL reads 00.

(v) Press the CLOCK DEPTH switch. The instrument will indicate the depth level and the corresponding load, for example as follows:

01 : 05
DEPTH LOAD
LEVEL

Record the data by hand.

Each time the CLOCK DEPTH switch is pressed the depth level reading will increase by one, and the load corresponding to each depth will be displayed. Depth level readings above 15 are not relevant. Convert each depth level number to actual depth in centimetres for the interval spacer being used.

Before making the next penetration, press RESET STORE and RESET DEPTH.

Depending on the purpose of the measurement and the homogeneity of the soil, a large number of measurements may be required. For example, on a relatively uniform loamy sand, a minimum of five and preferably ten penetrations are required to adequately characterize a 20 m x 2 m experimental plot.

Soil moisture samples or measurements should be taken whenever penetrometer measurements are made. Sufficient samples should be taken to characterize the soil moisture content of the profile at each penetration site. This does not mean a moisture sample at each penetration, but rather sampling those sites or treatments where moisture profile differences are likely.

7. SPECIAL PRECAUTIONS:

Soil penetration resistance increases roughly in proportion to soil matric suction. This explains why the penetrometer can be used to detect the depth of a wetting front, but also complicates the interpretation of penetration resistance profiles where there is a variable moisture content down the soil profile. If you want to investigate compacted layers or hardpans, they are best done when the soil is uniformly wet. This can occur two to three days after substantial rainfall or irrigation. Penetration measurements on stoney or gravelly soils are also of limited value, as the readings are strongly
skewed by the intersection of the probe with gravel or rock. Measurements can be made in heterogeneous soils, such as gradational or duplex soils, but interpreting results can be difficult, due to variability in the factors mentioned in the Field Procedure. These soils are inherently more variable, both vertically and horizontally than the more uniform loamy sands on which the bulk of penetrometer measurements in Western Australia have been made.

8. ANALYSIS OF RESULTS:

Core resistance is generally calculated by dividing the force required to push the core through the soil by the basal area of the core, giving units of pressure (e.g. MPa). This parameter is alternatively referred to as the core index, penetration resistance or mechanical impedance (Henderson 1989). The reading can also be used to index how easily the soil is deformed by traffic or tillage implements.

The accompanying table shows penetrometer readings (kg force) obtained from five penetrations in an unripped soil. Figure 1 shows the penetration resistance profiles and accompanying confidence intervals for the two plots. The penetrometer readings have been converted into pressure values by multiplying by a constant derived from the basal area of the cone. For making comparisons between plots, it is often useful to have a single index that describes the soil resistance profile in a single value. Two such indices are the maximum penetration resistance recorded in a given depth interval, or the mean resistance over the interval. The depth interval chosen can be the full profile tested, or a shallower profile for comparing treatment effects.
Penetrometer readings (kg force)

Unripped plot

<table>
<thead>
<tr>
<th>Depth interval (cm)</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>Mean</th>
<th>95% Confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0-3.5</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>1-3</td>
</tr>
<tr>
<td>3.5-7.0</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>1-4</td>
</tr>
<tr>
<td>7.0-10.5</td>
<td>5</td>
<td>4</td>
<td>10</td>
<td>5</td>
<td>10</td>
<td>7</td>
<td>3-11</td>
</tr>
<tr>
<td>10.5-14.0</td>
<td>17</td>
<td>16</td>
<td>19</td>
<td>13</td>
<td>22</td>
<td>17</td>
<td>13-21</td>
</tr>
<tr>
<td>14.0-17.5</td>
<td>25</td>
<td>30</td>
<td>28</td>
<td>21</td>
<td>34</td>
<td>28</td>
<td>22-34</td>
</tr>
<tr>
<td>17.5-21.0</td>
<td>33</td>
<td>37</td>
<td>33</td>
<td>34</td>
<td>44</td>
<td>36</td>
<td>30-42</td>
</tr>
<tr>
<td>21.0-24.5</td>
<td>38</td>
<td>40</td>
<td>37</td>
<td>41</td>
<td>47</td>
<td>41</td>
<td>36-46</td>
</tr>
<tr>
<td>24.5-28.0</td>
<td>42</td>
<td>44</td>
<td>39</td>
<td>45</td>
<td>50</td>
<td>44</td>
<td>39-49</td>
</tr>
<tr>
<td>28.0-31.5</td>
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<td>43</td>
<td>40-46</td>
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<td>31.5-35.0</td>
<td>37</td>
<td>43</td>
<td>38</td>
<td>44</td>
<td>46</td>
<td>42</td>
<td>37-47</td>
</tr>
<tr>
<td>35.0-39.5</td>
<td>36</td>
<td>42</td>
<td>33</td>
<td>35</td>
<td>41</td>
<td>37</td>
<td>32-42</td>
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<tr>
<td>39.5-42.0</td>
<td>32</td>
<td>39</td>
<td>31</td>
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<td>37</td>
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<td>31-40</td>
</tr>
<tr>
<td>42.0-45.5</td>
<td>29</td>
<td>36</td>
<td>30</td>
<td>35</td>
<td>33</td>
<td>33</td>
<td>29-36</td>
</tr>
<tr>
<td>45.5-49.0</td>
<td>26</td>
<td>33</td>
<td>28</td>
<td>30</td>
<td>31</td>
<td>30</td>
<td>26-33</td>
</tr>
<tr>
<td>49.0-52.5</td>
<td>24</td>
<td>29</td>
<td>25</td>
<td>28</td>
<td>28</td>
<td>27</td>
<td>24-30</td>
</tr>
</tbody>
</table>

Max. 0-52.5        | 42 | 44 | 40 | 47 | 50 | 45   | 40-50                   |
Mean 0-52.5        | 26 | 29 | 27 | 28 | 32 | 28   | 25-31                   |
Max. 0-39.5        | 42 | 44 | 40 | 47 | 50 | 45   | 40-50                   |
Mean 0-39.5        | 25 | 28 | 26 | 26 | 31 | 27   | 24-30                   |

Data for the ripped plot is shown in Figure 1.

9. ADDITIONAL COMMENTS:

Other penetrometers such as pocket penetrometers for assessing soil crusts are available, but they are of limited value in the field, because of a lack of electronic data recording and their restricted depth and accuracy. At best they can only be used as indicators of soil structural problems.
Figure 1. Soil penetration resistance as a function of soil depth for a ripped and unripped soil.
10. REFERENCES:


Henderson, C.W.L. (1989). The diagnosis, prediction and amelioration of subsoil compaction on the sandplains of the Northern Agricultural Region of Western Australia. M.Sc.(Agric.), U.W.A.


11. MAIN CONTACT PERSONS:

R. Hetherington, Albany.
R. Jarvis, Perth.
G. Reithmuller, Merredin.
6.3 AGGREGATE STABILITY

1. WHAT IS MEASURED?:

Slaking and dispersion of soil aggregates when immersed in water.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:

There are many methods of measuring aggregate stability. Two methods that use undisturbed soil aggregates are:

(i) stability to single water drop impact e.g. Wustamidin et al. (1983);
(ii) water stable aggregation by wet sieving (Yoder 1936; Kemper and Chepil 1965).

Alternative methods that use bulk soil samples include:

(i) dispersion percentage index (Richie 1963);
(ii) pinhole test (Sherard et al. 1976);
(iii) dispersion in relation to soil and solution chemistry (Rengesamy et al. 1984);
(iv) disc strength test (Cochrane 1989).

The Emerson method of aggregate stability measurement is simple and requires no special skills or laboratory facilities. The technique is well suited to the screening of a large number of soil types.

3. PREVIOUS USES OF THE METHOD:

The method was initially described by Emerson (1967) and has since been used extensively to classify soils according to their dispersive behaviour. This classification has been used to assess the erodibility of soils, suitability for earthwork construction and the likely reaction of the soil to particular land use systems. A review of the soil aggregate classification system has been written by Emerson (1983).

4. COST/EAVILABILITY OF EQUIPMENT:

The method requires no special equipment other than a supply of deionized or distilled water.

5. PRINCIPLES OF METHOD:

Soil aggregates are classified according to their slaking and dispersion characteristics when immersed in water.

Slaking is the process of cracking and fragmentation that occurs when the aggregate is wet rapidly. Slaking is regarded as a physical process and is largely due to the disruptive forces when the aggregate is immersed in water. Slaking can also result from the impact of raindrops.

Dispersion involves further breakdown of the soil aggregates; whereby the clay particles separate from each other and from the sand and silt particles and move into suspension in the surrounding water. Dispersion is highly dependent on the soil chemistry and the clay mineralogy, however no clear relationship exists to describe all soil types. The chemistry of the solution in which the aggregate is placed will also influence both the rate and extent of dispersion.
Emerson (1967) classified the slaking and dispersion of soil aggregates into 8 classes.

Class 1 - Complete dispersion of air dry aggregates.
Class 2 - Partial dispersion of air dry aggregates.
Class 3 - Dispersion after remoulding aggregates at field capacity moisture content.
Class 4 - Soils that do not disperse and contain gypsum or carbonate.
Class 5 - Dispersion after end-over-end shaking in a 1:5 soil: water extract.
Class 6 - No dispersion after-end-over end shaking in a 1:5 soil: water extract.
Class 7 - No slaking, however much aggregates swell.
Class 8 - No slaking and aggregates do not swell.

Loveday (1973) outlined a scoring system which is applied to the Emerson (1967) test and enables the calculation of a 'dispersion index' (DI) for the soil aggregates. The method used to obtain the DI is outlined below.

6. LABORATORY PROCEDURE:

(i) Separate aggregates of approximately 3 to 5 mm diameter from air dry soil samples.

(ii) Drop one aggregate into 50 mL of deionized or distilled water in a 100 mL beaker, note whether the aggregate slakes or not.

(iii) Leave the beakers undisturbed. The degree of dispersion is visually assessed and a score of 0, 1, 2, 3 or 4 is assigned at 2 and 20 hours after immersion in water. The scoring system is used in the following manner:

0 - Nil dispersion.
1 - Slight dispersion, indicated by a slight milky halo surrounding the aggregate.
2 - Moderate dispersion, a clear halo of dispersed clay is observed around the aggregate.
3 - Strong dispersion, considerable milkiness surrounds the aggregate and approximately half of the aggregate has dispersed.
4 - Complete dispersion, the dispersed clay will have separated completely from the soil aggregates and spread across the bottom of the beaker, only sand grains will be left where the aggregate was placed.

(iv) For those soils that Score 0, a sample of soil is then passed through a 2 mm sieve and wet to field capacity, preferably by equilibration at 100 cm of water suction or by wetting the soil until it becomes almost sticky when manipulated. The wet soil is mixed into a homogeneous paste using a spatula and aggregates of 5 mm diameter are moulded either using a constructed mould or between finger and thumb. The remoulded aggregates are then treated as above (steps ii and iii).

(v) The final dispersion index (DI) value for the soil is calculated in the following way:
\[
DI = (\text{air dry aggregate 2 hr score} + \text{air dry aggregate 20 hr score} + 8) \\
+ (\text{remoulded aggregate 2 hr score} + \text{remoulded aggregate 20 hr score})
\]
to give a value between 0 and 16, where 16 indicates complete dispersion and values less than 8 indicate dispersion occurred only after remoulding.

A simplified field procedure is described in Frost and Orr (1990).

7. **SPECIAL PRECAUTIONS:**

(i) Considerable variability in aggregate stability occurs both within and between soils, therefore a number of aggregates should be used for each sample and the soil DI quoted as a mean with a standard deviation.

(ii) Clay dispersion is sensitive to electrolyte concentration. Therefore distilled or deionized water must be used. Where the soil is to be irrigated, DI indexes should be measured in solutions with a similar chemistry to the irrigation water.

(iii) The moisture content at which the soil is remoulded is also critical. It is thus ideal to wet the soils to a water potential of 100 cm water suction. If this is not done then care should be taken not to overwet the soils.

(iv) The soils should not be too wet when sampled as remoulding may occur during the sampling and subsequent handling. Moist samples should be handled with care and should not be oven dried.

8. **ANALYSIS OF RESULTS:**

The DI for the soil aggregates can be interpreted in the following way:

\[
\begin{align*}
\text{DI} = 0, & \quad \text{soil aggregates are highly stable to wetting.} \\
\text{DI} > 1 \text{ and } < 8, & \quad \text{soil aggregates will disperse to varying degrees after remoulding at field capacity moisture content.} \\
\text{DI} > 8, & \quad \text{soil aggregates will disperse spontaneously to varying degrees when immersed in water.}
\end{align*}
\]

The final interpretation will depend on the individual application. For example, soils with a DI greater than 8 are likely to be responsive to gypsum and could be at risk with respect to piping failure in dam constructions, and severe gully erosion where the subsoil has a high DI. Soils with a DI less than 8 and greater than 0 will be susceptible to structural degradation with cultivation and may be responsive to gypsum.

9. **ADDITIONAL COMMENTS:**

The use of the DI is only semi-quantitative. The index can however be used as a quick and simple aggregate stability estimate for screening soil types and for comparing the effects of land use practices within one soil type. An example of the latter use can be found in Hamblin (1984).

10. **REFERENCES:**


11. MAIN CONTACT PERSONS:

P. Blackwell, Geraldton.
T. Proffitt, Merredin
H. Cochran, U.W.A.
F. Frost, Northam.
6.4 WATER REPELLENCY - THE "MED" TEST

1. WHAT IS MEASURED?:

The water repellency of a soil is determined by the molarity of ethanol droplets (MED) to penetrate the soil surface in 10 SECONDS.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:

"Water repellence" is a relative term as no surface actually exerts a repulsive force on a liquid. The term "repellent" relates to the surface contact between the wetting liquid and the soil, which is controlled by the contact angle and surface tension of the solid-liquid interface. The appropriate measurement is the contact angle to give the relative "repellence" of the soil. This can be measured in the laboratory by the capillary rise method (Emerson and Bond, 1963). The capillary rise method is time consuming because an identical sample must be fired at 250°C to remove the hydrophobic agencies, so a comparison between the wetting state and the non-wetting soil is obtained. The contact angle is then calculated by the following method.

\[ \frac{h}{\cos \theta} = \frac{h_0}{\cos 0°} \]

Where

- \( \theta \) = contact angle.
- \( h \) = capillary rise in non-wetting column of soil.
- \( h_0 \) = capillary rise when the contact angle is 0° (wetting soil).

A water drop penetration time (WDPT) method was devised (Letey, 1969) where the timing of the entry of a drop of water into a soil was recorded. This is restrictive and only indicates whether the soil is above or below 90° contact angle. Its usefulness is in rapid assessment of the soil, but with very limited accuracy.

Small ring infiltrometers (King 1981) have been used to assess the degree of water repellence. Also disc permeameters can measure the effects of non-wetting soils on infiltration rates by using ethanol in comparison to water as the infiltrating fluid (Tillman et al., 1989).

Contact angles have also been measured from photographs of water drops sitting on the flat surface of water repellent soils (Bond, 1968).

3. PREVIOUS USES OF THE METHOD:

The MED test has been used in WA on agricultural soils.

4. COST/AVAILABILITY OF EQUIPMENT:

The requirements for the MED test is a set of ethanol solutions with molarities ranging from 0 to 4.0 m at 0.2 m intervals. In some soils the upper limit may be 5.0 m. The solutions should be stored in glass, well-stoppered bottles. Plastic bottles either absorb or allow ethanol to escape, thus changing the molarities rapidly. A small syringe delivering a 0.1 mL drop should be used in applying the drop of ethanol solution to the soil surface. A stopwatch is required to time the entry of ethanol drops, but with experience of measurements, this timing can be estimated.
Absolute ethanol is essential in making up the different solutions. The sale and use of this grade of ethanol is controlled by the Commonwealth Government under its Customs Department. Therefore permits are required to purchase the ethanol. Usually the Department of Agriculture and its district offices already possess this permit, but this should be checked.

5. **PRINCIPLES OF THE METHOD:**

The increase in molarity of the ethanol solutions decreases the surface tension of the applied liquid and this is used to assess the critical surface tension at which the liquid penetrates the soil. When the surface tension of the liquid applied to the soil is lower than the critical surface tension the water drop should be absorbed instantaneously. However, King (1981) designated that the repellence was to be represented by the molarity of the aqueous ethanol to penetrate the soil surface in 10 seconds. This he called the Molarity of Ethanol Drop (MED) test.

King (1981) also showed that there was a direct relationship between contact angle and surface tension for a range of Australian soils, and therefore the MED test indirectly measures the contact angle.

6. **PROCEDURES:**

**OPERATION** - An appropriate ethanol solution is selected, say 0.28 M, from which a drop (0.1 mL) is applied to the flat surface of the test soil. The time for that drop to completely penetrate the soil surface is recorded. Another solution is tried until the recorded penetration time is closest to 10 seconds. Three replicate drops are used for each determination.

The MED test is not applicable to the field, because tests should be carried out in more controlled environment of the laboratory, and with dry soils (at least air dried).

Soil samples can be taken at any depth to measure water repellency down the profile, but the hydrophobic (non-wetting) material is concentrated in the top 50 to 100 mm of soil.

A sample of 50 to 100 g is necessary at any one position, but the number of samples taken should be calculated from the expected variability in the paddock. In most cases this is very high and a minimum of twenty samples should be taken for paddock sized surveys.

**Laboratory Analysis**

The field samples should be air dried or oven dried (not greater than 60°C) and gently sieved (< 1 mm). The soil sample is placed in a small container so that a flat upper surface is produced upon which the drop of ethanol is placed.

When the appropriate molarity is obtained, the soil should be tested with the two molarity intervals above and below, to further check the result.

7. **SPECIAL PRECAUTIONS:**

The molarity of the ethanol solutions change with time due to evaporation, absorption and inadvertent mixing. This is minimized by using good stoppers, glass bottles and expressing all solution from the syringe between testing each molarity. To check the molarity, a refractometer measuring specific gravity of the solution, will quickly indicate if new solutions are required. Solutions should not be stored for more than six months.
The MED test is sensitive to temperature (King 1981) and tests should be performed at close to 20°C for reliable results. If this is not possible corrections should be made - see King (1981).

The field sampling procedure is simple but it should be realized when taking samples after the break of the season, there is a great deal of variation in infiltration due to surface hollows, root channels and general fingering of water penetration. To overcome these problems it is more desirable to sample before the break of season.

8. ANALYSIS OF RESULTS:

The procedure is straight forward in that it produces direct results. Temperature compensations should be determined from iso-ratings of repellence (King, 1981) - Figure 1.

9. ADDITIONAL COMMENTS:

10. REFERENCE:


11. MAIN CONTACT PERSONS:

Dan Carter, Albany District Office.
Paul Blackwell, Geraldton District Office.
Bill Crabtree, Esperance District Office.

Figure 1. Iso-ratings of repellence.
7.1 CONSTANT HEAD WELL PERMEAMETER

1. WHAT IS MEASURED?:

Saturated hydraulic conductivity of the soil above a watertable.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:

A wide range of techniques has been developed to measure the saturated hydraulic conductivity of soils above and below a watertable. Table 1 summarizes the main methods cited in the literature. This review concentrates on the technique developed by Talsma and Hallam (1980) and updated by Reynolds et al. (1983) and Nash et al. (1986).

3. PREVIOUS USES OF THE METHOD:

The hydraulic conductivity of a soil is its ability to transmit water. An estimate of unsaturated hydraulic conductivity can be used to describe soil-water movement at specific sites while saturated hydraulic conductivity can be used to estimate groundwater movement on a landscape scale.

Problems associated with deriving reliable estimates of hydraulic conductivity from laboratory studies using "undisturbed" cores or repacked samples, have stimulated the development of in situ field techniques.

In situ techniques of estimating hydraulic conductivity can be used to estimate other hydrological processes. Talsma and Hallam (1980) used estimates of hydraulic conductivity to estimate runoff from various soil types in a catchment. Talsma et al. (1986) also sought relationships between landscape units and their hydraulic conductivity. Their estimates relied on the premise that surface soil properties reflected broader scale infiltration and redistribution processes.

4. COST/AVAILABILITY OF EQUIPMENT:

Constant head well permeameters (Reynolds et al. 1983) or 'Talsma tubes' as they are often called (after Talsma and Hallam 1980) can be made simply and cheaply. Talsma tubes as described in Talsam and Hallam (1980, p.142) or Reynolds et al. (1983, p 262) can be made for about $50.00. They consist of a small diameter acrylic tube inside a larger diameter tube with a rubber bung holding the small tube in place (Figure 1). The Tube is clamped to a tripod which is stationed over the hole.

The construction materials and instructions for use are summarized in Talsma and Hallam (1980) and in Reynolds et al. (1983).

Schofield and Bell (1990) have made an adaption for high permeable soils. A 40 L water storage column with additional air and water hoses are used.

5. PRINCIPLES OF METHOD:

The method, developed by Talsma and Hallam (1980) and updated by Reynolds et al., (1983) seeks to maintain a constant head of water within an auger hole. The head is maintained at a constant level from a reservoir by way of a Mariotte tube. Below the water surface in the auger hole flow occurs through the walls and base of the auger hole.
Figure 1. Constant head well permeameter (not to scale).
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2. Field

A. Below a watertable

1. Auger-hole method - bailing recovery test | Fine textured soils | Boersma (1965) |
| 2. Piezometer method - bailing recovery test | For most soils | Boersma (1965) |
| a) Fully slotted (confined aquifers) | - dependent on drilling techniques | Cooper et al. (1967) |
| b) Partially slotted | Installation and development procedure | Hvorslev (1951) |
| 3. Piezometer method - pump-in technique | For most soils/aquifers | Bouwer and Rice (1976) |
| 4. Slug test | As above | Sharp et al. (1977) |
| 5. Bore-hole dilution test | Care with reactivity of tracers | Freeze and Cherry (1979) |
| 6. Pumping test | Most accurate technique against which all others are compared | Brown et al. (1972) |

B. Above a watertable

| 2. Shallow well pump-in dry auger hole method | | Boersma (1965) |
| 4. Twin infiltration rings | | Talsma and Hallan (1980) |

3. Remote

1. Particle size analysis (Kozeny-Carmen Eqn) | Sample size problems/variability | Masch and Denny (1966) |
The hydraulic conductivity is determined from the rate of water loss in the outer acrylic tube provided certain conditions are met.

Flow is due to pressure and gravity. The equations are simplified if the effect of gravity can be minimized. This is possible by ensuring that the depth of water in the hole \(H\) is at least five times larger than the radius of the hole \(a\). Two ratios of \(H/a\) are recommended, 5 and 10.

\[
K = \frac{CQ}{2\pi H^2}
\]

Where \(K\) = saturated hydraulic conductivity \(m/s\), \(C\) = pressure gradient term which = 3.3 when \(H/a = 10\) \(= 2.2\) when \(H/a = 5\), \(Q\) = steady rate of water flowing into the hole \(m^3/s\), \(H\) = length of the wetted hole \(m\), should not exceed 0.2 m, \(a\) = radius of the hole \(m\).

The estimate of hydraulic conductivity assumes that the soil materials are homogeneous and isotropic. Where soils have an impeding layer within 2 * \(H\) of the bottom of the hole, Talsma and Hallam (1980) suggest an approximation that can be used.

\[
K = \frac{3Q \ln (H/a)}{\pi H (3H + 3S)}
\]

Where \(Q = H\) and \(a\) are is previously defined.

\(S\) = distance to the impermeable layer before the bottom of the hole \(m\).

6. FIELD PROCEDURE:

The permeameters fit easily into a 5 cm diameter auger hole.

With \(a = 2.5\) cm, the height of water in the hole = 12.5 cm for \(H/a = 5\) and 25 cm for \(H/a = 10\). Using 12.5 cm will result in the measurement of \(K\) coming from a narrower layer which is preferrable in soils with variable profiles.

The condition of the walls of the auger hole is critical in soils which have a high clay content. The moisture status is important when drilling as wet clay is likely to smear. There are no simple procedures which may be used to limit or negate the effects of smearing. However, soil removal by coring is an option. A bottle brush may be pushed lightly onto the walls to pull off the smeared coating and leave fresh ped faces open for water entry. This method has proved successful in mottled B horizons in the wheatbelt.

1. Determine the volume of water that is represented by each 1 cm fall in level in the outer tube.

2. Auger a hole to determine the soil profile. Select the depths at which measurements are to be made. In duplex soils, select the topsoil interval so that it is at least twice the interval distance above the subsoil clay. For example if the topsoil is 40 cm deep and the interval is to be 12.5 cm, the bottom of the hole cannot be deeper than 15 cm if equation 1 is to be used.
3. When the intervals have been decided, auger at least three holes to the bottom of the interval. From the three (or more) measurements, a geometric mean of the hydraulic conductivity can be calculated.

4. If the hole has been augered through moist or wet clay there may be smearing on the sides which will reduce the flow rate. Try to remove the smeared clay with a wire brush, test-tube brush or broom handle with nails driven through the handle.

5. Determine how deep the tube has to be lowered into the hole so that the bottom of the tube is at the top of the interval to be measured. Clamps which attach the tube to a tripod can be positioned on the tube so that it is at the correct depth.

If the hole radius, \( a = 2.5 \) cm and the interval to be measured is 2.5 to 15 cm (i.e. \( H = 12.5 \) cm) then the tube needs to be lowered 2.5 cm into the hole. For this arrangement, \( H/a = 12.5/2.5 = 5 \) and \( C = 2.2 \). Talsma and Hallam (1980) recommend that \( H/a = 10 \). This is possible in deep profiles. When \( a = 2.5 \) cm, \( H = 25 \) cm, \( H/a = 10 \) and \( C = 3.3 \).

6. Adjust the inner acrylic tube by sliding it through the rubber bung so that the inner tube is level with the bottom of the outer acrylic tube.

7. Add water to the hole so that the water level is above the level that will be maintained by the permeameter. This reduces the time taken for the flow to reach equilibrium.

8. With the clamp on the inner tube in place, fill the acrylic tubes with water. Place a piece of blotting paper over the tube bottom and lower the tube into the hole. Set the tube into supporting clamps at the correct depth. Release the clamp on the inner (air) tube when the water level in the hole falls below the bottom of the tube. As the water level in the hole falls, the filter paper will be removed. The water will flow out of the permeameter with a constant head \( H \) above the hole bottom.

9. Take regular readings of water outflow. Once the readings become regular, equilibrium has been reached and the readings can be stopped.

7. SPECIAL PRECAUTIONS:

1. The reservoir needs to be large enough to contain sufficient water for sandy soils.

2. Auger hole construction - try to prevent or repair any clay smearing. Pushing a core into the soil over the depth of interest can reduce the effect of smearing. Similarly, a bottle-brush type scraper may remove smeared clay, leaving the fresh peds open for water entry.

3. Use standard \( H/a \) ratios for ease of calculation.

4. Recognize that soils are very variable in vertical and horizontal directions. At least three measurements are required.

5. The upper limit of the hydraulic conductivity measured by the Reynolds et al. method is approximately:

\[ 1 \times 10^{-4} \text{ m/s (or 9.00 m/d)}. \]
If the Schofield and Bell (1990) adaption is used the upper limit is approximately 100 m/d.

Talsma and Hallam (1980) consider the limits are:

\[ 3 \times 10^{-4} \text{ m/s} \ (26.0 \text{ m/d}) \ - \text{upper limit} \]
\[ 1 \times 10^{-7} \text{ m/s} \ (9.00 \times 10^{-3} \text{ m/d}) \ - \text{lower limit}. \]

Nash et al. (1986) have suggested modifications for measuring below $10^{-7}$ m/s.

8. **ANALYSIS OF RESULTS:**

The field data can be plotted as cumulative flow (litres) against time (minutes) to determine the steady state flow of water ($Q$). Sometimes it is obvious from the recorded readings what $Q$ is. Equilibrium may be reached after only five minutes data for sandy soils or much later (30-100 mins) for clay soils. $Q$ needs to be converted to m$^3$/d for estimating $K$ as m/day or to m$^3$/s for estimating $K$ as m/s.

**Example calculation:**

\[ K = \frac{C \cdot Q}{2 \pi H^2} \]

If $H = 0.125 \text{ m}$ and $a = 0.025 \text{ m}$, then $C = 2.2$ (as $H/a = 5$)

If $Q = 20 \text{ mL/min} = 0.0288 \text{ m}^3/\text{d}$. 

\[ K = \frac{2.2 \times 0.0288}{2 \times 3.1416 \times (0.125)^2} \]

\[ = 0.645 \text{ m/d}. \]

9. **ADDITIONAL COMMENTS:**

Reynolds et al. (1983) goes through the theory and instrument construction in greater detail than has been done here. Nash et al. (1986) believe that the simplicity of the design proposed by Talsma and Hallam (1980) has been lost by Reynolds et al. (1983).

10. **MAIN REFERENCES:**

Amoozegar


11. MAIN CONTACT PERSONS:

Richard George, Bunbury.
Don McFarlane, Albany.

Constant head well permeameter
7.2 INFILTRATION AND SORPTIVITY USING DISK PERMEAMETERS

1. WHAT IS MEASURED?:

Water infiltration at a slight suction.

The infiltration plots obtained are used to estimate the sorptivity (S) and the saturated hydraulic conductivity (K sat) of unsaturated soils.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:

The methods described here are techniques for the in situ measurement of water infiltration into the soil surface. Other methods of measuring soil hydraulic properties are summarized in Table 1, Section 7.1. In situ measurements of soil surface hydraulic properties which include the impact of raindrops can be made using a rainfall simulator (e.g. Clothier et al. 1981).

3. PREVIOUS USES OF THE METHOD:

The sorptivity tower (disk permeameter) is a more recent technique. The development, theory and application of the technique is described by Clothier and White (1981) and White and Sully (1987). The disk permeameter adds water at a suction (which can be varied) which means that large pores and cracks do not conduct water. This gives an estimation of non-ponding infiltration rates or infiltration through the soil matrix.

4. COST/AVAILABILITY OF EQUIPMENT:

The sorptivity tower is a specialized piece of equipment (Figure 1). The tower is constructed from perspex. Two units are located at Northam, both of which were made by and purchased from the Engineering Research Station, W.A.W.A., Floreat Park for a cost of $400 each in 1985. The towers also require replaceable, wettable nylon meshing (Nytal 270-53 ASTM) and a stiffner to support the mesh. Suitable material for the support is collar interfacing (paper not plastic). The mesh can be purchased from - Swiss Screens, 15 Anvill Road, Seven Hills N.S.W.

5. PRINCIPLES OF METHOD:

The infiltration of water into soils has been the subject of extensive theoretical and experimental examination. The actual determination of the experimental parameters is simple. The pragmatic approach of Collis-George (1980) provides a relatively simple description of the infiltration processes and method for determining the parameters i, S and K* which are defined and discussed below.

The cumulative infiltration of water into a soil under ponded conditions can be divided into three processes which are to a large extent temporally distinct.

(i) \(i_1\) - an instantaneous component which is related to the filling of cracks or more open structural voids, units are (mm).
Figure 1. Cross-section of a sorptivity tower/disk permeameter (not to scale).

Figure 2. Example of infiltration plot I vs t.

Figure 3. Example of infiltration plot with I vs \( \sqrt{t} \) for calculation of \( i_1 \) and S.
(ii) \( S \sqrt{t} \) - a short term component where \( S \) is the sorptivity as defined originally by Philip (1957), the units of \( S \) are for example \( \text{mm sec}^{-1} \) with \( t \), the time since infiltration commenced being in seconds.

(iii) \( K^*t \), a steady state component where \( K^* \) is the steady state infiltration rate and is related to \( K_{\text{sat}} \). The units of \( K^* \) are \( \text{mm sec}^{-1} \).

The cumulative infiltration of water (\( I \)) at time \( t \) into a soil can thus be described by the following equation:

\[
I = i_1 + S \sqrt{t} + K^* t
\]

The determination of the components of equation 1 from the experimental data is described below. It is important however to understand the physical basis to the parameters \( i_1 \), \( S \) and \( K^* \) and how they relate to the soils physical condition.

\( i_1 \) - is only measured under ponded conditions i.e. using the ring infiltrometer. When water is ponded on a soil surface an initial rapid influx of water into large cracks and voids will occur. The value of \( i_1 \) may therefore be taken as an indicator of the degree of macro structure occurring at the soil surface. The value will depend on the moisture status of the soil. A dry soil can be extensively cracked leading to a high \( i_1 \) value. The same soil under moist conditions will have a reduced \( i_1 \).

\( S \) - the sorptivity of the soil is a measure of the interaction of the water with the soil matrix. Clay soils will thus have high \( S \) values whilst sandy soils will have lower values. The \( S \sqrt{t} \) component of the infiltration process dominates over the \( K^*t \) component for the early stages of infiltration. This is the period where water infiltration is controlled by the matrix uptake of the water from the soil surface, after the initial filling of the larger cracks and voids with water. The value of \( S \) will not only be dependent on soil texture but also on soil structure and antecedent moisture content. A soil which is at field capacity or wetter will have a low \( S \) value whilst the same soil may have a considerable \( S \) value when dry.

\( K^* \) - This is related to \( K_{\text{sat}} \) of the transmission zone. It is worth noting however, that the relationship between them is not well defined and will vary with soil type, particularly where impeding horizons are encountered during the course of the infiltration. For a homogenous profile, \( K^* \) is approximately equal to \( 1/3 \) \( K_{\text{sat}} \). \( K^* \) is the steady state infiltration rate and represents the maximum infiltration rate or infiltration capacity after the soil becomes saturated.

The values of \( i_1 \), \( S \) and \( K^* \) are calculated directly from plots of \( I \) versus \( t \) (Figure 2 and 3). It is important to note however that the values of \( S \) and \( K^* \) depend on the experimental conditions and in particular the head of water used.

6. **FIELD PROCEDURE:**

Infiltration volume is recorded directly from the reservoir (Figure 1). In general it is possible to obtain enough data for estimates of \( S \) and \( K^* \) in 30 minutes. The method by which this can be done is outlined below.

The tower must be level and must have a good contact with the soil surface. This can be achieved in the following way.
1. A ring is pushed into the soil (~1-2 cm) the diameter of which should be just larger than the base of the tower. The soil surface (which may be rough) is covered by a layer of coarse sand which provides a level base for the tower and ensures good contact between the tower and the soil.

OR

2. The method described by Clothier and White (1981) may be used, whereby a core is pushed into the soil and the soil excavated from around the core. The tower is placed on top of the core with a bed of fine sand between the soil surface and the tower base. This method would prove difficult on hardsetting soils when dry and on stony soils.

There is no one established technique for obtaining values of S and K* with the tower. The following technique has proved useful for a wide range of heavier textured soils (sandy loam to clay loams) both on freshly cultivated and compacted surfaces.

1. The seating for the tower is as described in the first method above.
2. A negative head of 5.0 cm is set on the tower mariotte device.
3. Infiltration is commenced and volumes recorded every 30 or 60 seconds for 10 to 20 minutes.
4. Infiltration is stopped by closing the air inlet and the head adjusted to give a -2.5 cm value.
5. Infiltration is recommenced and volumes recorded for another 10 to 20 minute period.

In most cases it has been found that a steady flow is achieved with the second infiltration at the slightly reduced head, within 10 minutes. This will not be the case for soils with particularly high S values. Alternatively for sandy textured soils with low S values or for very wet soils, steady state infiltration may occur at the -5.0 cm head. The actual values for the water heads suggested above were determined on a trial and error basis and may not be practical for all situations.

7. SPECIAL PRECAUTIONS:

1. Infiltration will have a horizontal component once the wetting front moves beyond the base of the ring. This horizontal component leads to an overestimation of K* and to a lesser extent S. Equations have been developed for the correction of S and K* (e.g. Tricker 1978), however the form of the equation varies with ring diameter and will vary according to the soil profile. Two options exist to overcome the problem of horizontal flow.

   (i) The use of an outer 'buffer' ring which as stated is of debatable use (Tricker 1978).

   and

   (ii) Pushing the ring or core (sorptivity tower) to a depth such that the wetting front never moves beyond it.

Alternatively, for the sake of speed and ease of operation, the ring can be inserted to a set depth for each measurement and K* be calculated at a set time whereby it is recognized that it is an overestimation. This latter option is generally acceptable provided the influence of an impeding layer is
not met by the wetting front during the course of the infiltration. As Collis George (1980) states, it should be recognised that the value of $K^*$ is not related to $K_{\text{sat}}$ by a universal function. Therefore it is better to use the experimentally measured values and ensure that the conditions under which they are measured are standardized as much as possible.

3. Inserting the rings into the soil surface will inevitably cause disruption of the soil surface which will lead to overestimates of $i_1$ and $S$. This problem is not encountered with the sorptivity tower due to the negative head of water being used.

Ponding water on the soil surface may result in slaking and/or dispersion. The results will be a drop in $K^*$. Whilst slaking and dispersion is an important process which controls infiltration under rainfall, ponding of water on the surface is not a good simulation of this process. The sorptivity tower on the other hand does not cause any disruption of the soil surface and is thus a better measure of the infiltration at a point of time.

4. The variability of the measurements is inevitably high due to soil heterogeneity and to the distribution of macropores and cracks. A statistical analysis of this variability may well be the object of the study (e.g. Sharma et al. 1980 and Sharma et al. 1987). However, where the requirement is to obtain an average value for a particular site, the variability can be reduced.

8. ANALYSIS OF RESULTS:

The value of $K^*$, $S$ and $i_1$ are determined in the following way.

Water infiltration in millimetres is plotted against time. The plot obtained will have a form similar to that shown in Figure 2. $K^*$ is equal to the slope of the linear portion of the plot. Collis George (1980) suggests that the slope is taken for the time period after which a linear regression of the data yields an $r^2$ value in excess of 0.99.

The value of $S$ and $i_1$ are obtained by plotting $(I-K^*t)$ vs. $\sqrt{t}$, which should yield a plot similar to that shown in Figure 3. The slope of the linear portion of the plot is equal to $S$ and the intercept is equal to $i_1$. If $K^*$ is not measurable (i.e. steady state infiltration was not reached), $S$ can be determined from a plot of $I$ vs $\sqrt{t}$ where the slope of the linear portion is equal to $S$.

9. ADDITIONAL COMMENTS:

A tower similar to a disk permeameter can also be used to add water with a positive head (White and Sully 1987).

10. REFERENCES:


11. **MAIN CONTACT PERSONS:**

P. Blackwell, Geraldton.
J. Prince, South Perth.
T. Proffitt, Northam.

Disk permeameter and Wesdata logger
7.3 INFILTRATION AND SORPTIVITY USING RING INFILTROMETERS

1. WHAT IS MEASURED?:

Ponded Water Infiltration

The infiltration plots obtained are used to obtain estimates of the sorptivity (S) and the saturated hydraulic conductivity (Ksat) of unsaturated soils.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:

The method described here is a technique for the in situ measurement of water infiltration into the soil surface. Another in situ method of water infiltration using disc permeameters is given in section 7.2. In situ measurements of soil surface hydraulic properties which include the impact of raindrops can be made using a rainfall simulator (e.g. Clothier et al. 1981).

3. PREVIOUS USES OF THE METHOD:

Ring infiltrometers have been used widely to describe the infiltration characteristics of soils; e.g. Sharma et al. (1980) and Sharma et al. (1987).

4. COST/AVAILABILITY OF EQUIPMENT:

It is recommended that the double ring infiltrometer method is used rather than the single ring method. Rings should be made from material such as 16 gauge galvanised steel with the lower edge sharpened to facilitate insertion into the soil, and should be at least 20 cm deep. Common diameters are 30 cm for the inner ring and 60 cm for the outer ring. However, larger diameter rings have been used (60 and 120 cm respectively) with reputedly greater accuracy. Infiltration rate can be determined from the rate of change in water level within the inner ring (i.e. falling head method). Alternatively, a constant head reservoir (e.g. a calibrated Mariotte bottle) can be used. These can be easily constructed (Figure 1) and give greater control of the water level inside the ring.

5. PRINCIPLES OF METHOD:

The infiltration of water into soils has been the subject of extensive theoretical and experimental examination. The actual determination of the experimental parameters is simple. The pragmatic approach of Collis-George (1980) provides a relatively simple description of the infiltration processes and method for determining the parameters i1, S and K* which are defined and discussed below.

The cumulative infiltration of water into a soil under ponded conditions can be divided into three processes which are to a large extent temporally distinct.

(i) i1 - an instantaneous component which is related to the filling of cracks or more open structural voids, units are (mm).

(ii) S \sqrt{t} - a short term component where S is the sorptivity as defined originally by Philip (1957), the units of S are for example mm sec⁻¹ with t, the time since infiltration commenced being in seconds.

(iii) K*t, a steady state component where K* is the steady state infiltration rate and is related to Ksat. The units of K* are mm sec⁻¹.
The cumulative infiltration of water (I) at time t into a soil can thus be
described by the following equation:

\[ I = i_i + S \sqrt{t} + K* t \]  

(1)

The determination of the components of equation 1 from the experimental data
is described below. It is important however to understand the physical basis
to the parameters \(i_i\), \(S\) and \(K*\) and how they relate to the soils physical
condition.

\(i_i\) - is only measured under ponded conditions i.e. using the ring
infiltrometer. Leave of water into large cracks and voids will occur. The
value of \(i_i\) may therefore be taken as an indicator of the degree of macro
structure occurring at the soil surface. The value will depend on the
moisture status of the soil. A dry soil can be extensively cracked leading to
a high \(i_i\) value. The same soil under moist conditions will have a reduced
\(i_i\).

\(S\) - the sorptivity of the soil is a measure of the interaction of the water
with the soil matrix. Clay soils will thus have high \(S\) values whilst sandy
soils will have lower values. The \(S/\sqrt{t}\) component of the infiltration process
dominates over the \(K* t\) component for the early stages of infiltration. This
is the period where water infiltration is controlled by the matrix uptake of
the water from the soil surface, after the initial filling of the larger
cracks and voids with water. The value of \(S\) will not only be dependent on
soil texture but also on soil structure and antecedent moisture content. A
soil which is at field capacity or wetter will have a low \(S\) value whilst the
same soil may have a considerable \(S\) value when dry.

\(K*\) - This is related to \(K_{sat}\) of the transmission zone. It is worth
noting however, that the relationship between them is not well defined and
will vary with soil type, particularly where impeding horizons are encountered
during the course of the infiltration. For a homogenous profile, \(K*\) is
approximately equal to \(1/3 K_{sat}\). \(K*\) is the steady state infiltration rate
and represents the maximum infiltration rate or infiltration capacity after
the soil becomes saturated.

The values of \(i_i\), \(S\) and \(K*\) are calculated directly from plots of I versus t
(Figure 2 and 3). It is important to note however that the values of \(S\) and \(K*\)
depend on the experimental conditions and in particular the head of water used.

6. FIELD PROCEDURE:

There are two techniques available for ponded infiltration with rings:

(a) **Single ring**

This technique uses one ring of a known diameter gently pushed into the soil.
Water is ponded on the soil surface and the volume that infiltrates is
recorded with time.

(b) **Double ring**

Water is ponded in both (one larger than the other) rings and infiltration
recorded from the inner, 'measuring' ring. Swartzendruben and Olson (1961)
report that this technique is reasonably accurate when measuring one
dimensional (vertical) infiltration in soils with no impermeable layers. The inner ring should be sufficiently large to obtain representative infiltration rates, and the outer 'butter' ring large enough to be an adequate buffer to minimise the effects of lateral flow on the infiltration rate obtained in the inner ring. Whether the outer ring does in fact prevent lateral flow is uncertain (e.g. Tricker 1978). Note that infiltration rate per unit area can vary markedly with size of ring, decreasing asymptotically with increasing ring diameter (Marshall and Stirk 1950).

Detail

1. Rings

The diameter of the inner ring should be greater than 15 cm (30 cm diameter is commonly used). Cross rods can help to stabilise the ring and keep it in the circular shape. Note that the smaller the diameter, the greater the variability in the values of S and K*. The outer ring can be either metal, similar to the inner ring but with a diameter of at least twice that of the inner ring, or else it can be an earthen dam surrounding the inner ring. Ring height should be at least 20 cm. The main limitation to ring size is the practical problem of pushing large rings into the soil and supplying the amount of water required.

Rings should be pushed/driven into the soil far enough to prevent lateral leakage when water is ponded in them (approximately 8-10 cm deep). It is important that the inner ring enters the soil vertically and not irregularly as this results in poor bonding between the ring wall and the soil, and disturbs the soil core within the ring. Before inserting the ring(s) it is often useful to cut through the vegetation with a knife where the cutting edge of the ring is to enter the soil.

2. Water supply

The control of the head of water in the ring may strongly influence the values of S and K*. This may not be important where rough estimates are required. However, for comparative work (e.g. between soil units in a catchment) it is desirable to keep the experimental conditions as consistent as possible. The usual technique for supplying water and maintaining a constant head is to use a calibrated Mariotte bottle (Figure 1).

The head of water may also be maintained by topping up the ponded water in the ring at set time intervals to a fixed marker in the ring. Try to maintain equivalent water levels in the inner and outer rings in order to prevent lateral water movement between rings. Alternatively, no attempt at maintaining a constant head may be made and the volume that is infiltrating is measured from a graduated marker placed in the ring itself.

3. Commencement of infiltration

It is desirable to commence the infiltration run instantaneously. Try not to leave the water sitting in the ring too long before measuring. This can be done by lining the ring with a sheet of plastic. Water is ponded in the ring to the required head and infiltration commenced at time t = 0 by pulling the sheet out of the ring.

4. Recording of infiltration volume

Record the volumes infiltrating at short intervals in the early stages, becoming longer with time. The actual intervals will depend to an extent on
Figure 1. Cross-section of a constant head device (mariotte bottle).

Figure 2. Example of infiltration plot $I$ vs $t$.

Figure 3. Example of infiltration plot with $I$ vs $\sqrt{t}$ for calculation of $i_1$ and $S$. 
the soil type. In general, recording intervals of 30 secs for the first 3-8 minutes should be maintained. After this period recording intervals may be stretched according to the rate at which the infiltration is taking place. The calculation of $S$ requires that the nonlinear part of the infiltration curve (Figure 2) be described adequately. Record infiltration until a constant or steady state infiltration rate is obtained if $K^*$ is required. This can be determined by plotting the data as they are recorded. Several hours may be required to reach steady state infiltration. The time period required for the estimation of $S$ will be less than 20 minutes.

7. **SPECIAL PRECAUTIONS:**

Infiltration using the single ring method will have a horizontal component once the wetting front moves beyond the base of the ring. This horizontal component leads to an over estimation of $K^*$ and to a lesser extent $S$.

Equations have been developed for the correction of $S$ and $K^*$ (e.g. Tricker 1978). However, the form of the equation varies with ring diameter and will vary according to the soil profile. The problem of horizontal flow can be overcome by use of an outer 'buffer' ring, although Tricker (1978) questions the accuracy of this technique.

Alternatively, for the sake of speed and ease of operation, the ring can be inserted to a set depth for each measurement and $K^*$ be calculated at a set time whereby it is recognized that it is an over estimation. This latter option is generally acceptable provided the influence of an impeding layer is not met by the wetting front during the course of the infiltration. As Collis George (1980) states, it should be recognized that the value of $K^*$ is not related to $K_{sat}$ by a universal function. Therefore it is better to use the experimentally measured values and ensure that the conditions under which they are measured are standardized as much as possible.

Inserting the rings into the soil surface will inevitably cause disruption of the soil surface which can over estimate $i_j$ and $S$. Ponding water on the soil surface may result in slaking and/or dispersion. This will result in a drop in $K^*$. Whilst slaking and dispersion are important processes which control infiltration under rainfall, ponding of water on the surface is not a good simulation of these processes.

Variability in measurements will inevitably be high due to soil heterogeneity and due to the distribution of macropores and cracks. A statistical analysis of this variability may well be the object of the study (e.g. Sharma et al. 1989, 1987). However, where an average value for a particular site is needed, the variability can be reduced by using larger rings (Tricker 1978) or by using a sorptivity tower/disc permeameter (Section 7.2) (Clothier and White 1981).

8. **ANALYSIS OF RESULTS:**

The value of $K^*$, $S$ and $i_j$ are determined in the following way.

Water infiltration in millimetres is plotted against time. The plot obtained will have a form similar to that shown in Figure 2. $K^*$ is equal to the slope
of the linear portion of the plot. Collis George (1980) suggests that the slope is taken for the time period after which a linear regression of the data yields an $r^2$ value in excess of 0.99.

The value of $S$ and $i_1$ are obtained by plotting $(I-K^* t)$ vs. $\sqrt{t}$, which should yield a plot similar to that shown in Figure 3. The slope of the linear portion of the plot is equal to $S$ and the intercept is equal to $i_1$. If $K^*$ is not measurable (i.e. steady state infiltration was not reached), $S$ can be determined from a plot of $I$ vs $\sqrt{t}$ where the slope of the linear portion is equal to $S$.

9. ADDITIONAL COMMENTS:

Under most conditions infiltration rate is much greater than evaporation rate so the error from evaporation can be neglected. Evaporation can be reduced by covering the inner ring.

Tests with double ring and single ring infiltrometers have shown that the number of measurements needed to characterise an area may be relatively large.

With single rings on an extensively uniform soil, Burgy and Luthin (1957) found that each of 6 separate measurements came within 30% of the general mean. Slater (1957) found that 15 measurements using rings of 10.5 cm diameter were necessary to ensure a standard error within 20% of the mean.

10. REFERENCES:


11. MAIN CONTACT PERSONS:

T. Proffitt, Northam.
SECTION 8: HYDRAULIC PROPERTIES OF AQUIFERS

8.1 SLUG TESTS

1. WHAT IS MEASURED?

Slug tests measure the saturated hydraulic conductivity of soil, which is below the watertable or piezometric surface as measured with a well or piezometer.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:

Slug tests estimate the hydraulic conductivity adjacent to the well (approximately 1 to 5 sq. metres) and are inferior to pump tests (Section 8.2) which estimate over hundreds to thousands of square metres.

Two varieties of slug tests can be conducted.

1. Slug withdrawal.
2. Slug addition.

The reader is referred to papers on slug addition tests by Cooper et al. (1967), Papadopulos et al. (1973) and Bouwer and Rice (1976). Slug addition tests have been documented by Sharp et al. (1977).

3. PREVIOUS USES OF THE METHOD:

Slug tests have been conducted in most parts of the agricultural areas on various aquifer and aquitard materials. A summary of the range of values obtained and materials investigated is given in Table 2 (Section 8.3).

4. COST/AVAILABILITY OF EQUIPMENT:

Slug test equipment is easy to make, simple to use and cheap to operate. All that is required is a manual water level probe (Section 3.3) and a bailer or sealed aluminium tube. The water level probe is attached to a tape measure while the bailer needs sufficient rope attached to it. Ploppers and Fox whistles cost between $10-30 while bailers and aluminium cylinders can be made for about $30-60.

More expensive electronic sounding equipment may be needed for deep holes (depth to water 20-40 m) or where the tape adheres to the P.V.C. bore casing, preventing accurate water level recordings. Electronic sounders cost $300-500.

5. PRINCIPLES OF METHOD:

A sudden change in water level in a bore is caused by adding or subtracting a slug of water from the bore. Adding or subtracting a cylinder of known volume achieves the same effect. The rate of recovery of the water level is related to the hydraulic conductivity of the surrounding aquifer. The longer the recovery period the less permeable the formation and vice versa.

The slug test method relies on there having been no change in the permeability to the aquifer materials due to the drilling method. If muds have been used when drilling, these should be removed by developing the bore. These aspects are discussed by Sageev (1986).
6. **FIELD PROCEDURE:**

Slug tests can be conducted at any time of the year.

Before the tests are begun, details of the holes drilling procedures and piezometer construction should be noted. It is important to develop piezometers prior to the slug test. The reader is referred to hydrogeologic text books (e.g. Driscoll 1986) for developing procedures.

**Field Work**

1. Check the bore construction detail, drilling and development history.
2. Locate the bore and record its details on Table 1.
3. Remove a slug of water (usually equivalent to 1-2 m from the bore). Immediately record the new water level ($Y_1$) pressing the stopwatch simultaneously.
4. Measure the depth to the watertable at each time unit suggested on Table 1.

Complete the recovery schedule until the bore has almost completely reached its original level.

Permeable materials will recover in 10-20 minutes while less permeable may take several hours. Where piezometers have not recovered within 60 minutes, abandon the later stage of the test.

**Alternative:** Use a sealed aluminium cylinder or iron bar to displace a known amount of water. Calibrate it in 40 or 50 mm P.V.C. pipe. For slug withdrawals, lower the cylinder or bar below the water level and allow time for the level to equilibrate before withdrawing it. It is possible measure the falling water table for a slug addition and obtain a repeat measurement of recovery when the slug is withdrawn.

**Calculation**

1. Calculate $Y_t$ and $Y_0$ as shown on Table 1.
2. Plot $Y_t$ against $t$ on semi log graph paper with $t$ on the linear axis $Y_0$ (Figure 1).
3. Draw a straight line through the origin, incorporating the points plotted. If the points curve away from the line dramatically, draw the line so it only incorporates early time data (< 5 to 10 minutes). In the example the line curves after only 2 minutes which is earlier than most bores.
4. Determine the slope ($S$) of the line. For example on Figure 1 the slope has been calculated between 0 and 4 and between 0 and 10 minutes using

$$S = \frac{\log (Y_t/Y_0) - \log^1}{t/1440}$$

$t$ is divided by 1440 to convert minutes to days.
Table 1. Field measurements and calculations

<table>
<thead>
<tr>
<th>Site:</th>
<th>Bore No:</th>
<th>Date:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **SWL** = Standard water level.
- **D** = depth of bore.
- **TD** = Total depth.
- **W** = depth to SWL (inc PVC).
- **L** = Slotted length.
- **r_w** = drill hole radius.
- **r_c** = radius of casing.
- **Y_o'** = depth after bailing (at t = Y).
- **Y** = rise in SWL over time.
- **t** = time (sec).
- **Y_o** = height of water removed.

<table>
<thead>
<tr>
<th>RADIUS OF BORE</th>
<th>cm</th>
<th>CONDUCTED BY:</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC</td>
<td>cm</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TOTAL DEPTH</th>
<th>cm</th>
<th>FARMERS NAME:</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>cm</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NEW WATERTABLE AFTER BAILING</th>
<th>cm</th>
<th>COMMENTS ON BORE:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y_o'</td>
<td>cm</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ORIGINAL S.W.L.</th>
<th>cm</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>cm</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WATER REMOVED/ADDED</th>
<th>cm</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Y_o' - W</td>
<td>cm</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TIME DEPTH (d)</th>
<th>cm</th>
<th>TIME DEPTH</th>
<th>cm</th>
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<tr>
<td>(mins)</td>
<td></td>
<td>(mins)</td>
<td></td>
</tr>
<tr>
<td>(sec)</td>
<td></td>
<td>Y_t = d - W</td>
<td>Y_t/Y_o</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
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<th>DEPTH</th>
<th>TIME</th>
<th>DEPTH</th>
<th>COMMENTS</th>
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<td>0.15</td>
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<td></td>
<td></td>
</tr>
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<td>0.45</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
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<td></td>
<td></td>
</tr>
<tr>
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<td></td>
<td></td>
</tr>
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<td>1.45</td>
<td>50</td>
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<td></td>
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</tr>
<tr>
<td>2</td>
<td>60</td>
<td></td>
<td></td>
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<td>2.30</td>
<td>70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>80</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>4</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

* Y_t = depth below original S.W.L. = d - W.
### Table 2.

**Calculation Sheet: Slug Tests**

**SITE:** VASSE  
**DATE:** 9/8/1985

<table>
<thead>
<tr>
<th>Bore No.</th>
<th>Original Wet Slotted Length L</th>
<th>Original Column of Water H</th>
<th>Bore Radius r_c</th>
<th>Auger Radius r_w</th>
<th>L / r_w</th>
<th>C</th>
<th>ln H / r_w</th>
<th>ln r_e / r_w</th>
<th>Slope S</th>
<th>Hydraulic Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>V18</td>
<td>1.815</td>
<td>0.94</td>
<td>0.02</td>
<td>0.04</td>
<td>453.8</td>
<td>256</td>
<td>3.16</td>
<td>[1.1 ( \frac{C}{\ln (\frac{H}{r_w}) + \left(\frac{L}{r_w}\right)} )]^{-1}</td>
<td>144.9</td>
<td>( \frac{1.15 \times 0.94 \times 2.47 \times 144.9}{1.815} ) = 0</td>
</tr>
</tbody>
</table>

\[
\text{Slope } S = \frac{1.15 \times r_e^2 \times \ln \left( \frac{r_e}{r_w} \right)}{L} \quad \text{m/day}
\]
Figure 1.

\[ t = \frac{4}{1440 \text{ days}^-1} \]

\[ S = \frac{\log y_e - \log y_f}{4/1440} \]

\[ \log 0.4 - \log 0.0028 \]

\[ = \text{143.2 days}^-1 \]
5. Complete the calculation on Table 2 to determine the hydraulic conductivity.

Values of $C$, which is a function of $r_w$, can be read off Table 3.

Table 3. Values of C as a function of $L/r_w$

<table>
<thead>
<tr>
<th>$L/r_w$</th>
<th>C</th>
<th>$L/r_w$</th>
<th>C</th>
<th>$L/r_w$</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.4</td>
<td>50</td>
<td>2.7</td>
<td>350</td>
<td>9.3</td>
</tr>
<tr>
<td>6</td>
<td>1.46</td>
<td>60</td>
<td>3.0</td>
<td>400</td>
<td>9.8</td>
</tr>
<tr>
<td>7</td>
<td>1.52</td>
<td>70</td>
<td>3.35</td>
<td>450</td>
<td>10.3</td>
</tr>
<tr>
<td>8</td>
<td>1.58</td>
<td>80</td>
<td>3.6</td>
<td>500</td>
<td>10.6</td>
</tr>
<tr>
<td>9</td>
<td>1.64</td>
<td>90</td>
<td>3.8</td>
<td>600</td>
<td>11.1</td>
</tr>
<tr>
<td>10</td>
<td>1.7</td>
<td>100</td>
<td>4.2</td>
<td>700</td>
<td>11.5</td>
</tr>
<tr>
<td>15</td>
<td>1.75</td>
<td>150</td>
<td>5.6</td>
<td>800</td>
<td>11.8</td>
</tr>
<tr>
<td>20</td>
<td>1.85</td>
<td>200</td>
<td>6.8</td>
<td>900</td>
<td>12.1</td>
</tr>
<tr>
<td>30</td>
<td>2.1</td>
<td>250</td>
<td>7.9</td>
<td>1000</td>
<td>12.3</td>
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<tr>
<td>40</td>
<td>2.4</td>
<td>300</td>
<td>8.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

7. SPECIAL PRECAUTIONS:

Special precautions should be taken to insure that the hole has been properly drilled and developed. The Rotary Air Blast Drill rig (HM12) is less likely to smear clay on the sides of the hole than the auger rig (HM7).

8. ANALYSIS OF RESULTS:

A calculation sheet is provided (Table 2) with a worked example.

9. ADDITIONAL COMMENTS:

10. REFERENCES:


11. MAIN CONTACT PERSONS:

R. George, Bunbury.
D. McFarlane, Albany.
F. Lewis, Northam.
1. WHAT IS MEASURED?:

The transmissivity and storativity of an aquifer or aquitard.

Transmissivity can be calculated from measurements in the pumped bore. Storativity requires measurements in an observation bore adjacent to the pumping bore. Saturated hydraulic conductivity can be determined from the transmissivity and aquifer thickness.

Bore efficiency is a measure of the head losses within and immediately adjacent to the pumping bore (i.e. excluding the head loss caused by regional flow through the aquifer). Efficiency can be calculated from data collected during step-drawdown or constant discharge tests.

The main reasons for carrying out pump tests are to determine:

(a) The hydraulic properties of the aquifer; these help to evaluate the groundwater resources of a basin.

(b) The existence and location of sub-surface boundaries which may affect (beneficially or adversely) the long term performance of a pumping bore.

(c) The long term pumping rate for a particular bore.

(d) The performance of a particular groundwater basin.

Definitions

Hydraulic Conductivity [K] m/d or m/s - The ability of the material to transmit water. It is defined as the rate of flow of water through a unit cross-sectional area under a unit hydraulic gradient at a temperature of 16 degrees Celsius.

Transmissivity [T] m²/d - The product of saturated hydraulic conductivity (K) and aquifer thickness (b).

Storage Coefficient or Storativity [S] m³/m³ or non-dimensional - The volume of water an aquifer releases from storage per unit area of the aquifer per unit drop in hydraulic head (i.e. watertable in a unconfined aquifer and a piezometric surface in a confined aquifer).

Specific Yield [S_y] m³/m³ or a non-dimensional - The storage coefficient for unconfined aquifers.

Standing Water Level [S.W.L.] m - The depth from ground level to the water level outside the range of influence of any pumping bore.

Static Head m or Kpa - This is the height above ground level that water would stand if the casing were extended upwards. It can also be called the artesian head.

Drawdown - The distance from the S.W.L. that the water level in a bore or well has been lowered during pumping.

Residual Drawdown - The distance from the S.W.L. that the water level in a well or bore remains lowered after pumping ceases.
Recovery - The amount by which the water level in a bore has risen after pumping ceased. It is the difference between the Residual Drawdown and the hypothetical drawdown if pumping had not ceased. When the water level returns to S.W.L., recovery is said to be complete.

Available Drawdown - For a particular pump installation this is distance between the S.W.L. and the pump suction or the depth of water over the pump suction.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:

Laboratory tests of cores, provide point values of hydrologic properties. Slug tests provide in situ measurements from the immediate vicinity of the screened section. Pump tests provide in situ measurements that are averaged over a large aquifer volume.

3. PREVIOUS USES OF THE METHOD:

Numerous pump tests have been carried out on sites around Merredin.

4. COST/AVAILABILITY OF EQUIPMENT:

You need:

- electric submersible pump;
- generator;
- electrical cable and control box;
- tripod with pulley, winch and stainless steel cable;
- P.V.C. rising main;
- gate valve and discharge line.

There are three electric submersible pumps available in the Department of Agriculture. The availability and suitability of these pumps can be discussed with Richard George. There is also a range of generators and ancillary equipment available.

If department pumps and equipment are unavailable or unsuitable, complete pumping units can be hired from private groundwater consultants (e.g. Australian Groundwater Consultants, hire rate $100/day) or pump contractors (Malcolm Thompson and Co, hire rate on application).

5. PRINCIPLES OF METHOD:

Pump tests provide the most reliable method of obtaining quantitative data on the hydraulic characteristics of aquifers. Water is removed from a well and the reaction of the aquifer is measured.

The normal reaction is the creation of a cone-like zone of depression surrounding the well (Figure 1). This cone is unique in shape and lateral extent and is dependent primarily on the time since the start of testing, volume or rate of water withdrawn and the hydraulic characteristics of the aquifer. Measurements of water levels are taken at set times (Figure 2).

There are two ways to analyse the data: (1) steady state or equilibrium methods yield values of transmissivity and hydraulic conductivity; and (2) transient or non-equilibrium methods yield storativity and boundary conditions. The principal difference between the two methods is that the transient method permits analyses of groundwater conditions which change with...
time and involve storage, whereas the steady state method does not. This section will only involve the transient method.

Analyses of results of systematic observations of water level changes and of other test data yield values of aquifer characteristics. The extent and reliability of these analyses are dependent on features of the test including duration of test, number of observation wells, and method of analysis.

Test analyses also require an understanding of the hydrologic and geologic setting of the aquifer. Conditions that should be known include: the location, character, and distance of nearby bodies of surface water; the depth, thickness, and stratigraphy of the aquifer; and the construction details of the pumping and observation wells. Despite knowledge of the conditions that influence a test, the variability of an aquifer from the ideal on which analyses are based, and imperfections of the testing procedure, prevent the results being very accurate.

6. FIELD PROCEDURE:

In order to accurately analyse pump test data, it is important to know the following:

(a) the type and size of the bore or well;
(b) the total depth of the bore or well;
(c) the details and dimensions of the facility for the entry of water (be it a screen, slotted casing or open bottom);
(d) the details of the strata penetrated during drilling and where water was encountered;
(e) the standing water level, metres below ground level;
(f) the depth to the pump inlet, metres below ground level;
(g) the type of pump being used, including diameter (O.D.) of pump and column;
(h) details of time, discharge and drawdown from an accurate pump test which has been carried out on the bore.

The most satisfactory pump testing unit is an electric submersible pump fitted with a discharge valve (gate valve) to regulate flow. To measure the discharge rate (for low flows) from the pump, use a container of known volume, hold it at the outlet and measure the time to fill. If flow rates are large, use calibrated orifice plates which will also keep the flow rate constant.

It is best to use an electrical dipmeter to measure the water levels in the pumped bore. The simplest device is a reel of twin flex electric cable weighted with a sinker that is lowered into the bore; the other end is plugged into a standard voltmeter set to measure resistance (Section 3.3).

It is necessary to run a 20 or 25 mm polythene tube inside the pump bore casing through which the water-level device can pass. This prevents false readings caused by turbulence from the pumping. Before starting every test it is essential to record the measurement of static water level and depth of the pump inlet. During pumping the indicator wire is lowered until the end contacts the water. The drawdown is the tape reading minus the S.W.L.

Measure water levels to within 5 mm. For observation bores a "plopper" attached to the end of a tape is sufficiently accurate.

Normally, two types of pump tests are used:
(a) a constant rate discharge test; and
(b) a step-drawdown test.

**Constant Rate Discharge Test**

As the name indicates, this test involves pumping the bore at a constant discharge rate (± 5%). Drawdown measurements are taken at the following times after pumping has begun - 1, 2, 3, 4, 6, 8, 10, 15, 20, 25, 30, 45, 60, 75, 90, 100, 120 minutes, then each half an hour to six hours and then hourly from then until the end of the test (Figure 2). Also record the time of day that the pump test started.

If a reading is missed, then a reading should be taken as soon as possible and the time of this reading noted. It is more important to get the actual time of measurement than to obtain measurements precisely at the times given above.

Measurements of the pump's discharge rate should be taken at the start of the test, at 15 minutes and at half hour intervals thereafter. Discharge varies with the head and since this increases as the water level falls, it will be necessary to regulate the discharge valve during the test to maintain a constant discharge rate. The valve should not be fully open at the beginning of the test.

Measure the recovery immediately after the pumping ceases. Residual drawdown measurements should be taken at - 1, 2, 3, 4, 6, 8, 10, 15, 20, 25, 30, 40, 45, 60, 75, 90, 100, 120 minutes and then hourly until the water level is within 15 cm of S.W.L. Again, if a reading is missed then take one as soon as possible and note the actual time of this reading.

Unless there is reliable information available on the pumping characteristics of the well or bore it is necessary to run some short (half hour) trial pumping runs to decide on the rate for the test. A suitable rate is when the drawdown after 30 minutes is about half of the available drawdown. Record the details of these trial runs and allow the bore a reasonable time to recover before carrying out the main test.

**Step-Drawdown Test**

This test is done in steps holding the discharge constant between steps. Determine a maximum likely discharge rate for the bore. Divide this maximum discharge by four or five (depending upon the number of steps). The discharge rate throughout each step should be constant.

Take drawdown measurements throughout each step making each step a new stage (Figure 3). For instance, if the first step ended at 60 minutes, then the drawdown measurements in the second step would be taken at 61, 62, 63, 64 minutes etc. as indicated previously in the constant discharge test. If the second step ended at 120 minutes then the drawdown measurements in the third step should be taken at 121, 122, 123 minutes etc.

The advantage gained by using this step drawdown test is that the turbulent head loss associated with the discharge from the bore can be accurately determined and a long term pumping rate from the bore can be estimated regardless of whether or not the long term rate is in excess of twice the test discharge rate.

After the step drawdown test, residual drawdown measurements can be taken as outlined in the constant discharge test.
Observation Bores

Where adjacent bores are available, measure the drawdown in these bores and the times at which they are measured. Record accurately. Use the same frequency as given for the pumped bore. It is also important to measure the distance between the observation bore and the pumped bore. At least one, and preferably two, observation bores should be installed and their screens located in the aquifer being pumped. Deeper and shallower holes can also be constructed.

Observations During the Test

It is possible that the aquifer structure adjacent to the bore might change during a test i.e. it might collapse or development may take place.

To help interpret the test data it is good practice to comment on the clarity (turbidity) of the water at various stages of the test. If possible, place the outlet over a 200 L drum so that the volume of sediment can be measured at the end of the test. Sediment loads should not exceed 1 L of fine sand per day's pumping.

Mechanical Breakdown

If the pump stops during a long pumping test record when the stoppage occurred and when pumping recommenced. If possible, take some residual drawdown readings while the pump is stopped. It is possible to analyse the data provided the delay does not exceed two hours in a 24 hour test or 4 hours in a 100 hour test. Once the pumping has been recommenced continue the test so that the period of pumping is as originally intended i.e. the length of the test will now be the intended duration plus the length of the stoppage.

Table 1 lists the recommended tests and duration of pumping.

Table 1. Recommended pump testing procedures

<table>
<thead>
<tr>
<th>Type of bore</th>
<th>Pumping time (hours)</th>
<th>Recovery time (hours)</th>
<th>Type of test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stock or domestic</td>
<td>4-8</td>
<td>2</td>
<td>Constant discharge</td>
</tr>
<tr>
<td>Irrigation</td>
<td>24</td>
<td>6</td>
<td>As above plus</td>
</tr>
<tr>
<td>Investigation (general)</td>
<td>24-28</td>
<td>6-12</td>
<td>Step drawdown</td>
</tr>
<tr>
<td>Town Water Supply or Research</td>
<td>100</td>
<td>24</td>
<td></td>
</tr>
</tbody>
</table>
7. SPECIAL PRECAUTIONS:

8. ANALYSIS OF RESULTS:

The most common methods of analysing pump test data are described.

Assumptions underlying all the methods in this section are:

- the aquifer has a seemingly infinite area;
- the aquifer is homogeneous, isotropic and of uniform thickness over the area influenced by the pumping test;
- prior to pumping, the potentiometric surface was (nearly) horizontal;
- the aquifer is pumped at a constant discharge rate;
- the pumped well penetrates the entire aquifer and thus receives water from the entire thickness (> 80%) of the aquifer by horizontal flow;
- the flow to the well is in an unsteady state, i.e. the drawdown differences with time are negligible and the hydraulic gradient is not constant with time;
- the water removed from storage is discharged instantaneously with decline of head;
- the diameter of the pumped well is very small, i.e. < 30 cm and the storage in the well is neglected.

Confined Aquifer

There are two common methods for calculating aquifer characteristics from time-drawdown data. Both approaches are graphical. The first involves curve matching on a log-log plot (the Theis method) and the second involves interpreting a semilog plot (the Copper Jacob method).

These methods deal only with confined aquifers. A confined aquifer is one in which a completely saturated permeable formation is bounded above and below by low permeability layers.

In Western Australia many aquifers in lateritic soil profiles are semi-confined (Figure 8). The confining layers of these aquifers are leaky. The hydraulic conductivity of the confining layer may be small compared with the aquifer material, but as the radius of influence of the pumped bore increases, the area through which the confining layer is contributing water becomes large and the volume of water contributed can be a significant part of the total water discharged.

Therefore, the amount of water being contributed by the aquifer is not equal to the discharge from the bore. So the equations for confined aquifers in a semi-confined aquifer will give erroneous results.

Theis Method: Theis devised a simple graphical method of superposition that makes it possible to obtain solutions for T and S. His solution makes use of an integral known as the "well function", W(u). When W(u) and 1/u are plotted a "type curve" is produced (Figure 4). This curve is commonly called the "Theis curve".

The procedure to be followed is:

(i) plot drawdown (s) versus time (t) for the observation bore on transparent log-log paper with time on the horizontal axis;
(ii) place the plotted curve of s versus t on top of the type curve of W(u) versus 1/u, keeping the axes parallel (Figure 5). Adjust the curves until most of the observation data points fall on the type curve;
(iii) select a match point and read off values of \( W(u), \frac{1}{u}, s \) and \( t \);

(iv) calculate the Transmissivity, \( T \), and Storage Coefficient, \( S \), from the following equations:

\[
T = \frac{0}{4 \pi s} \cdot W(u)
\]

\[
S = \frac{4 T u t}{r^2}
\]

(v) before calculating the Storage Coefficient, \( S \), from the above equation ensure that the units of \( T \) and \( t \) are such that \( S \) will be dimensionless.

The scale of the logarithmic paper on which drawdown and time are plotted must be the same as the scale of the type curve paper.

Example: Table 2 gives the drawdown in a bore in an aquifer. The type curve solution is shown in Figure 6 as a plot of drawdown versus time (in minutes) on log-log paper. There is no need to convert the time units from minutes to days before plotting. The conversion can be done prior to the calculation of \( S \) from the equation.

Cooper-Jacob Method: Under the assumed conditions the non-steady state flow, equations can be modified to give straight line solutions. This is the semilog method of analysis developed by Cooper and Jacob (1946) where "s" is plotted against "t" on semilog graph paper with "t" on the logarithmic scale.

The procedure is as follows:

(i) plot on semilog graph paper, drawdown versus time with time on the logarithmic scale;

(ii) calculate \( \Delta s \), the drawdown per log cycle;

(iii) Transmissivity is determined by the equation \( T = \frac{2.30}{4 \pi \Delta s} \)

(iv) Storage Coefficient is determined from \( S = \frac{2.25 T t_0}{r^2} \)

\( t_0 \) is determined by extending the "time drawdown" line back until it intersects the zero drawdown line. Example: Using the modified non-steady state flow equations above, the transmissivity and Storage Coefficient are calculated from the data in Table 2. The semi-log plot and analysis are presented in Figure 7.

Note: Transmissivity can be determined using data from either a pumped bore or an observation bore. However, Storage Coefficient can only be calculated from data obtained at an observation bore. This is because drawdown in the pumped bore is influenced by non-linear head loss, and the effective radius of the bore is unknown.

Semi-confined Aquifer

The drawdown in a semi-confined aquifer follows the Theis equation for unsteady state flow in a confined aquifer but there are two parameters added to cover leakage:

\[
T = \frac{0}{4 \pi s} \cdot L(u,v)
\]
The storage coefficient is unchanged:

\[ S = \frac{4\text{Tut}}{r^2} \]

The family of type curves for \( L(u,v) \) versus \( u \) are shown in Figure 9.

The procedure for analysis is:

(i) on log-log paper of the same scale as the type curve, plot drawdown (on the vertical scale) versus time (on the horizontal scale);
(ii) overlay the plot on the type curve, keeping the axes of the two plots parallel, and fit your curve to one of the type curves;
(iii) select the match point and record values of \( L(u,v) \), \( \frac{1}{u} \), \( s \) and \( t \);
(iv) record the \( v \) value of the type curve fitted;
(v) compute Transmissivity;
(vi) compute storage coefficient;
(vii) make sure that the units used are consistent.

9. ADDITIONAL COMMENTS:

Advantages and Disadvantages of Pumping Tests

Estimating the potential of an aquifer from pump tests is a standard step in evaluating a groundwater resource. In practice, there is much art to successful pump testing. Kruseman and de Ridder (1983) give detailed advice on the design of pumping-test geometries and Walton (1970) provides many case histories.

Pump tests give both hydraulic conductivity (through the relation \( K = T/b \)) and storage properties from a single test. In aquifer-aquitard systems it is also possible to obtain information on important leakage properties of the system if observations are made in the aquitards as well as the aquifers.

There are two disadvantages, one scientific and one practical. The scientific limitation is the randomness of interpreting pump-tests. Unless there is very clear geological evidence to direct groundwater hydrologists in their interpretation, there are difficulties in predicting the effects of any proposed pumping scheme. The fact that a theoretical curve can be matched by your data does not prove that the aquifer fits the assumptions on which the curve is based.

The practical disadvantage of the method lies in its expense. The installation of pumping wells and observation bores or piezometers to obtain aquifer coefficients is probably only justified in cases where there is a proposed use for the aquifer. Alternatively, if aquifer and aquitard characteristics are unknown, the pump test provides a very important method of obtaining such information. Pump tests are one of the only reliable methods to obtain this data.

10. REFERENCES:


The best references for general groundwater theory are:


Specialized texts dealing with pumping tests and groundwater resource evaluation are:


11. **MAIN CONTACT PERSONS:**

Richard George, Ross George and Don McFarlane (Department of Agriculture).
Michael Martin (Geological Survey of Western Australia).

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**Figure 1. Drawdown around a pumping bore.**
<table>
<thead>
<tr>
<th>TIME (HR.)</th>
<th>ELAPSED (MIN.)</th>
<th>WATER LEVEL (M)</th>
<th>DRAWDOWN (M)</th>
<th>PIEZOM (CM)</th>
<th>DISCHARGE RATE (M³/HR)</th>
<th>REMARKS</th>
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Figure 2. Pumping test data - constant rate test.
Figure 3. Pumping test data - multi-rate test.
Figure 5. Curve matching.

Table 2. Drawdown of water level in an observation bore (N-2) 122 m from a bore being pumped at constant rate of 2,720 m³/day

<table>
<thead>
<tr>
<th>Time since pumping started $t_m$ (minutes)</th>
<th>Bore N-2 r = 122 m Observed drawdown s (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.05</td>
</tr>
<tr>
<td>1.5</td>
<td>0.08</td>
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<td>2.0</td>
<td>0.12</td>
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<td>2.5</td>
<td>0.14</td>
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<td>4</td>
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</tr>
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<td>5</td>
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<td>0.88</td>
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</table>
Figure 6. Type curve solution for the data in Table 2.
Example from Bore N-2 in Table I

From equation

\[ T = \frac{2.3Q}{4\pi \times \Delta s} \]

\[ Q = 2720 \text{ m}^3/\text{day} \]

From plot

\[ \Delta s = 0.39 \text{ m} \]

\[ T = \frac{2.3 \times 2720 \text{ m}^2/\text{day}}{4\pi \times 1.39} \]

\[ = 1270 \text{ m}^2/\text{day} \]

From equation 6.29

\[ S = \frac{2.25Tt_o}{r^2} \]

\[ t_o = 10^{-3} \text{ days} \]

\[ S = \frac{2.25 \times 1270 \times 10^{-3}}{1.48 \times 10^4} \]

\[ = 1.93 \times 10^{-4} \]

Figure 7. Cooper-Jacob method for a confined aquifer with constant discharge

Q, constant r and varying t.
Figure 8. Aquifer types in Western Australian agricultural areas.

Pump test (pumped for five days at 230 m³/day)
Figure 9. Type curves for non-steady radial flow in an infinite leaky aquifer.
Plot \( s \) versus \( \frac{t}{r^2} \) and superpose

From match values:

\[
T = \frac{Q}{4\pi} \frac{L(u,v)}{s}
\]

\[
S = \frac{4Tu_t}{r^2}
\]

\[
K' = 4T \frac{v^2}{r^2}
\]

Alternate Method

Plot \( s \) versus \( \frac{t}{r^2} \) for some constant \( t \) and superpose on dashed curves.

Compute \( T \) and \( S \) as at left.

\[
\frac{K'}{b'} = \frac{S}{1} \frac{v^2}{u^2}
\]

TYPE CURVES FOR NONSTEADY RADIAL FLOW IN AN INFINITE LEAKY AQUIFER
8.3 HYDRAULIC PROPERTIES OF AGRICULTURAL AQUIFERS DETERMINED FROM PREVIOUS TESTS

1. WHAT IS MEASURED?

As pump tests are expensive, hydraulic properties from previous tests are summarized for use in crude calculations and for comparing with new test data.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:

Pump tests (Section 8.2) are considered to be the most reliable method for measuring the hydraulic properties of aquifers. Slug tests are less accurate (Section 8.1). Table 1 in Section 7.1 contains a summary of the techniques available for measuring the hydraulic conductivity of soils and aquifers. The transmissivity and storage-coefficient of an aquifer can only be obtained from pump tests (Section 8.2).

4. PREVIOUS USES OF THE METHOD:

Aquifer parameters have been estimated from short-term pump tests (24-100 hours) and the trends projected over longer periods to estimate the effect of prolonged pumping.

Research in the south-west has used slug test analyses, as the low permeability of weathered materials may preclude pumping significant quantities of water from a bore. In some cases higher yielding bores have been found. Table 1 summarizes results from some of the known pump tests conducted in the agricultural areas.

Slug tests conducted on a range of aquifer materials have been analysed using the Bouwer and Rice (1976) method (Table 2). In these areas, most piezometers were drilled into the pallid zone of the laterite profile; others were drilled into saprolite grits or alluvial sediments. The drilling procedure and bore construction details are generally not recorded in technical reports or papers.

5. COST/AVAILABILITY OF EQUIPMENT:

Pump test equipment can be borrowed from the Principal Research Officer, Hydrology and Water Resources Branch at South Perth. This equipment includes two submersible pumps, one generator and other sundries.

Slug test materials can easily be assembled on cost between $10-500. Cost depends on whether an electronic water-level probe or plopper (fox-whistle) is used.

6. PRINCIPLES OF METHOD:

Refer to Sections 8.1 and 8.2.

7. FIELD PROCEDURE:

Refer to Sections 8.1 and 8.2.
<table>
<thead>
<tr>
<th>Location</th>
<th>Author</th>
<th>T (m²/day)</th>
<th>K (m/day)</th>
<th>S</th>
<th>Aquifer</th>
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</thead>
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<td>Lemon Catchment</td>
<td>M. Martin</td>
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<td>0.20-0.46</td>
<td>4.6 x 10⁻⁴ - 7.3 x 10⁻³</td>
<td>Pallid zone</td>
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<tr>
<td>Meringee Farm</td>
<td>M. Martin</td>
<td>1.03-6.93</td>
<td>0.11-0.38</td>
<td>1.3 x 10⁻³ - 9.1 x 10⁻³</td>
<td>Pallid zone</td>
</tr>
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<td>Harris River</td>
<td>M. Martin</td>
<td>22.3-109.2</td>
<td>1.0-5.0</td>
<td>1.8 x 10⁻³ - 4.1 x 10⁻²</td>
<td>Pallid zone</td>
</tr>
<tr>
<td>Nundagong</td>
<td>P.R. George</td>
<td>25-30</td>
<td>1.0</td>
<td>1.9 x 10⁻²</td>
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<td>P.R. George</td>
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<td>6.0 x 10⁻³</td>
<td>Sap. grit</td>
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<td>1.0 x 10⁻³</td>
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<td>Manjimup</td>
<td>L. Furness</td>
<td>N/A</td>
<td>0.006</td>
<td>N/A</td>
<td>Pallid zone</td>
</tr>
<tr>
<td>Manjimup</td>
<td>L. Furness</td>
<td>N/A</td>
<td>0.014</td>
<td>N/A</td>
<td>Pallid zone</td>
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<tr>
<td>Manjimup</td>
<td>L. Furness</td>
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<td>0.022</td>
<td>N/A</td>
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<tr>
<td>Manjimup</td>
<td>L. Furness</td>
<td>N/A</td>
<td>0.04</td>
<td>N/A</td>
<td>Pallid zone</td>
</tr>
<tr>
<td>Manjimup</td>
<td>L. Furness</td>
<td>N/A</td>
<td>0.032</td>
<td>N/A</td>
<td>Pallid zone</td>
</tr>
<tr>
<td>Cuballing</td>
<td>R.J. George and R. Engel</td>
<td>59</td>
<td>5.9</td>
<td>4.9 x 10⁻⁴</td>
<td>Sap. grit</td>
</tr>
<tr>
<td>Wallatin</td>
<td>R.J. George</td>
<td>(i) 6.5</td>
<td>0.7</td>
<td>1.2 x 10⁻²</td>
<td>Sap. grit</td>
</tr>
<tr>
<td>Creek</td>
<td>R.J. George</td>
<td>(ii) 4.0</td>
<td>0.4</td>
<td>0.9 x 10⁻²</td>
<td>Sap. grit</td>
</tr>
<tr>
<td>E. Belka</td>
<td>R.J. George</td>
<td>6.3</td>
<td>0.5</td>
<td>1.6 x 10⁻⁴</td>
<td>Sap. grit</td>
</tr>
<tr>
<td>Ardath</td>
<td>R.J. George</td>
<td>&lt; 1</td>
<td>&lt; 0.1</td>
<td>N/A</td>
<td>Fractured Rock</td>
</tr>
<tr>
<td>Frankland</td>
<td>R. Engel</td>
<td>10</td>
<td>1.3</td>
<td>2.3 x 10⁻³</td>
<td>Sap. Grit</td>
</tr>
</tbody>
</table>
Table 2. Slug tests in agricultural areas

<table>
<thead>
<tr>
<th>Location</th>
<th>Author</th>
<th>Number of observations</th>
<th>Estimate of hydraulic conductivity m/day</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Del Park</td>
<td>Bestow 1976</td>
<td>N/A</td>
<td>0.034</td>
<td>Weathered granite</td>
</tr>
<tr>
<td>2. Dwellingup</td>
<td>Peck et al. 1980</td>
<td>N/A</td>
<td>0.006</td>
<td>Weathered granite</td>
</tr>
<tr>
<td>3. Bakers Hill</td>
<td>Peck et al. 1980</td>
<td>N/A</td>
<td>0.005</td>
<td>Weathered granite</td>
</tr>
<tr>
<td>4. Collie West</td>
<td>Peck et al. 1980</td>
<td>N/A</td>
<td>0.003</td>
<td>Weathered granite</td>
</tr>
<tr>
<td>5. Collie East</td>
<td>Peck et al. 1980</td>
<td>N/A</td>
<td>0.002</td>
<td>Weathered granite</td>
</tr>
<tr>
<td>6. Upper Helene</td>
<td>Peck et al. 1980</td>
<td>N/A</td>
<td>0.047</td>
<td>Weathered granite</td>
</tr>
<tr>
<td>7. E. Perenjori</td>
<td>Henschke</td>
<td>N/A</td>
<td>0.026</td>
<td>Weathered granite</td>
</tr>
<tr>
<td>8. Dangin</td>
<td>Henschke</td>
<td>N/A</td>
<td>0.011</td>
<td>Weathered granite</td>
</tr>
<tr>
<td>9. E. Brookton</td>
<td>Henschke</td>
<td>N/A</td>
<td>0.004</td>
<td>Weathered granite</td>
</tr>
<tr>
<td>10. W. Narrogin</td>
<td>Engel</td>
<td>10</td>
<td>0.031</td>
<td>Weathered granite</td>
</tr>
<tr>
<td>11. W. Narrogin</td>
<td>Engel</td>
<td>20</td>
<td>0.006</td>
<td>Weathered dolerite</td>
</tr>
<tr>
<td>12. W. Narrogin</td>
<td>George, R.J.</td>
<td>8</td>
<td>0.086</td>
<td>Weathered granite</td>
</tr>
<tr>
<td>13. Cuballing</td>
<td>Engel</td>
<td>10</td>
<td>0.031</td>
<td>Weathered granite</td>
</tr>
<tr>
<td>14. E. Wheatbelt</td>
<td>George, R.J.*</td>
<td>39</td>
<td>0.57</td>
<td>Saprolite grits</td>
</tr>
<tr>
<td>15. E. Wheatbelt</td>
<td>George, R.J.*</td>
<td>30</td>
<td>0.55</td>
<td>Alluvial sediments</td>
</tr>
<tr>
<td>16. E. Wheatbelt</td>
<td>George, R.J.*</td>
<td>28</td>
<td>0.065</td>
<td>Weathered granite</td>
</tr>
<tr>
<td>17. E. Wheatbelt</td>
<td>George, R.J.*</td>
<td>18</td>
<td>0.10</td>
<td>Sandplain soils</td>
</tr>
</tbody>
</table>

* Bores drilled with a rotary air blast rig (HM12).

8. SPECIAL PRECAUTIONS:

Errors in the calculation or estimation of hydraulic properties arise from:

- pump/equipment failure;
- recording errors;
- interpretation errors (methodology);
- incorrect drilling procedures;
- poor development procedures.

Wherever possible, the rotary air blast rig (HM12), or mud-flush rotary drilling techniques should be used. Common problems encountered during pump tests have been discussed in Section 8.1 and 8.2. Table 3 shows the effect of conducting slug tests on holes drilled using the rotary auger (HM7) and the rotary air blast (HM12) rigs. It also compares the slug withdrawal and slug addition techniques.
Table 3. The influence of drilling technique and test method on hydraulic conductivities from the same geologic unit, Wallatin Creek palaeochannel sediments

<table>
<thead>
<tr>
<th>Drilling technique</th>
<th>Hydraulic conductivity (m/day)</th>
<th>Slug withdrawal technique</th>
<th>Slug addition technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotary air blast (HM12)</td>
<td>0.21 (47%)*</td>
<td></td>
<td>0.31 (69%)</td>
</tr>
<tr>
<td>Auger drill (HM7)</td>
<td>0.01 (2%)</td>
<td></td>
<td>0.09 (20%)</td>
</tr>
</tbody>
</table>

* Pump tests on a rotary air blast hole yielded a hydraulic conductivity of 0.45 m/day. The figures in brackets are compared with this figure.

These results suggest that disruption to the aquifer during drilling was less with the rotary air blast than with the auger rig. It also indicates that slug test results are less accurate than pump tests. Most of the differences arise from the difference in the sample size or sphere of influence. Pump tests affect an area 4 to 5 orders of magnitude larger than do slug tests.

9. ANALYSIS OF RESULTS:
See Sections 8.1 and 8.2.

10. ADDITIONAL COMMENTS:
See Sections 8.1 and 8.2.

11. REFERENCES:
See Sections 8.1 and 8.2.

12. MAIN CONTACT PERSONS:
Richard George, Bunbury.
Don McFarlane, Albany.
SECTION 9: DRILLING

9.1 INTRODUCTION AND AVAILABILITY OF DRILLING EQUIPMENT

1. WHAT IS MEASURED?:

Subsurface sampling of soil and aquifer materials. Establishment of wells and piezometers.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:

Hand augers for shallow holes or powered drill rigs (Section 9.2).

3. PREVIOUS USES OF THE METHOD:

(1) Collect soil samples at depth.
(2) Determine groundwater levels.
(3) Install P.V.C. pipe to monitor groundwater levels over time.
(4) Determine groundwater quality.
(5) Install observation bores for pump tests.
(6) Salt storages (includes calibration of EM equipment Section 10.2).
(7) Piezometer nests for vertical hydraulic gradients.
(8) Depth of bedrock.

4. COST/AVAILABILITY OF EQUIPMENT:

There are a number of drill rigs available in the Department. Contact the person in charge of bookings (see below) to find out what is available.

(1) Trailer mounted auger drilling rig capable of drilling to 3 m and powered by a 5HP petrol engine is available from:

Ian Wardell-Johnson
NARROGIN WA 6312

(2) Gemco 110, a trailer mounted auger drilling rig with vacuum brakes capable of drilling to 10 m and powered by a 25HP petrol engine is available from:

David Quinlan
MERREDIN WA 6415

(3) Hydraulic auger rig mounted on the tray top of a Toyota Landcruiser is powered by the vehicle. It is capable of drilling to 3 m. The advantages of this unit is the ease of use and its accurate hole location. It is available from:

Dave Tennant
SOUTH PERTH WA 6151

(4) Gemco HM7 hydraulic auger rig. Powered by a 4.1 litre Ford petrol engine. Capable of drilling to 50 m. The complete rig sits on the back of a Ford 8t truck powered by a petrol engine and is available from:

Arjen Ryder
ALBANY WA 6330
Gemco HM12 hydraulic rotary air blast rig (RAB). Powered by a Deutz air cooled diesel engine. Capable of drilling to 50 m. Fluid injection is available for difficult soils. The rig is mounted on the back of a 8 t 4WD Isuzu truck. A 250 cfm air compressor, towed behind the truck is used to supply air. Available from:

Ed Solin
SOUTH PERTH WA 6151

The capital cost of drill rigs vary markedly from $5000 for a petrol driven trailer mounted rig up to $60,000 (1986) for the Gemco HM12.

The rigs are listed in order of increasing complexity and difficulty of use.

All of the drill rigs require periodic maintenance including replacing drill bits, refacing augers and servicing the engines.

5. PRINCIPLES OF METHOD:

Augers or rods are rotated via a gearbox connected by direct drive or hydraulics to an engine. The speed of rotation can be adjusted for various soil types by shifting a lever on the gearbox. Rate of descent of the augers is controlled by the operator, either with a hydraulic ram or a hand winch and wire (Narrogin rig). A drill bit attached to the first auger or rod, cuts the soil. Flights on the augers bring the cuttings to the surface. Rods which are hollow and have no flights, as used with the RAB rig, have air blasted down them and through the drill bit. Drill bits of larger diameter than the rods allow the cuttings to be blown to the surface, past the outside of the rods.

6. FIELD PROCEDURE:

The location of boreholes depends on what is being measured. Electromagnetic and magnetometer surveys can be used to locate drilling sites.

Operating drilling rigs is a matter of becoming familiar with the controls. The principles of operation are the same on all rigs. Field control and adjustments vary in complexity from rig to rig. Narrogin's trailer mounted rig is the simplest. It has one gear, on or off (speed of rotation is fixed) and the rate of descent is controlled by a winch which the operator turns. Augers come in various lengths and diameters. The most common being 1.8 m * 50 mm. Each auger is drilled into the ground and once an auger has reached its drilling limit, another is attached to it.

Experience is the best teacher. To gain experience, help an experienced operator on their drilling programme. Once confident, you can organize your own drilling programme and maybe involve someone else who needs experience.

The time required to drill a hole depends on its depth and the materials encountered while drilling. Drilling rates decline progressively with depth so it is normal for the first half of a deep hole to be drilled in a quarter of the time taken to drill the complete hole. It is possible to drill between 30-100m a day with the Gemco rigs.

7. SPECIAL PRECAUTIONS:

When controlling the rate of descent, let the drill bit do the cutting and do not put the complete weight of the trailer or vehicle on the augers. The
Rotary air-blast drilling rig
extra weight causes augers to bend, making them wobble in the hole. Once bent, it is usually cheaper to replace the auger than to repair it.

Augers are connected together with a pre-stressed hexagonal rod and pin. Avoid excessive jarring in the rotation and descent of the augers as hexagonal rods are easily broken or twisted.

Generally the operator develops a feel for the equipment and soil conditions which enables a judgement to be made of the appropriate settings for the controls. The aim is to get the holes dug quickly and efficiently without causing excessive wear and tear on the machinery.

The Gemco HM12 rotary air blast rig requires much more training than the other rigs.

The quality of work determines the quality of any result (e.g. salt storages from drill samples). Contamination from any source needs to be avoided.

8. ANALYSIS OF RESULTS:

9. ADDITIONAL COMMENTS:

The two Gemco rigs use different methods of bringing cuttings to the surface. A comparison has been done of salt storages on soil samples collected from both rigs at the same location. The results show similar salt storages up to 10 m, however beyond this depth the Gemco HM7 (auger) rig shows signs of contamination and a lag. It is assumed that the RAB rig blows all its cuttings to the surface with minimal time lag from the depth being drilled while the HM7 augers take longer to bring a sample to the surface at depths greater than 10 m. This means that a sample taken with the HM7 when its at say 30 m might really be the cuttings from 20-25 m.

10. REFERENCES:

11. MAIN CONTACT PERSONS:

For the rigs mentioned in this section contact the persons involved.

Richard George, Bunbury.
Ed Solin, Perth.
Arjen Ryder, Albany.
9.2 DRILLING TECHNIQUES

1. WHAT IS MEASURED?:

Provides the ability to sample and describe deep soil profiles and their associated groundwater systems.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:

Drilling is an expensive and time consuming operation. It is the main method of determining subsurface conditions.

Geophysical methods (e.g. electromagnetic terrain conductivity, magnetometry) provide another source of information. Geophysical techniques can help site drill holes and can help extrapolate findings from drill holes to other areas.

3. PREVIOUS USES OF THE METHOD:

Drilling programmes have been the basis of catchment investigations of salinity problems. Over a thousand wells and piezometers have been installed using drilling rigs. The most common reason for drilling is to provide information on:

(1) Depth of watertable (unconfined aquifer) or potentiometric surface (confined aquifer).
(2) Salinity of the groundwater.
(3) Lithology or geology of the area.
(4) Direction and gradients of groundwater flow.
(5) Hydraulic properties of the saturated materials.
(6) Rate of watertable rise and response to either natural or man-induced changes of the hydrologic cycle.
(7) Salt storage.
(8) Rate of change of groundwater salinity.
(9) Find potable or stock supplies of water.
(10) Reclaim salt-affected land by pumping.

4. COST/AVAILABILITY OF EQUIPMENT:

The Department of Agriculture operates two main drilling facilities, a rotary auger 'GEMCO' HM7 rig and a larger rotary air blast (R.A.B.) GEMCO HM12 truck mounted machine. Details of these and other machines are given in Section 9.1. Discussion in this section is limited to the HM7 (auger rig) and HM12 (R.A.B. rig).

Details of charges for special projects can be obtained from the Principal Research Officer, otherwise the rigs work on a user pays and repairs system. Training of new personnel is required before either rig can be used.

5. PRINCIPLES OF METHOD:

The drilling of piezometers and production wells, their design, construction and maintenance is a detailed subject. Further aspects of piezometer and bore construction and installation is covered in Driscoll (1986) and Freeze and Cherry (1979).
Drilling provides access to the underlying groundwater system and enables samples of soil and water to be taken. Piezometers and observation wells also supply information of the hydraulics of the flow system. Flow in a groundwater system is governed by Darcy's law which states that $V$ (specific discharge) is a function of gradient of flow ($i = \Delta h/L$) and the aquifer's hydraulic conductivity ($K$) such that:

$$v = Ki$$  

(1)

$\Delta h$ = difference in hydraulic head along the flowline  
$L$ = distance between the head measurements.

The flow of an aquifer, $Q$ ($m^3$/day) is the product of the specific discharge and the cross-sectional area ($A$) through which flow occurs,

$$Q = kiA$$  

(2)

It is often assumed (Dupuit-Forschheimer assumption) that the gradient of the watertable or piezometric surface is the gradient of groundwater flow (i.e. vertical gradients are small relative to horizontal gradients).

Piezometers and wells provide the means of measuring the hydraulic gradient (Figure 1).

Fig 1. Determination of hydraulic gradients from piezometers.

Piezometers must be sealed along their length but open at the slotted section. Adjacent piezometers with slots at different depths are used to measure the vertical hydraulic gradient. Vertical gradients give an indication of whether recharge, or discharge is occurring. Piezometers located at the same depth of an aquifer measure the horizontal gradients between the piezometers.
6. **FIELD PROCEDURE:**

6.1 **Construction of Piezometers**

**Step 1**

After drilling the hole the augers or rods are removed. The required length of P.V.C. tubing is immediately inserted into the hole. The length of slotting required is dependent on the thickness of the aquifer. In most investigations carried out, 2 m of machine slotted (0.8-1.2 mm) P.V.C. is placed on the end of the column and the end is capped. It is usual to first drill a hole to bedrock and install a piezometer with the slots above bedrock. If a piezometer nest is to be installed, a hole is drilled to a few metres below the watertable. This provides the maximum vertical distance over which the measurement of vertical gradients is made. If the aquifer is less than 8 m thick, only one piezometer is usually installed.

**Step 2**

A gravel or sand filter pack (Table 1) is poured around the annulus formed between the drill hole walls and the slotted P.V.C. The amount of sand required can be calculated by subtracting the volume of the piezometer tubing from the volume of the drilled hole. When a very productive or unconsolidated material is struck it may be necessary to increase the volume of sand screening used because the cavity is enlarged. In other cases the annulus around the P.V.C. may collapse and it is not possible to get sand around the slots.

<table>
<thead>
<tr>
<th>Geologic material</th>
<th>Optimum grain size*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pallid zone sandy clays</td>
<td>0.8-1.6 mm</td>
</tr>
<tr>
<td>Sands (fine and medium)</td>
<td>1.6-3.2 mm</td>
</tr>
<tr>
<td>Gravels and sands (coarse)</td>
<td>3.2-6.4 mm</td>
</tr>
</tbody>
</table>

* Commercial filter packs.

Using the correct grain size in a piezometer is not as critical as in production bores, in which case samples need to be analysed for particle size distribution (Driscoll 1986).

**Step 3 - Grouting**

Bentonite clay or cement grouts are used to isolate the screened section and sand screen from the remainder of the aquifer to ensure that water does not leak down the annulus and enter the bore.

A bentonite or cement slurry is made up with water and poured down the annulus so as to form a 1 to 2 m plug above the screened section. The remainder of the piezometer is then back-filled with cuttings from the drill hole and cemented at the surface to prevent inflow of water and protect the installation.
Step 4

Once the annulus has been packed the piezometer tubing remaining above ground level should be cut off to about 20 cm above ground. This should prevent sheep from breaking the tubing. In most cases a cement collar should be installed for protection from fire and animals. Finally a slit is cut into the pipe below the cap to ensure the air in the tube is at atmospheric pressure.

If artesian (flowing) conditions occur and a significant amount of P.V.C. is required above the ground it is advisable to use a reinforcing sleeve (cement pipe etc.) to stabilize and protect the P.V.C. A manometer can be attached to allow readings to be made if the top of the casing is too high to read.

Step 5

Developing (surging or jetting of the hole to remove fine materials surrounding the slots) a production well or piezometer is critical. During developing, fine grained materials are progressively removed from the annulus, and into the piezometer until bridging or an ideal grain size distribution is achieved which prevents sediment from entering the bore.

Poorly developed production wells can destroy pumps and disrupt pump tests by continually developing the bore during pumping. Poorly developed piezometers will have lower hydraulic conductivities in slug tests.

Two methods of development are recommended. Both are difficult in low permeability materials. Jetting and surging of water and compressed air respectively agitates the screening materials and aquifer. These procedures move sediment from the aquifer and screen by continuously disturbing the materials. Sediment that accumulates in the bore is blown from the piezometer by compressed air or by sludge pumps.

Small compressors (12-50 cfm at 100 psi) are capable of developing piezometers and shallow (100 mm) production wells. However the development of production wells is best achieved using much larger compressors (200-350 cfm at 100-200 psi). Overpumping and surging is a useful development technique.

There is no time limit on the development of a bore. Some bores take 1-2 hours while others take much longer. Development is achieved when water can be extracted without sediment. A detailed account of developing procedures is available in Driscoll (1986).

6.2 Drill Sampling Procedures

Samples are obtained from cuttings recovered during drilling. Samples arrive at the surface by either being wound up the auger flights (HM7 rig) or blasted to the surface in the airstream (HM12). The HM12 rig is capable of coring, however at present we do not have the equipment for coring.

Sampling above the watertable is usually accurate with both rigs. However the HM12 rig has the advantage of sending samples to the surface in the airstream. In auger drilling there is a lag and a risk of contamination (Section 8.1). Below the watertable both rigs have difficulty in delivering uncontaminated samples. In difficult materials, which have low yields and become sticky down the hole, it is sometimes necessary to add water and drilling mucks with the HM12 rig. This blows water and samples to the surface but may contaminate the samples with tank water and mud. These activities
should be noted and appropriate comments made on well-log reports and other publications. In very permeable materials the HM12 rig may also remove clay materials in the water stream when either adding water or drilling productive aquifers.

Drill samples should be stored in pre-marked polythene bags. Most analyses require less than 100 g of sample however additional sample should be taken for storage. Storing small samples in plastic vials is useful for demonstrations of material for field days.

7. SPECIAL PRECAUTIONS:

7.1 Drilling Method

In clayey soils the auger drilling rig (HM7) smears clay on the sides of the hole resulting in poor installation and development. It therefore affects the calculation of hydraulic properties. In Section 8.3 a table shows the effect of drill technique on hydraulic conductivity. On the basis of these results and field observations, it is recommended that auger drilling only be used for the following purposes:

1. depth to a watertable;
2. depth to bedrock;
3. basic soil and water sampling.

Rotary air drilling should be used in all other cases. In very sandy materials and sticky clays, mud-rotary drilling may be necessary.

7.2 Piezometer Installation

Several difficulties arise when installing piezometers. Care should be taken to avoid:

1. creating a downhole cavity;
2. leaving drill cuttings down the hole;
3. underestimating screen length;
4. incorrect slot size;
5. incorrect choice of casing size;
6. over-glueing P.V.C. joints (i.e. they become sloppy and the pipes may separate and fall down the hole);
7. using the hydraulics of the rig to push the casing through clay plugs.

8. ANALYSIS OF RESULTS:

Record the details of drill installation technique, borehole construction and development (Table 2), including details of analyses conducted (e.g. chloride or the name of the geophysical log).
Table 2. Well log reports - drilling results

<table>
<thead>
<tr>
<th>Project bore No.</th>
<th>Rig type</th>
<th>Catchment</th>
<th>Casing depth</th>
<th>Date drilling</th>
<th>Depth drilling</th>
<th>Location</th>
<th>Quality</th>
<th>Grid reference</th>
<th>Yield</th>
<th>Land unit</th>
<th>Depth to bedrock</th>
<th>Slotted length</th>
<th>Watertable depth</th>
<th>Samples</th>
</tr>
</thead>
</table>

Results

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Description of cuttings</th>
<th>Interpreted zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>From</td>
<td>To</td>
<td></td>
</tr>
</tbody>
</table>

9. ADDITIONAL COMMENTS:

Drilling equipment is expensive and it must be maintained and care must be taken to avoid damaging the gear and its operators. Safety equipment including steel capped boots, eye protection, helmets and earmuffs are recommended. It is essential that operators have training on the rigs with experienced operators before using it unsupervised. Care and maintenance of the HM12 rig is especially important.

10. REFERENCES:


11. MAIN CONTACT PERSONS:

Richard George, Catchment Hydrology, Bunbury.
Arjen Ryder, Catchment Hydrology, Albany.
Maurice Eales, Horticulture, South Perth.
Ed Solin, Catchment Hydrology, South Perth.
SECTION 10: GEOPHYSICAL TECHNIQUES

10.1 PROTON PRECESSION MAGNETOMETRY

1. WHAT IS MEASURED?:

The strength of the vertical component of the earth's magnetic field.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:

Flux gate magnetometers are not as good in lateritic terrain.

3. PREVIOUS USES OF THE METHOD:

Field magnetometers have been used to map dolerite dykes which have been responsible for forcing saline groundwaters to the soil surface (Engel et al. 1987, McFarlane et al. 1987).

Airborne magnetometers have been used for similar reasons in the Yornaning Catchment in the Cuballing Shire.

4. COST/AVAILABILITY OF EQUIPMENT:

The Department own a Geometrics 856A proton precession magnetometer (cost $7,400 in 1984) contact Don Bennett, Bunbury. A Geometrics G816 proton precession magnetometer can be loaned from the Geophysics Section of the Mines Department (Contact: Laszlo Kevi (09) 222 3333) or Tim Negus, Department of Agriculture, Narrogin.

Tesla 10 Pty Ltd ((09) 364 8444) have a magnetometer on a trailer which can be pulled behind a vehicle for rapid traverses. Enquire about cost per ha.

It may also be possible to hire magnetometers from geophysical consultants i.e. Mackie Martin, or mining companies from Curtin University.

5. PRINCIPLES OF METHOD:

Ferrimagnetic minerals (e.g. magnetite, ilmenite, maghemite) in rocks and soils distort the earth's magnetic field. Such distortions can be detected either from contour maps of the field or from profiles.

In agricultural areas, dolerite dykes usually contain more ferrimagnetic minerals than granite and granitic gneiss. Therefore, a contour map of the earth's magnetic field usually shows a linear magnetic high over the dyke, even when the dyke is covered by alluvium or a deeply weathered profile.

Other rocks which produce "magnetic highs" are greenstones (basis and ultrabasic rocks common in the goldfields) and banded iron formations (a sedimentary rock containing iron-rich beds). Neither of these rocks are common in agricultural areas. Some gneisses and granites also contain abnormally high amounts of ferrimagnetic minerals. However, the anomalies caused by such rocks are usually broad. Lateritic ironstones often give high erratic readings.
Proton precession magnetometer
6. **FIELD PROCEDURE:**

Magnetometers are susceptible to magnetic storms caused by sun spot activity. It is advisable to ring IPS Radio and space service, duty forcaster on (02) 414 8329 during office hours or (02) 414 8330 for a recorded message to find out whether a storm is likely during the survey.

**Setting up the Magnetometer**

1. Clearing a key sequence.
   
   CLEAR

2. Taking and Storing a Reading.
   
   READ, STORE

3. Recalling from memory - last reading taken.
   
   RECALL (continue pressing RECALL to decrement press ENTER increment)

4. Recalling from Memory - specific station number.
   
   RECALL, SHIFT, (station)+, (station)+, (station)+, ENTER

5. Tuning the magnetometer.
   
   READ, TUNE, SHIFT, +, +, ENTER

   
   READ, RECALL, ERASE, ERASE

   - last group of readings.

   RECALL, SHIFT, (station)+, (station)+, (station)+, ENTER, ERASE, ERASE

   - entire memory.

   RECALL, SHIFT, 0, ENTER, ERASE, ERASE

7. Time and Line Number read.
   
   TIME (press while reading is being displayed - see RECALL)

8. Line Number set.
   
   TIME, SHIFT, (line)+, (line)+, (line)+, ENTER

   
   AUTO, TIME, SHIFT, (day)+, (day)+, (day)+, ENTER

10. Julian day and time set.
    
    AUTO, TIME, SHIFT, (day)+, (day)+, (day)+, (hour)+, (hour)+, (min)+, (min)+, ENTER
11. Output in.
   OUTPUT, ENTER

12. Output stop.
   OUTPUT, CLEAR

13. Setting auto mode.
   AUTO, SHIFT, (seconds)+, (seconds)+, ENTER

   AUTO, CLEAR

In magnetic surveys the relative strength of the earth's field is important rather than its absolute strength. Therefore it is not necessary to calibrate the magnetometer against a known standard. However, it is necessary to check for instrument drift and diurnal variations in the earth's field during the survey. With one magnetometer this can be achieved by periodically returning to a base station to record the reading through time. Any drift can then be distributed through the readings. With two magnetometers, one can be left at the base station to automatically take and record readings. Base stations should not be in areas where the magnetic readings vary markedly over short distances.

A series of traverses are selected with the lines at right angles to the object of interest. This may be the strike of the rocks or the likely location of a dolerite dyke. It is good practice to have traverses sub-parallel to groundwater flow lines so that any obstructions to flow will be detected.

Usually a navigator with a measuring wheel marks positions on the ground where readings are to be taken. Measurement intervals are every 50 m where there are small variations in readings to every 5 m where there are large variations i.e. dyke areas.. Traverses are usually 100 to 120 m apart. The operator of the magnetometer follows the navigator but keeps at least 20 m behind the metallic wheel. Readings can be recorded in the magnetometers memory or in a field notebook.

7. SPECIAL PRECAUTIONS:

It is necessary to ensure that the operator is not wearing any metallic object (keys, belt buckle, ring, watch, steel-capped boots etc.), or that readings are taken close to metallic objects (cars, fences, electricity lines etc.).

Do not use copper top batteries, use duracell or NiCad's.

8. ANALYSIS OF RESULTS:

The magnetic reading and its position (northing, easting) are entered onto computer disk and sent to the GIS group for contouring.

If you want to see the data quickly, use a spreadsheet programme i.e. LOTUS123 and produce hardcopies of each transect. Then stagger the transects on a light table and the result should look like Figure 1.
9. ADDITIONAL COMMENTS:
Details for setting up the magnetometer are included with the instrument being used.

10. REFERENCES:


11. MAIN CONTACT PERSON:
Richard George, Bunbury. Magnetometer bookings.
Don McFarlane, Albany.
Fay Lewis, Northam.

Figure 1. Contour map produced by GIS
10.2 ELECTROMAGNETIC TERRAIN CONDUCTIVITY

1. WHAT IS MEASURED?

Apparent electrical conductivity of the ground.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:

In situ bulk soil electrical conductivity measurements using four-electrode techniques (e.g. Wenner array), the EC-probe and soil sampling.

3. PREVIOUS USES OF THE METHOD:

Electromagnetic induction (EM) provides a method of mapping soil salinity. Williams and Baker (1981, 1982) used EM methods to map regional salinity and found areas with relatively high sub-surface salinity could readily be defined. Similar work has been done in Western Australia (Engel et al. 1989).

Rhoades and Corwin (1981) compared the EM technique with resistivity methods and found good correlations. They recommended the EM devices to be sufficiently accurate for field measurement of salinity profiles and for diagnosing saline seeps. Similarly, Cameron et al. (1981) compared the Wenner array method with EM for mapping salinity. All instruments gave a clear delineation between areas of high and low salt content. While EM methods were much less time consuming, they could not be used to obtain detail on salt distribution with respect to depth.

4. COST/AVAILABILITY OF EQUIPMENT:

A range of EM units are available. Three devices which have successfully been used for salinity mapping, and prices (as of 1990) are shown.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
<th>Price (1990)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM31</td>
<td>Continuous reading, terrain conductivity meter (3.7 m length)</td>
<td>$20,000</td>
</tr>
<tr>
<td>EM34-3</td>
<td>Variable depth, terrain conductivity meter (10, 20, 40 m lengths)</td>
<td>$33,000</td>
</tr>
<tr>
<td>EM38</td>
<td>Continuous reading, terrain conductivity meter (1 m length)</td>
<td>$10,000</td>
</tr>
</tbody>
</table>

The Department of Agriculture has two of these units (EM31 and EM38). The CSIRO in Canberra and Department of Conservation, Forests and Lands, Victoria have EM34-3 units.

Baden Williams
CSIRO
Division of Water and Land Resources
CANBERRA ACT 2601

Phil Dyson
DCFL
Land Protection Division
BENDIGO VIC. 3353

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The manufacturer of EM equipment is:

Geonics Limited
1745 Meyerside Drive
Mississauga
ONTARIO L5T 1C5
CANADA

The Australian agents are:

Geoterrex (Pty) Ltd
13 Whiting Street
ARTARMON NSW 2064
Phone: (02) 437 3866

The Western Australian representative is:

Noel Mattocks
Tesla-10 Pty Ltd
41 Kishorn Road
APPLECROSS WA 6153
Phone: (09) 364 8444
An EM31 can be hired from this company.

5. **PRINCIPLES OF METHOD:**

With EM techniques, an electric current is induced in the soil and so contact electrodes are not needed as with Wenner resistivity equipment. It is also possible to take continuous readings along a transect. EM instruments consist of two coils (transmitter and receiver) which are separated by a fixed distance in the case of the EM31 and EM38, while in the case of the EM34-3, the distance between coils can be varied.

When the meter is switched on, the transmitter coil at one end of the instrument is energized with an alternating electric current. This current generates a primary magnetic field into the ground which, in turn, induces small eddy currents (in any conductive material) which generate their own secondary magnetic field. The receiver coil, at the other end of the instrument, responds to both the primary and secondary magnetic fields. The ratio between these magnetic fields is measured by the voltage induced in the receiver coil. This voltage is linearly related to terrain conductivity i.e. the more salt, the higher the voltage reading.

The apparent electrical conductivity of the soil depends on the same properties as the soil resistivity measured by electrical resistivity methods. The depth of soil measured depends on the frequency of the transmitter (fixed for EM31 and EM 38), intercoil spacing, coil orientation relative to the soil surface, and to a lesser extent on soil conductivity. The instruments are able to provide an accurate measure of the bulk conductivity of the soil and are able to detect variations in its spatial distribution.

The characteristics and uses of three of the common ground conductivity meters are outlined below.
The spacing between the coils is one metre, as the instrument was designed specifically for measuring ground conductivity in the root zone. Measurements are usually made by laying the instrument on the ground in both the horizontal and vertical dipole modes. This gives information as to whether the conductivity is increasing or decreasing with depth. In the horizontal dipole mode the surface horizons contribute most to the recorded EM value, i.e. the instrument is most sensitive to conductive material near the surface. Up to 60% of the signal response is from within 0.5 m. In the vertical dipole mode the instrument can detect salinity to a depth of about 1.2 m. Up to 70% of the signal response comes from below 0.5 m and only 30% from within 0.5 m. If surface layers are conductive, the depth of penetration is much less due to "short circuiting" of the signal.

For rapid reconnaissance surveys in salinity mapping, the instrument can be suspended 0.1 m above the ground surface with a sling strap. The operator can observe the relative changes while walking a traverse. However there is some loss of depth penetration in this mode and placing the instrument on the ground is preferable.

The instrument has a fixed intercoil spacing of 3.7 m with the coils arranged coplanar. It is usually used in the reconnaissance mode, where it is carried on a sling and operated continuously. It can also be laid on the ground for horizontal and vertical dipole measurements. When the coils are parallel to the earth (vertical dipole mode) measurements can be made to twice the depth as when coils are perpendicular to the earth (horizontal dipole mode). In a uniform soil 50% of the conductivity response is from the 0-2.5 m depth range with the instrument in its normal carrying position (vertical mode). On the soil surface in the horizontal mode, 50% of the signal response is from 0-3 m, while on the soil surface in the horizontal mode, 50% of the response is from 0-1.4 m. Hence by varying the height of the instrument and the coil orientation relative to the soil surface, the variation in apparent EC with depth can be assessed.

This is the largest of the ground electrical conductivity meters and can be operated at intercoil spacings of 10, 20 and 40 m. It is operated in the horizontal dipole mode.

All of the ground conductivity meters are calibrated to read electrical conductivity (apparent) ECa, in units of milli-siemens per metre (mS/m). Table 1 summarizes the approximate depth of penetration for the various EM instruments when in the horizontal and vertical dipole modes (from McNeill 1985).

Table 1. Maximum depth of current penetration by EM meters

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Intercoil spacing (m)</th>
<th>Maximum depth of penetration (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Horizontal dipole</td>
</tr>
<tr>
<td>EM38</td>
<td>1.0</td>
<td>0.75</td>
</tr>
<tr>
<td>EM31</td>
<td>3.7</td>
<td>3.0</td>
</tr>
<tr>
<td>EM34-3</td>
<td>10.0</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td>20.0</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td>40.0</td>
<td>30.0</td>
</tr>
</tbody>
</table>
6. **FIELD PROCEDURE:**

**EM38**

(1) **Battery test**

Before operation, check the battery condition as follows: with the range switch in any position press button marked "BATT". For a good battery the pointer of the meter will go beyond the mark "B". If the pointer reads below the mark "B", the batteries should be replaced. (Use rectangular 0061/9volt batteries.)

(2) **Field calibration**

At the commencement of the survey, choose a relatively uniform surface for calibration. Ensure that there is no interference from nearby metallic objects (N.B. EM instruments are particularly sensitive to metallic loops e.g. rings). A good location for calibration is on a large bedrock outcrop. The calibration is carried out in three steps.

(a) **Inphase nulling:** Lift the instrument to arm height (e.g. 2 m above ground) and set the range switch to a convenient scale (e.g. 100 mS/m). Press the mode switch toward the "I/P" mark and set the pointer of the meter to zero (null) by using the I/P Coarse Zero control and then I/P Fine Zero control.

(b) **Instrument zero:** Keeping the instrument at arm height take readings in both the horizontal (H) and vertical (V) positions, leaving the range switch in whatever position gives a readable signal. The reading in the horizontal position should be one-half of the reading in the vertical position i.e. \( EM_v - 2EM_h = x \), where \( x = 0 \). If \( x \) does not equal 0, adjust the "Q/P ZERO" Control by an amount \( x \), to obtain the correct reading ratio (NB: Q/P ZERO should be around 66).

(3) **Survey procedure**

Place instrument on the ground in the horizontal dipole mode (vertical position) and take a reading. Then lay the instrument flat and take a second reading. If the ground is severely saline, select the 1,000 mS/m range and read the green scale marked 0-1.0 (in this case 0.5 = 500 mS/m and 1.0 = 1,000 mS/m). For highly saline ground set the range switch to the 300 mS/m scale and read the red scale (in this case 1.5 = 150 mS/m and 3.0 = 300 mS/m). For mild to moderately saline ground select the 100 mS/m range and read the green scale (0.5 = 50 mS/m and 1.0 = 100 mS/m). For non-saline to mildly saline ground use the 30 mS/m range and read the red scale (1.5 = 15 mS/m and 3.0 = 30 mS/m).

**EM31**

(1) **Initial set-up procedure**

(a) Using the identifying labels on the tubes select the transmitter coil tube, align it with respect to the main tube, insert it and fix it with the clamp.

(b) Check the battery condition, plus and minus, by setting the Mode switch (MODE SELECTOR SWITCH) to the OPER position and the Range switch to the +B and -B positions respectively. If the needle reads inside the BATT mark on the meter, the batteries are in good condition, otherwise replace the batteries with a fresh set of C size alkaline batteries.
(c) Check the zero reading by setting the Mode switch to the OPER position and the Range switch to 1,000 mS/m. If a zero adjustment is required adjust the DC ZERO CONTROL located under the front panel to obtain a zero reading. To do this the battery pack must be removed to gain access to the controls.

(d) Align and connect the receiver coil tube to the main frame tube. The instrument is now ready for the functional checks.

(2) Equipment functional checks

Field calibration should be carried out on a known surface, such as pavement or exposed bedrock, and should be checked twice daily. The range switch is set at 30 mS/m for the following tests.

N.B.: Calibration or zeroing is best carried out on large bedrock outcrops.

(a) Set the Mode switch to the COMP position and adjust the meter reading to zero using the COARSE and FINE COMPENSATION controls.

(b) To check the phasing of the instrument set the Mode switch to the PHASE position. Note the meter reading and rotate the COARSE control one step clockwise. If the meter reading remains the same, the phasing is already correct; return the COARSE control to its original position (one step counter clockwise) and no further adjustment is necessary.

If there was a difference in the meter readings taken before and after the COARSE control was rotated one step clockwise, then a phase adjustment is required. With the COARSE control in its original position adjust the PHASE potentiometer about 1/4 turn clockwise and note the new meter reading. Rotate the COARSE control one step clockwise, take a reading, and return the COARSE control to its original position. If the difference in meter readings has decreased, repeat the procedure using a further clockwise adjustment of the PHASE potentiometer, until rotating the COARSE control the one step clockwise produces no change in the meter reading.

If, on the other hand, the difference in meter readings was increased, the PHASE potentiometer should be rotated in a counter clockwise direction instead and the procedure described above repeated until there is no change in the meter readings.

Always remember to set the COARSE control back to its original position. This can be confirmed by setting the Mode switch in the COMP position and checking that the meter reads zero. If it does not read zero, repeat steps (a) and (b).

(c) To check the sensitivity of the instrument, set the Mode switch to the COMP position and rotate the COARSE control clockwise one step. The meter should read between 75% and 85% (22 to 26 mS/m) of full scale deflection (inside black mark). It is unlikely that the sensitivity of the instrument will vary, however it may be useful to record the actual meter reading for comparison at a later date.

Return the COARSE switch to its original position and the EM31 is now ready to make terrain conductivity measurements.
Operating procedure

(a) Wearing the instrument with the shoulder strap adjusted so that the instrument rests comfortably on the hip, switch the Mode switch to the OPER position and rotate the Range switch so that the meter reads in the upper two thirds of the scale. The full scale deflection is now indicated by the Range switch and the instrument is reading the terrain conductivity directly in mS/m.

(b) The EM31 can be operated continuously while moving from one station to the next or to extend battery life, the instrument can be switched off between stations.

(c) For maximum accuracy, place the instrument on the ground.

EM34-3

As the Department does not currently possess this instrument, the field procedure will not be discussed here. Procedures for its operation can be found in the EM34-3 manual.

Survey technique

It is recommended that prior to commencement, survey lines and measurement stations be carefully laid out, and the survey performed in a systematic fashion with the resulting data plotted accurately for each station. A common error is to have survey lines too short, so that the anomalous region is not defined adequately.

A survey team commonly consists of four persons. One as navigator, another with the EM31, another with the EM38 and another with the magnetometer. The navigator takes a compass, measuring wheel, air photo and marks on the ground where readings are to be taken. The other members follow at intervals of 20 m to prevent instruments interfering with each other. In this way EM and magnetometer measurements can be made.

The EM31 has good spatial resolution and measurement stations should be 10 m apart for maximum resolution. This spacing is smaller than often necessary. A 20-50 m line interval is more common. For a grid survey, transect lines should be within 100 m spacings. A tie line which connects previously surveyed points is useful to check for 'drift' over the survey.

7. SPECIAL PRECAUTIONS:

EM induction is affected by a number of factors. These factors are listed below and need to be taken into account when carrying out an EM survey.

(1) Moisture content.
(2) Porosity.
(3) Clay type and content.
(4) Soil water salinity.
(5) Soil water temperature.
(6) Foreign disturbances (powerlines, fences etc.).

With EM instruments, soil moisture provides a medium through which electrical currents, which are related to ionic concentration, can be transmitted. Therefore a threshold level of soil moisture is needed to obtain meaningful results. In the case of the EM38, moisture content would be more critical than for the EM31 which can be used during the summer period. Use of the EM38
should be mainly in winter and spring. In some soils, salts will be leached in winter, and summer and autumn readings of the EM38 will be higher provided the site is moist enough to obtain a reading. Seasonal surveys at the same site show little difference in EM31 readings, but larger difference with the EM38.

The EM31 is somewhat sensitive to underground conductors (e.g. large pipes) and responses are usually recognized by large meter fluctuations which occur within a short distance. Care should be taken near obvious metallic conductors (fences, powerlines, vehicles etc.) especially when calibrating the instruments. It would be advisable to keep a distance of at least 20 m from such objects. In order to determine whether the reading is influenced by such structures, the instrument should be rotated to determine if there is a maximum and minimum reading which appears related to the structure.

It is possible that edge effects will occur over a very good conductor which has similar dimensions as the intercoil spacing. As well soil minerals such as maghaemite and lateritic (pisolitic) gravels may affect the reading. Finally electrical static during thunderstorms can produce "noisy" readings.

8. ANALYSIS OF RESULTS:

Where transects are taken, data may be plotted up in cross-sectional form. For gridded surveys, contour maps can be drawn up. Testa-10 and the Department's GIS system can be used to plot the data.

The field data sheet should provide the following information: Date, Time, Farmer's property, Locality, Grid reference and Transect number and description. Long distance transect lines should be set up with a compass, with some easily recognizable targets to aim for. Records and comments in the log book are very useful when interpreting features at a later date.

9. ADDITIONAL COMMENTS:

Table 2 gives an approximate idea of the readings to be expected from an EM38 (horizontal mode) in soils of various salinities. These ranges will vary somewhat with soil type and moisture.

Table 2. Indicative soil electrical conductivity versus salinity

<table>
<thead>
<tr>
<th>Salinity</th>
<th>EM31 (mS/m)</th>
<th>(mS/m) Horizontal EM38 dipole</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>0–40</td>
<td>0–35</td>
</tr>
<tr>
<td>Slight</td>
<td>40–80</td>
<td>35–70</td>
</tr>
<tr>
<td>Moderate</td>
<td>80–120</td>
<td>70–150</td>
</tr>
<tr>
<td>High</td>
<td>120–200</td>
<td>150–250</td>
</tr>
<tr>
<td>Extreme</td>
<td>&gt; 200</td>
<td>250+</td>
</tr>
</tbody>
</table>

The apparent conductivity from the instruments (ECa) can be converted to electrical conductivity extract (E Ce) or EC 1:5 readings by taking readings at sites where the soil salinity has already been measured (e.g. drill holes) and regressing ECa against E Ce.
10. REFERENCES (includes additional papers not referred to in text):


11. MAIN CONTACT PERSONS:

Richard George, Bunbury (EM31, Magnetometer)
Ruhi Ferdowsian, Albany (EM38)
Don McFarlane, Albany
10.3 SEISMIC REFRACTION

1. WHAT IS MEASURED?

The depth of weathering. This can give the bedrock profile along a traverse.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:

Drilling determines the depth of bedrock at a point. Drilling along a transect can give an interpolated bedrock profile. Drill hole information is crucial to calibrate/check seismic refraction results.

3. PREVIOUS USES OF THE METHOD:

In 1912 Gutenberg had discovered the earth's core and calculated its depth (about 3,000 km) by refraction techniques with data derived from earthquakes (Dobrin 1976). The existence and profile of bedrock highs have been investigated in a number of catchments in Western Australia (Street 1985, Kevi 1987).

4. COST/AVAILABILITY OF EQUIPMENT:

Seismic refraction equipment is available from the Mines Department (contact: Laszlo Kevi (09) 222 3333). The Mines Department require notification of a proposed survey before the financial year budgets are compiled to plan the forthcoming years work programme.

5. PRINCIPLES OF METHOD:

Successful refraction relies on a significant contrast in the velocity at which vibrations (sound waves) are propagated through different geological media. The acoustic velocity of the underlying medium must be significantly greater than the acoustic velocity of the overlying medium (as is generally the case). Typically the velocity in the weathered zone will be in the order of 1,000 ms\(^{-1}\) whereas the velocity through granite is in the order of 5,000 ms\(^{-1}\).

Seismic refraction records the time taken for the first arrival of energy from the source (usually dynamite) to geophones spread along the line of a transect.

Consider a seismic wave generated from a point on the surface. The energy (sound waves) travel out in hemispherical wave fronts. The first arrival of energy at a geophone located close to the source will be the wave that travels horizontally at the velocity of propagation through the weathered layer (Vw). When the spherical wave fronts from the source strike the interface where the velocity changes the energy (waves) will be refracted into the lower medium according to Snells Law. At a critical angle of incidence the wave will be refracted along the interface at the velocity of propagation of the underlying layer (Vb). When the source-geophone distance is large enough the first arrival of energy will come from the wave that travels down to the interface, along the interface and up from the interface because the time gained in travel through the higher velocity material makes up for the longer wave path (Figure 1).

The source geophone distance is known and the first arrival time of energy is measured. From this the depth to the higher velocity layer (basement) can be calculated.
6. **FIELD PROCEDURE:**

Usually the area of interest has been defined by several previous drill holes (e.g. installing piezometers). A grid should be drawn up to adequately address the area of interest whilst making full use of any previously drilled holes (i.e. holes drilled to basement should be located at the intersections of transects to maximise use of the data). This also assists calibration of the profiles in the analysis of results.

The lines of transect need to be surveyed. Shot holes are usually drilled prior to the recording instruments arriving in site. However, shot holes should be loaded immediately after the hole is drilled to achieve maximum shot depth which assists in coupling the source with the surrounding medium to ensure as much energy as possible is transmitted in a downwards direction. The pitfall with pre-loading shot holes is loading an inappropriate charge size.

The field equipment typically consists of a 200 m cable which is laid out along the transect. Twenty four geophones are attached to the cable along its length and one end of the cable is plugged into the recording instruments. Reciprocal shots are then fired at each end of the 200 M spread. In this way a line of transect is divided into 200 m sections.

7. **SPECIAL PRECAUTIONS:**

Refraction techniques are inapplicable where there are duricrusts, silcretes, calcrites or hard pans within or at the top of the weathering profile. Initial drilling in the area of interest can indicate the presence of hard layers but offers no guarantee as silcretes or calcrites are often discontinuous and hard to predict.
Treat the 200 m cable very carefully as it typically contains 108 very fine wires that are easily broken and a nightmare to fix. Do not drive over the cable or pull it with a jerk.

Exercise caution at all times when working with explosives. Explosive work should not be carried out on days when there is increased risk of static electricity, i.e.: during storms (both electrical storms and dry dust storms). Radio transmitters should not be used within 100 m of an electrical detonator - whether the detonator is buried or not.

8. ANALYSIS OF RESULTS:

All analysis are done out by the Mines Department and a report on the survey is compiled.

9. ADDITIONAL COMMENTS:

The storage, handling and use of explosives in Western Australia is strictly regulated and must be supervised by an authorised person. There are a number of people with explosives licences in the Department of Agriculture and these people should be contacted for further information (and/or their help to save costs). For example, Macushla Casey at Merredin.

10. REFERENCES:


11. MAIN CONTACT PERSON:

Russell Speed, Moora.
Lasslo Kevi, Mines Department, Perth.
10.4 NATURAL-GAMMA LOGGING

1. WHAT IS MEASURED?:

Natural-gamma logging measures the radiation emitted by rocks and soils. It is principally used for identifying clay layers in sedimentary sequences using down-the-hole equipment.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:

Natural-gamma logging helps interpret drill hole sequences. Electric, sonic, gamma-gamma, and resistivity logs also give an indication of stratigraphy. These and other borehole geophysical methods are summarized in Keys and MacCary (1971) and Telford et al. (1985).

3. PREVIOUS USES OF THE METHOD:

Natural-gamma logging has been used successfully on the Swan Coastal Plain where thick sediments can be differentiated into various stratigraphic units. Some units supply groundwater to Perth. Recently profiles in the eastern wheatbelt have been logged to help interpret sedimentary and weathering sequences.

Logging is frequently used to help locate well-screens of production bores. It has also been used in exploration geology where radioisotopes of uranium or hydrocarbons have been detected. The petroleum industry has provided the impetus for much of the natural-gamma logging research and development.

4. COST/AVALIABILITY OF EQUIPMENT:

A Gearhart-Owen natural gamma logging unit can be booked through the Geophysical Section of the Geological Survey of Western Australia. The unit is mounted in a four wheel drive vehicle and needs an experienced operator. Bookings can be made with Mr Laslo Kevi, Mines Department, Perth.

It is normal to provide accommodation for the operator and assist in the logging. No charge is currently made on the materials or use of the equipment. However it is essential to consult the Geophysics section for advice and book the unit in advance.

5. PRINCIPLES OF METHOD:

Gamma ray emissions are produced from naturally occurring radio-isotopes in the regolith. The abundant isotopes normally encountered are potassium-40 and the daughter products of the uranium and thorium decay series. Standard gamma probes do not generally distinguish individual radioisotopes, however they can produce diagnostic lithological information.

The commonly occurring potassium minerals contain a small percentage of potassium-40, and are abundant in feldspar and mica. Granitic and gneissic terrains are composed of these minerals and quartz. The weathering of feldspathic and micaceous minerals into clay materials can concentrate the gamma-emitting components through ion exchange and adsorption. However, quartz remains non-radioactive and inert due to its higher resistance to weathering and it is therefore not subject to the process of radioisotopic accumulation from other sources.
Sedimentary materials are produced by fluviatial, colluvial and aeolian processes. Sediment transport and deposition is a function of the transporting medium and the length of transport. Phases of erosion and deposition over geological periods of time produce units rich in clay or sand.

Gamma logging can indicate the dominant grain size in a profile since clay materials tend to have a higher radioisotopic concentration and signal while sands, primarily composed of quartz, have lower emissions. These empirical relationships are discussed in detail in Keys and MacCary (1971).

In summary, natural-gamma logs do not have a unique response directly attributable to the physical properties of the aquifer. However when the method is used in a known environment, relative readings can be used to detect materials with different particle sizes.

6. **FIELD PROCEDURE:**

The gamma logging unit is driven to the site and positioned over the cased or uncased drill hole. If the hole is likely to collapse it should be cased. The gamma rays are capable of passing through P.V.C. or steel casing. The source or probe can be lowered down 50 mm PVC, or larger and is waterproof.

The gamma tool is lowered into the hole on a cable drive by an electric winch. The operator sets up the control programme and establishes any input data. The gamma logging procedure records a continuous graph while descending and ascending. The descending plot is used to establish the minimum and maximum count rates necessary so that the ascending graph is contained between the borders of the plot. Once the machine is set up on site, a 30 m profile may take only ten minutes to log.

7. **SPECIAL PRECAUTIONS:**

The natural-gamma logging technique is particularly useful in locating the upper and lower boundaries of permeable or impermeable sedimentary deposits. There is little scope for its application in deeply weathered igneous or metamorphic materials. If zones of radioisotopic enrichment were to be investigated then gamma spectrometry should be used. Initial geological logging of the hole is usually the best technique to determine whether a sedimentary environment has been located. Gamma logging is useful to improve on the drill log made during drilling.

Gamma logging equipment is affected by the probe's proximity to the soil surface. Unless special precautions are taken, logging can only commence at depths greater than 1-2 m.

Natural-gamma logs are influenced by zones in which heavy radioactive elements are concentrated. Granitic and gneissic materials comprise small amounts of radioactive elements. These can become mobile in active groundwater bodies when optimal hydrochemical conditions occur. Anomalies can therefore be expected even in recognized sediments and especially within deeply weathered profiles. The main sources of these anomalies are radium, uranium, lead, copper and zinc as well as the potassium and thorium facies.

Gamma logging probes currently used by the Geological Survey Department can operate in 50 mm or larger diameter bore casings. The current depth limit is 3,000 metres.
8. ANALYSIS OF RESULTS:

A summary of a lithologic log interpreted during the drilling phase and a natural-gamma log is in Appendix 1. Usually the results of geochemical analysis are recorded on similar graphs and the results compared.

This Merredin example shows that a sedimentary profile exists to at least 15 m. Zones of sandy material were identified by count rates of less than 80 Counts Per Minute (CPM), while clay materials near the surface and at depth had a significantly higher count rate. A significant amount of 'noise' is evident in the deeply weathered clay materials. This is probably due to high concentrations of the radio-isotopes described previously, however no analyses have been done to verify this assumption.

9. ADDITIONAL COMMENTS:

Six digit grid reference co-ordinates must be supplied to the operator for recording onto Geological Survey files.

10. REFERENCES:


11. MAIN CONTACT PERSONS:

Richard George, Bunbury.
### RESULTS

<table>
<thead>
<tr>
<th>Depth</th>
<th>Description of Sample</th>
<th>Log</th>
<th>Mineralogy</th>
<th>Geophysical Log</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 m</td>
<td>grey brown loamy sand</td>
<td></td>
<td>qtz, feldspar (coarse)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>a/a and iron</td>
<td></td>
</tr>
<tr>
<td>5 m</td>
<td>grey brown sand, poorly sorted red brown sandy clay</td>
<td></td>
<td>kaolin clays a/a rounded qtz.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>occasional mica</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>and rounded feldspar.</td>
<td></td>
</tr>
<tr>
<td>10 m</td>
<td>white clayey sand well sorted</td>
<td></td>
<td>coarse qtz</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>some mica</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>finer qtz, iron stained feldspar.</td>
<td></td>
</tr>
<tr>
<td>15 m</td>
<td>grey clayey sand</td>
<td></td>
<td>fresh hematite or maghemite</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fine qtz</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fine qtz and clark minerals</td>
<td></td>
</tr>
<tr>
<td>20 m</td>
<td>Purple black sandy clay</td>
<td></td>
<td>qtz dominant</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Red purple sandy clay (angular)</td>
<td></td>
<td>kaolinitic clays</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ochre red, black sandy clay</td>
<td></td>
<td>a/a</td>
<td></td>
</tr>
<tr>
<td></td>
<td>inc lighter/pallid clay</td>
<td></td>
<td>qtz dominant</td>
<td></td>
</tr>
<tr>
<td>25 m</td>
<td>Pallid sandy clay, coarse texture v. angular.</td>
<td></td>
<td>kaolinitic clays</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>inc fresh minerals</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yellow mustard sandy clay</td>
<td></td>
<td>a/a</td>
<td></td>
</tr>
<tr>
<td>30 m</td>
<td>a/a</td>
<td></td>
<td>inc fresh minerals</td>
<td></td>
</tr>
<tr>
<td></td>
<td>At 33 m Yellow brown s. clay</td>
<td></td>
<td>qtz dominant</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BEDROCK AT 34.0 m</td>
<td></td>
<td>kaolinitic clays</td>
<td></td>
</tr>
</tbody>
</table>

**Project No.**: 86/01/M01  
**Purpose**: INVESTIGATION  
**Rig Type**: R.A.B.  
**Date**: FEBRUARY 1986  
**Location**: MERREDIN CATCHMENT  
**Grid Reference**: PL230152  
**Land Unit**: COLLGAR  
**Soil Type**: LOAMY SAND  
**Casing Depth**: 33.0  
**Depth Drilled**: 34.0  
**Salinity + Yield**: 2410 m^3/yr
SECTION 11: TRANSPERSION

11.1 STEADY STATE POROMETER

1. WHAT IS MEASURED?:

The diffusive resistance of plant leaves.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:

Ventilated chamber (Section 11.2), Penman-Monteith equation (Section 11.3) and Bowen ratio (Section 11.4).

3. PREVIOUS USES OF THE METHOD:

Estimating transpiration of irrigated crops (crop water requirements) and transpiration of plants and recharge areas.

4. COST/AVAILABILITY OF EQUIPMENT:

John Morris Scientific Pty Ltd supply an instrument for approximately $14,000. There are several porometers in the Department. These may be available depending on the crop being studied and the time of year required (see Main Contact Persons).

5. PRINCIPLES OF METHOD:

The water loss from a leaf is determined by maintaining a constant vapour density in the cuvette that is in contact with the transpiring leaf. This is achieved by pumping dry air into the cuvette at an appropriate measured rate to obtain a balance (at a predetermined humidity) between the flux of water transpired by the leaf and the flow of moist air out of the cuvette. Stomatal resistance is determined directly from the measured parameters.

6. FIELD PROCEDURE:

Before any measurements are made the cuvette should be acclimatized to ambient conditions. To do this allow the instrument to operate with the null adjust valve closed and the sensor head clamp opened.

Each time the instrument is turned on the null point must be set, a 20-80% relative humidity range is recommended.

To Ambient: With the null adjust valve closed and the cuvette open, press HUM SET for 1 second.

Below Ambient: Hold the HUM SET switch closed. After 6 seconds open up the null adjust valve, and the humidity will begin to decrease. When the humidity reaches the desired level, release the HUM SET button to establish that humidity as the null point.

Above Ambient: Clamp a leaf into the cuvette with the null adjust valve closed. When the humidity in the cuvette reaches the desired level, press the HUM SET button for about 1 second to lock in that valve as the null point.
Making a measurement:

Clamp the sample into place in the cuvette and observe the null adjust meter.

If the needle is far left of centre, the cuvette humidity is below the null point. Begin closing the null adjust valve (turn clockwise) to reduce the dry air flow into the cuvette. If the leaf is transpiring, the humidity will eventually rise to the null point.

If the needle is far right of centre, the cuvette humidity is above the null point. Begin opening the null adjust valve (turn counter-clockwise) to increase the flow of dry air into the cuvette. This dry air flow will eventually more than offset the transpiration of the leaf, and the humidity will fall toward the null point.

If the null adjust meter needle is on scale, the humidity is close to the null point.

When the needle centres and is stable, a steady state condition is in effect at the null point humidity. If the needle is slightly off centre but stable, a steady state condition is in effect, but the cuvette humidity is not exactly at the null point. This is not important, as long as the null adjust meter is on scale.

Typically, it takes 10 to 20 seconds to achieve a steady state on a sample having a diffusive resistance less than 5 s/cm. Samples with higher resistances can take longer.

Record the reading

When a steady state is achieved, toggle the HOLD switch to the left to examine on the display.

7. SPECIAL PRECAUTIONS:

Try to work facing the sun to prevent shading the leaf before or during a measurement. Orientate the sensor head to the leaf, not vice versa; the leaf should have the same orientation while being measured that it had before being clamped in the sensor.

Be aware of the leaves you are measuring, their age, health and position in the canopy and also of the health and size of the plant, all these factors influence the stomatal conductance.

Measurements cannot be made on wet leaves.

8. ANALYSIS OF RESULTS:

The data collected can be used to determine stomatal response to such factors as light, soil water conditions, temperature, wind etc. How the data is analysed will depend on the treatments and the trial design. Enough consistent data must be collected, averaging this type of data presents problems.

The stomatal conductance data can be used to predict crop water use by entering data into a computer program written to calculate transpiration using the Penman-Monteith equation (Section 11.3). This computer program was developed by H. Borg and P. Scott.
9. ADDITIONAL COMMENTS:

The porometer needs to be sent to the Eastern States for servicing every 12 months.

10. REFERENCES:

L1-1600 Steady State Porometer Instruction Manual.

11. MAIN CONTACT PERSONS:

J. Campbell-Clause, Midland.
Dr K. Siddique, South Perth.
P. Scott, South Perth.
11.2 VENTILATED CHAMBER

1. WHAT IS MEASURED?

Measures the vapour pressure of air entering and leaving a plastic chamber under forced draught conditions. Together with a knowledge of the velocity of air moving through the chamber, temperature, and the dimension of the chamber, evapotranspiration can be calculated.

2. ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:

Many alternative methods of measuring or estimating evapotranspiration are available. A useful summary is given by Stewart (1984).

3. PREVIOUS USES OF THE METHOD:

The method has been used by Nulsen (1984), Greenwood and Beresford (1979), (1980), Greenwood, et al. (1981), Greenwood et al. (1982), (1985a), (1985b), in situations ranging from grazed pasture to individual trees.

4. COST/AVAILABILITY OF EQUIPMENT:

Equipment is not commercially available as a unit. Components must be purchased individually and built into a system. The main components are:

<table>
<thead>
<tr>
<th>Item</th>
<th>Approximate cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infra-red Gas Analyzer</td>
<td>$10,000</td>
</tr>
<tr>
<td>Water Bath</td>
<td>$3,000</td>
</tr>
<tr>
<td>Chart Recorder</td>
<td>$3,500</td>
</tr>
<tr>
<td>Transformers</td>
<td>$800</td>
</tr>
<tr>
<td>Fans</td>
<td>$800 each</td>
</tr>
<tr>
<td>Chambers</td>
<td>$250 each</td>
</tr>
<tr>
<td>Heated Lines</td>
<td>$200 each</td>
</tr>
<tr>
<td>Automatic Sampler</td>
<td>$2,000</td>
</tr>
</tbody>
</table>

Numerous ancillary items may be required. Concurrent measurements of solar radiation, windspeed, temperature, and relative humidity are desirable and add further expense.

Currently systems are used by Peter Farrington (CSIRO) and Phil Scott (WADA).

5. PRINCIPLES OF METHOD:

The ventilated chamber encloses a sample of vegetation and forces an air current over it. The air leaving the chamber carries with it moisture removed from the enclosed soil and vegetation, and thus has a higher moisture content than air entering the chamber. Samples of the ingoing and outgoing air are pumped via heated lines to the Infra-Red Gas Analyzer (IRGA) which measures the vapour pressure of the sampled air. The IRGA is used in the differential mode whereby sample air is constantly compared with air at known vapour pressure. This allows calibration of the system. Reading the difference in vapour pressure between ingoing and outgoing air from the chart recorder, and knowing the air velocity through the chamber and air temperature, the amount of water lost from the enclosed soil and vegetation can be calculated. The system can be largely computer controlled, but care must be taken to ensure adequate flexibility in the program.
Calculations

The density of water vapour is given by:

\[ \sqrt{V} = \frac{L_w}{C_v R_w T} \]  

(1)

where \( \sqrt{V} \) = density of water vapour (g m\(^{-3}\)).
\( L_w \) = vapour pressure (mb).
\( C_v \) = compressibility factor of water (assumed \( C_v = 1 \)).
\( R_w \) = gas constant (4.6150 x 10\(^6\) erg g\(^{-1}\) K\(^{-1}\)).
\( T \) = temperature of water vapour (K).

with conversion of units:

\[ \sqrt{V} = \frac{216.68 L_w}{T} \quad (g \; m^{-3}) \]  

(2)

With an air velocity, \( V \) (m s\(^{-1}\)), moving through a chamber of cross-sectional area, \( A \) (m\(^2\)), and covering ground area, \( G \) (m\(^2\)), evapotranspiration, \( ET \), is given by:

\[ ET = \frac{216.68 \times L_w \times V \times A}{(\theta C + 273.2) \times G} \; (g \; m^{-2} \; s^{-1}) \]  

(3)

This can be converted to an equivalent depth of water and a more appropriate time scale.

\( (g \; m^{-2} \; s^{-1}) \times 3.6 = \text{mm hr}^{-1} \)

6. FIELD PROCEDURE:

There are endless permutations of the size and design of chambers, but basically they should be designed with a specific type of vegetation in mind. Outlet size and positioning is critical to the performance of the chamber. "Visqueen" plastic is the most suitable material - it transmits 98% of radiation in the photosynthetically active spectrum. A stronger material is called "Solaweave", but it transmits less light.

Where several chambers are being used to compare different vegetation, chambers should be identical and oriented similarly in the field.

Small aquarium pumps are suitable for sampling the ingoing and outgoing air. The sample air should be homogenized in a chamber, and delivered to the IRGA through special heated lines (delivery rates of air to the IRGA are important). The input of heat is necessary to prevent any condensation of water vapour from the sample. An automatic sampler can be used to time-share the IRGA between several incoming air streams.

Depending on the site, power may have to be provided by a portable generator.
7. SPECIAL PRECAUTIONS:

With such an array of equipment, numerous problems can occur. Briefly, the main pitfalls to be aware of are:

(a) Condensation anywhere in the system can give rise to erroneous readings. As previously mentioned, condensation in the sample delivery lines can be avoided by heating them. Within the ventilated chamber itself, however, condensation must be allowed to evaporate at ambient temperature - this may take some time! This limits the effectiveness of the method in cold, cloudy and wet conditions.

(b) Air velocity through the chamber must be measured accurately as the calculation is sensitive to this parameter.

(c) The accuracy of the method should be checked with "recovery tests" - the injection of a known quantity of water vapour into the system, and its subsequent recovery.

(d) Although, under rigorous conditions, evapotranspiration from the sample vegetation can be measured precisely, bias is introduced because of the artificial environment. Therefore, the method is best suited to comparative, rather than absolute work.

8. ANALYSIS OF RESULTS:

e.g. Data from Bowelling mixed pasture, 1518-1530 hours on August 28, 1986.

(a) IRGA Calibration: Chart was calibrated such that one mm on the chart represented 0.0282 mb of vapour pressure.

(b) Data: Mean vapour pressure difference between ingoing and outgoing air was 17.9 mm x 0.0282 = 0.5048 mb.

i.e. \( L_w = 0.5048 \text{ mb} \).

\[ T = 12.5^\circ\text{C} \ (286.7^\circ\text{K}) \].

\[ V = 0.43 \times \text{ m s}^{-1} \].

\[ G = 3 \times 5 = 15 \text{ m}^2 \].

\[ A = 1.73 \times 3 = 5.19 \text{ m}^2 \].

Using equation 3.

\[ ET = \frac{216.68 \times 0.5048 \times 0.43 \times 5.19}{285.7 \times 15} \]

\[ = 0.057 \text{ g m}^{-2} \text{ s}^{-1} \]

Converting to mm hr\(^{-1}\)

\[ ET = 0.057 \times 3.6 \]

\[ = 0.2 \text{ mm hr}^{-1} \]

By sampling throughout the day, a picture of diurnal water use patterns can be built up. The area under a diurnal water use curve can be integrated to give a figure in mm day\(^{-1}\).
9. **ADDITIONAL COMMENTS:**

The method is labour intensive and the equipment is not very portable. It measures evapotranspiration of the sample in the chamber. Be cautious when equating this with the natural environment.

Instantaneous, portable chambers have been used successfully elsewhere, (e.g. Reicosky and Peters 1977).

10. **REFERENCES:**


**Other References**

11. MAIN CONTACT PERSONS:

P.R. Scott 368 3371
R.A. Nulsen 368 3484
E.A.N. Greenwood (CSIRO) 387 0215
11.3 PENMAN-MONTEITH EQUATION

1. **WHAT IS MEASURED?:**

Calculates an estimate of actual evapotranspiration over a vegetative surface.

2. **ALTERNATIVE METHODS OF ESTIMATION/MEASUREMENT:**

Bowen ration (Section 11.4), ventilated chamber (Section 11.2).

3. **PREVIOUS USES OF THE METHOD:**

Not yet used by the Department although it has been used in agricultural areas by the CSIRO.

4. **COST/AVAILABILITY OF EQUIPMENT:**

The equipment is not commercially available as a unit. Components must be built into a system. Essential components are a net radiometer, soil heat flux plates, a porometer, a psychrometer and an anemometer array. Total cost is about $10,000 per unit.

5. **PRINCIPLES OF METHOD:**

After the incoming and outgoing radiant fluxes have been accounted for, the energy available at an evaporative surface is the net radiation, \( R_n \). Some of this net radiation goes to heating the environment (sensible heat flux, \( H \)) some goes to heating the soil (soil heat flux, \( G \)) and some goes to evaporating water (latent heat flux, \( LE \)). \( H \), \( G \) and \( LE \) must balance \( R_n \).

\[
R_n = H + LE + G
\]  
(1)

Note: All terms in equation (1) can be either positive or negative and all must be in the same units e.g. W/m\(^2\).

The flux density of latent heat \( LE \) can be calculated from:

\[
LE = (\sqrt{Cp/\alpha}) \left( e^* (T_s) - e \right)/(r_a + r_s)
\]  
(2)

Similarly the flux density of sensible heat is the temperature gradient divided by the appropriate resistance.

\[
H = \sqrt{Cp} \left( T_s - T_a \right)/r_a
\]  
(3)

where \( T_s \) = the surface temperature.  
\( T_a \) = ambient temperature.  
\( \sqrt{\text{density of air}} \).  
\( Cp \) = specific heat of air.  
\( \alpha \) = psychrometric constant.  
\( e^* \) = saturated water vapour deficit.  
\( e \) = vapour pressure deficit.  
\( r_a \) = aerodynamic resistance.  
\( r_s \) = stomatal resistance divided by leaf area index (LAI).

is not really a constant. At 25°C with a pressure of 1013.25 mb,  
\( = 0.67 \text{ mb} \cdot \text{°K}^{-1} \).
Equations (1), (2) and (3) can then be combined to give the Penman-Monteith combination equation:

\[
\text{LE} = \frac{S(R - G) + \sqrt{Cp \left[ e(T_a) - e \right]}}{S + \left( 1 + \frac{r_s}{r_a} \right)}
\]

Note that surface temperature \( T_s \) has been eliminated and that \( e(T_a) - e \) is simply the vapour pressure deficit. \( S \) is the slope of saturation vapour pressure versus temperature curve at mean temperature.

All factors in equation (4) are easily obtainable (with the right equipment) except \( r_s \) and \( r_a \) and therein lies a problem.

\[
r_s = \frac{r_{st}}{LAI}
\]

\( r_{st} = \) mean leaf diffusive resistance obtained by porometry.
\( LAI = \) ratio of stomatous leaf area to ground area.

Note that for leaves with stomata on both sides the individual resistance operate in parallel thus:

\[
r_{st} = \frac{1}{\left( \frac{1}{r_{ab}} + \frac{1}{r_{ad}} \right)}
\]

where \( r_{ab} = \) resistance of abaxial surface.
\( r_{ad} = \) resistance of adaxial surface.

Aerodynamic resistance - under conditions of neutral stability:

\[
r_a = \frac{[\ln \left( z - d \right) / z^*]^2}{k^2u}
\]

where \( k \) is von Karman's constant (0.4)
\( u \) is the mean horizontal wind velocity (MS\(^{-1}\))
\( d \) = zero plane displacement
\( z^* \) = roughness length

- under conditions of non-neutral stability

\[
r_a = \frac{4.72 [\ln \left( z - d \right) / z^*]^2}{1 + 0.54u}
\]

Thus at least one measurement of wind speed is needed. \( z^* \) and \( d \) can be estimated from crop height, \( h \).

6. FIELD PROCEDURE:

Measurement of the meteorological parameters \( T_a, T_s \) (required to compute \( e \)), \( u \) (required to compute \( r_a \)) and \( R_n \) are made at some height above the crop canopy. The height depends on the crop height but for most agricultural crops about 1 m would suffice.

The measurements should be taken where fetch is adequate (see Section 11.4 on Bowen ratio method for an explanation of fetch requirements).

Soil heat flux should be measured with at least two soil heat flux plates buried just beneath (3-5 mm) the soil surface.
Measurements should be integrated over the period of measurement.

7. SPECIAL PRECAUTIONS:

This technique is inappropriate for heterogeneous vegetation and where fetch is limited.

8. ANALYSIS OF RESULTS:

The data is taken from Sharma (1984). They were collected at Salmon Catchment near Wellington dam during August 1977.

Average solar radiation for the month = 115 Wm\(^{-2}\). Using an empirical relationship between solar radiation and \(R_n\) this was equivalent to:

\[
R_n = 62 \text{ Wm}^{-2}.
\]

\[
T_a = 10^\circ \text{C (mean monthly)}.
\]

\[
(e^*-e) = 1.5 \text{ mb}.
\]

The forest was 30 m high (\(h\)) and thus zero plane displacement (0.7*\(h\)) was 21 m and roughness length (0.1*\(h\)) was 3 m. The mean wind speed at 35 m was 3 ms\(^{-1}\).

From equation (7):

\[
r_a = \frac{\ln (35-21)/3}{k^2} = 5 \text{ sm}^{-1}
\]

The measured mean stomatal resistance \(r_{st}\) was 200 sm\(^{-1}\) and the LAI = 4. Thus from equation (5):

\[
r_s = \frac{200}{4} = 50 \text{ sm}^{-1}
\]

Substituting into equation (4):

\[
LE = 0.85(62) + \frac{[(1.256)(990)(1.5)]/5}{0.85 + 0.67 (1+10)} = 52 \text{ Wm}^{-2}
\]

This is an equivalent depth of 56 mm for the month.

(Note: This figure only applies if the canopy was dry for the month. If the canopy is wet for any period then \(r_s = 0\)).

For identical environmental conditions the ratio of evaporation from a wet canopy (\(LE_w\)) to evaporation from a dry canopy (\(LE_d\)) is given by:

\[
\frac{LE_w}{LE_d} = \frac{s + (1 + r_s/r_a)}{s + r_s} = 5.4
\]

where \(r_s\) is the surface resistance of the dry canopy.

For the example \(LE_w/LE_d = 5.4\)
9. ADDITIONAL COMMENTS:

It can be tedious and labour intensive to obtain values of $r_g$ and LAI.

10. REFERENCES:


11. MAIN CONTACT PERSONS:

R.A. Nulsen, South Perth (09) 368 3484