TECHNICAL REVIEW

PRACTICAL GUIDELINES FOR TEST PUMPING IN WATER WELLS

ICRC

REFERENCE

ICRC

International Committee of the Red Cross
19, avenue de la Paix
1202 Geneva, Switzerland
T +41 22 734 60 01 F +41 22 733 20 57
E-mail: shop@icrc.org www.icrc.org
© ICRC, February 2011

Front cover: Christian Farnsworth/ICRC

TECHNICAL REVIEW

PRACTICAL GUIDELINES FOR TEST PUMPING IN WATER WELLS

FOREWORD

The practical guidelines for test pumping presented in this publication reflect years of hands-on experience in borehole exploitation in both rural and urban settings, from Africa to the Middle East and Asia.

Working in cooperation with the water and habitat team from the regional delegation of the International Committee of the Red Cross (ICRC) in Nairobi, Richard Boak – author of this publication and a seasoned hydrogeologist and engineer – strikes the right balance between theoretical and practical knowledge. There is no doubt that his work will greatly help the ICRC's water and habitat engineers address technical dilemmas under difficult field conditions.

In the water-stressed regions beset by armed conflict or rife with tension where ICRC engineers work, groundwater is the most suitable source of drinking water. A good understanding of borehole technology, along with a comprehensive analysis of the local situation that places human dignity and the needs of the community at the forefront while addressing wider environmental concerns, is a key element of any successful operation providing people with sustainable and cost-effective solutions.

This is the second publication on the topic of water and habitat in the ICRC's new "Reference" series. Together with *Borehole Drilling and Rehabilitation,* it constitutes a reference package essential for the ICRC's water and habitat engineers in the field. *Practical Guidelines for Test Pumping in Water Wells* is an important contribution to the efforts of the ICRC's Water and Habitat Unit to promote good field practices among its staff and among other humanitarian players.

I am extremely grateful to Laurent Wismer, former ICRC Regional Water and Habitat Engineer in Nairobi, for his contribution to this publication, and to Jean Vergain and Thomas Nydegger, expert hydrogeologists, who provided invaluable guidance throughout the editing of the text.

Philippe Dross
Head of Water and Habitat
International Committee of the Red Cross

Abstract

Groundwater is frequently chosen as the most suitable source of drinking water, supplies of which are brought to the surface by rehabilitating existing boreholes or drilling new ones. Pumping tests are a practical way of obtaining an idea of the borehole's efficiency and its optimal production yield. Much of the specialized knowledge and technical expertise needed for this purpose can be gained from the standard literature. However, field operations in remote areas or in difficult conditions often require flexibility and imagination in avoiding or solving technical problems. These guidelines are intended mainly as a practical tool and therefore contain a minimum of theory. They are aimed at water and habitat engineers working in the field who are undertaking or supervising borehole drilling or rehabilitation programmes and are not conversant with pumping-test procedures. The end result should be a cost-effective facility capable of supplying drinking water for many years.

Christian Farnsworth / ICRC

TABLE OF CONTENTS


Wojtek Lembrik / ICRC

1. INTRODUCTION

Background

The International Committee of the Red Cross (ICRC) provides support, through its Assistance Division, to victims of armed conflict around the world. One of the Division's main tasks – carried out by its Water and Habitat (WatHab) Unit – is to provide people with clean drinking water. Groundwater is frequently chosen as the most suitable source, and supplies of drinking water are obtained by rehabilitating existing boreholes or drilling new ones. This is done either by the ICRC itself, using its own staff and equipment, or by contractors working under the supervision of ICRC staff.

WatHab engineers need to be able to determine the 'success' and sustainability of a rehabilitated or new borehole as a source of drinking water. In most cases, the borehole characteristics that the engineers are looking for are efficiency and optimal production yield. Pumping tests are a practical way of obtaining some idea of these characteristics. WatHab engineers have a wide range of technical backgrounds and levels of experience, and not all are trained as hydrogeologists. Practical guidelines on pumping tests are therefore required.

Purpose

These guidelines are aimed at WatHab engineers working in the field who are undertaking or supervising a borehole-drilling or rehabilitation programme and are not conversant with pumping-test procedures. Intended mainly as a practical tool, with a minimum of theory, the guidelines should enable readers to:

- → Understand the importance and aims of pumping tests, and know what different types of test are available.
- → Understand which borehole or aquifer parameters can be derived from each type of test, and what the meaning and limitations of such parameters are.

- → Select the type of test to undertake in a particular situation, depending on what parameters are needed and what equipment is available.
- → Supervise the contractor, if one is being used to conduct the test.
- → Interpret the results of tests carried out in simple hydrogeological environments, and understand when certain interpretation methods cannot be used.
- → Know where to look if additional information or specialist techniques are required.

These guidelines are designed to cover three types of borehole that WatHab engineers commonly need to test, namely:

1. Small boreholes designed to be fitted with a handpump and requiring a simple test that takes a few hours and can be done by any WatHab engineer using minimal equipment.
2. Medium-sized boreholes designed to be fitted with a motorized pump (generally for medium-sized communities or health/detention facilities supplied by small piped networks) and requiring a more comprehensive test conducted by an experienced WatHab engineer with reasonable knowledge of hydrogeology.
3. Large production boreholes intended for urban or large-scale distribution and requiring sophisticated tests usually carried out by a specialized contractor under the supervision of a WatHab engineer.

Since WatHab engineers often work under difficult conditions in remote locations, none of the techniques described in these guidelines requires a computer or other sophisticated equipment. It is very rare that measuring points other than the borehole itself are available, so the guidelines concentrate only on information that can be obtained by pumping the borehole.

Limitations of test pumping

Hydrogeology is not an exact science. Groundwater levels and pumping rates measured during pumping tests provide some indication of the behaviour or state of 'health' of the groundwater system. These tests undoubtedly provide valuable information, help us to understand the groundwater system, and inform our decisions. However, there are no magic formulas in hydrogeology, and decisions should be based on a wider understanding of the regional geology, hydrogeology and environment. It is no use blindly inserting data from pumping tests into equations.

Terminology and further reading

A glossary of common hydrogeological terms is provided in Annexe A for the benefit of people without specific training. For in-depth information on the basic principles of groundwater flow, the theory behind pumping-test analysis, groundwater exploration, borehole drilling and construction, wider issues of groundwater protection and resource management, and hydrogeology in general, the reader is referred to Annexe D, which gives references and suggestions for further reading.

Some explanation is needed for the use of the terms 'borehole' and 'well.' In general, 'borehole' means a vertical cylindrical hole of relatively small diameter for abstracting water, usually constructed using a drilling rig. 'Well' means a vertical hole of relatively large diameter dug by hand to access the water table. 'Borehole' is sometimes used to refer to both boreholes and wells, or vice versa, but this is usually clear from the context.

Picture 1: Borehole drilling

2. BASICS OF TEST PUMPING

What is a pumping test?

The basic concept of a pumping test is very simple: water is abstracted (removed by pumping or bailing) from a well or borehole, thus lowering the water level. The water level in the abstraction borehole and the pumping rate are monitored over time, along with various other parameters if possible (such as water levels in observation boreholes). The way in which the water levels respond to the pumping is then analysed to derive information about the performance characteristics of the borehole and the hydraulic properties of the aquifer.

In reality, the situation is much more complicated. There are many different types of test from which to choose (intermittent or continuous, short or long in duration, low or high pumping rates, etc.). What other parameters or water features should be monitored in addition to the obvious ones, i.e. the water level and pumping rate in the borehole being tested? Can conclusions about long-term behaviour be extrapolated with confidence from the results of a short pumping test? The main problem with investigating groundwater (in contrast to measuring the flow in a river, for example) is that one is effectively working blindly, because it is impossible to see into the aquifer and directly observe its behaviour. One can infer information about the borehole and aquifer only by observing how the water level changes in response to pumping.

Why do we undertake pumping tests?

Pumping tests can be undertaken for a wide variety of reasons, including the following:

- → To determine the reliable long-term yield (or 'safe' yield) of a borehole, and therefore whether or not the borehole can be regarded as a 'success,' and how many people it will be able to supply.
- → To assess the hydraulic performance of a borehole, usually in terms of its yield-drawdown characteristics. How much drawdown does it take to yield a certain amount of water?

- To derive the hydraulic properties of the aquifer. Pumping tests are the classic (and perhaps the only) way to derive *in situ* aquifer hydraulic properties, such as transmissivity and the storage coefficient, or to reveal the presence of any hydraulic boundaries.
- To test the operation of the pumping and monitoring equipment, to make sure that everything is working safely and efficiently, and if applicable, to confirm that the contractors have done their job properly.
- To determine the effects of abstraction on neighbouring abstractions (sometimes referred to as derogation).
- To determine the environmental impact of the abstraction. All groundwater abstraction eventually has an impact; it is only a matter of where, when and whether or not the impact is acceptable.
- To provide information on water quality. Is the water quality suitable for the intended use? Is it stable in the long term? Are there likely to be any problems such as drawing in saline or polluted water after extended periods of pumping?
- To optimize operational pumping regimes (especially from multiple-borehole sources), including selecting the most suitable pumping plant for long-term use, and estimating probable pumping and/or treatment costs.
- To help determine the correct depth at which the permanent pump should be installed in the borehole (the subjects of pump choice and installation are covered in other guidance documents).

It is important for WatHab engineers to define the aims of each test *before* the test is carried out, as this will greatly influence the choice of test and the parameters that need to be monitored. Just look through the above list and select which aims apply to each planned pumping test.

Main types of pumping test

There are many different types of pumping test from which to choose. The main types that are applicable to the situations faced by WatHab engineers are as follows:

1. **Step test:** Designed to establish the short-term relationship between yield and drawdown for the borehole being tested. It consists of pumping the borehole in a series of steps, each at a different discharge rate, usually with the rate increasing with each step. The final step should approach the estimated maximum yield of the borehole.
2. **Constant-rate test:** Carried out by pumping at a constant rate for a much longer period of time than the step test, and primarily designed to provide information on the hydraulic characteristics of the aquifer. Information on the aquifer storage coefficient can be deduced only if data are available from suitable observation boreholes.
3. **Recovery test:** Carried out by monitoring the recovery of water levels on cessation of pumping at the end of a constant-rate test (and sometimes after a step test). It provides a useful check on the aquifer characteristics derived from the other tests but is valid only if a foot-valve is fitted to the rising main; otherwise water surges back into the borehole.

These tests can be carried out singly or in combination. A full test sequence usually starts with a step test, the results of which help to determine the pumping rate for the constant-rate test, with a recovery test completing the sequence. The test design can be adapted for use in small, medium or large boreholes, the main differences being the pumping rates, the length of test and the sophistication of the monitoring system. Each type of test will be described in more detail in subsequent chapters.

3. PREPARATIONS FOR TEST PUMPING

Introduction

Before commencing any pumping test, there are certain basic preparations that should be made. These include gathering information about the borehole or well that is about to be tested. The outcome of the preparations may influence the choice of test and will certainly increase the value of the results obtained from the test.

Basic monitoring equipment

The two parameters that must be measured in any pumping test are the water level in the pumped borehole and the rate at which water is being abstracted (pumped or bailed). The basic equipment necessary for monitoring these two parameters is as follows:

Picture 2: Manual dipping

MONITORING WATER LEVELS

The hand-held water-level monitor, commonly known as a "dipper," is the most practical, robust and easily available method of monitoring water levels in boreholes and wells. The dipper probe is lowered down the borehole, and when it reaches the water surface, an electrical circuit is completed and a 'bleep' is heard. The water level is then read off a graduated tape, usually to a resolution of the nearest centimetre. The water level is typically recorded in metres below a local measuring datum, such as the lip of the borehole casing. Manual dipping is widely trusted as a reliable and relatively trouble-free way of obtaining water-level data, but it is not without its problems, for instance:

- Different people visiting the same site can inadvertently use different local datums for taking the reading. If they do not record this fact, there may be confusion when comparing readings in the future.
- The graduated dipper tape can suffer from stretch due to age, temperature or misuse, introducing a systematic inaccuracy, especially if different dippers are used.
- If the water level is falling or rising quickly, as during the early stages of a pumping test, it can be difficult to take manual readings fast enough, although this problem improves with practice.
- It can be difficult to get a 'clean' water-level reading from the borehole, especially if there is water cascading down the side of the borehole, or there is turbulence at the water surface.
- The dipper can become stuck, entangled or wrapped around the pump, rising main, electrical cables, or other items down the borehole. This can be avoided by the use of a dip tube (an open-ended plastic tube installed in the borehole specifically for the dipper to go down), which also solves the problem of cascading water and turbulence.

Picture 3: Pressure-transducer installation

The main alternative to manual dipping is to install a pressure transducer in the borehole. The transducer is placed in a known position down the borehole (below the water level) and it measures the pressure at that point. This information can be used to deduce the height of the water above that point, and therefore the water level in the borehole.

Transducers (with built-in dataloggers) have an obvious advantage: they can be left unattended for long periods, while still taking frequent water-level readings. In practice, however, they can pose the following problems:

- Transducers are expensive compared to manual dipping, and they cannot always cope with rough field conditions and high temperatures.
- Transducers are manufactured to cope with different pressure ranges, and if the wrong type of transducer is used, it may be damaged and the data corrupted.
- If the transducer or datalogger malfunctions, or the battery runs out, the data obtained since the last download may be lost, and the test may have to be repeated.

Despite these drawbacks, dataloggers are becoming more common, and provide a useful means of checking pumping tests undertaken by contractors (in cases where continuous field supervision cannot be maintained). Other, less commonly used methods for measuring water levels include: float-and-counterweight, pneumatic (bubbler), 'plopper,' chalked tape, vibrating-wire piezometer, acoustic doppler and water whistle.

MONITORING PUMPING RATES

There are many methods of measuring pumping rates, of which the most common, or the ones most likely to be of use to WatHab engineers, are as follows:

Picture 4: Bucket and stopwatch

Bucket and stopwatch: The simplest method of measuring relatively low pumping rates is to use a bucket and a stopwatch. Arrangements are made for the discharge from the pump to flow freely into a bucket of known volume, and the time taken for the bucket to fill is recorded. The flow rate is then calculated by dividing the volume of the bucket by the time taken to fill it. For this method to be precise, it should take a minimum time of about 100 seconds to fill the bucket. If necessary, use a larger container of known volume, such as an oil drum.

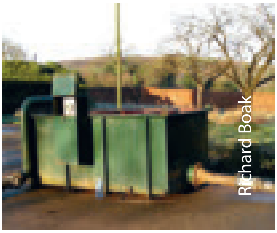
Flow meters: Where more sophisticated equipment is available, pumping rates can be measured using flow meters, of which there are various types. Shown on the right is the flow meter supplied with the ICRC's standard test-pumping kit. This uses spring-loaded pistons that are deflected by the flow of water, and the flow rate is read off the graduated scales. It is important to double-check the flow rate by using another method, to operate the gauge correctly, and to keep the equipment in good condition.

Picture 5: Flow meter

Water meters: Some 'flow' meters actually record the cumulative volume of water passing through the meter, so it is necessary to take readings at known times and to calculate the flow rate, after confirming what units the meter is using. In order to be accurate, flow meters should be installed according to the manufacturer's instructions, with the correct lengths of straight, level pipe before and after the meter.

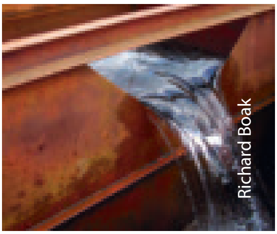
Picture 6: Water meter

Weir tanks: A weir tank is a thin-plate 'V-notch' gauging weir within a self-contained tank. Weir tanks must be installed exactly level, and there must be an accurate method of measuring the water level inside the tank, plus a conversion table supplied by the tank manufacturer (to convert the water levels into flow rates). See BS ISO 14686:2003 for more information about constructing and using weir tanks.



Picture 7: Weir tank

Locally made weir tanks: Alternatively, small weir tanks can be made using local materials, sometimes even a converted oil drum. These weir tanks should be calibrated by an independent flow-measurement method, in order to ensure reliable data. For accurate results, care should be taken to follow design advice (see BS ISO 14686:2003), especially about the thin-plate 'V-notch' itself. The example shown on the right is not a standard design since the lip of the 'V-notch' is too wide; this affects the way in which the water flows through the notch.



Picture 8: Locally made weir tank

Whichever method is used, it is important to measure the pumping rate frequently during the test since it will probably fall as the water level drops, and an average pumping rate needs to be calculated for use in the test analysis.

Other equipment available

Before choosing the type of test to conduct, WatHab engineers should establish what equipment is available, practicable or affordable. In addition to the water-level and flow-monitoring equipment described above, potential equipment includes the following:

- Motorized pump: Commonly an electrical submersible pump. Check whether or not a suitable power supply is available; many submersible pumps require a three-phase power supply, so ordinary mains electricity is not always suitable.
- Generator: Necessary if a motorized pump is being used in remote locations, or if the local electricity supply is unsuitable or unreliable. Make sure that there is sufficient fuel available for the planned length of the test.
- Rising main: To carry the water up the borehole from a submersible pump; it can be made of flexible tubing or lengths of rigid pipe connected together.
- Manually-operated valves: Installed between the rising main and the discharge pipes, to control the pumping rate if the pump is operated at a fixed speed.
- Discharge pipes: To carry the water far enough away from the borehole so that it does not recirculate (that is, flow back down into the borehole, or quickly soak into the ground and affect the groundwater levels close to the borehole being tested).
- Water-quality monitoring equipment: See separate discussion below about water-quality monitoring.
- Surface water flow-gauging equipment: It is sometimes necessary to monitor the flow in a nearby river or stream to establish whether or not the groundwater abstraction is affecting the flow or causing infiltration from the river (which may represent a health risk because of poor surface-water quality).

- Bailers: Necessary for a bailer test (described later, under "recovery tests").

Whatever equipment is used, it should be maintained in good condition and used correctly (according to the manufacturer's instructions). It should also be designed so that it can be operated safely, and if necessary, should be calibrated to give reliable and accurate data. Equipment should be tested when it is in position, before a pumping test is begun, in order to ensure that it is all working properly and to determine pump or valve settings that will give appropriate pumping rates.

Information collection

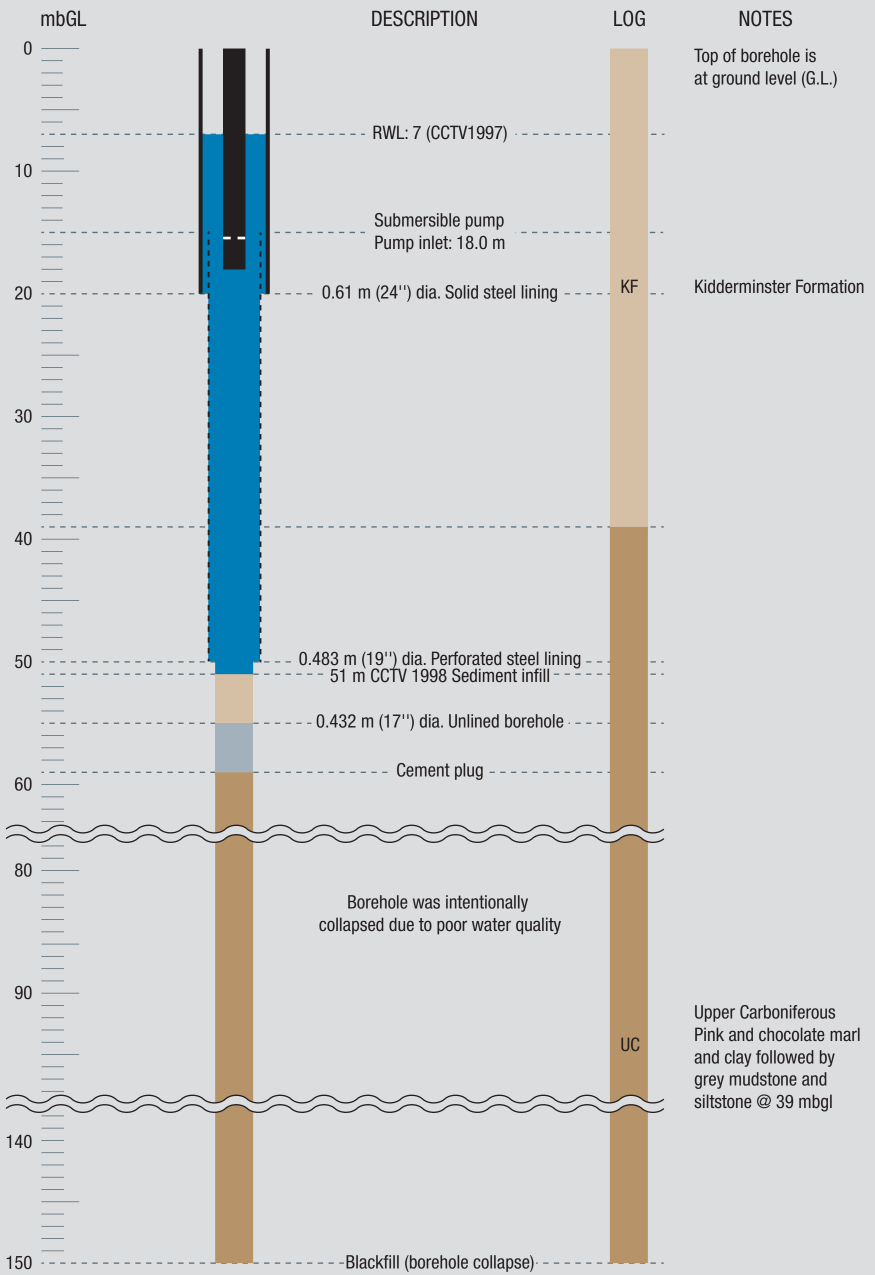
When planning a pumping test, it is useful to gather together all the information that can be found about the aquifer and the borehole itself. The results from the pumping test will be added to the information, and will improve your understanding of the local groundwater system. Try to collect information on the following:

- Similar boreholes: Are there any other boreholes in the area (especially in the same geological formation)? What are the typical water levels and yields, and what is the quality of the water, from those boreholes? Are the boreholes being pumped at the moment? Ideally, other boreholes in the area should not be pumped during your pumping test, or for at least 24 hours before the start of the test (and they might serve as observation boreholes). What drawdown can be expected in the borehole about to be tested? At what depth should the pump intake be set so that it remains well below the water level during the test?
- Basic geology: Are the rocks crystalline basement, volcanic, consolidated sediments or unconsolidated sediments? Groundwater occurs in these rocks in different ways, and behaves in different ways.
- Aquifer configuration: Is the aquifer confined, unconfined or leaky? Many test-pumping methods of analysis (including the ones described in these guidelines)

assume that the aquifer is confined. However, the methods are often still valid for use in unconfined aquifers, as long as the drawdown is small compared with the saturated thickness of the aquifer. 'Small' is not defined in the literature, and the saturated thickness of the aquifer is not often known with any degree of accuracy, so the validity of the method of analysis is, unfortunately, a matter of judgement.

- Borehole construction: How deep is the borehole, and of what diameter? Has solid casing, screen or gravel pack been installed? Note that if the total depth of the borehole is unknown, a dipper can be used to measure this, by taking the battery out (so that it doesn't bleep continuously) and lowering the dipper probe until the base of the borehole is felt. Take care not to get the dipper tape entangled with the pump or rising main. If there is any risk of this happening, use a weight on the end of a long piece of cord or thin rope.
- Installed equipment: If a pump is already installed in the borehole, what are its type and capacity, and at what depth is the pump's intake? Can the pumping rate be varied?
- Historical or background water levels: Information about the historical behaviour of the groundwater level is very useful. Does the water level vary much from wet season to dry season? In the period before the test takes place, is the water level already falling or rising or is it stable? What is the current water level?
- Local knowledge: Residents often have a surprisingly good understanding of how the groundwater in the area behaves. For example, how does the water level respond to rainfall? Can borehole yields be maintained? Is the water safe for drinking, and does the water quality change over time?
- Monitoring access: When planning a pumping test on an existing borehole, find out if there is access through the borehole headworks for the dipper or temporary pump. If you have not seen a particular borehole before, you may arrive at the site with all your equipment ready to

Figure 3.1 Borehole construction diagram



conduct the test, only to find that there is a solid borehole head-plate with no easy access down into the borehole.

There may not be much information available, in which case the planned pumping test will be the starting point for your understanding of the local groundwater system. It is good discipline to write down all the data collected so the work does not have to be duplicated in the future. A form for recording basic borehole information can be found in Annexe E.

AIRLIFTING

If the pumping test is being conducted on a new borehole soon after it has been drilled, then airlifting is a potential source of useful information. Airlifting consists of pumping compressed air into a borehole through a high-pressure air line, sometimes with the air line within an 'eductor' pipe, which acts as a rising main. The compressed air is discharged well below the water level, and if this is done correctly, it forces water out of the borehole, acting as a crude pumping method. Airlifting is routinely carried out as part of the process of drilling and completing a new borehole, when it is primarily used to clean and 'develop' the borehole. In simple terms, developing a borehole means pumping it hard until all the drill cuttings, mud and suspended sediment have been removed and the water runs clear. Airlifting is normally carried out while the drilling rig is still in place over the borehole, but it can be done separately using a portable air compressor. Although not a substitute for a pumping test, airlifting can nevertheless provide useful information about the yield of a borehole, and can help decide what pumping rate should be used for the pumping test. Ask the drillers to measure the discharge from the airlifting process. Other useful hydrogeological information can be gained from the drilling process, such as:

- Water strikes: The depth at which water was first encountered, and the drilling depths at which significant inflows of water were encountered, can indicate the depth and yield of individual fissures and fractures, and help decide the positioning of casing and screen.

- Rate of drilling: The daily progress with drilling can indicate the hardness of the rock layers that are being penetrated, giving an idea of the differences between the layers and the relative chances of obtaining water.
- Head at different depths: The static water level measured in the borehole as drilling progresses can give clues about the presence of vertical hydraulic gradients.

Water hygiene

The links between water quality and public health are well known, and much has been written on the importance of good sanitation and hygiene, the protection of groundwater resources and the improvement of traditional water sources. It is essential that the principles of good water hygiene not be forgotten during test pumping. Things to look out for include the following:

- Make sure that contaminated water cannot enter the borehole during test pumping, especially when using temporary pumping equipment in an open borehole, and when there is water spillage or run-off from rainfall during the test.
- Provide adequate sanitation facilities for the field staff and test-pumping crew, and insist that they follow good hygiene practices, particularly hand-washing. Also, if one of the workforce has symptoms such as persistent diarrhoea or prolonged unexplained fever, recommend that he or she not work on the test.
- Ensure that all equipment that will come into contact with the groundwater or the wellhead (pumps, pipes, valves, dippers, samplers, bailers, ropes, tools, etc.) has been cleaned properly before use, especially if it has previously been in contact with contaminated water. Don't forget to flush contaminated water out of pump chambers, valves and rising mains.
- If mechanical equipment such as mobile generators, air compressors and drilling rigs is being used, make sure that it is in good condition, with no leaks of hydraulic fluid, lubricating oil or diesel or other fuels. Items such as drip-trays and absorbent mats should be available in case of leaks or spills.

- → Make adequate arrangements for the temporary storage of drums or containers of fuel, oil or other hazardous substances, and enforce good practices for refuelling, so that there is no danger of contaminating the water supply during the test pumping.
- → Make sure that the borehole has been secured when you leave it, so that foreign objects, animals or dirty water cannot enter.

When preparing instructions or terms of reference for test-pumping contractors, include these points as requirements or conditions (see Chapter 7 for more on this subject).

Picture 9: Hand-held turbidity meter

Water-quality monitoring

Although the focus of most pumping tests is on monitoring water levels and pumping rates, water-quality monitoring can be an important part of the test, and should be considered at the planning stage. As mentioned above, there is a strong link between water quality and public health, and even if a certain borehole can sustain a high yield, the water produced by it may be unsuitable for drinking. Bear in mind that water-quality problems are not always immediately obvious – witness the controversy about high arsenic levels in groundwater in Bangladesh. Fluoride is a common problem in groundwater in certain parts of Africa. This document is not the place for an extended discussion of groundwater quality, but for planning purposes, it is important to decide whether or not water-quality monitoring needs to be included in the test-pumping programme. Water-quality monitoring during a pumping test can help answer key questions such as:

- Is the water quality suitable for the intended use (particularly for drinking)?
- Is the water quality stable in the long term?
- Does the water quality change with the pumping rate?
- Is there a pumping rate above which the water quality suddenly deteriorates?
- Is any treatment necessary before the water can be used?
- Is the groundwater vulnerable to pollution, or to ingress of contaminated surface water?

When planning a pumping test, therefore, take into account the following practical issues:

- Some parameters, such as electrical conductivity, temperature, pH and turbidity, must be measured at the well-head, or very soon after the water has come out of the ground. Readings are usually taken with hand-held probes.
- Measuring some parameters involves collecting samples in bottles, for subsequent analysis by a field testing kit or in a laboratory. Make sure that there is a suitable sampling point included in the discharge arrangements, so that good clean samples can be obtained, without splashing from the ground, for example.
- Unless there is a field testing kit available, samples for microbiological analysis need to be kept cool and must reach a laboratory within a certain time limit. Is this practicable?
- Electrical conductivity can be correlated with total dissolved solids, thus providing a useful field indicator of water quality (especially salinity). Observe how the conductivity changes during the test, particularly during a step test as the pumping rate progressively increases.
- Don't forget simple clues such as the appearance, smell and colour of the water. Make notes of these during the test. Do they change?
- Some boreholes produce sand, which can damage pumping equipment and fill up storage tanks. If this is suspected, collect a sample of the discharge water in a clear container. Set it aside, allow the sand to settle, and

Picture 10: Evidence of sand production

then measure the depth of sand. Using the same container, take more samples at intervals, and record how the sand content changes.

→ With all water-quality sampling, record basic information such as the time and date of sampling, and the name and location of the borehole.

4. STEP TEST

Introduction

The step test (sometimes referred to as the step-drawdown test) is designed to establish the short-term relationship between yield and drawdown for the borehole being tested. It consists of pumping the borehole in a sequence of different pumping rates, for relatively short periods (the whole sequence can usually be completed in a day). There are many different ways to perform a step test, but the most common practice is as follows:

- → Start with a low pumping rate, and increase the rate with each successive step, without switching off the pump between steps.
- → Aim for four or five steps in total, with the pumping rates roughly spread equally between the minimum and maximum rates.
- → All steps should be of the same length in time, with somewhere between 60 and 120 minutes per step being common.
- → The pumping rate for the final step should be at or beyond the intended operational pumping rate when the borehole is fully commissioned. Of course, this depends on whether the pump being used for the step test is capable of that pumping rate.

Figure 4.1 Outline of step test

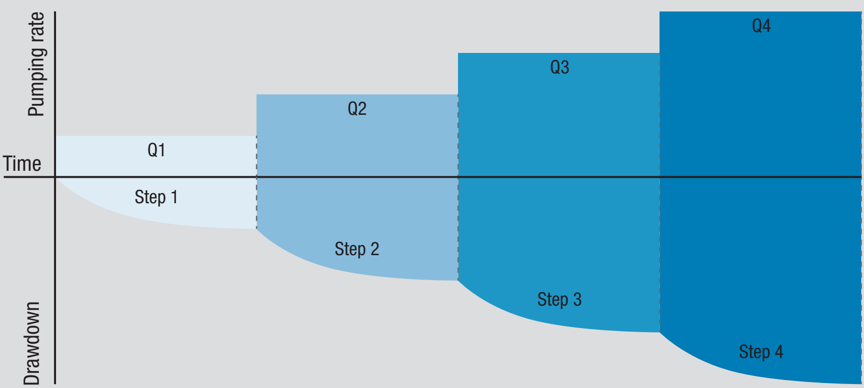


Figure 4.1 illustrates a typical series of pumping rates (*Q*) and the behaviour of the water level. It is immediately clear why it is called a step test.

Equipment and limitations

The equipment necessary for conducting a step test is as follows:

- A motorized pump complete with power supply, rising main, valves and discharge pipes, set up in such a way that the discharge rate can be changed to achieve the rates required for the different steps. Most pumps work at fixed speed, so this is usually achieved by 'throttling' the pump using a valve, and progressively opening the valve to achieve successively greater discharge rates.
- A stopwatch to measure the time of pumping and recovery.
- A dipper to measure the water levels.
- A method of measuring the pumping rate (bucket and stopwatch, flow gauge, etc.).
- A notebook, or a standard form, and a pencil, to record the test data.
- Linear graph paper and ruler to plot the results.

As mentioned above, step tests are primarily designed to provide information about the borehole performance characteristics (the yield-drawdown relationship). It is possible to use step-test results to estimate aquifer transmissivity, and methods for doing this can be found in the main hydrogeological textbooks (see Annexe D for examples). However, the present guidelines focus on borehole performance. Step-test results are not very good for predicting the behaviour of a borehole under long-term pumping, for which a constant-rate test should be used.

Picture 11: Gate valve in discharge pipe

Setting pumping rates: It is advisable to spend time, on the day before the step test itself, experimenting with the valve settings that are necessary to produce the required pumping rates for each step. Manually operated gate or globe valves are commonly used, and these are operated by a screw handle. Fully close the valve, then open it to the fully open position, counting the number of turns of the handle that are made between fully closed and fully open. Experiment with opening the valve different numbers of turns from the fully closed position, to achieve the different pumping rates for the steps, and make a note of the results.

Choosing step length: In practice, the length of each step depends on the number of steps and the total time available for the test (which is usually one day), but 60, 100 or 120 minutes are common step lengths. Ideally, the water level in the borehole will approach equilibrium at the end of each step, but this cannot always be achieved. Even if the water level has not reached equilibrium at the end of each step (in other words, if it is still falling slowly), the results from the test will still be useful. They provide a 'snapshot' of borehole performance under certain conditions, and can be compared with the results from the same test (same pumping rates and step length) repeated at another time, to see if the borehole performance has changed. If at the end of the planned time for the first step the water level is still falling quickly, the decision may be taken to extend the length of the step (and extend the length of subsequent steps to match). Further details on the theory and practice of step tests can be found in Clark (1977).

Step-test procedure

Assuming that all the equipment is ready and people have been assigned their tasks, the procedure for conducting a step test is as follows:

1. Choose a suitable local datum (such as the top of the casing) from which all water-level readings will be taken, and measure the rest-water level. The water level must be at rest before the start of the test, so the test should not be conducted on a day when the borehole is being drilled or developed, or when the equipment is being tested.
2. Open the valve to the setting for the first step (determined by prior experiment, as described above) and switch the pump on, starting the stopwatch at the same time. Do not keep changing the valve setting to achieve a particular pumping rate (a round number in litres per minute, for example). Rather, aim for an approximate rate and measure the actual rate (see 4) below).
3. Measure the water level in the borehole every 30 seconds for the first 10 minutes, then every minute until 30 minutes have elapsed, then every 5 minutes until the end of the step (the length of each step having been decided during the test preparations). If you miss the planned time for a water-level reading, write down the actual time the reading was taken. Record all the readings on the standard step-test form (Annexe E).
4. Measure the pumping rate soon after the start of the step, and then at intervals during the step (every 15 minutes would be reasonable). If there is a noticeable change in the rate of increase of drawdown or the pump sounds different, then measure the pumping rate at those times as well. If the pumping rate changes significantly (say by more than 10%), then adjust the valve setting to maintain as steady a pumping rate as possible throughout the step. Be careful not to over-adjust and make the problem worse.

5. At the end of Step 1, open the valve further, to the setting for Step 2, note the time (or restart the stopwatch) and repeat the procedures for measuring water levels and pumping rates (see 3) and 4) above).
6. Repeat the procedure for subsequent steps, progressively increasing the pumping rate for each step.
7. At the end of the final step (which will probably be Step 4 or 5), switch the pump off, note the time (or restart the stopwatch), and measure the water-level recovery at the same measurement intervals as for measuring the drawdown in each step. Continue for at least the length of a step, and ideally for much longer, until the water level approaches the pre-test level. See Chapter 6 for a full explanation of the recovery period.

Analysis and interpretation

There are many different ways to analyse step-test results, some of them very sophisticated, but the present guidelines describe simple methods that concentrate on borehole performance. The reader is referred to the standard textbooks (see Annexe D) for details of complex methods of analysis.

JACOB'S EQUATION

The theory of groundwater hydraulics assumes that during pumping from a borehole, the flow conditions in the aquifer are laminar. If this is the case, then drawdown in the borehole is directly proportional to the pumping rate. However, turbulent flow may occur in the aquifer close to the borehole if pumping takes place at a sufficiently high rate, and the final path of the water from the aquifer, through the gravel pack and screen, into the borehole and the pump intake itself is nearly always subject to turbulent flow conditions. This results in 'well losses,' meaning that additional drawdown is required to get the water into the pump. If turbulent flow is present, Jacob suggested that drawdown in a borehole can be expressed by the following equation (explained at length in Kruseman and de Ridder [1990]):

$$s = BQ + CQ^2 \qquad \textit{Equation 4.1}$$

where s is the drawdown, Q is the pumping rate, and B and C are constants. If all the terms in Equation 4.1 are divided by Q, it becomes:

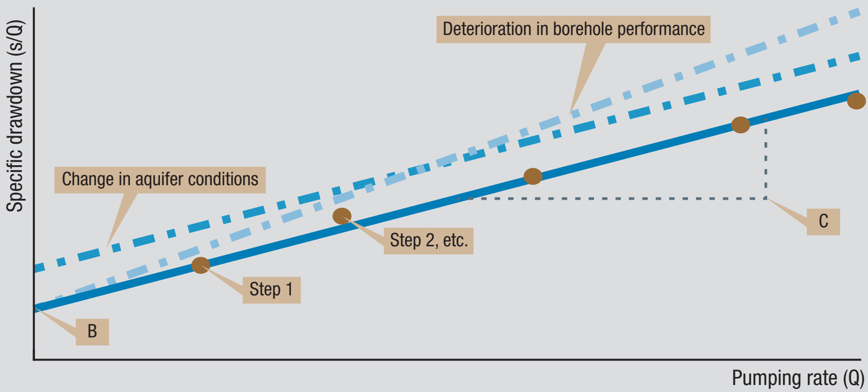
$$s/Q = B + CQ \qquad \textit{Equation 4.2}$$

which is the equation of a straight line (if s/Q is plotted against Q on linear graph paper). Note that the term s/Q is called the specific drawdown, and the inverse (Q/s) is called the specific capacity. So, for this analysis of the step test results, do the following:

1. Calculate the average pumping rate for each of the steps in the test (take all the measurements of the pumping rate recorded during Step 1 and calculate the average; now repeat the procedure for the other steps). If there were five steps in the test, you should end up with five values for the pumping rate (Q_1, Q_2, Q_3, Q_4 and Q_5).
2. Take the water-level readings from the very end of each step (in metres below datum) and convert them into drawdowns, by subtracting the rest-water level. Again, for a test with five steps, you should end up with five values of drawdown (s_1, s_2, s_3, s_4 and s_5).
3. Calculate the specific drawdowns from the pairs of values (s_1/Q_1, s_2/Q_2, etc.). Now draw a graph of s/Q against Q on linear graph paper (by plotting s_1/Q_1 against Q_1, s_2/Q_2 against Q_2, etc.), as shown in Figure 4.2 below. Draw a best-fit line through the points (the solid blue line in Figure 4.2): the intercept of the line on the y-axis represents the constant B, and the gradient of the line represents the constant C.

The values for B and C can then be used in Equation 4.1 above to calculate the expected drawdown for the other pumping rates or, with a little rearrangement of the equation, the expected pumping rate for a given drawdown. If the step test is repeated at a later date and the best-fit line (in Figure 4.2) has shifted vertically (different B) but has the same gradient (C), that represents a change in aquifer conditions. If *B* is the same but *C* has increased, then the borehole performance has deteriorated, probably due to a factor such as clogging of the screen. Jacob's equation is often used to calculate borehole efficiency, but there is a lot of confusion about borehole efficiency, and the reality is much more complex (see Box 4.1). When analysing step-test results, it is much more practical to concentrate on understanding the borehole performance characteristics, as will now be described.

Figure 4.2 Step-test analysis



BOREHOLE PERFORMANCE CURVES

Borehole performance curves are best plotted on a graph of water level against pumping rate. Water levels are used (in metres below datum) instead of drawdowns so that seasonal variations can be plotted on the same graph if the borehole is tested again at a different time of year. Such graphs are very useful tools for managing boreholes: operational data and various constraints can be plotted in addition to pumping-test data. The procedure is as follows:

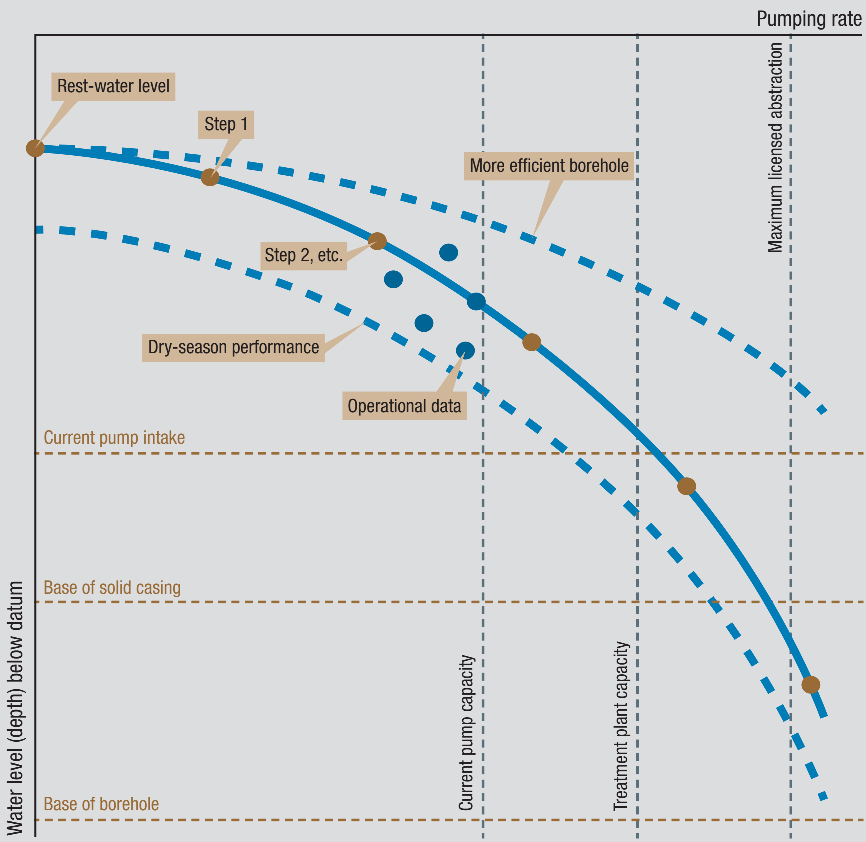
1. Prepare a graph with pumping rates on the x-axis and water levels on an inverted y-axis, as shown in Figure 4.3. Plot the rest-water level (measured just before the start of the step test) against a zero pumping rate.

Box 4.1 Borehole efficiency

The drawdown in a pumped borehole or well can be considered as consisting of two components: the **aquifer loss** (head losses as the water flows through the aquifer towards the well) and the **well loss** (head losses as the water flows into the well itself, often through gravel pack and screen). In the Jacob step-test equation ($s = BQ + CQ^2$), the terms BQ and CQ^2 are sometimes regarded as representing the aquifer loss (assumed to be laminar flow) and the well loss (turbulent flow) respectively. Furthermore, the same terms are sometimes used to calculate well efficiency, using the equation: Efficiency = $BQ/(BQ + CQ^2)$. However, this equation actually shows only the proportion of the total losses that can be attributed to laminar flow, which is not the same as well efficiency. Analysis of test-pumping data from real wells has shown that the situation is not so simple, because the term BQ often includes well losses, and the term CQ^2 sometimes includes aquifer losses. In practice, it is very difficult to measure directly the proportion of drawdown attributable to well losses. Driscoll (1986) provides a graphical method involving extrapolating lines on distance-drawdown graphs, but this requires several observation wells at different distances from the pumping well, a luxury that is unlikely to be the case in countries where the ICRC is operating. Instead, the focus of step tests should be on establishing yield-drawdown relationships. Borehole efficiency is likely to be an issue only in the case of large boreholes with high pumping rates. For these, the emphasis should be on good well design and construction, because the main factors contributing to excess drawdown are (Driscoll [1986]): well screen with insufficient open area; poor distribution of screen openings; insufficient length of well screen; poorly designed filter packs; inadequate well development; and poor placement of well screen.

2. Take the water-level reading from the end of each step (in metres below datum) and plot it against the average pumping rate for each step (Q_1, Q_2, etc.). Draw a smooth curve through these points (including the rest-water level). This is the characteristic performance curve for that borehole; it can be used to predict the drawdown for other pumping rates, and vice versa.

Figure 4.3 Borehole performance diagram



3. To use the graph as a management tool, keep it as a source of reference and update it by plotting operational data (single points on the graph) every time the borehole is visited. This will build up a picture of the typical behaviour of the borehole at different times of year (annotate the points with dates). If applicable, plot various constraints on the graph as vertical or horizontal lines. Vertical lines represent factors that limit the pumping rate, such as: maximum capacity of the installed pump; permitted maximum pumping rate (if there is an abstraction licensing regime in the area); capacity of a water-treatment plant; or capacity of a

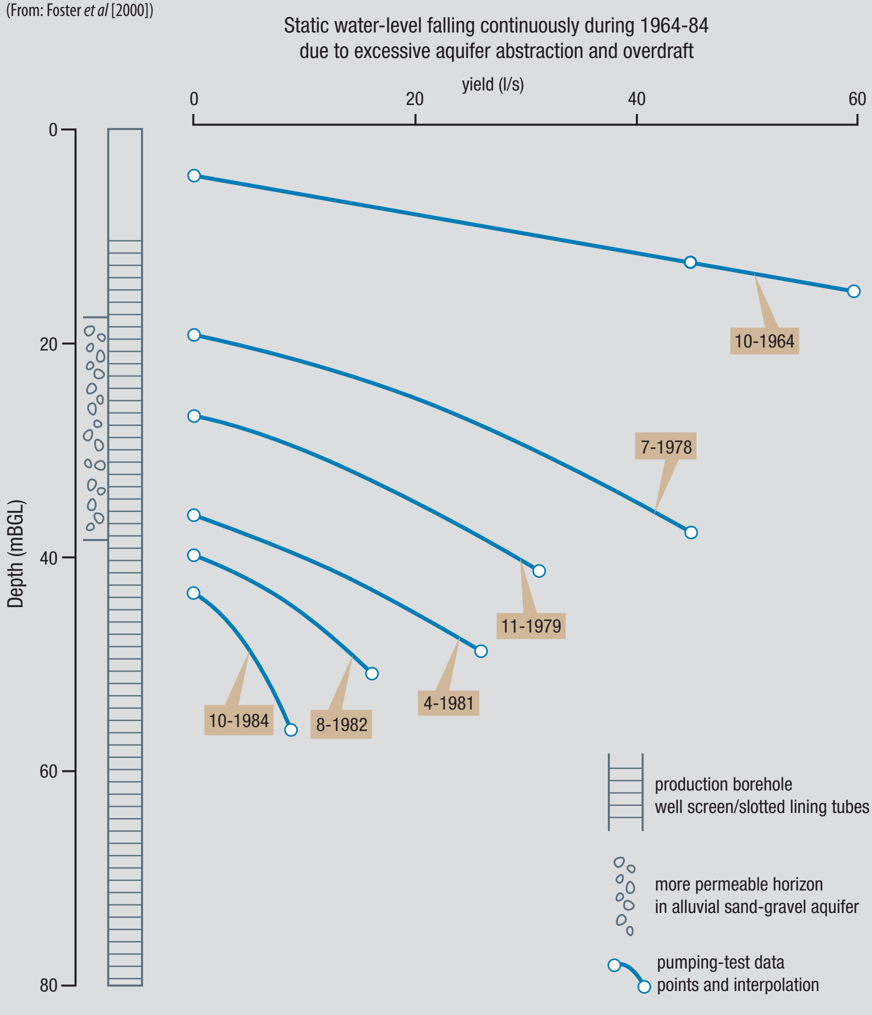
downstream booster pump. Horizontal lines represent factors that limit the water level in the borehole, such as: depth of the installed pump intake; base of the solid casing; or total depth of the borehole.

This graph helps the borehole operator to visualize at a glance factors that can affect management decisions, such as whether more water could be obtained from the borehole if the pump intake were to be lowered, or if a bigger pump were to be installed. The shape of the curve can also reveal a lot of information. An ‘efficient’ borehole will have a flatter curve (see Figure 4.3), because it can sustain a given pumping rate with less drawdown than a less efficient borehole. Some curves steepen dramatically above a certain pumping rate (behaviour sometimes called ‘drop-off’), indicating that the borehole is approaching its limits and that it would be wise to operate it at a point before the drop-off occurs. The curve is thus a convenient tool for deciding the optimal production yield of the borehole.

If the step test is conducted again at a different time of year or after an interval of a few years, changes in the position or shape of the curve can help to diagnose problems such as clogging of the screen (which would steepen the curve, because more drawdown would be required to sustain a given pumping rate), or changes in the behaviour of the aquifer (which would shift the curve vertically). An example of step-test results over many years revealing a progressive deterioration in the operational performance of a production borehole in a heavily abstracted alluvial aquifer is shown in Figure 4.4. The maximum yield decreased from 60 to 10 litres per second over the period 1964-84, while pumping lift increased from 15 to 55 m. The deterioration was largely due to the dewatering of the most productive aquifer horizon (Foster *et al* [2000]).

It is important to remember that step tests involve pumping for relatively short periods, and the results need to be treated with caution, especially if the water level has not reached equilibrium (is still falling) at the end of each step. Data from repeated step tests are most valuable for comparison if the tests are conducted in exactly the same way, with the same length of step and similar pumping rates. In order to get a good idea of the long-term performance of a borehole, there is no substitute for a constant-rate test, which is the subject of the next chapter.

Figure 4.4 Borehole deterioration
(From: Foster *et al* [2000])



5. CONSTANT-RATE TEST

Introduction

The constant-rate test is the most common type of pumping test performed, and its concept is very simple: the borehole is pumped at a constant rate for an extended period (from several hours to several days or even weeks) while the water levels and pumping rates are monitored. If the most value is to be gained from constant-rate tests, water levels should be monitored in an observation borehole as well as in the pumping borehole (or better still, several observation boreholes at different distances from the pumping borehole). As this is rarely possible in most places where the ICRC operates, the present guidelines concentrate on what to do with the data obtained from the pumping well alone. Data from constant-rate tests can be analysed to derive the transmissivity of the aquifer. The storage coefficient of the aquifer can be calculated only if data from observation boreholes are available, which is assumed not to be the case here.

Equipment and limitations

The equipment necessary for conducting a constant-rate test is as follows:

- A motorized pump complete with power supply, rising main, valves and discharge pipes. Particular care needs to be taken with the discharge arrangements for constant-rate tests, especially if the test is going to last for several days. Make sure that the water will not recirculate back into the borehole or create a nuisance by accumulating in or flowing to an inconvenient location. Discharging into a natural flow channel at some distance from the borehole is usually the best option.
- A stopwatch to measure the time of pumping and recovery.
- A dipper to measure the water levels. If available, a transducer with built-in datalogger is very valuable, because it continues to collect data while the people responsible for manual dipping are resting.
- A method of measuring the pumping rate (bucket and stopwatch, flow gauge, or weir tank).

- A notebook, or a standard form, and a pencil, to record the test data.
- Semi-log graph paper and a ruler to plot the results.

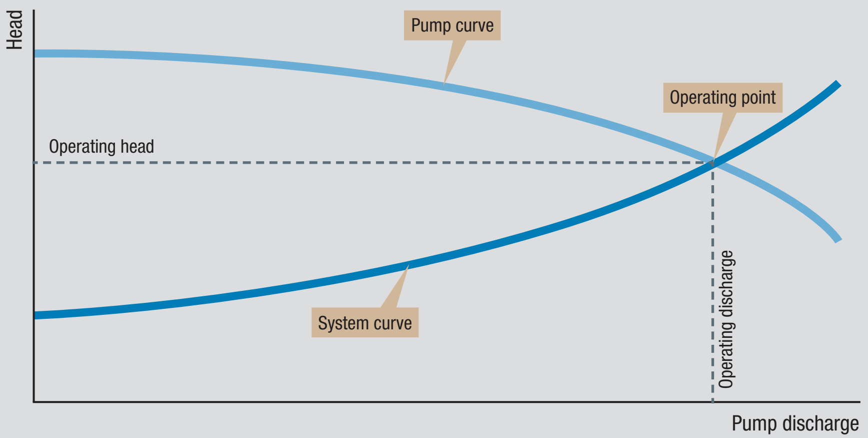
Picture 12: Discharge into surface-water channel

The two main decisions to make with a constant-rate test are the pumping rate and the length of the test:

- Pumping rate: Typically, the chosen pumping rate is equal to the intended operational pumping rate when the borehole is fully commissioned, although some hydrogeologists prefer to set the test pumping rate 25-50% higher than the intended operational pumping rate. Information from a step test is very helpful in deciding this pumping rate. The chosen rate also depends on how the borehole is going to be operated. Some boreholes are pumped at a high rate to fill up a storage tank or reservoir in a relatively short period, and then the water is used gradually (by gravity) from storage. The pumping rate for the test can either be the actual pumping rate when the pump is switched on, or the average long-term pumping rate (including the operational non-pumping periods). If the focus of the test is on long-term sustainability, then it would be better to use the average pumping rate.

Box 5.1 Pump performance

The discharge rate of a centrifugal pump depends on several factors, such as power and efficiency; the most important factor, however, is the total hydraulic head against which the pump is working. Total head includes static head and friction losses in the pumping and discharge system. During a pumping test in a borehole, as the water level in the borehole falls, the total head that the pump is working against will increase, and the discharge rate will fall. This relationship is illustrated by pump-performance curves, which can be defined for each type of pump (and can usually be provided by the pump manufacturer). The practical relevance of undertaking pumping tests is that it can be difficult to maintain a constant discharge rate if the total head changes significantly, which is inevitably the case during most pumping tests, especially at the start of the test. Careful pump selection is the best solution, so that the pump is not operating at the extremes of its performance. Under given operating conditions, a pump will tend towards a preferred operating point (see diagram below), where the pump-performance curve intersects with the system curve (representing the combined hydraulic characteristics of the intake and delivery system, including pipes and valves).



→ Length of test: Ideally, a constant-rate test should be long enough for the water level to reach or at least approach equilibrium. How long it takes to do this depends on the hydraulic properties of the aquifer. Again, the step-test results will help in understanding how the aquifer responds to pumping. For a small or medium borehole, one or two days should be sufficient, but for a large borehole expected to supply a large population, one or two weeks are common.

Many aquifers behave differently in the wet season compared with the dry season; if possible, constant-rate tests should therefore take place at the relevant time of year. For example, if the borehole is intended as a source of water for critical drought periods, then it should be tested during the dry season, otherwise a false impression will be gained of the aquifer's performance. Another good reason to conduct a test during a dry period is that the groundwater levels may be influenced by recharge from heavy rainfall, which makes it more difficult to interpret the test results.

Maintaining a steady pumping rate during a constant-rate test is sometimes a problem, especially if the chosen pumping rate results in a large drawdown. This is because for centrifugal pumps (the most commonly used type of pump) there is a relationship between pumping rate and pumping head; see Box 5.1 for more information. Incidentally, the pump must be set at a depth that is several metres below the deepest water level expected during the test.

Constant-rate test procedure

Assuming that all the equipment is ready and people have been assigned their tasks, the procedure for conducting a constant-rate test is as follows:

1. Choose a suitable local datum (such as the top of the casing) from which all water-level readings will be taken, and measure the rest-water level. The water level must be at rest before the start of the test, so the test should not be conducted on a day when the borehole is being drilled or developed, or when the step test is taking place.

2. Open the valve to the appropriate setting and switch the pump on, starting the stopwatch at the same time. Do not keep changing the valve setting to achieve a particular pumping rate (a round number in litres per minute, for example). Rather, aim for an approximate rate and measure the actual rate (see 4) below).
3. Measure the water level in the borehole every 30 seconds for the first 10 minutes, then every minute until 30 minutes have elapsed, then every 5 minutes until 2 hours have elapsed. After 2 hours, observe how quickly the water level is still falling, and decide an appropriate frequency for water-level readings until the end of the test. If the water level is falling very slowly, then a reading every 30 minutes or even every hour may be sufficient. If the test is to continue for several days, review the measurement frequency depending on the behaviour of the water level. If you miss the planned time for a water-level reading, write down the actual time the reading was taken. Record all the readings on the standard form (Annexe E).
4. Measure the pumping rate soon after the start of the test, and then at intervals during the test (every 15 minutes would be reasonable for the first few hours, then decide a suitable frequency for the remainder of the test). If there is a noticeable change in the rate of increase of drawdown, or if the pump sounds different, then measure the pumping rate at those times as well. If the pumping rate changes significantly (say by more than 10%), then adjust the valve setting to maintain as steady a pumping rate as possible throughout the test, but be careful not to over-adjust and make the problem worse.
5. At the end of the test, switch the pump off, note the time (or restart the stopwatch), and measure the water-level recovery at the same measurement intervals as for measuring the drawdown. Continue until the water level has recovered to the pre-test level, or at least approaches that level. See the next chapter for a full explanation of the recovery period.

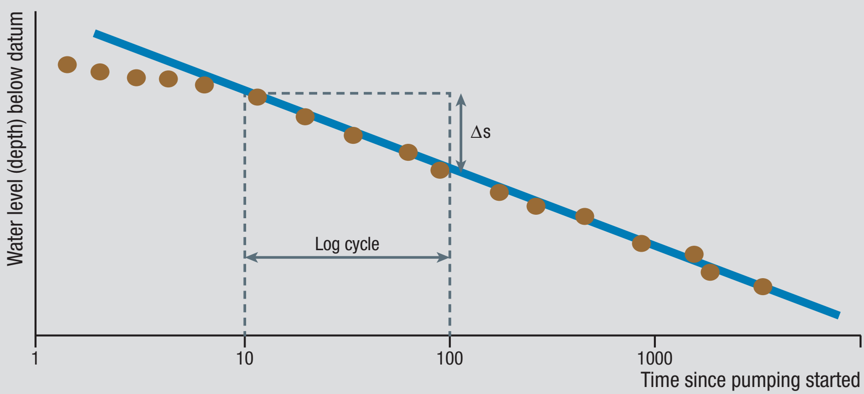
If there is a problem during the test, such as an interruption to the power supply or a pump failure, then use your judgement, depending on when the problem occurs and how long it is likely to last. For example, if something goes wrong in the first few minutes, wait for the water level to recover and start again. If the failure occurs well into the test and can be solved quickly, just restart the pump and carry on. If it is going to take a long time to solve, it may be better to allow full recovery of the water level and start again. For long constant-rate tests, it is especially important to ensure that there is an adequate fuel supply to last the planned duration of the test.

Analysis and interpretation

The method of analysis presented here is called the Jacob (sometimes referred to as the Cooper-Jacob) straight-line method, which is based on a simplification of the Theis method (see Annexe D for further reading on the subject). The procedure is as follows:

1. Prepare a graph on semi-log graph paper, with water levels on the (linear) *y*-axis, in metres below datum, and time on the (logarithmic) *x*-axis (time since the start of pumping, in minutes). See Figure 5.1. Note that drawdowns can be plotted on the *y*-axis instead of water levels, if preferred – this does not affect the analysis.

Figure 5.1 Constant-rate test analysis



2. Plot the water levels against time for the duration of the test. The data should plot roughly as a straight line. Draw a best-fit line through the data, ignoring the early data and concentrating on middle to late data.
3. From this line, measure a parameter known as Δs, which is the difference in water levels (in metres) over one log cycle (best understood by looking at Figure 5.1).
4. Calculate the average pumping rate for the duration of the test, Q, in m^3/day.
5. Insert the values of Q and Δs into the formula below to calculate the transmissivity T. Make sure that the correct units have been used, in which case the units of T will be m^2/day.

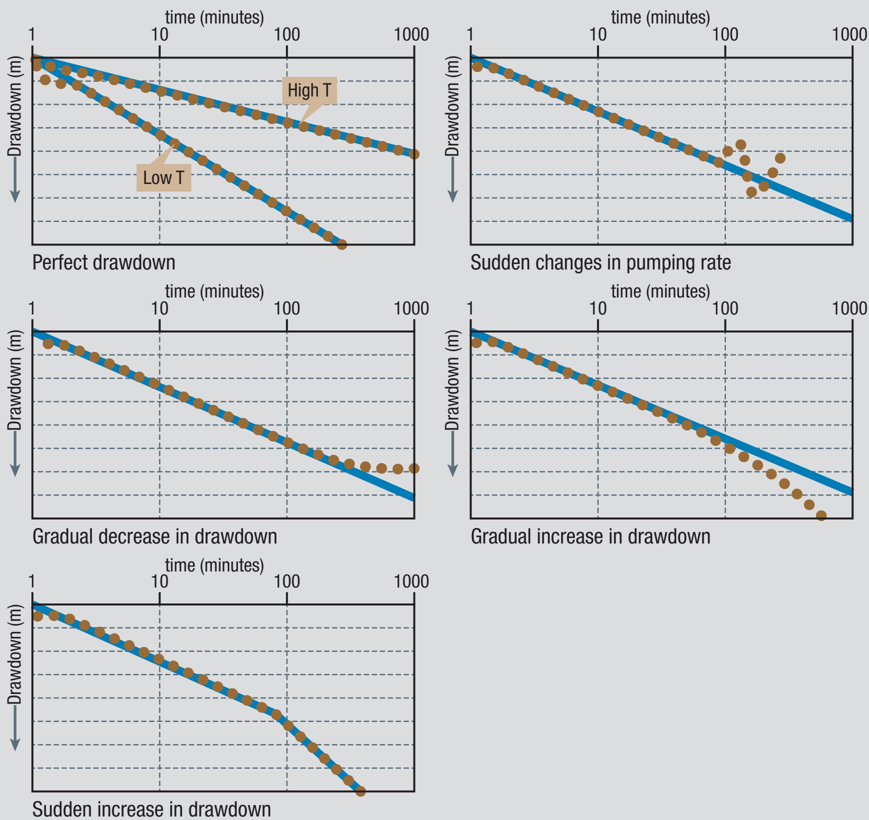
$$T = 0.183\ Q/\Delta s$$

When a fine line was fitted to the data points in 2) above, the early data were ignored because they tend to be affected by the volume of water stored in the borehole itself, and the points would probably not have fallen on the straight line. If there are other deviations from the straight line, first look for explanations such as sudden changes in the pumping rate or heavy rainfall during the test. Different types of deviation from the standard Jacob straight line are commonly observed, as shown in Figure 5.2 and described below (the figure and the explanations are taken from MacDonald *et al* [2005]).

→ Gradual decrease in drawdown: This occurs because the aquifer is gaining water from another source, either because the aquifer is leaky, or because the expanding cone of depression has intercepted a source of recharge, such as surface water. This is an encouraging sign for the borehole as a sustainable water source, and the transmissivity value should be measured using the data before the leakage is observed.

→ Gradual increase in drawdown: This indicates that the aquifer properties away from the borehole are poorer than those closer to the borehole. This can be because

Figure 5.2 Deviations from straight line during constant-rate test
(From: MacDonald *et al* [2005])



the aquifer is limited in extent (in other words, the expanding cone of depression has encountered a hydraulic barrier), or because shallow parts of the aquifer are being dewatered. This is not an encouraging sign, and indicates that less water is available than appeared at first. If the test has been continued long enough (for the data to stabilize on a new straight line), calculate the transmissivity from the late data.

→ Sudden increase in drawdown: This can result from the dewatering of an important fracture or the interception of a hydraulic barrier. Such behaviour is of serious concern and indicates that the borehole may dry up after heavy usage or during the dry season. All is not lost, however, as the borehole may still be usable, at a lower pumping rate.

During a constant-rate test, it is worth roughly plotting the data in the field as the test proceeds, in case these deviations are observed. Decisions can then be made about extending or shortening the planned test length, or trying a different pumping rate.

We have now calculated a transmissivity value in m^2/day, but the question is, what does that value mean? Is a value of 10 m^2/day good or bad? The answer mainly depends on what the intended yield of the borehole is. MacDonald *et al* (2005) carried out modelling using typical assumptions and parameters applicable to emerging countries, and came to the conclusion that for a borehole supplying 5,000 litres per day (20 litres per person for 250 people), the transmissivity value of the aquifer should be at least 1 m^2/day. An aquifer with a transmissivity value of 10 m^2/day would be capable of yielding around 40,000 litres per day. By comparison, a public water-supply borehole in a typical sandstone aquifer in England capable of yielding about two million litres per day would have a transmissivity value of 300 to 400 m^2/day when tested. Highly productive aquifers, capable of supporting major abstractions, can have transmissivity values of 1,000 to 2,000 m^2/day.

In fact, a calculated transmissivity value is most useful for comparison with other boreholes in similar hydrogeological environments or geographical areas. This is why it is important to keep good records of pumping tests. An overall picture of groundwater development potential in a certain region can be built up from the results of many tests, ideally plotted on a map. As with all mathematical equations, the method of analysis described here should not be applied blindly. Comparison with other tests should give an idea of whether or not the results of a particular test are reasonable. If the calculated transmissivity value is orders of magnitude different from the typical values mentioned above, it is probably because the wrong units have been used for input to the equation, and these should be double-checked.

Unfortunately, there is no magic formula to predict the maximum yield of a borehole from parameters such as transmissivity. In practice, the long-term sustainable yield of a borehole depends on many factors, including: regional hydrogeology (aquifer boundaries, recharge, seasonal variations in water level, etc.); the way the borehole is operated (intermittent or continuous pumping); the impact on the environment and whether other sources of water are being affected by the abstraction. Data from individual pumping tests should be assessed alongside background information and long-term monitoring to build up a picture of how a borehole behaves.


ICRC

6. RECOVERY TEST

Introduction

The recovery test is not strictly a pumping test, because it involves monitoring the recovery of the water level after the pump has been switched off. We have already come across it in the final stages of the procedures for undertaking step tests and constant-rate tests. It has been given a chapter to itself because recovery data are not always given the attention they deserve. Recovery tests are valuable for several reasons:

- They provide a useful check on the aquifer characteristics derived from pumping tests, for very little extra effort – just extending the monitoring period after the pump has been switched off.
- The start of the test is relatively 'clean.' In practice, the start of a constant-rate test, for example, rarely achieves a clean jump from no pumping to the chosen pumping rate. Switching a pump off is usually much easier than starting a pump, and the jump from a constant pumping rate to no pumping can be achieved fairly cleanly.
- Similarly, recovery smoothes out small changes in the pumping rate that occurred during the pumping phase, and there is no problem with well losses from turbulent flow. This results in more reliable estimates of aquifer properties when the recovery data are analysed.
- The water levels in the borehole are easier to measure accurately in the absence of turbulence caused by the pumping (especially in the early stages of the test, when water levels are changing quickly). Some people find that it is easier to take readings quickly with a dipper when the water level is rising than when it is falling.
- Recovery tests represent a good option for testing operational boreholes that have already been pumping at a constant rate for extended periods. In these cases, the recovery test can be performed when the pumps are first switched off, followed by a constant discharge test when the pumps are switched back on again.

Equipment and limitations

The equipment required for a recovery test is very simple (if we ignore the fact that all the pumping equipment is still in place from the pumping period that immediately preceded the recovery test):

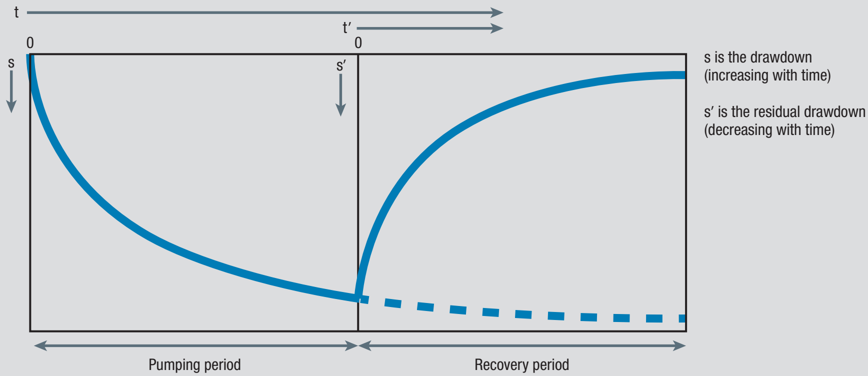
- A stopwatch to measure the time of recovery.
- A dipper to measure the water levels (or a transducer with built-in datalogger, if available).
- A notebook, or a standard form, and a pencil, to record the test data.
- Semi-log graph paper and ruler to plot the results.

Ideally, the duration of the recovery test should be as long as is necessary for the water to return to its original level, which, theoretically, would be as long as the duration of the pumping phase of the test programme. In practice, however, the recovery test is often shorter, partly for reasons of cost (keeping equipment and personnel on the site). It should not be too short however, because as described in relation to the constant-rate test, the data from the early part of the test are affected by well storage. If the data from the constant-rate test have been roughly plotted in the field on semi-log graph paper, this will give some idea of the length of time before the data become useful for calculating transmissivity (when they fall on a straight line).

The pump should not be removed from the borehole while the recovery test is taking place, because the sudden removal of the submerged volume of the pump and rising main will cause a sudden change in the water level in the borehole. For a similar reason, there must be a non-return valve (called a foot-valve in this context) at the base of the rising main. In the absence of a foot-valve, when the pump is switched off, the contents of the rising main will flow back down into the borehole and cause a sudden change in the water level in the borehole. Having said that, unless the foot-valve can be opened from the surface, the rising main will be full of water, and therefore heavy, when it is removed from the borehole. Thus, it may not always be practicable to carry out a recovery test.

In theory, the recovery curve should be a mirror image of the drawdown curve, as long as it is measured from the extension to the drawdown curve. This is illustrated in Figure 6.1, which also introduces the concept of residual drawdown (*s′*), the difference between the original water level before the start of pumping and the water level measured at a time (*t′*) after the pump was switched off.

Figure 6.1 Explanation of recovery-test terminology
(From: Kruserman and de Ridder [1990])



In practice, the water level may not actually recover to the original rest level for a variety of reasons, such as:

- The aquifer might be of limited extent with no recharge having taken place, in which case the recovered rest-water level may be lower than the original one (conversely, if recharge occurs during the test, recovery may occur sooner than expected).
- Some confined aquifers are not perfectly elastic, so they behave differently on recovery (they have a different storage coefficient).
- In unconfined aquifers, air may be trapped in pore spaces on rewetting of the dewatered portion of the aquifer.

Recovery-test procedure

The procedure for undertaking a recovery test is as follows:

1. Switch the pump off and start the stopwatch at the same time.
2. Measure the water level in the borehole in the same way as for the start of the pumping test, that is, every 30 seconds for the first 10 minutes, then every minute until 30 minutes have elapsed, then every 5 minutes until 2 hours have elapsed. After 2 hours, observe how quickly the water level is still rising, and decide an appropriate frequency for water-level readings until the end of the test. If the water level is rising very slowly, then a reading every 30 minutes or even every hour may be sufficient. If you miss the planned time for a water-level reading, write down the actual time the reading was taken. Record all the readings on the standard form (Annexe E). Make sure the same datum is used for measuring water levels as for the pumping phase.

Analysis and interpretation

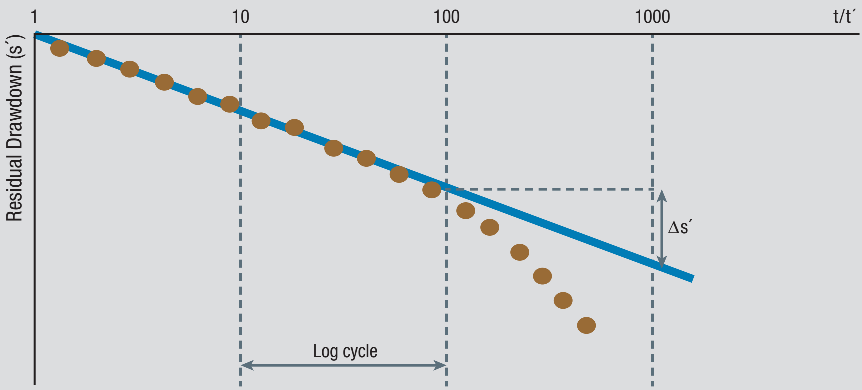
Methods of analysis for recovery tests are supposed to be used only if the pumping was at a constant rate during the pumping phase, with the water level at or approaching equilibrium. Recovery data following an extended constant-rate test are therefore preferable (as opposed to after a step test). As before, a simple analytical method will be presented here; the reader is referred to the reading list (Annexe D) for more complex methods. The procedure for analysing recovery data is as follows:

1. Take all the water levels measured during the recovery phase (in metres below datum) and convert them to residual drawdowns (s′) by subtracting the original rest-water level measured just before the start of the pumping phase.
2. The time elapsed since the start of the recovery phase (in minutes) is denoted by t′. For all the residual drawdowns, calculate t, which is the time elapsed since the very start of the pumping phase of the test (in minutes, as illustrated in Figure 6.1). For example, if the pumping

phase was 600 minutes long, for recovery readings taken at times *t′* of 1, 10 and 100 minutes, the respective times t would be 601, 610 and 700 minutes.

3. For all these pairs of times, divide *t* by *t′*.
4. Prepare a graph on semi-log graph paper, with residual drawdown s′ on the (linear) *y*-axis, in metres, and t/t′ on the (logarithmic) *x*-axis. See Figure 6.2.

Figure 6.2 Recovery-test analysis



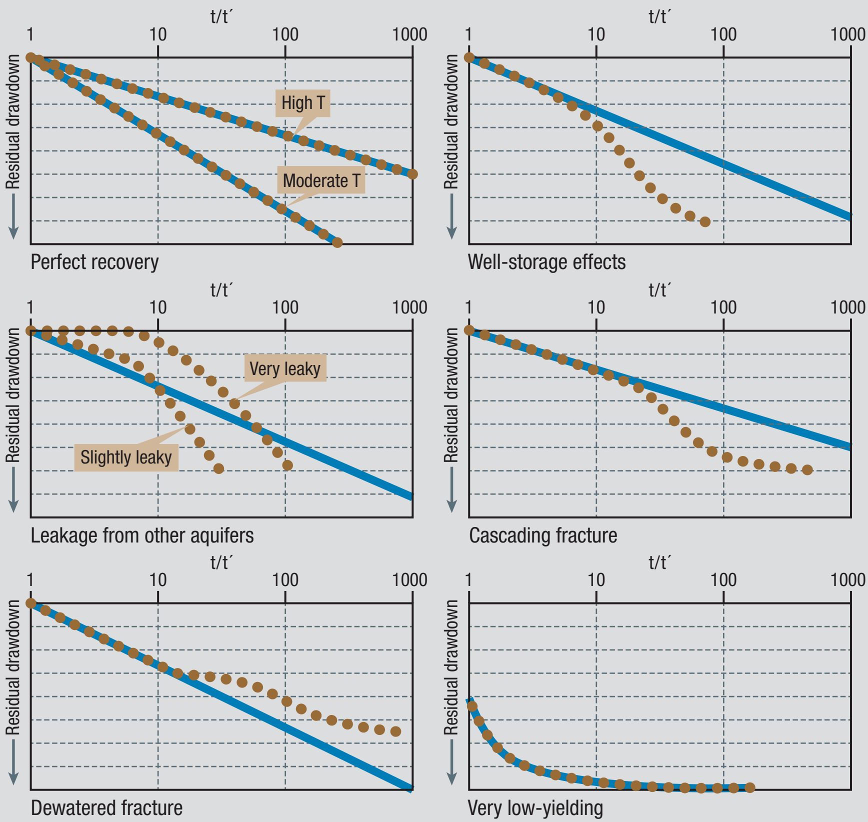
5. Plot s′ against t/t′ for the duration of the test, noting that time runs from right to left on this graph. The data should plot roughly as a straight line. Draw a best-fit line through the data, ignoring the early data (those on the right-hand side) and concentrating on middle to late data. Under normal circumstances, the line should trend towards $t/t' = 1$ when $s' = 0$.
6. From this line, measure a parameter known as $\Delta s'$, which is the difference in residual drawdowns (in metres) over one log cycle (best understood by looking at Figure 6.2).
7. Calculate the average pumping rate for the duration of the pumping phase of the test, *Q*, in m³/day. This should already have been done during the analysis of the constant-rate test.

8. Insert the values of Q and $\Delta s'$ into the formula below to calculate the transmissivity T. Make sure that the correct units have been used, in which case the units of T will be m^2/day.

$$T = 0.183\ Q/\Delta s'$$

As in the analysis of data from the constant-rate test, the early data were ignored because they tend to be affected by the volume of water stored in the borehole itself, and the points will probably not fall on the straight line. Several types of deviation from the straight line are commonly observed, as shown in Figure 6.3 and explained briefly below.

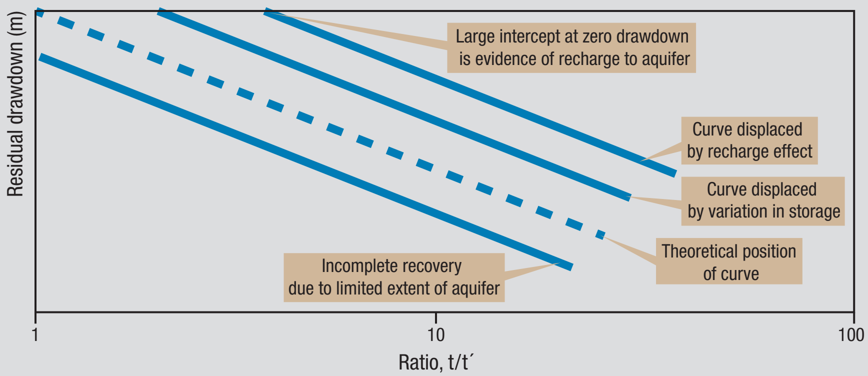
Figure 6.3 Deviations from straight line during recovery test
(From: MacDonald *et al* [2005])



- Well-storage effects: The water level does not recover as quickly as it should do in theory, because water is required to fill up the volume of the borehole itself.
- Leakage from other aquifers: The aquifer being tested is receiving water from other aquifers or aquifer layers by vertical leakage.
- Cascading fracture: As the water level recovers, it eventually submerges a fracture from which water was cascading (when the water level was below the fracture).
- Dewatered fracture: The rate of recovery is affected by the fact that a fracture was dewatered during the pumping phase.
- Very low-yielding: The recovery is very slow, and likely to be dominated by the need to fill up the volume of the borehole.

There are other ways in which the line on the graph can differ from what was expected, if real aquifer conditions are different from theoretical conditions: these are illustrated in Figure 6.4.

Figure 6.4 Differences between real and theoretical aquifer conditions
(After: Driscoll [1986])



Todd (1980) points out that the initial recovery rate of a borehole after pumping stops can be a way of recognizing an inefficient borehole. If the borehole is inefficient, the well losses will be large, and this component of the drawdown will recover rapidly by drainage into the borehole from the aquifer. Todd's rough rule of thumb is: if a pump is shut off after 1 hour of pumping and 90% or more of the drawdown is recovered after 5 minutes, then it can be concluded that the borehole is unacceptably inefficient.

As mentioned at the end of the previous chapter, the method of analysis described here should not be applied blindly, and comparison with other tests (particularly the constant-rate test immediately preceding the recovery test) should give an idea of whether or not the results are reasonable.

Bailer test

The bailer test is a special type of test designed to be performed by hand with simple equipment (a motorized pump is not needed). Its results can be analysed with a minimum of training to gain an idea of whether or not a borehole is likely to be successful when equipped with a hand-pump. It is mentioned here because the analysis is done using the recovery data. The bailer test is unlikely to be used very often by ICRC WatHab engineers, but full details are given in Annexe F for information. It may be the only test that it is possible to conduct in very remote locations, or in aquifers of very low permeability.


Marc Bleich / ICRC

7. FINAL COMMENTS

Large-diameter wells

One of the assumptions built into the theory behind nearly all methods of analysing test-pumping data is that the volume of water stored in the borehole or well itself is negligible. When describing the analysis of constant-rate and recovery tests in earlier chapters, we pointed out that data from the early stages of a test are often affected by storage, and should not be included in the analysis. For large-diameter wells, however, the assumption of negligible storage breaks down completely, and it becomes very difficult to analyse pumping-test data meaningfully (certainly without a computer). Conducting pumping tests in large-diameter wells is difficult from a practical point of view as well since, unless a high-capacity pump is used, it is difficult to induce sufficient drawdown in a short time, and the behaviour of the water level is dominated by the large storage volume. The most practical approach when dealing with large-diameter wells is to concentrate on the following:

→ Local knowledge: With the help of the local community, try to derive approximate yield information by counting the number of containers (of known volume) that are filled from the well every day. How does the water level respond to this level of abstraction? Can water be collected at any time of day, or does the well have to be allowed time to refill? How does this behaviour change during the dry season? What are typical wet and dry season rest-water levels? Use a simplified version of the performance diagram (Figure 4.3) to summarize and visualize the information.

→ Recovery rate: Pump water from the well as quickly as possible until the well is nearly empty, then monitor the way in which the water level recovers (using a dipper and stopwatch). Using an estimate of the dimensions of the well, an approximate 'yield' can be derived, in [volume] per [time]. Of course, this test must be carried out with the agreement of the local community, so that they are not deprived of their water source at a critical time. It would be wise to discharge the water in such a way that it can be used, and is not wasted.

Choice of pumping test

Faced with a particular borehole or well, what type of pumping tests should a WatHab engineer conduct? This question has been left to the final chapter, because the answer depends on all the factors, assumptions, limitations, equipment constraints, methods of analysis and uncertainties that have been discussed throughout these guidelines. Table 7.1 gathers all the important information in one place, and thus serves as a quick-reference guide for WatHab engineers.

Table 7.1 Guide for selecting pumping tests in different situations

Type of test	Parameters derived from the test (using simple methods of analysis)	Typical length of the whole test	Limitations of the test
Step test	Specific drawdown. Specific capacity. Qualitative assessment of borehole performance (yield-drawdown). Pumping rate for constant-rate test.	1 day	Must be able to vary the pumping rate. Not very good at predicting long-term aquifer behaviour.
Constant-rate test	Aquifer transmissivity. Storage coefficient, if observation borehole available. Qualitative assessment of ability to maintain the planned yield.	From 1 or 2 days up to 1 or 2 weeks	Difficult to keep the pumping rate constant. Aquifer parameters may be different in wet season compared to dry season. Must have a good discharge system.
Recovery test	Aquifer transmissivity. Qualitative assessment of well losses (related to borehole efficiency).	Several hours to several days	There must be a foot-valve fitted to a rising main. Pump cannot be removed during test.
Bailer test	Qualitative assessment of whether or not the borehole is capable of supporting a hand-pump.	Several hours	Water level should be shallower than about 15-20 m. Not suitable for high-permeability aquifers or large diameters.

	Applicability to certain situations		
	Small borehole (to be fitted with a hand-pump)	**Medium borehole (motorized pump, serving a medium-sized community)**	**Large borehole (motorized pump, serving a large community)**
	Applicable if a pump is used that is suitable for low pumping rates (and the pumping rate can be varied).	Applicable, and recommended, if a suitable method of varying the pumping rate is available.	Highly applicable, and an essential part of the test-pumping programme. Repeat the test to detect changes in performance. Will probably need a contractor.
	Applicable if a constant pumping rate can be maintained with a small pump.	Highly applicable, and an essential test to conduct. Pumping rate must be at or above the intended operational rate.	Highly applicable, and an essential test to conduct. Pumping rate must be at or above the intended operational rate. Will probably need a contractor.
	Applicable if a constant-rate test has been conducted. Bailer test (below) is a form of recovery test.	Highly applicable, and recommended, as a complement to the constant-rate test.	Highly applicable, and an essential test to conduct after the constant-rate test.
	Highly applicable. In fact, the bailer test is specifically designed for this type of borehole.	Not applicable	Not applicable

Managing contractors

With the right training, experience and equipment, all the tests described in these guidelines can be carried out in-house by the ICRC. However, we recognize that it may be necessary to employ specialist contractors to undertake some pumping tests, especially tests on large boreholes involving high pumping rates or long periods of pumping. The practical procedure for conducting and analysing a pumping test is essentially the same whether it is carried out in-house or by a contractor. For a WatHab engineer in the position of commissioning and supervising an external contractor, Annexe G contains a checklist of things to look out for, presented as a series of questions. Note that not all the questions are applicable to every situation. Annexe G also contains another list, with many of the checklist questions rephrased as statements that the WatHab engineer can include (if applicable) in a contractor's terms of reference.

Common mistakes

The most common mistakes made while test pumping include the following:

- Not finding out in advance whether there is access through the borehole headworks for the monitoring equipment or for a temporary pump.
- Choosing the wrong-sized pump for the test. Too small, and it may not be capable of imposing sufficient draw-down. Too big, and the pump may run dry.
- Not installing the pump deep enough in the borehole, so that the pump runs dry before the test is finished.
- Installing the pump too deep in the borehole, so that there is insufficient space between the pump intake and the base of the borehole.
- Insufficient fuel available (if a generator is being used), so that the test is interrupted.
- No spare batteries for the dipper and other monitoring equipment.
- Not experimenting with pumping rates in advance, so that it takes several attempts to achieve a steady rate.

- Discharging water too close to the borehole being tested, so that it recirculates down the borehole.
- Water levels being influenced by other abstractions, tides or heavy rainfall during the test, making test interpretation very difficult.
- Conducting the test at the wrong time of year (conditions too wet or too dry).
- Different people using different measuring datums, so that water-level results are not consistent.
- Forgetting to bring essential equipment to a remote site, or taking equipment that has not been tested or is not functioning correctly.
- Not familiarizing yourself with the equipment in advance (not knowing how to operate it correctly).
- No foot-valve installed on the rising main, so that the recovery-test results are affected.

All these mistakes can be avoided with careful planning and preparation, for which the checklist in Annexe G is a useful *aide-mémoire*.

Long-term monitoring

Finally, a few words on long-term monitoring. The value of background information and historical water levels was emphasized in Chapter 3, in the context of planning pumping tests. The same principle applies when looking to the future. It is very difficult to fully understand a groundwater system or a particular water source just on the basis of a relatively short test-pumping programme. Even a constant-rate test lasting several weeks is short in comparison to the operational life of the borehole. Groundwater is often slow to respond to 'events' such as recharge and abstraction, and long-term data on water levels and pumping rates are essential for gaining a full understanding of the 'efficiency' or optimal production yield of a particular borehole or well. It is strongly recommended that a long-term monitoring programme be established, based on the following practical advice:

Picture 13: Marking the local datum by annotating photo

- Keep good records, with each borehole clearly identified by a unique name or reference number, and all data, information, photos, field notes, and reports about a borehole clearly referenced, to avoid confusion.
- When monitoring water levels, make sure that the same datum is used every time (for quoting water level, in metres below datum), especially if different people carry out the monitoring. Mark the datum clearly, or identify it in a photo or diagram. If the datum changes unavoidably, then record the fact, and adjust the water-level data accordingly.
- For all monitoring parameters, make sure the units are specified, and be careful when converting units for calculations.
- Use a borehole-performance diagram (as in Figure 4.3) as a tool for summarizing and visualizing long-term monitoring data as well as one-off test-pumping data.
- When constructing new boreholes or rehabilitating existing boreholes, make sure that the design includes access points for future tests.

ANNEXES

Annexe A Glossary

Abstraction: Removal of water from groundwater or surface water, usually by pumping.

Aquiclude: Geological formation through which virtually no water moves.

Aquifer: Sub-surface layer or layers of rock or other geological strata of sufficient porosity and permeability to allow either a significant flow of groundwater or the abstraction of significant quantities of groundwater.

Aquitard: Poorly permeable geological formation that does not yield water freely, but which may still transmit significant quantities of water to or from adjacent aquifers.

Cone of depression: Depression in the water table or piezometric surface around a groundwater abstraction (approximately cone-shaped, centred on the abstraction).

Confined aquifer: Saturated aquifer that is isolated from the atmosphere by an overlying impermeable formation (an aquiclude).

Derogation: Abstraction of water that affects the ability of an adjacent abstractor to obtain as much water as previously, or that increases the drawdown required.

Drawdown: The vertical distance between the static water table or piezometric surface (rest-water level) and the surface of the cone of depression.

Hydraulic conductivity: A measure of the rate at which water can flow through a porous medium (transmissivity is hydraulic conductivity multiplied by saturated thickness).

Laminar flow: Water flowing smoothly in thin layers, with no intermixing between the layers.

Leaky aquifer: An aquifer, sometimes referred to as semi-confined, whose upper (or lower) boundary is an aquitard.

Porosity: The proportion of a rock or sediment mass that consists of voids or pores; the groundwater resides in or flows through these pores.

Recharge: The process by which water (usually originating as rainfall) is added to groundwater, or the amount of water added to groundwater in a given period.

Recovery: The period after a borehole pump is switched off, during which the water returns to its rest level.

Specific capacity: The quantity of water a given borehole can produce per unit of drawdown.

Storativity: A dimensionless measure (also known as **storage coefficient**) of the amount of water released from or taken into storage in an aquifer per unit surface area for a unit change in hydraulic head.

Transmissivity: A measure of the ease with which water can flow through a saturated aquifer (the product of hydraulic conductivity and saturated thickness).

Turbulent flow: Water flowing in such a way that water particles follow irregular paths and intermix completely.

Unconfined aquifer: Aquifer in which the water table is exposed to the atmosphere through unsaturated overlying material.

Water table: The surface of a body of unconfined groundwater where the pressure is equal to the atmospheric pressure.

The reader is referred to the bibliography (Annexe D) for more information on all of these terms.

Annexe B List of pictures

Annexe C List of figures and tables

Annexe D References and further reading

REFERENCES (sources specifically referenced in the text)

BS ISO 14686:2003: *Hydrometric Determinations – Pumping Tests for Water Wells – Considerations and Guidelines for Design, Performance and Use*. British Standard.

Clark L. (1977). "The analysis and planning of step draw-down tests." *Quarterly Journal of Engineering Geology and Hydrogeology*, Vol.10, pp.125-143.

Driscoll F. (1986). *Groundwater and Wells*. Second edition, St Paul, MN, Johnson Filtration Systems Inc.

Foster S., Chilton J., Moench M., Cardy F. and Schiffler M. (2000). *Groundwater in Rural Development: Facing the Challenges of Supply and Resource Sustainability*. Technical Paper No. 463, World Bank, Washington DC, March 2000.

Kruseman G. and de Ridder N. (1990). *Analysis and Evaluation of Pumping Test Data*. Second edition, Publication 47, Wageningen, Netherlands, International Institute for Land Reclamation and Improvement.

MacDonald A., Davies J., Calow R. and Chilton J. (2005). *Developing Groundwater: A Guide for Rural Water Supply*. Bourton on Dunsmore, Practical Action Publishing.

MacDonald A., Barker J. and Davies J. (2008). "The bailer test: A simple effective pumping test for assessing borehole success." *Hydrogeology Journal*, Vol. 16, No. 6, pp. 1065-1075, September 2008.

Todd D. (1980). *Groundwater Hydrology*. Second edition, Chichester, John Wiley & Sons.

FURTHER READING

Conducting pumping tests on boreholes and wells has long been a standard technique for investigating borehole characteristics and aquifer properties, and much has been written on the subject. In particular, the reader is referred to the following publications:

- BS ISO 14686:2003, *Hydrometric Determinations. Pumping Tests for Water Wells. Considerations and Guidelines for Design, Performance and Use.* This is the updated British Standard code of practice for test pumping of water wells, and it provides good descriptions of how to plan, carry out, and present the data from pumping tests.
- Driscoll F. (2008), *Groundwater and Wells*, third edition, published by Smyth Companies. Found on the bookshelves of most hydrogeologists (at least in the earlier editions), this comprehensive book gives practical descriptions of all aspects of designing, drilling, developing, test pumping and equipping boreholes and wells.
- Kruseman G. P. and de Ridder N. A. (1990), *Analysis and Evaluation of Pumping Test Data*, second edition, published by the International Institute for Land Reclamation and Improvement. This is the standard textbook on analysing and evaluating pumping-test data, covering all conditions: confined, unconfined, leaky, steady-state, unsteady-state, anisotropy, multilayered systems, partial penetration, etc. It includes case studies.

For general coverage of all aspects of hydrogeology, there is a growing body of literature and many books from which to choose. The following is a useful selection:

- Brassington R. (2007), *Field Hydrogeology*, third edition, published by John Wiley & Sons. A popular textbook, concentrating on practical methods for hydrogeological fieldwork; it includes a chapter on test pumping.
- Fetter C. (2001), *Applied Hydrogeology*, fourth edition, published by Pearson Education. A good textbook for those who want a more mathematical approach to hydrogeology, and more about water chemistry.

- Freeze R. and Cherry J. (1979), *Groundwater*, published by Prentice-Hall. One of the best-known textbooks on groundwater, this has become a classic.
- Price M. (1996), *Introducing Groundwater*, second edition, published by Chapman & Hall. Very accessible introductory textbook on groundwater; includes a section that discusses pumping tests against the theoretical background of groundwater hydraulics.
- Todd D. and Mays L. (2005), *Groundwater Hydrology*, third edition, published by John Wiley & Sons. Updated version of a classic textbook that is easy to read and informative, and still widely quoted as an authority.

Here are a few books on hydrogeology in Africa:

- Adelana S. and MacDonald A. (eds) (2008), *Applied Groundwater Studies in Africa*, published by Balkema. This is No. 13 in a series of selected papers on hydrogeology from the International Association of Hydrogeologists. Chapter 9 contains a particularly useful paper on the subject of African hydrogeology and rural water supply, including a summary of the groundwater potential of the main hydrogeological environments.
- MacDonald A., Davies J., Calow R. and Chilton J. (2005), *Developing Groundwater*, published by Practical Action Publishing. Referenced several times in these guidelines, it is a welcome addition to the literature, providing very practical advice.
- Wright E. P. and Burgess W. G. (eds) (1992), *The Hydrogeology of Crystalline Basement Aquifers in Africa*, Special Publication No. 66, Geological Society of London. A collection of papers reporting research carried out mainly in Malawi and Zimbabwe.

Finally, here are some websites that contain useful information:

- www.iah.org (International Association of Hydrogeologists)
- www.groundwateruk.org (UK Groundwater Forum)
- www.igrac.nl (International Groundwater Resources Assessment Centre)
- www.whymap.org (Worldwide Hydrogeological Mapping and Assessment Programme)
- www.africanwater.org (African Water Page)
- www.worldbank.org (search under GW-MATE for the World Bank briefing note series)
- www.ramsar.org (Ramsar Convention on Wetlands)

Annexe E Standard forms

Annexe E contains standard forms for recording the following:

- Basic borehole information
- Step-test data
- Constant-rate-test data
- Recovery-test data

Print or photocopy as many blank forms as needed.

Basic borehole information form

Borehole name:	
Name of person completing form:	
Date of form completion:	
Borehole location: (village, parish, district, etc.)	
Grid reference or latitude/longitude:	
Total borehole depth:	
Borehole diameter:	
Borehole construction: (describe what is known about casing, screen, gravel pack, etc.)	
Type of pump installed:	
Depth of pump intake:	
Any other relevant information:	

Sketch map of borehole location:
(showing landmarks like buildings, fences, trees, roads, and, if applicable, locations of other boreholes or water features in the area)

Step-test data form

Borehole name:	**Borehole location:**
Date of test:	**Name of person completing form:**
Rest-water level (m below datum):	**This step number:**
Start time of this step:	**Planned duration of step:**
Target pumping rate for this step:	**Calculated average pumping rate for this step:**

Time elapsed since start of step (min.)	Water level (m below datum)	Calculated drawdown (m)	Pumping rate	Comments
0.5				
1				
1.5				
2				
2.5				
3				
3.5				
4				
4.5				
5				
5.5				
6				
6.5				
7				
7.5				
8				
8.5				
9				
9.5				
10				
11				
12				
13				
14				
15				
16				
17				
18				
19				

Time elapsed since start of step (min.)	Water level (m below datum)	Calculated drawdown (m)	Pumping rate	Comments
20				
21				
22				
23				
24				
25				
26				
27				
28				
29				
30				
35				
40				
45				
50				
55				
60				
65				
70				
75				
80				
85				
90				
95				
100				
105				
110				
115				
120				

Constant-rate-test data form

Borehole name:	**Borehole location:**
Date of test:	**Name of person completing form:**
Rest-water level (m below datum):	**Start time of test:**
Target pumping rate:	**Calculated average pumping rate:**

Time elapsed since start of step (min.)	Water level (m below datum)	Calculated drawdown (m)	Pumping rate	Comments
0.5				
1				
1.5				
2				
2.5				
3				
3.5				
4				
4.5				
5				
5.5				
6				
6.5				
7				
7.5				
8				
8.5				
9				
9.5				
10				
11				
12				
13				
14				
15				
16				
17				
18				
19				
20				
21				

Time elapsed since start of step (min.)	Water level (m below datum)	Calculated drawdown (m)	Pumping rate	Comments
22				
23				
24				
25				
26				
27				
28				
29				
30				
35				
40				
45				
50				
55				
60				
65				
70				
75				
80				
85				
90				
95				
100				
105				
110				
115				
120				

Recovery-rate-test data form

Borehole name:	**Borehole location:**
Date of test:	**Name of person completing form:**
Original rest-water level (m below datum):	**Start time of recovery:**
Average pumping rate during pumping period:	**Length of pumping period (minutes):**

Time elapsed since start of recovery t′ (min.)	Water level (m below datum)	Calculated residual drawdown s′ (m)	Time since start of pumping, t (minutes)	Calculated ratio t/t′	Comments
0.5					
1					
1.5					
2					
2.5					
3					
3.5					
4					
4.5					
5					
5.5					
6					
6.5					
7					
7.5					
8					
8.5					
9					
9.5					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					
21					

Time elapsed since start of recovery t′ (min.)	Water level (m below datum)	Calculated residual drawdown s′ (m)	Time since start of pumping, t (minutes)	Calculated ratio t/t′	Comments
22					
23					
24					
25					
26					
27					
28					
29					
30					
35					
40					
45					
50					
55					
60					
65					
70					
75					
80					
85					
90					
95					
100					
105					
110					
115					
120					

Annexe F Bailer test

Introduction

The bailer test is a simple test designed specifically for rural water-supply projects in developing countries. It requires nothing more than basic hand-held equipment, and can be carried out after minimal training. The test consists of removing water from the borehole with bailers to lower the water level, and then monitoring the way in which the water level recovers to its starting point. Similar methods have been used for many years, often under the name of 'slug test' but a systematic and practical bailer-test method has now been developed and published. Intensive testing of the method in Nigeria by the British Geological Survey has established that the bailer test is almost as efficient as longer constant-rate tests in predicting the likelihood of borehole success. Most of the material in Annexe F is derived from MacDonald *et al* (2005) and (2008), who define a 'successful' borehole as one that can sustain a hand-pump serving 250 people at 20 litres per person per day; in other words, a yield of 5 m^3 per day. The ICRC prefers to use 8 to 10 m^3 per day as a yield threshold, and the method presented here has been adjusted to correspond to this higher threshold.

The bailer test is particularly suitable for low-permeability aquifers, which are common throughout sub-Saharan Africa, where only a very low abstraction rate can be sustained. However, because the bailer test relies on manual labour to pull water out of a borehole intensively for 10 minutes, it is really suitable only for boreholes in which the water level is shallower than about 15 to 20 m below ground. Also, it is suitable only for boreholes, as opposed to large-diameter wells, because the water level must be lowered sufficiently to measure changes realistically. If the aquifer is very permeable, the drawdown may be too small and the recovery too fast to be accurately recorded (although in this case, the test will still have shown that the borehole can sustain a hand-pump). More detailed analysis of the data from a bailer test can determine the transmissivity of the aquifer, but this requires a computer program, and is not discussed here.

Equipment

The equipment for conducting a bailer test, shown in Figure D.1, is as follows:

- Two bailers for removing water from the borehole. A bailer is a long cylindrical bucket that can easily fit in the borehole and that will remove approximately 4 to 5 litres with each bail. Such a bailer can readily be made from steel pipe in a local workshop. The volume of the bailer can be calculated from the formula $\pi r^2 h$ (where π is 3.14, r is the inside radius of the pipe, and h is the length of the pipe). For example, a bailer with an inside diameter of 75 mm and a length of 1 m would have a volume of 4.4 litres. A rope about 20 m long should be attached to the top of each bailer.
- A stopwatch to measure the time of pumping and recovery.
- A dipper to measure the water levels.
- A notebook, or a standard form, and a pencil to record and analyse the test data.

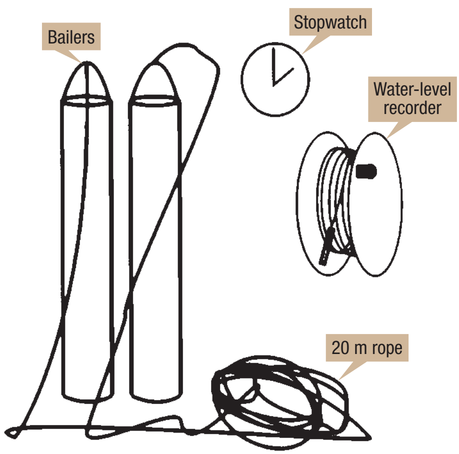


Figure D.1: Bailer-test equipment
From: MacDonald *et al* (2008)

Bailer-test procedure

Assuming that all the equipment is ready and people have been assigned their tasks, the bailer-test procedure consists of the following steps:

1. Choose a suitable local datum (such as the top of the casing) from which all water level readings will be taken, and measure the rest-water level. The water level must be at rest before the start of the test, so the test should not be conducted on a day when the borehole is being drilled or developed..
2. Bailer A is lowered into the borehole and submerged. The stopwatch is started the moment Bailer A is full and starts to be hauled out of the borehole. While Bailer A is being emptied, Bailer B is quickly lowered into the borehole and removed as soon as it is full. This procedure continues, alternating the two bailers, for a duration of 10 minutes, in which time around 20-50 bails should have been abstracted (depending on the distance to the water level). A good target to aim for would be 40 bails in 10 minutes (one every 15 seconds); the test results are more accurate if the rate of bailing is fairly constant throughout the test. The people doing the bailing need to pace themselves so that the rate of bailing does not start too fast, then slow down as the water level drops and the people become tired. The total number of bails removed from the borehole during the 10-minute 'pumping' period should be counted carefully, and written down. Bailing must stop after exactly 10 minutes.
3. As soon as the bailing stops, the time is noted (or the stopwatch is reset) and the water level is measured with the dipper every 15 seconds for 10 minutes, then every 30 seconds for a further 20 minutes. A standard form for recording bailer-test data is provided below. Make sure that, in addition to the water-level data, all the information requested is recorded, including the volume of the bailers and the number of bails removed.

Analysis and interpretation

The method of analysis presented here will determine whether or not the borehole is likely to be able to sustain a yield of 8 to 10 m^3 per day. To analyse and interpret bailer-test results, follow these steps:

1. Convert all the measured water levels into drawdowns by subtracting the rest-water level (space is provided on the bailer-test data form for the calculated drawdowns).
2. Identify the maximum drawdown (s_{max}), which is calculated from the first water level measured after the bailing stops.
3. Using the form provided on the last page of this annnexe, calculate the total volume of water abstracted from the borehole during the test and the average pumping rate for the test.
4. Calculate s_{50}, which is half of the maximum drawdown ($s_{50} = s_{max}/2$); also calculate s_{75}, which is the drawdown when the water level has recovered to a quarter of the maximum drawdown ($s_{75} = s_{max}/4$).
5. Read from the recorded data the time when s_{50} and s_{75} occurred (we will call these t_{50} and t_{75} respectively).
6. Measure or estimate the borehole diameter. If the borehole is open-hole or cased but with no gravel pack, then the diameter is the drilled diameter. If the borehole already has a gravel pack, then the effective diameter of the borehole is somewhere between the casing diameter and the drilled diameter. Since the porosity of the gravel is usually around 30%, the diameter can be approximated through the following calculation: 0.3 x (drilled diameter – casing diameter) + casing diameter.
7. Use the pumping rate and the effective borehole diameter to find the correct set of guideline values in Table D.1 below. If the values for s_{max}, t_{50} and t_{75}, calculated on the basis of the test, are all less than the guideline values in the table, then the borehole is likely to be able to sustain a yield of 8 to 10 m^3 per day. If the calculated values are all greater than the guideline values, then

the borehole is unlikely to be able to maintain that yield (although it may still be a useful water source if a lower yield is acceptable). If some of the calculated values are greater than the guideline values and some smaller, or if they are very close to the guideline values, then it may be advisable to test the borehole further using a constant-rate test.

Table D.1 Guideline values for bailer-test analysis 8 to 10 m^3 per day

Borehole Diameter	Pumping rate (litres per minute):	7	10.5	14	17.5	21
100 mm	Maximum drawdown, s_{max} (m)	2.54	3.81	5.08	6.35	7.62
	Time for half recovery, t_{50} (minutes)	6	6	6	6	6
	Time for three-quarters recovery, t_{75} (minutes)	11	11	11	11	11
125 mm	Maximum drawdown, s_{max} (m)	2.22	3.33	4.43	5.54	6.64
	Time for half recovery, t_{50} (minutes)	7	7	7	7	7
	Time for three-quarters recovery, t_{75} (minutes)	16	16	16	16	16
150 mm	Maximum drawdown, s_{max} (m)	1.89	2.84	3.78	4.73	5.67
	Time for half recovery, t_{50} (minutes)	9	9	9	9	9
	Time for three-quarters recovery, t_{75} (minutes)	21	21	21	21	21
200 mm	Maximum drawdown, s_{max} (m)	1.35	2.03	2.71	3.39	4.06
	Time for half recovery, t_{50} (minutes)	17	17	17	17	17
	Time for three-quarters recovery, t_{75} (minutes)	35	35	35	35	35

(The authors are grateful to Alan MacDonald for recalculating the guideline values for a 10 m^3 per day threshold)

Table D.2 Guideline values for bailer-test analysis 5 m^3 per day

Borehole Diameter	Pumping rate (litres per minute):	7	10.5	14	17.5	21
100 mm	Maximum drawdown, s_{max} (m)	3.5	5.3	7.1	8.8	10.6
	Time for half recovery, t_{50} (minutes)	6	6	6	6	6
	Time for three-quarters recovery, t_{75} (minutes)	14	14	14	14	14
125 mm	Maximum drawdown, s_{max} (m)	2.9	4.3	5.7	7.1	8.5
	Time for half recovery, t_{50} (minutes)	9	9	9	9	9
	Time for three-quarters recovery, t_{75} (minutes)	21	21	21	21	21
150 mm	Maximum drawdown, s_{max} (m)	2.3	3.4	4.6	5.7	6.9
	Time for half recovery, t_{50} (minutes)	12	12	12	12	12
	Time for three-quarters recovery, t_{75} (minutes)	28	28	28	28	28
200 mm	Maximum drawdown, s_{max} (m)	1.5	2.3	3.1	3.8	4.6
	Time for half recovery, t_{50} (minutes)	19	19	19	19	19
	Time for three-quarters recovery, t_{75} (minutes)	46	47	47	47	47

Table D.2 shows guideline values to indicate whether or not a borehole is likely to be able to sustain a yield of 5 m^3 per day.

If s_{max}, t_{50} and t_{75} are all less than the values shown in these tables, the borehole is likely to be successful.

If s_{max}, t_{50} and t_{75} are all much greater than the values in these tables, the borehole is unlikely to be successful.

If some are greater and some are less, then consider conducting a constant-rate test.

Bailer-test data form

Borehole name:	**Borehole location:**
Date of test:	**Name of person completing form:**
Rest-water level (m below datum):	**Start time of test:**
Period of pumping (should be 10 minutes):	**Number of bails removed:**

Time since bailing stopped (minutes)	Water level (m below datum)	Calculated drawdown (m)	Time since bailing stopped (minutes)	Water level (m below datum)	Calculated drawdown (m)	Time since bailing stopped (minutes)	Water level (m below datum)	Calculated drawdown (m)
0.25			8			20		
0.5			8.25			20.5		
0.75			8.5			21		
1			8.75			21.5		
1.25			9			22		
1.5			9.25			22.5		
1.75			9.5			23		
2			9.75			23.5		
2.25			10			24		
2.5			10.5			24.5		
2.75			11			25		
3			11.5			25.5		
3.25			12			26		
3.5			12.5			26.5		
3.75			13			27		
4			13.5			27.5		
4.25			14			28		
4.5			14.5			28.5		
4.75			15			29		
5			15.5			29.5		
5.25			16			30		
5.5			16.5					
5.75			17					
6			17.5					
6.25			18					
6.5			18.5					
6.75			19					
7			19.5					

Bailer-test data form

Borehole name:	**Borehole location:**
Date of test:	**Name of person completing form:**

Calculation procedure	
A = Total number of bails removed	
B = Volume of each bailer (litres)	
C = Total volume of water extracted (A × B) (litres)	
D = Length of bailing period (minutes)	
E = Average pumping rate for the test (C ÷ D) (litres per minute)	
s_{max} = Maximum drawdown (first drawdown after bailing stopped) (m)	
s_{50} = Half maximum drawdown (50% recovery) (s_{max} ÷ 2) (m)	
t_{50} = Time at which water level recovered to s_{50} (minutes since bailing stopped)	
s_{75} = Quarter maximum drawdown (75% recovery) (s_{max} ÷ 4) (m)	
t_{75} = Time at which water level recovered to s_{75} (minutes since bailing stopped)	
Borehole diameter (mm) Use drilled diameter if no screen and gravel pack installed. Calculate effective diameter if there is a gravel pack, in which case, if screen diameter is F and drilled diameter is G, an approximation of effective diameter would be: 0.3(G – F) + F	

For the appropriate pumping rate and borehole diameter, compare the calculated values of s_{max}, t_{50} and t_{75} with the values given in tables D.1 and D.2 on pp. 92-93.

Annexe G Checklist when supervising contractors

No.	Item to check	Notes
GENERAL		
1	**Certification:** Can the contractor provide evidence of technical qualifications and business registration?	
2	**Reputation:** Is there any reason to believe that the contractor has a reputation for unreliability or unsafe practices?	
3	**Health and safety:** Does the contractor provide appropriate safety equipment (hard hats, safety boots, etc.)?	
4	**Training:** Have all the crew employed by the contractor been properly trained to conduct pumping tests?	
5	**Maintenance:** Is all equipment maintained regularly, operated correctly, and kept in good condition?	
6	**Sanitation:** Does the contractor make sure that the test-pumping crew follow good hygiene procedures?	
7	**Cleanliness:** Is all equipment cleaned properly, especially after being used in contaminated water?	
8	**Leakage:** Is equipment provided (drip trays or absorbent mats) to collect drips and spillages?	
9	**Fuel storage:** Are fuel and other hazardous substances stored properly at a safe distance from the borehole?	
10	**Sub-contracting:** Has the contractor sub-contracted any aspect of the work? Is this acceptable?	
PREPARATIONS FOR THE TEST		
11	**Objectives:** Have clear objectives been set for the test? What information are you trying to gain from the test?	
12	**Background information:** Have you collected information on geology, the borehole, historical water levels, etc.?	
13	**Borehole identity:** Has the contractor confirmed that the correct borehole is being tested?	
14	**Type of test:** Is it clear what type of test, or sequence of tests, is going to be carried out?	
15	**Monitoring water levels:** Is the dipper in good condition and working properly? Do you need a reserve dipper?	
16	**Datum:** Has a local datum been identified and agreed for measuring all water levels?	
17	**Pumping rate:** Is there a suitable method in place for measuring the pumping rate? Is it calibrated?	
18	**Other monitoring:** What other parameters or water features need to be monitored?	
19	**Standard forms:** Are there sufficient standard forms available for recording the test data?	
20	**Other boreholes:** Are there any other boreholes in the vicinity that could influence the test if they are being pumped?	
21	**Access:** Is there access through the borehole head-plate for all monitoring equipment?	
22	**Water quality:** If applicable, is there a convenient point for taking water-quality samples?	
23	**Microbiology:** If applicable, can water samples be kept cool until analysed for microbiological parameters?	
24	**Power supply:** Is a suitable power supply available? How reliable is it?	
25	**Generator:** If a generator is being used, is sufficient fuel available for the duration of the pumping period?	

No.	Item to check	Notes
26	**Rising main:** Is the rising main fitted with a foot-valve? Can the rising main still be removed easily?	
27	**Valves:** Is there a valve in place that can be used to control the pumping rate?	
28	**Discharge:** Can the water be discharged without affecting the test (by recirculation)?	
29	**Use of water:** Have arrangements been made for the discharge water not to be wasted?	
30	**Equipment testing:** Has all the equipment been tested when in position? Is it working properly?	
31	**Pump-intake depth:** Has the pump intake been set well below the lowest expected water level during the test?	
32	**Contamination:** Is the borehole protected from dirty water running back into it during the test?	
33	**Public safety:** Have arrangements been made to prevent public access (especially by children) to working areas?	
34	**Rest-water level:** Has this been measured just before the test? Was the water level stable at the time?	
35	**Monitoring frequency:** Is it clear how frequently the water level and other parameters are going to be measured?	
STEP TEST		
36	**Number and the length of steps:** For a step test, have the number of the steps and length of each step been agreed?	
37	**Pumping rates:** Have target pumping rates for each step been agreed and practised before the test?	
38	**Interruptions:** Were there any interruptions to pumping during the steps? If so, why did they occur?	
CONSTANT-RATE TEST		
39	**Pumping rate:** Has a target pumping rate been agreed and practised before the test?	
40	**Constant rate:** Was the pumping rate maintained fairly constant throughout the pumping period?	
41	**Interruptions:** Were there any interruptions to pumping during the test? If so, why did they occur?	
RECOVERY TEST		
42	**Foot-valve and rising main:** Was the water level affected by the lack of a foot-valve or before the removal of the pump?	
AFTER THE TEST		
43	**Contamination:** Has the borehole been secured (foreign objects, animals, dirty water cannot enter)?	
44	**Data quality:** Are all the standard forms complete, with all the necessary information filled in?	
45	**Demobilization:** Are you satisfied that the test is complete and that all equipment can be demobilized?	
46	**Test analysis:** Did the contractor use appropriate methods to analyse the test data?	
47	**Long-term monitoring:** Has a plan been made for long-term monitoring of this borehole?	
48	**Access:** Has provision been made to ensure easy access for future monitoring?	
49	**Archiving:** Have the test data, records and any other notes all been copied and safely archived?	

Statements to be included in contractors' terms of reference

This table contains many of the questions from the checklist above, rephrased as statements that can be used in terms of reference or contract documents drawn up for test-pumping contractors. They will not all be applicable in every situation, so copy and paste as required.

GENERAL
Certification: Evidence of technical qualifications and business registration (such as copies of registration certificates) should be provided.
Health and safety: Appropriate safety equipment (such as hard hats and safety boots) must be provided for all test-pumping crew working on the site.
Training: All the crew employed by the contractor must have been properly trained in conducting pumping tests.
Maintenance: All equipment used in the tests should be kept in good condition, maintained regularly, and operated correctly.
Sanitation: Adequate sanitation facilities should be provided for the test-pumping crew, and the crew should follow good hygiene procedures during the test, to avoid contamination of the water supply.
Cleanliness: All equipment should be cleaned properly before it is used for test pumping, especially if it has previously been used in contaminated water.
Leakage: Appropriate equipment, such as drip trays or absorbent mats, should be provided to collect drips and spillages of fuel or other hazardous substances.
Fuel storage: Fuel and other hazardous substances must be stored properly at a safe distance from the borehole that is being tested and other water sources in the area.
Sub-contracting: The contractor must not sub-contract any aspect of the work without written permission.
PREPARATIONS FOR THE TEST(S)
Borehole identity: The contractor should confirm that the correct borehole is being tested, especially if there are several boreholes in the vicinity.
Monitoring water levels: Equipment used for monitoring water levels, such as dippers and pressure transducers, must be in good condition and working properly.

Datum: The local datum used for measuring all water levels must be clearly identified and recorded.
Pumping rate: The contractor should define what method is to be used for measuring the pumping rate and what procedures are to be put in place (such as calibration) to ensure that the measurements are accurate.
Standard forms: Whenever possible, test data should be recorded on standard forms, to facilitate record keeping and test analysis.
Water quality: If applicable, a convenient point for taking water-quality samples should be provided as part of the discharge arrangements for the test.
Microbiology: If samples are being taken for microbiological analysis, facilities should be provided to keep the samples at the correct temperature until they can be delivered to a laboratory (unless the analysis is being conducted with a field testing kit).
Generator: If a generator is being used, sufficient fuel must be provided for the planned duration of the pumping period, to ensure that there are no interruptions to pumping.
Rising main: If a recovery test is to be conducted, the rising main must be fitted with a foot-valve.
Valves: A suitable method of controlling the pumping rate, such as a valve, should be provided.
Discharge: The water from the test should be discharged at a safe distance from the borehole, so that it does not recirculate and affect the results of the test, and so that it does not cause flooding.
Use of water: If requested, arrangements should be made for the discharge water to be provided for local use rather than be wasted.
Equipment testing: All the equipment must be tested once it has been installed so as to make sure it is working properly.
Pump-intake depth: The pump intake should be set well below the lowest expected water level during the test.
Contamination: The borehole should be protected from dirty water running back into it during the test.
Public safety: Arrangements should be made to prevent public access (especially by children) to the work site.
Rest-water level: The rest-water level must be measured and recorded just before the test.

DURING THE TEST(S)
Length of test: The pumping should continue for the agreed length of time (including individual steps during a step test) unless the contractor is instructed otherwise by the test supervisor.
Pumping rates: The borehole must be pumped at or close to the agreed pumping rate (including individual steps during a step test) unless the contractor is instructed otherwise by the test supervisor.
Monitoring: Parameters such as the pumping rate and the water level must be measured at the agreed intervals unless the contractor is instructed otherwise by the test supervisor.
Interruptions: The contractor must inform the test supervisor of any interruptions to the pumping or monitoring, giving reasons for the interruptions and their duration.
AFTER THE TEST(S)
Contamination: The borehole must be secured, so that foreign objects, animals, or dirty water cannot enter.
Data quality: The standard forms should be completed neatly and legibly, with all the necessary information filled in, and handed over to the test supervisor.
Demobilization: The equipment and crew should be demobilized only when the test supervisor is satisfied that all testing has been completed properly.
Archiving: The test data, records and any other notes should be copied and safely archived.

MISSION

The International Committee of the Red Cross (ICRC) is an impartial, neutral and independent organization whose exclusively humanitarian mission is to protect the lives and dignity of victims of armed conflict and other situations of violence and to provide them with assistance. The ICRC also endeavours to prevent suffering by promoting and strengthening humanitarian law and universal humanitarian principles. Established in 1863, the ICRC is at the origin of the Geneva Conventions and the International Red Cross and Red Crescent Movement. It directs and coordinates the international activities conducted by the Movement in armed conflicts and other situations of violence.

ICRC

4033/002 02.2011 1000