The bailer test: a simple effective pumping test for assessing borehole success

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Abstract

A new pumping test method has been designed around the practical requirements of those working in rural water supply projects in developing countries. The bailer test needs only simple equipment and can be completed in under one hour. The test involves removing 20-50 bails from a borehole over a 10-minute period and then measuring the recovery. The test is analysed using large-diameter-well analysis (which accounts for well storage) and is appropriate for testing low productivity aquifers (transmissivity 0.1–10 m^2d^{-1}), where water levels are shallow (<20 m depth). The bailer test was developed and trialled in a rural water supply project in Nigeria where it was found to predict similar transmissivity to 5-hour constant rate tests ($r^2 = 0.9$). Analysis of the test was further simplified to provide guidelines for field staff such as community health workers. The likelihood of a borehole sustaining a handpump for 250 people can be indicated by measuring the maximum drawdown and time for 50% and 75% recovery from a bailer test and comparing to a simple table. This simplified test is now being used in this and other rural water supply projects, and has been modified to indicate whether a borehole can sustain higher yields for small-scale irrigation.

Keywords: Africa, Nigeria, hydraulic testing, water supply, groundwater development

Introduction

The pumping test is one of the most important techniques available to the hydrogeologist (Renard 2005). Properly carried out tests can give information ranging from the efficiency of a borehole to the aquifer properties (such as transmissivity, storativity, aquifer geometry) or the influence of overlying strata. Pumping tests are carried out routinely in developed countries – mainly to ’prove‘ the yield of a borehole before commissioning for supply, but also to understand the local hydraulics (Kruseman and deRidder 1990; Meier et al. 1998). The accumulation and analysis of such data can give important information on the regional variations in aquifer properties and help to constrain groundwater models (e.g. MacDonald and Allen 2001, Oden and Neimi 2006; Brunner et al. 2007).

Despite the many advantages of carrying out pumping tests on completed boreholes, they are not carried out routinely on community boreholes to be equipped with handpumps, particularly in sub-Saharan Africa. If a borehole produces any quantity of water it is generally assumed to be successful. There are several reasons for this: pressure to meet drilling targets; lack of appropriate equipment and techniques for testing relatively low yielding boreholes; and the scarcity of trained hydrogeologists working on rural water-supply projects. However, the high failure rate and poor sustainability of rural water-supply boreholes in much of the developing world, particularly in Africa, makes the information that pumping tests give increasingly important. Knowing the performance of a borehole when it is installed makes it easier to work out reasons for failure at a later date: falling water-levels, poor initial yield (making pump failure more common), or management and finance issues.

At first sight it may appear unnecessary to develop a new pumping test when so many different methods already exist. However, the needs of those involved in rural water-supply projects in sub-Saharan Africa, particularly those in low-permeability aquifers, are different to those in more developed countries. Based on the needs and experience of the staff and partners at WaterAid and UNICEF in West Africa, the following criteria were identified that a pumping test would ideally meet:

1. *Simple and rapid to carry out*. The test should be simple – not requiring sophisticated equipment or engineering prowess to conduct. Ideally, community members should be able to participate in the test. The test should be able to be completed within a few hours - the shorter the duration of test, the more likely it will be performed, since it puts less finance and time burdens on projects and communities.
2. *Cheap and robust equipment*. The equipment must be robust and where possible locally available and maintained.
3. *Appropriate level of information.* The test should be effective at indicating whether a borehole is likely to easily sustain a handpump. Additional information on aquifer properties, although useful for regional studies of hydrogeology, is of secondary importance.
4. *Effective.* The test must be effective for the low permeability environments found throughout much of sub-Saharan Africa (where transmissivity typically ranges over 0.1 to 10 m^2d^{-1}) and indicate whether a borehole will sustain the yield of a handpump, which generally has yields of between 0.1 and 0.3 $l\ s^{-1}$.
5. *Easy to analyse.* The tests should not rely on elaborate methods of analysis requiring computers or complex manipulation of data.

This paper proposes an appropriate pumping test (the bailer test) which meets the above criteria. The bailer test combines the speed and simplicity of the slug test, with the slow and easily measurable recovery of the constant-rate test.

The bailer test procedure

The bailer test was based loosely on similar tests undertaken as part of site investigations – but rarely interpreted quantitatively (Brandon 1986). A similar field method in shallow auger holes has been used successfully by irrigation engineers for many years (Ritzema 1994) to estimate soil permeability – although analysis is empirical and based on evidence from narrow, shallow boreholes. Other simplified pumping test methods have been designed specifically for use in developing countries (e.g. CIEH 1982, 1988), but these can require 5 hours of pumping, and still require a significant degree of technical knowledge. Sometimes yields from airlifting are used to estimate the success of a borehole, but these are highly unreliable (MacDonald et al. 2005)

The test developed here comprises removing water from a borehole for 10 minutes using a bailer, and then monitoring the recovery of the water-levels for about 30 minutes. The equipment is cheap and low technology. The most sophisticated equipment is the water-level recorder

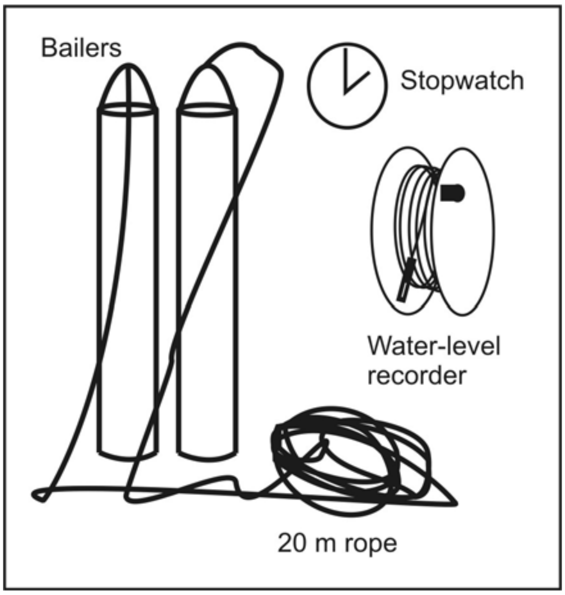

Figure 1 The equipment required for carrying out a bailer test. The bailer is made locally from a one-metre length of 75-mm diameter pipe.

(dipper), indispensable equipment for any groundwater studies. The test can be conducted successfully after minimal training and completed within an hour on most boreholes. Analysis of the data can be undertaken at three levels of complexity, varying from a quick 'rule of thumb' to a reliable estimate of the transmissivity of the aquifer.

The equipment required for carrying out the bailer test is shown in Figure 1 and a photograph of the test being carried out is shown in Figure 2. The bailer is a narrow bucket about one metre long, made to fit down the casing of the borehole (usually 75-mm diameter which gives a volume of 4.4 litres). The equipment and field procedure are discussed in detail in MacDonald et al. (2005). A summary of the procedure is given here.

1. The rest water-level is measured.
2. Bailer A is lowered down the borehole; as the full bail is removed the stopwatch is started. This is repeated using a second bailer (B) as the water in Bailer A is emptied. This procedure continues for ten minutes, during which time 20-50 bails should have been abstracted, depending on the depth to water-level.
3. After ten minutes bailing, the stopwatch is reset and water-level measured every 30 seconds for a further 30 minutes.

Before discussing the theoretical assumptions and limitations of the bailer test, it is worth noting some practical considerations:

1. The test will only be appropriate where the water-table is shallow, ideally less than 15 - 20 m. In case of deeper water-levels, it becomes difficult to remove bails at the rate required.
2. The test is designed for boreholes penetrating aquifers with transmissivity from 0.1 to 50 m^2d^{-1}. In more permeable aquifers, the drawdown is too small and the recovery too fast to be accurately recorded, or give an approximately steady pumping rate using bails. In aquifers

Figure 2 Community members carrying out a bailer test at Edumoga village, Oju, Nigeria.

with transmissivity less than 0.1 m^2d^{-1}, recovery can be too slow to measure within 30 minutes. However, despite not being able to estimate transmissivity, the test will show whether the borehole can sustain a handpump by the very fact that drawdown is too small to be recorded (high permeability) or recovery too slow (low permeability).

3. The test is designed for use in boreholes, not large-diameter-wells. Removing 40 bails in 10 minutes would not significantly alter the water-level within a large-diameter-well. Traditional large-diameter-well techniques and analysis would be more appropriate for use in large-diameter-wells (e.g. Barker and Herbert 1989; Mace 1999). However, a similar approach to the bailer test could be designed for large-diameter-well by using another pumping method, such as a suction pump.

Analysis of the bailer test

Designing a quick and practical test is only the first step towards developing a usable pumping test; success depends on the test being appropriately analysed and giving information relevant to the needs of the user. As a first step towards finding an appropriate analysis method several basic assumptions are made. The aquifer is assumed to be confined (or if unconfined, that the drawdown is less than about 10% of the aquifer thickness), homogeneous, isotropic and the abstraction rate constant over the duration of the test. Three main analysis types are possible: Theis Recovery analysis, slug test analysis using the Hvorslev (1951) method, and large-diameter-well analysis (Papadopulos and Cooper 1967). These are discussed in turn below.

Krusemann and deRidder (1990) and Herbert (1990) suggest that Theis Recovery analysis is not appropriate for short tests when transmissivity is low due to well storage effects. Through modelling, Herbert (1990) demonstrates that Theis Recovery will only give accurate estimates of transmissivity if the time after the start of recovery is greater than $25\, r_c^2 / T$, where r_c is the radius of the borehole casing (at the water table) and T is the transmissivity. For short tests in low permeability environments, water-levels would have fully recovered by the time Theis Recovery becomes valid.

For slug test analysis to be appropriate, the flow of water into the borehole during pumping must be negligible, so that the head change can be considered instantaneous. Butler (1997) gives an excellent account of the slug test procedure and analysis. Mace (1999) used slug test analysis to calculate transmissivity from a series of wells when withdrawal of the “slug” was not instantaneous. He found that reasonable results (within 10%) could be gained if $(t_p\ T)/ (4\ r^2) < 1$, where t_p is the duration of pumping and r is the radius of the borehole/well. Thus, in small diameter boreholes in low transmissivity aquifers, the non-instantaneous removal of slugs invalidates the use of slug test analysis.

The most promising technique for analysing bailer test data is large-diameter-well analysis. Based on the method of Papadopulos and Cooper (1967), large-diameter-well analysis takes into consideration water stored in the borehole (well storage) and therefore can effectively deal with the problems encountered by Theis Recovery and slug test analysis. It is most appropriate when the proportion of water taken from well storage during the test, λ, is less than 0.95 (Barker and Herbert 1989):

$$\lambda = \frac{\pi r_c^2 s_p}{Q t_p} \tag{1}$$

where r_c is the well/borehole radius; s_p, the drawdown at the end of pumping, Q the average pumping rate and t_p the period of pumping. Figure 3 shows the validity of the large-diameter-well analysis for standard borehole radii over the relevant range of transmissivity. It is apparent that large-diameter-well analysis is appropriate for the given pumping length and rate of the bailer test and over the radii and transmissivity values encountered in rural water-supply programmes in Africa.

In practice, large-diameter-well analysis can be conducted in a variety of ways: curve matching, nomograms and fitting data using a computer model. Where the computers are available, an easy method is use of the code BGSPT (Barker and Macdonald 2000). BGSPT is a freely available computer programme which numerically solves the generalised well function developed by Barker (1985, 1988) for large-diameter-wells in fractured aquifers and incorporates many other well functions as special cases (e.g. that of Papadopulos and Cooper (1967)). It evaluates the solution using numerical Laplace transform inversion and achieves a fit to data by least squares through a series of iterations. The software can be used for both inverse and forward modelling (i.e. to simulate curves, and to analyse data). Where computers are not readily available, curve matching or nomograms can be used. Curve matching (as given, for example, by Kruseman and deRidder (1990) for confined aquifers and Boulton and Streltsova (1976) for unconfined aquifers) is complex to undertake, requiring large families of types curves. An appropriate analysis method for use where computers are not easily available is the nomogram method presented by Barker and Herbert (1989). The data required are: the drawdown at the end of pumping, the time

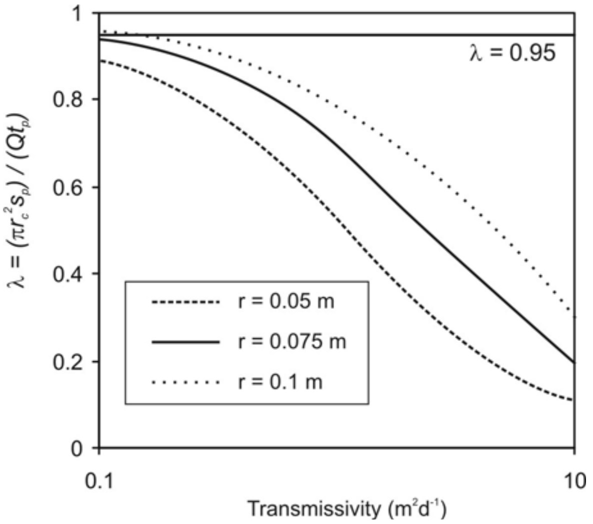

Figure 3 λ value $\pi r_c^2 s_p / Q t_p$ calculated for various values of transmissivity and borehole radius, r, (using BGSPT) where Q = 25 m^{3}d^{-1} and t_p is 10 minutes. According to Barker and Herbert (1989), large-diameter-well analysis should be appropriate when λ is less than 0.95.

for 25%, 50% and 75% recovery, borehole radius, pumping rate and length of pumping. These data are inserted into equations and nomograms used to estimate transmissivity.

For the remainder of this paper, large-diameter-well analysis using BGSPT software is used to perform all simulations and analysis.

Validity of test

Constant pumping rate

The most obvious assumption of the large-diameter-well analysis that the bailer test does not satisfy is the requirement for the pumping rate to be constant. In the bailer test, abstraction is by the removal of 20-50 bails over 10 minutes (approximately 0.1 – 0.3 ls^{-1}); the bails are not evenly spaced but can vary as personnel become tired and the drawdown increases. The effect of both these deviations (i.e. pulsed and reducing abstraction) from the ideal assumptions was explored by forward modelling using large-diameter-well analysis with BGSPT, which can take into account well storage and also variations in pumping rate.

Figure 4 shows the recovery from simulating abstracting 174 litres in 10 minutes from 40 equal and identically spaced bails for a variety of transmissivity values. The simulated recovery from abstracting the same quantity of water from constant rate pumping is shown for comparison. The recovery curves are practically identical. Re-analysing the simulated bailer data with large-diameter-well analysis assuming a constant pumping rate gives transmissivity values that are within 1% of the true transmissivity. Therefore abstracting using 40 bails, instead of a constant pumping rate has no significant effect on the analysis.

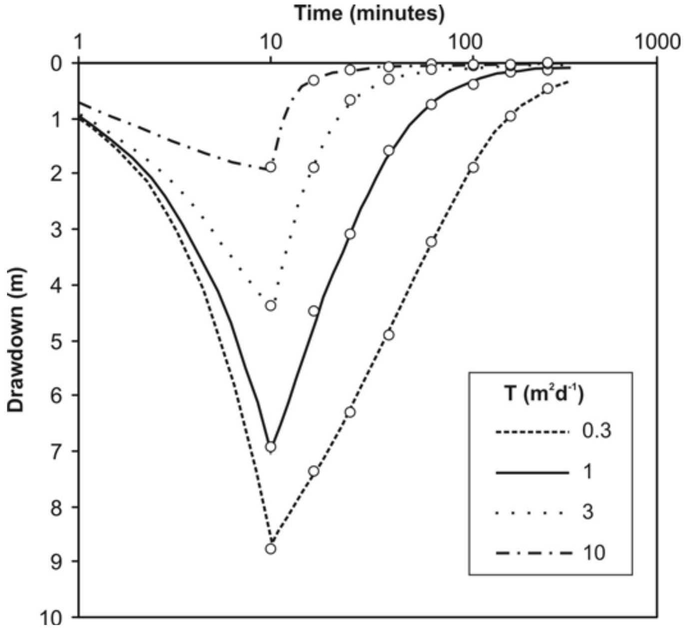

Figure 4 Drawdown and recovery from a simulated constant rate pumping test (lines) compared to a simulated bailer test (circles) abstracting an equivalent volume of water in the same time period. Drawdowns are modelled for a confined aquifer with S = 0.001 and borehole radius 0.075 m; 174 litres are abstracted over a 10-minute period. Simulations are undertaken with BGSPT, taking into account well storage.

As discussed above, a particular problem with the bailer test is that the rate of bailing can decrease with time, as people get tired. To examine what effect this would have on estimating transmissivity, five scenarios were modelled using BGSPT (and thus taking into account well storage) each with an average pumping rate, Q, of 25 m^3d^{-1}:

1. constant pumping rate;
2. pumping rate reducing linearly from 1.5Q to 0.5Q in 40 steps;
3. pumping rate reducing linearly from 2Q to 0 in 40 steps;
4. 2Q for first half of test, 0 for second half;
5. 0 for first half of test, 2Q for second half.

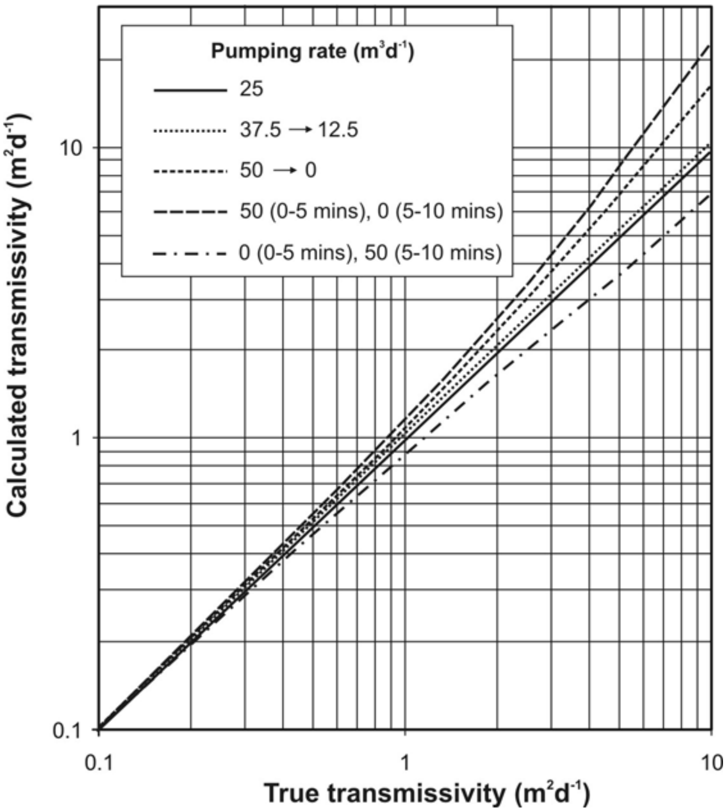

Figure 5. Transmissivity calculated from a bailer test (Q = 25 m^{3}d^{-1}, t_p = 10 minutes) under various pumping regimes, plotted against true transmissivity. For transmissivity up to 10 m^{2}d^{-1} errors are less than 5% for changes in pumping rate up to 65%.

Recovery data were simulated for the five scenarios for a borehole with radius of 0.075 m in a confined aquifer with storage coefficient 0.001 over a range of transmissivity values using BGSPT. The recovery data were then re-analysed with large-diameter-well analysis assuming a constant pumping rate of 25 m^{3}d^{-1} throughout the test.

Figure 5 indicates that the test is relatively insensitive to moderate changes in pumping rate, particularly if the transmissivity is less than about 1 m^{2}d^{-1}. If the pumping rate declines by up to 65% (scenario 2) then the error calculating transmissivity by assuming a constant (average) pumping rate is approximately 5% for true transmissivity as high as 10 m^{2}d^{-1}. For scenario 3, where the pumping rate reduces to zero, the errors become significant at transmissivity values above 1 m^{2}d^{-1} (25% at 3 m^{2}d^{-1} and 65% at 10 m^{2}d^{-1}). Scenarios 4 and 5 give two extremes: all the abstraction in one half of the test. Under these extreme scenarios, errors are below 15% for transmissivity less than 1 m^2d^{-1}, but can rise to 40% for transmissivity of 3 m^2d^{-1} and over 100% at transmissivity above 10 m^2d^{-1}.

Under normal circumstances, the pumping rate of the bailer test should not need to vary by more than 50% (i.e. reducing by half the number of bails in one minute). By reducing the number of bails abstracted during the first half of the test when water-levels are shallow, an abstraction rate that does not vary by more than 50% is easily achievable. Bailer tests carried out in Nigeria usually had a pumping rate of about 5 bails a minute for the first half of the test, reducing to 3 bails a minute by the end of the test. This variation would cause an error of less than 5% in the measured transmissivity, assuming the average abstraction is accurately known (easily achieved by counting bails and timing the period of bailing).

Confined assumption

The bailer test has been primarily designed for a simple rapid test in low-yielding environments, such as crystalline basement or low permeability sediments. Where available, groundwater is often found at the base of the weathered zone within semi-confined fractures from 10 to 30 m below ground surface; rest water-levels often rise to about 5 m below ground surface (see Wright and Burgess 1992, Chilton and Foster 1995), indicating that groundwater is semi-confined within fractures. Since the bailer test is short and drawdown small, the aquifer conditions are unlikely to change significantly during the test. However, even in unconfined situations, Papadopulos and Cooper (1967) large-diameter-well analysis can be valid if drawdowns within the aquifer are kept small to keep the flow in the aquifer approximately horizontal and thus to minimise vertical flow.

The effect of vertical flow (e.g. leaky conditions) on the estimation of transmissivity from the 10-minute bailer test was modelled using BGSPT. A leaky situation was modelled with the vertical permeability of the aquifer equal to the horizontal permeability (the worst case scenario). The transmissivity of the aquifer used in the simulation was 1 m^2d^{-1} and storage coefficient 0.001. A bailer test was then simulated under these leaky conditions, and the results reanalysed using a standard large-diameter-well analysis (using BGSPT), that did not account for leakage. The modelling predicted that the estimation of transmissivity would be affected by less than 1% by the presence of vertical flow over the short 10-minute duration of the test. Therefore, the 10-minute bailer test can be reliably used in unconfined and leaky conditions

Interpreting test results

It is generally agreed that the analysis of data from single well tests can estimate transmissivity with confidence, and at a worst case in dual porosity and heterogeneous environments, transmissivity may be overestimated by a factor of 2 (e.g. Black 1985; Beckie and Harvey 2002 Sanchez-Vila et al. 1999, Halford et al. 2006). However, evaluating transmissivity has little immediate benefit to those responsible for making decisions about whether a borehole is successful or not. The knowledge has to be applied and translated into an estimate of how productive a borehole will be and whether it will sustain a handpump.

By making some generalisations and carrying out simple modelling, a rough guide can be given to show the significance of transmissivity values. To model the significance of transmissivity values, various data are required: the average pumping rate, the maximum allowable drawdown, the rough borehole diameter, the length of the dry season and an estimate of the storage coefficient of the aquifer.

Average pumping rate. Most organisations involved in rural water-supply suggest that community boreholes or wells should supply no more than 250 people. Twenty-five litres per day per person is a figure often used as a minimum – currently this is higher than used in much of sub-Saharan Africa. These two figures give an average daily abstraction of 6.25 m^3d^{-1}. Assuming abstraction over a 12-hour period, this gives a pumping rate of 0.145 ls^{-1} for 12 hours a day.

Maximum allowable drawdown. Boreholes throughout rural Africa are often shallow, 30-50 m. Rest water-levels are generally less than 10 m. Most research into groundwater occurrence in low permeability crystalline basement indicates that the major inflows are at the *base* of the weathered zone (e.g. Chilton and Foster 1995). With this in mind, a maximum permissible drawdown of 15 m is not unreasonable. If this drawdown is exceeded, the pump will stop operating until water-levels recover. Where the weathered zone is thin, 15 m may be an overestimation of the drawdown permissible. In these situations, large diameter wells are likely to be more appropriate.

The length of the dry season. If the shallow aquifer is assumed to recharge during the wet season, then effective unsteady state aquifer behaviour (and groundwater depletion) starts at the end of the rains and continues until the rains start the next year. For much of Africa the dry season last for 6 months (180 days).

Borehole diameter. Several borehole diameters are used in rural water-supply programmes: boreholes are often drilled at approximately 160 mm (6 - 7-inch) and completed with 100 or 125 mm screen. More rarely, boreholes are drilled at 200 mm with 150 mm screen. If a formation stabiliser is used, then the effective diameter will be the screened diameter plus the pore space in the annulus. Changes in borehole diameter were found to affect drawdown by only a fraction of a millimetre after 180 days, therefore modelling was continued with a diameter of 125 mm.

The storage coefficient. Estimates of storage coefficient can vary significantly for poorly permeable rocks. For weathered crystalline basement aquifers a long-term storage coefficient of 0.01 is thought reasonable (Wright and Burgess1992). However, for fractured aquifers, specific yield may be much lower, 10^{-4}, for boreholes that contain sufficient water to test pump.

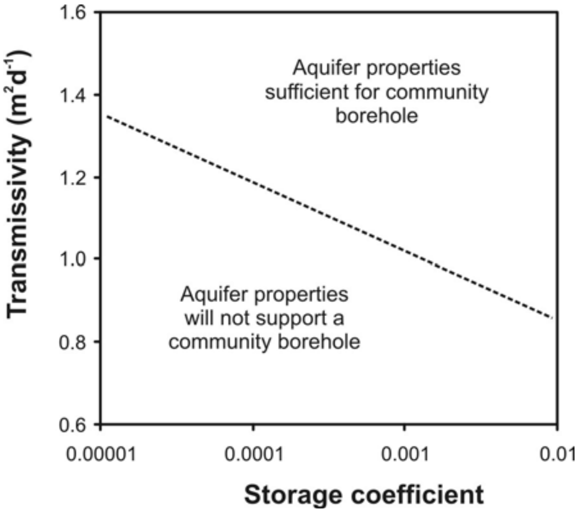

Figure 6 Aquifer properties required to sustain a community borehole for 250 people. Modelling was undertaken using BGSPT. (Yield of 0.145 ls^{-1}, 12 hours a day for 6 months. Criteria for failure was drawdown of greater than 15 m).

These criteria were modelled with large-diameter-well analysis (accounting for well storage) using BGSPT. Pumping was taken as 0.145 ls^{-1} for 12 hours and 0 for 12 hours for a total of 180 days. The results of the modelling are shown in Figure 6. The drawdown does not have a high dependency on the storage coefficient. A transmissivity of 1 m^2d^{-1} would be adequate for a hand-pump serving 250 people if the storage coefficient is greater than 0.001. Where the storage is less, a slightly greater transmissivity (1.35 m^2d^{-1}) would be required.

Data from Nigeria

The effectiveness of the bailer test was tested during a rural water-supply project in the local government areas of Oju and Obi, south-eastern Nigeria (Figure 7). The people of Oju and Obi (approximately 400,000) experience severe water shortages during the annual dry season when unprotected ponds, seepages and hollows are the primary sources of domestic water. These sources become less reliable towards the end of the dry season and many fail altogether. Consequently, women and children have to walk long distances (often greater than 10 km) to get limited supplies of generally poor quality water.

Figure 7 **The location of the study area: Oju and Obi local government areas..**

The area is underlain by low permeability sediments: Cretaceous aged mudstones with minor sandstones, siltstone and limestone (the Asu River Group, the Eze-Aku Group and the Awgu Shale) and occasional dolerite intrusions. This environment proved particularly challenging, and standard approaches in the area to develop sustainable groundwater supplies had failed However, 3 years of research by the British Geological Survey demonstrated that sustainable community water supplies could be developed within the mudstones if boreholes were sited with care (MacDonald et al. 2001; MacDonald et al. 2005). Where present, groundwater is found in fractures in the upper 40 m of the mudstone, and the degree of fracturing is related to clay

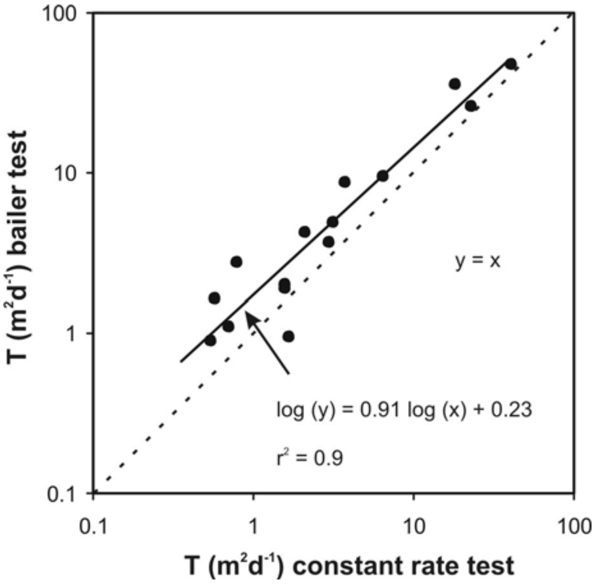

Figure 8 Comparison between transmissivity calculated from a bailer test and a longer constant rate test for a series of boreholes in Oju and Obi.

mineralogy and very low grade metamorphism. The knowledge and tools developed during this investigation have been incorporated by local government and the NGO WaterAid to develop a successful community water-supply project in the area (Davies and MacDonald 1999).

To examine the effectiveness of the bailer test, fifteen boreholes were chosen covering a range of yields. The boreholes were constructed between 15 and 50 m deep, were drilled at 150-mm diameter and completed at 125 mm, with no gravel pack. Bailer tests were undertaken in each borehole and analysed using BGSPT. Five-hour constant-rate tests were also carried out in the boreholes and the recovery data analysed using the Theis Recovery method (Kruseman and de Ridder 1990). The data are plotted on Figure 8.

The bailer test accurately determines transmissivity calculated from the five-hour test with a correlation r^2 of 0.9. Therefore, for these examples in Nigeria, the bailer test gave comparable data to that calculated from the much longer (costlier) and more cumbersome constant rate recovery test. The bailer test gives slightly higher estimates of transmissivity than the longer rate

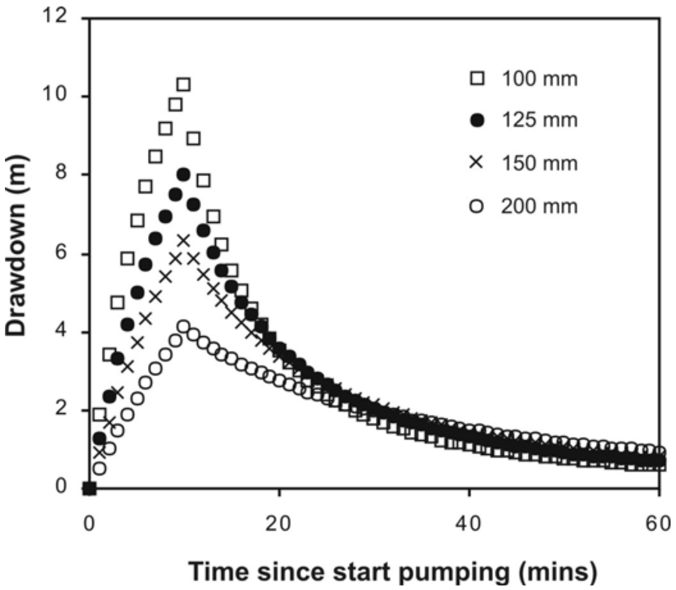

Figure 9 Simulated drawdown and recovery using BGST, accounting for well storage, for bailer tests in boreholes with diameter 100 – 200 mm. $Q = 25$ m^{3}d^{-1}; $t_p = 10$ minutes, $S = 0.001$ and $T = 0.85$ m^{2}d^{-1}.

test. These differences become more significant where the transmissivity is less than approximately 1 m^{2}d^{-1}, the borderline for a sustainable borehole

Further simplification

So far this paper has described the development of the simple bailer test and shown its effectiveness. However, the analysis of the test is still a little more complex than desired, requiring either the use of nomograms (Barker and Herbert 1989) or a computer code (BGSPT). By making several generalisations and undertaking a little more modelling it is possible to simplify the analysis. As described in the introduction, the need for pumping tests in rural water-supply boreholes in Africa is to answer the question “can this borehole sustain a handpump ?” A rule of thumb for the bailer test answers this question: yes, no or maybe.

Figure 6 shows transmissivity and storage coefficient values that produce an acceptable drawdown at the peak of the dry season for a borehole supplying 250 people. These aquifer properties can be used to simulate expected drawdown and recovery rates for a bailer test. Using drawdown and recovery rates (rather than transmissivity) to give guidelines on borehole success adds another layer of uncertainty to the interpretation. Borehole radius (i.e. well storage) and pumping rate also affect drawdown and recovery. As discussed previously, the short duration of the test and low permeability mean that borehole storage has a high influence on observed drawdown and recovery (Figure 9). Therefore to have effective guidelines for borehole success, the borehole radius and abstraction rate must be accounted for.

Drawdown and recovery curves were simulated for various borehole diameters and pumping rates with aquifer parameters which should be sufficient to sustain a handpump throughout a six month dry season. The length of the test was fixed as 10 minutes. Maximum drawdown, and the time for 25%, 50% and 75% recovery were recorded in Table 1. In all cases 25% recovery occurs very quickly and is not particularly diagnostic, particularly if water-level measurements are only taken every half minute. Maximum drawdown, 50% and 75% recovery, however, are easily measured within one hour and are diagnostic of aquifer conditions.

Table 1 Simulated maximum drawdown and recovery times (in minutes) for a 10-minute bailer test undertaken in various diameter boreholes at different effective pumping rates (using BGSPT accounting for well storage).

	Pumping rate →	**10 m^3d^{-1}**		**15 m^3d^{-1}**		**20 m^3d^{-1}**		**25 m^3d^{-1}**		**30 m^3d^{-1}**	
Borehole diameter		S1*	S2**	S1*	S2**	S1*	S2**	S1*	S2**	S1*	S2**
100 mm	Max drawdown (m)	4.1	5.0	6.1	7.6	8.1	10.1	10.2	12.6	12.2	15.1
	25% recovery (mins)	2.2	2.8	2.2	2.8	2.2	2.8	2.2	2.8	2.2	2.8
	50% recovery (mins)	5.9	7.0	5.9	7.0	5.9	7.0	5.9	7.0	5.9	7.0
	75% recovery (mins)	14.4	15.1	14.4	15.1	14.4	15.1	14.4	15.1	14.4	15.1
125 mm	Max drawdown (m)	3.2	3.8	4.7	5.7	6.3	7.6	7.9	9.5	9.5	11.4
	25% recovery (mins)	3.1	4.1	3.1	4.1	3.1	4.1	3.1	4.1	3.1	4.1
	50% recovery (mins)	8.6	10.5	8.6	10.5	8.6	10.5	8.6	10.5	8.6	10.5
	75% recovery (mins)	20.9	22.8	20.9	22.8	20.9	22.8	20.9	22.8	20.9	22.8
150 mm	Max drawdown (m)	2.5	2.9	3.7	4.4	5.0	5.8	6.2	7.3	7.4	8.7
	25% recovery (mins)	4.2	5.8	4.2	5.8	4.2	5.8	4.2	5.8	4.2	5.8
	50% recovery (mins)	11.7	14.8	11.7	14.8	11.7	14.8	11.7	14.8	11.7	14.8
	75% recovery (mins)	28.3	32.2	28.3	32.2	28.3	32.2	28.3	32.2	28.3	32.2
200 mm	Max drawdown (m)	1.6	1.8	2.4	2.7	3.2	3.6	4.0	4.0	4.82	5.5
	25% recovery (mins)	6.9	10.0	6.9	10.0	6.9	10.0	6.9	10.0	6.9	10.0
	50% recovery (mins)	19.2	25.6	19.2	25.6	19.2	25.6	19.2	25.6	19.2	25.6
	75% recovery (mins)	46.8	55.9	46.8	55.9	46.8	55.9	46.8	55.9	46.8	55.9

*S1 is simulation for aquifer parameters T = 0.85 m^2d^{-1} and S = 0.01

**S2 is simulation for aquifer parameters T = 1.35 m^2d^{-1} and S = 0.00001

Table 2 Guidelines for success of rural water-supply boreholes using the 10-minute bailer test. If the maximum drawdown and time for 50% and 75% recovery are less than that quoted here, then the borehole is likley to be successful.

	Pumping rate →	**10 m^3d^{-1}**	**15 m^3d^{-1}**	**20 m^3d^{-1}**	**25 m^3d^{-1}**	**30 m^3d^{-1}**
Borehole diameter	(Number of standard bails)*	(16)	(24)	(32)	(40)	(48)
100 mm	Max drawdown (m)	3.5	5.3	7.1	8.8	10.6
	time for 50% recovery (mins)	6	6	6	6	6
	time for 75% recovery (mins)	14	14	14	14	14
125 mm	Max drawdown (m)	2.9	4.3	5.7	7.1	8.5
	time for 50% recovery (mins)	9	9	9	9	9
	time for 75% recovery (mins)	21	21	21	21	21
150 mm	Max drawdown (m)	2.3	3.4	4.6	5.7	6.9
	time for 50% recovery (mins)	12	12	12	12	12
	time for 75% recovery (mins)	28	28	28	28	28
200 mm	Max drawdown (m)	1.5	2.3	3.1	3.8	4.6
	time for 50% recovery (mins)	19	19	19	19	19
	time for 75% recovery (mins)	46	47	47	47	47

*standard bailer is 4.4 litres (1-m long 75-mm pipe)

Certain rationalisations can be made to produce simpler guidelines (Table 2). To minimise the chance of a borehole being wrongly diagnosed as successful, some contingency is built in to the standards: (1) the fastest simulated recovery times from Table 1 are taken for each borehole diameter; and (2) the maximum drawdown shown in Table 2 is actually the drawdown after 1 minute of recovery (since the drawdown is unlikely to be able to be taken at the exact time pumping stops – but would generally be able to be measured within 1 minute). Having all three measurements (maximum drawdown and time for 50% and 75% recovery) is a useful check against mistakes. If the borehole diameter has been underestimated then the test may indicate a 'pass' for drawdown, but 'failure' on recovery. If the diameter has been overestimated, then the test may indicate a 'failure' on drawdown, but 'pass' for recovery. In both cases such results would indicate that a longer test which is less susceptible to borehole-diameter effects should be undertaken. In practice, the borehole diameter should be estimated by taking into account the drilled borehole diameter, the thickness and the porosity of the gravel pack, and the diameter of the screen: diameter = porosity of gravel pack × (drilled diameter – casing diameter) + casing diameter (see MacDonald et al. 2005).

Table 3 Bailer test results for Oju and Obi. Transmissivity (T) estimates for the boreholes (by constant rate test, or numerical analysis of bailer test) are given for comparison

Borehole	*diameter*	*p-rate*[a]	*max dd*[b]	$t_{50\%}$	$t_{75\%}$	*bailer test scores*				*T*
	(mm)	m^3d^{-1}	(m)	*(mins)*	*(mins)*	*max dd*	$t_{50\%}$	$t_{57\%}$	*overall*	m^2d^{-1}
BGS1	125	26.4	7.1	33	63	fail	fail	fail	fail	0.27
BGS2b	150	27.6	2.1	3.5	8.5	pass	pass	pass	pass	4.0
BGS4	150	21.6	2.5	16	40	pass	fail	fail	retest	0.7
BGS6	150	25.9	0.45	3	6	pass	pass	pass	pass	18.5
BGS12	150	25.1	3.1	7.5	16	pass	pass	pass	pass	1.1
BGS13	150	27.6	11	75	170	fail	fail	fail	fail	0.14
BGS15	150	23.3	2.15	8.5	21	pass	pass	pass	pass	1.6
BGS16	150	16.4	1.3	8	16	pass	pass	pass	pass	2.1
BGS17	150	25.1	2.0	8	23	pass	pass	pass	pass	1.4
BGS19	150	25.9	1.0	2.5	7	pass	pass	pass	pass	5.0
BGS20	150	39.7	0.13	7		pass	pass	pass	pass	27
BGS21	150	27.6	1.4	6	15	pass	pass	pass	pass	4.0
BGS26	150	12.1	2.75	193	193	fail	fail	fail	fail	0.024
BGS27	150	13.1	4.0	93	215	fail	fail	fail	fail	0.08
BGS30	150	26.8	4.7	63	113	pass	fail	fail	fail	0.36
BGS33	150	30.2	0.02			pass			pass	51
BGS34	150	25.9	0.86	2.5	10	pass	pass	pass	pass	6.5
BGS35	150	25.9	0.35	2.5	12	pass	pass	pass	pass	23
BGS37	150	19.9	2.8	5	17	pass	pass	pass	pass	0.70
BGS40	150	11.2	9.0	38	93	fail	fail	fail	fail	0.15
BGS41	150	19.9	4.1	51		pass	fail	fail	retest	0.25
BGS42	150	25.1	3.6	8.5	15	pass	pass	pass	pass	0.80
BGS44	150	24.2	6.5	26	45	fail	fail	fail	fail	0.10
BER2	125	20.7	16.5			fail			fail	<0.01

[a] p-rate is pumping rate
[b] dd is drawdown

These criteria were tested against a further 24 bailer tests undertaken in Oju and Obi where some other longer pumping test had been undertaken (Table 3). The bailer test identifies success or failure in all but two of the tests. These two borderline cases (BGS37 and BGS42) were assigned passes when a longer test indicated transmissivity of 0.8 m^2d^{-1}, just below the pass rate. The longer tests showed breakaway drawdown and recovery curves indicated a reduction of transmissivity as the cone of depression extends. In both cases, numerical analysis of the bailer test gave transmissivity greater than 1 m^2d^{-1}. Unfortunately, breakaway curves will not be detected with such short tests, but as discussed above, it is better than undertaking no test at all.

Currently, the bailer test is being used by WaterAid and local government staff in Nigeria to good effect. It is being carried out as a check against the claims of contract drillers that boreholes are successful. Community members are helping to carry out the test.

Conclusions

1. A short bailer test has been designed around the practical requirements of rural water-supply workers. The test requires simple equipment, and can be completed in one hour.
2. Since the test is short and permeability generally low, the data are best analysed using large-diameter-well analysis which allows for well storage. Transmissivity can be calculated using computer software (e.g. BGSPT), curve matching or nomograms.
3. ’Pumping’ using bails instead of constant rate has negligible effect on analysis.
4. Declining yields during the test (due to deeper water-levels and pumpers’ fatigue) only becomes significant (more than 5%) if the pumping rate declines by more than 65% during the test.
5. The test is designed for confined or semi-confined conditions, which are generally met over the short duration of the test.
6. For use in rural water-supply programmes with boreholes of 100 – 200 mm diameter supplied with hand pumps, transmissivity of approximately than 1 m^2d^{-1} indicates a successful borehole (specifically 0.85 m^2d^{-1} for $S = 0.01$; 1.35 m^2d^{-1} for $S = 10^{-5}$).
7. For a set of 15 boreholes in Nigeria, bailer tests were found to predict similar transmissivity to a five-hour constant rate test ($r^2 = 0.9$)
8. The test has been further simplified to indicate ‘yes/no/maybe’ for the borehole sustaining the yield of a hand-pump by measuring the maximum drawdown and time for 50% and 75% recovery.

In summary, the test is theoretically sound for low permeability environments, and could be widely applied for testing and proving the ‘success’ of low yielding rural water-supply boreholes. The test is also being used to estimate the success of higher yielding boreholes for small scale irrigation (MacDonald et al. 2005).

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