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Borehole Sustainability in Rural Africa: An analysis of routine field data

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Handpump-equipped boreholes are one of the most common water supply technologies adopted in rural Africa, but often demonstrate low levels of sustainability. In addition to operational problems with the pump, the borehole itself may cease to provide adequate quantities of safe drinking water only a short time after construction. This can have a significant negative impact on poor rural communities, particularly in the dry season when alternative water sources are scarce. A study of 302 boreholes in Ghana aimed to investigate rapid-onset borehole failure in relation to field data typically available following drilling and development. The study showed that the likelihood of borehole failure increased by a factor of six when drilling occurred during the wet season, and discovered a strong correlation between monthly precipitation and respective failure rates for boreholes drilled in each month. The potential for borehole failure also increased significantly when the initial yield was below the guideline value of 10 l/min. There was no indication, however, that a higher guideline value would be a cost-effective measure to reduce failure rates.

Introduction

Groundwater provides potable water to an estimated 1.5 billion people worldwide daily (DFID, 2001) and has proved the most reliable resource for meeting rural water demand in sub-Saharan Africa (MacDonald & Davies, 2002). Boreholes equipped with handpumps are a common technology adopted by poor rural communities, and there are currently approximately 250,000 handpumps in Africa (HTN, 2003). In 1994 it was estimated that 40-50% of handpumps in sub-Saharan Africa were not working (Diwi Consult & BIDR, 1994). This is backed up by more recent data from Uganda (DWD, 2002) and South Africa (Hazelton, 2000), which indicate similar operational failure rates. An evaluation in Mali in 1997 found 90% of pumps inoperable just one year after installation (World Bank, 1997). The primary reason for these high failure rates, and hence low sustainability, is insufficient attention to operation and maintenance of the pump (Harvey & Reed, 2004). This borehole itself, however, is sometimes the source of the problem. This study aims to investigate cases in which it is the borehole, rather than the pump, that has failed.

The term borehole failure as used here refers to a situation in which a borehole which is deemed 'successful' at the time of drilling subsequently fails to deliver a sufficient yield of safe water throughout the year. This does not necessarily refer to the structural failure of the borehole itself, but may occur due to a number of reasons, including depletion of groundwater levels in weathered aquifers and insufficient recharge of fractured aquifers resulting in dry boreholes. Failure may also occur as a result of: a reduction in yield; plugging of the formation around the well screen by fine particles; sand pumping due to siltation, incrustation or corrosion of casing and screens; and structural collapse of casing and screens, often as a result of corrosion due to low-pH (acidic) waters (Driscoll, 1995). Over abstraction of water from the aquifer, and the ingress of pollutants may also result in borehole failure. Boreholes which are ephemeral in nature due to seasonal fluctuations in yield and water level, are also classified as failures, since although water was available directly following drilling it is not available on a continuous basis.

Most rural water supply boreholes in Africa are drilled by private contractors or Non-Governmental Organisations (NGOs). In general, operating staff have limited technical knowledge and equipment, and often lack basic knowledge regarding the hydrogeological conditions within which they are working. There is also often a lack of effective Government regulation or supervision. Consequently, the quality of workmanship varies considerably, as does the ability to identify, predict and mitigate against possible borehole failure.

This paper is based on research conducted in Ghana in a project area covering parts of Eastern, Ashanti and Brong Ahafo regions, which for the purposes of this study will be known as the Greater Afram Plains (GAP). The study focused on boreholes drilled by World Vision, Ghana between October 1995 and March 2003 under phase III of the Ghana Rural Water Project (GRWP). The research considered 'rapid-onset' borehole failure, or boreholes that fail within seven years of drilling. The focus on boreholes that fail within a few years of construction was based on the crucial need to minimise such occurrences in the interests of efficiency and effectiveness. The study does not preclude the need to address longer-term borehole failure, and findings are likely to remain relevant to both categories.

Rapid-onset borehole failure may have a significant negative impact on members of the user community, who have contributed financially to the construction of the water point and are often trained to ameliorate mechanical problems with the handpump, but have no capacity to resolve borehole problems. Negative effects are felt most strongly during the dry season when alternative water sources are most scarce, and yet, due to lowering groundwater levels, it is at these times that boreholes are most likely to dry up.

Research objective

The study aimed to analyse data routinely collected during borehole drilling and development in order to determine the relationship, if any, between each data variable and subsequent failure of boreholes, and so determine whether these data can be used to predict or mitigate against failure. The focus was on practical field data, as collected and recorded by drilling teams, rather than specialist hydrogeological monitoring data. The rationale behind the selection of these variables was based simply on the likelihood of availability of such data. This data links with the overall objective of identifying existing field practice(s) that may have a detrimental affect on borehole sustainability, in order to recommend any appropriate adjustments to field procedures.

Borehole ‘success’

One of the main problems faced in addressing borehole failure is that there is often no clear definition of borehole success at the drilling stage. According to senior staff of GRWP a borehole should only have been deemed successful if at the time of drilling the measured ‘yield’ was at least 10 litres per minute (l/min). Borehole ‘yield’ can be loosely defined as the maximum rate at which a borehole can be pumped without lowering the water level in the borehole below the pump intake. It is important to note that this is not the same as the ‘safe’ or ‘sustainable’ yield of an aquifer which is an essentially subjective concept (Foster *et al.*, 2000).

The borehole yields recorded by GRWP drilling teams were estimated during a 6-hour constant rate pumping test. The yield was determined by the maximum pumping rate reached within the permitted drawdown for the borehole and handpump. Despite the guideline figure of 10 l/min, in examining borehole records it was noted that in some cases boreholes with measured yields of as low as 7 l/min were classed as ‘successful’ and were subsequently equipped with handpumps. Consequently all drilled boreholes were classified as either successful or unsuccessful, or ‘wet’ or ‘dry’, largely at the discretion of the field supervisor. Where there was no water in the borehole at all, or where there was a very high yield, this task became easy.

The hydrogeology of the GAP is typified by Palaeozoic consolidated sedimentary rocks, locally referred to as the Voltaian Formation. These consist mainly of sandstones, shales, arkoses, mudstones, laterites and limestones (Gyau-Boakye & Dapaah-Siakwan, 1999). The Voltaian formation has little or no primary porosity, hence groundwater occurrence is associated with the development of secondary porosity resulting from jointing, shearing, fracturing and weathering. This has consequently given rise to two main types of aquifer, the weathered zone and the fractured zone aquifers, both of which are found in the GAP. There is no clear demarcation between aquifer types, but where water is held in fracture zones, borehole siting is, in general, a significantly more arduous task than where it is contained in the weathered zone (World Vision, 2003).

All study boreholes were sited by GRWP hydrogeologists. Geophysical surveying methods (electromagnetic EM34 and resistivity) were used for siting in approximately one third of cases. The overall ratio of wet-to-dry boreholes for the five selected districts of the GAP was as follows:

• Wet boreholes drilled:	492
• Dry boreholes drilled:	303
• Overall success rate:	62%

A point of interest is that the overall drilling success rate for Phase I and Phase II of GRWP (1985-1995) in the GAP was 55%, while this rose to 62% for Phase III with the introduction of geophysics for the more difficult sites. Drilling success rates are broken down by district in Figure 1. As can be seen from the graph the success rate in each of the five districts varied from 56% to 68%. These success rates will be revisited later in this paper in relation to subsequent borehole failures.

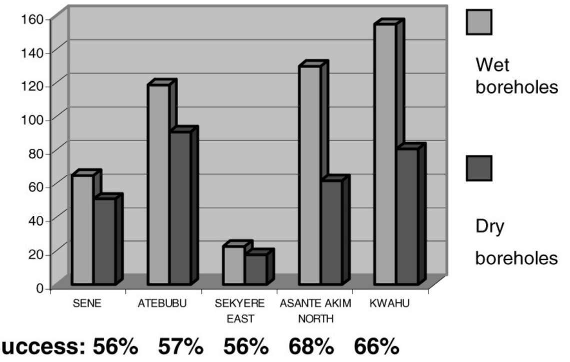

Figure 1. Boreholes drilled in the GAP (1995-2003)
Source: World Vision, Ghana, 2003

Since the GRWP drilling programme continued throughout the year, the success rates quoted do not necessarily indicate that these wells remained wet all year round. Several boreholes observed were drilled during the wet season and were reported to dry up in the dry season. This led to water being available for only 6-8 months of the year in some cases. Such situations are classed as examples of where boreholes have ‘failed’ and are included in this study.

Borehole ‘failure’

For the purposes of this study borehole failure is defined as when a borehole, which was recorded as successful, or ‘wet’ immediately after drilling, subsequently fails to deliver a sufficient yield of safe water throughout the year. A handpump borehole can be defined as successful if it is able to supply water to a population of 250 people, requiring 25 litres per person per day, where pumping takes place over a 12 hour period (MacDonald *et al.*, 2002). Assuming constant operation of the pump over the 12-hour period this gives a required yield of 8.7 l/min. In order to allow for gaps in pumping and water spillage sufficient yield is defined as 10 l/min. However, for a design population of 250 this still equates to 10.4 hours of pumping which may not be very convenient for users. The value of 10 l/min is therefore set as a **minimum** guideline value only. Wurzel (2001) suggests that the absolute maximum delivery rate of a handpump is 1 cubic metre per hour (m3/hr), or 16.7 l/min, though in reality this is rarely achieved.

It is important to note that a water supply borehole may also be deemed to have 'failed' if the water provided by it is unsafe for human consumption. The GRWP Water Quality unit conducted an analysis of the following inorganic (chemical) parameters for each borehole: Na, K, Ca, Mg, As, Fe, Mn, Si (SiO_2), HCO_3, Cl, F, NO_3, PO_4 and NO_2. In total, 306 wells were sampled and analysed in the GAP by March 2003; 94% of those sampled in the GAP satisfied the WHO Drinking Water Guideline values and Ghana Standards Board (GSB) standards for all chemical parameters evaluated. The only parameter of public health concern detected was Fluoride. Fluoride concentrations above the WHO guideline figure and the maximum contaminant limit (mcl) of 1.5mg/l were detected in six boreholes (3%). Since excessive Fluoride can lead to the development of dental and skeletal fluorosis (WHO, 1997) these boreholes were also deemed to have failed. Since the field practices of drilling and development teams cannot have a significant influence on Fluoride concentration, this study focused only on those boreholes that had failed physically, i.e. in which there was insufficient quantity of water.

Borehole or handpump?

The first step in assessing borehole failure is to determine the frequency of the problem in relation to other operational failures. A survey of 492 handpump-equipped boreholes in the GAP was conducted in which all water points were visited towards the beginning of the wet season (March 2003) and those that failed to deliver adequate water were assessed to determine whether this was due to mechanical failure of the pump or failure of the borehole. This survey indicated that 64 point sources and hence 13% of all water points had failed. This is a relatively low failure rate for a project which has been running for seven years (in comparison to the figures quoted in the introduction) and is testament to the committed ongoing support provided to communities by World Vision Ghana. The water point survey produced the following results:

• Total number of water points visited:	492
• Total number of failed handpumps:	42
• Handpump failure rate:	8.5%
• Total number of failed boreholes:	22
• Borehole failure rate:	**4.5%**

The results indicate that the failure rate for handpumps was almost double that for boreholes. However, where a handpump had failed it was not possible to determine whether or not the borehole had also failed, which means that the proportion of failed boreholes may have been higher than that indicated. This means that in the case of GAP rapid-onset borehole failure accounted for **at least** one-third of all water point failures, which makes it a significant problem.

Variables investigated

In order to determine the possible causes of borehole failure, the following variables were analysed for each borehole. These were:

- Initial recorded yield of borehole;
- Borehole depth in relation to dynamic water level;
- Depth of cylinder below dynamic water level; and
- Season during which drilling took place.

These criteria were based on existing field data, to discover whether there are 'hidden' clues, which can help determine the possible causes of borehole failure. Due to incomplete construction and assessment data for some boreholes, the total sample size was reduced to 302.

In addition to the above variables, the borehole failure rate in each district was compared to the respective borehole siting success rate to determine if there was any correlation between the two factors. Since boreholes in the study area were drilled over a seven-year period the age of failed boreholes was also analysed to determine the percentage of boreholes drilled each year that subsequently failed. This was used to determine whether there was an overall trend in increasing failure with age, as would be expected.

The quality of borehole installation (Photograph 1) was not considered as a variable since all boreholes were drilled, developed and constructed following consistent practice by GRWP drilling teams, consisting exclusively of World Vision employees. Random assessments indicated that the quality of workmanship was of a consistently high standard. Also, the study aimed to analyse routine or commonly available field data using a replicable process, and since borehole cameras are not widely available in rural Africa, their use was precluded in the study.

One major criticism of the approach described is that it does not consider the hydrogeological conditions in which different boreholes are drilled. The reasons for this are two-fold. Firstly, this information is often simply not available and personnel engaged in drilling may have limited understanding of the geological environment in which they are operating. Secondly, the time and resource constraints under which drilling teams are operating demand practical strategies to mitigate against borehole failure, which do not require hydrogeological expertise. It is accepted that in an ideal scenario, the hydrogeological conditions for each

Photograph 1. Borehole installation

borehole would be assessed fully, but experience shows that there is often a lack of definitive information and expertise to make this feasible (World Vision, 2003). The density of boreholes in the study area was deemed sufficient to ensure that there were both operational and failed boreholes in each major geological zone, but it was not possible to determine local variations in relation to specific boreholes. It should, again, be emphasised that the study focused on practical field actions which may affect source sustainability and which can be rectified relatively easily if required.

Figure 2 presents a summary of the main variables assessed for each borehole, whether failed or operational. The respective mean values are provided for initial recorded yield (Y) in l/min; depth of borehole (D); static (or rest) water level (SWL); dynamic water level (DWL) measured during pumping test; cylinder depth (C); depth of cylinder below dynamic water level (C-DWL); and depth between dynamic water level and the bottom of the borehole (D-DWL), all in metres.

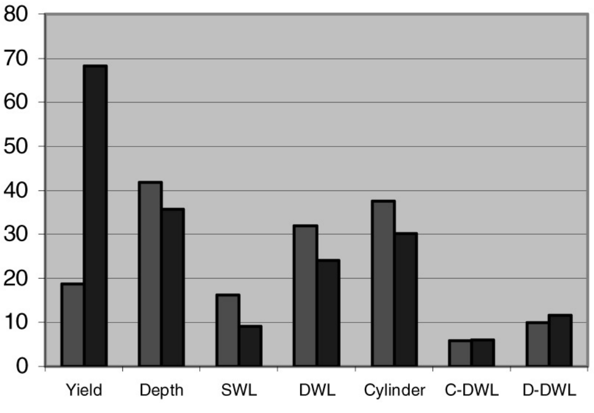

Figure 2. Summary of Data Means

As can be seen from the graph, the most apparent contrast between operational and failed boreholes was the difference between the mean values for initial yield. The mean yield for operational boreholes was 68.2 l/min, while that for failed boreholes was only 18.7 l/min. The variations in depths are less significant, but the mean values for failed boreholes are consistently greater than those for operational boreholes. Means for total depth, static and dynamic water levels are 6-8 metres greater for failed than operational boreholes. The mean value for cylinder depth below dynamic water level (C-DWL) is almost identical for both datasets at 6m, indicating consistent practice among installation teams. Similarly, the mean total depths of borehole in relation to dynamic water level (D-DWL) are very similar. These findings are examined in more detail below.

Initial yield

The initial maximum yield of each successful borehole was measured during and immediately after drilling. The mean maximum yield of 18.7 l/min for boreholes that subsequently failed was a quarter of that for operational boreholes. The respective mode was 10 l/min and the median 15.8 l/min.

The data showed that 40% of all boreholes with initial yields below 10 l/min, and which were deemed 'successful' following drilling, subsequently failed. This is significantly higher than the overall borehole failure rate of 4.5%, and indicates that this guideline figure should not be ignored.

The Government Community Water and Sanitation Agency (CWSA) has recently proposed new guidelines which stipulate that boreholes to be fitted with handpumps should have a minimum yield of 13 l/min, rather than the previously stated figure of 10 l/min (CWSA, 2003). Table 1 summarises the yields of the failed boreholes in each district in relation to the new threshold.

From the data available it can be seen that 45% of all the failed boreholes recorded had yields of less than 13 l/min but more than 10 l/min at the time of development. However, that yields should be relatively low is to be expected and caution should be taken in drawing conclusions. The total number of successful boreholes with yields between 10 and 13 l/min in the five selected districts was 85, while the total number of failed boreholes with low yields was 10. This indicates that only 12% of the total number of boreholes with yields between 10 and 13 l/min at the time of development subsequently failed. Therefore, adopting the CWSA standard for the selected areas would result in significantly fewer failures (10) but considerably more un-utilised but seemingly perfectly adequate boreholes (75). This indicates that the new figure is not likely to be a cost-effective measure in reducing borehole failure, since the number of abandoned boreholes is likely to increase significantly, meaning that 'wasted' drilling costs would far outweigh any potential benefit to a relatively small number of communities. Even where a drilled borehole has insufficient yield and a replacement borehole is rapidly drilled, there is no guarantee that this will have sufficient yield, meaning that a community might remain without an improved water supply all together.

Table 1. Initial yields of failed boreholes in the GAP

District	Total no. of failed boreholes	No. of failed boreholes with yield 10-13 l/min	Total no. of boreholes with yield 10-13 l/min
Sene	11	6	18
Atebubu	8	3	33
Sekyere East	0	0	5
Asante-Akim N	2	1	22
Kwahu N & S	1	0	7
TOTAL	**22**	**10**	**85**
% of failed boreholes with initial yields between 10 and 13 l/min:		**45%**	
% of boreholes with initial yields between 10 and 13 l/min that subsequently failed:			**12%**

Relative depths

Further variables addressed in the study were the depth of the borehole, static water level, dynamic water level and the depth to the handpump cylinder. These figures do not reveal a great deal other than the fact that, on average, failed boreholes are deeper than operational ones due to lower static and dynamic water levels, and hence average cylinder depths are also greater. The average depths of the cylinder and base of the borehole below the dynamic water level (C-DWL and D-DWL) would appear to have no bearing on whether a borehole fails in this case, since the values are almost identical for both borehole categories. What may be most significant is the relationship between borehole yield and depth, which indicates that the difference in depth does not compensate for the vast difference in yield. This suggests that boreholes with low yields should be drilled to greater depths below the DWL than those with higher yields. This was not being done in the study area.

Seasonal drilling

To provide a realistic picture of borehole sustainability, pumping tests should ideally be undertaken at the peak of the dry season, when water levels are at their deepest (MacDonald *et al.*, 2002). In practice, however, pumping tests are conducted immediately after drilling while the drilling team is still on site.

World Vision's drilling programme under GRWP was operational throughout the year and consequently boreholes were drilled in both the wet and the dry seasons. Table 2 shows the breakdown of borehole failures by season.

The table indicates that 86% of those boreholes that failed were drilled during the wet season. Based on proportional time periods and the fact that roughly equal numbers of boreholes were drilled in each season, this figure should be only 50% (corresponding to 6 months of the year). This indicates that wet season drilling is approximately six times more likely to lead to borehole failure than dry season drilling.

Table 2. Summary of failed boreholes in the GAP by season drilled

District	No. of failed boreholes drilled in wet season*	No. of failed boreholes drilled in dry season	Total no. of failed boreholes
Sene	10	1	11
Atebubu	6	2	8
Sekyere East	0	0	0
Asante-Akim N	2	0	2
Kwahu N & S	1	0	1
TOTAL	**19**	**3**	**22**
Percentage of failed boreholes drilled in the wet season			**88%**

* Wet season is taken as from 1st February to 31st July

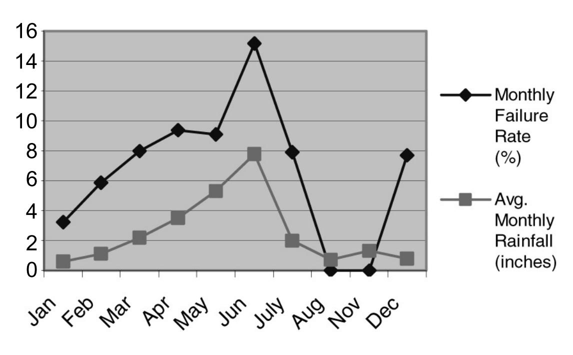

Figure 3. Monthly failure rate vs rainfall

Figure 3 shows the pattern of average monthly rainfall figures in relation to the proportion of failed boreholes as a percentage of all boreholes drilled for each month of the year. The months of September and October were excluded due to an inadequate sample size for each month, with only 2 and 6 boreholes respectively. The precipitation figures used are average monthly totals, rather than actual totals for precise months when drilling took place.

The graph demonstrates a clear relationship between the wettest months and highest failure rates, and the correlation coefficient for this relationship is strongly positive ($r = 0.865$, $df = 9$, $p<0.01$). This reinforces the finding that wet season drilling is considerably more likely to lead to borehole failure than drilling during the dry season, and suggests that drillers were not making sufficient steps to take seasonal fluctuations in water levels into account during operations. The consistent depth of cylinder installation with respect to DWL, regardless of time of year, supports this assumption. Wurzel (2001) suggests a systematic approach whereby drillers drill an additional 10 metres after sufficient yield is attained to allow for seasonal variation. It is not clear, however, how effective this measure is in countering seasonal water table fluctuations, since the approach was not adopted by the GRWP drillers.

Siting and failure rates

The relationship between borehole siting success rate and borehole failure rate by district is illustrated in Figure 4.

The purpose of this analysis was to determine whether or not rapid-onset borehole failure is more likely in hydrogeologically complex zones, i.e. those areas where borehole siting rates are low. The graph shows a weak inverse relationship between the two variables, which is reinforced by a relatively weak negative correlation (r = -0.48, df = 4, p<0.001). This illustrates that districts with low siting success rates are marginally more likely to have high borehole failure rates, but this relationship is not particularly strong. This can be seen from the example of Sene and Sekyere East districts, which both had borehole siting success rates of 56%, and yet Sene had 11 failed boreholes and Sekyere East had none.

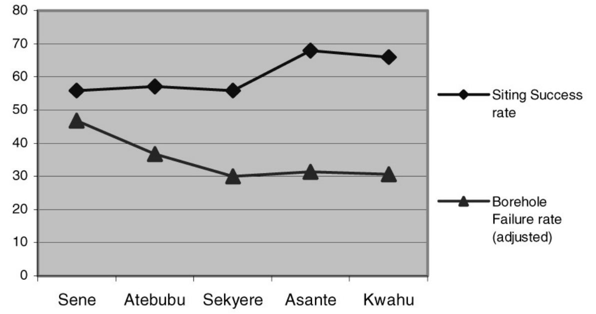

Figure 4. Siting success and borehole failure

Failure over time

It is a logical expectation that the number of failed boreholes will increase with age, and this can be seen in Figure 5. The annual failure rate reduces with decreasing age, so that no failed boreholes were drilled in 2001 and 2002, while there was a maximum number drilled in 1996 (only a very small number of boreholes were drilled in 1995). This suggests that boreholes take at least one or two years before they 'fail', and failure rates increase considerably from five years. It should be noted, however, that the survey of water points was conducted during March when the wet season had already started, so it is possible that some ephemeral boreholes contained water that had not done so during the recently ended dry season. This means that the actual total of failed boreholes may be even higher than indicated.

Discussion

Borehole sustainability, or lack of it, is rarely given significant attention in rural water supply programmes in Africa. Whilst it is not as severe a problem as inadequate handpump operation and maintenance, it does have potentially serious and negative effects on rural communities. In order to obtain detailed information as to why boreholes are failing, thorough assessments of construction and installation are required using borehole cameras. This is an expensive option and without strong institutional will it is not likely to happen in most rural African contexts. Routine field data cannot provide all the answers, but they can provide indicators to aspects of field practice which can be improved to increase sustainability.

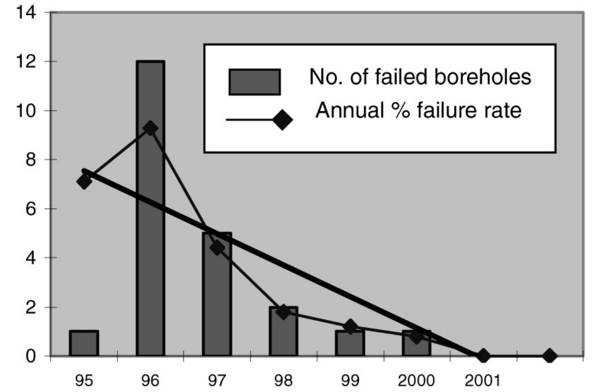

Figure 5. Failed boreholes by year of drilling

Without longitudinal data on groundwater levels it is impossible to determine whether borehole failures are related to groundwater depletion trends. World Vision, Ghana has now recognised this problem and has recently introduced a system for quarterly monitoring of groundwater levels in boreholes. This is of crucial importance if we are to understand more about the hydrogeological environments in which we work, and to discover why systems fail. Many conventional handpump models do not facilitate easy monitoring of groundwater, and yet an inspection panel can be easily incorporated into existing designs, as used in Ghana (Photograph 2).

Photograph 2. Water level measurements

Conclusions

In order to find out more about borehole sustainability the simple solution is to obtain more hydrogeological information about the areas in which drillers are operating, and to employ more highly qualified and experienced personnel. The reality is, that this is often not possible and there are likely to always be contractors who do a reasonably competent technical job, but who do not have the level of knowledge required to gain a detailed understanding of hydrogeology. Most drillers, whether NGO or private contractors, record routine field data, such as that described, during water borehole drilling and development. This study examines whether this field data can be used to help predict borehole sustainability. The research findings suggest that there is, indeed, a limited amount of useful information that can be deduced from this data, the key points being:

- The initial measured yield of a borehole is the single largest factor that influences subsequent borehole failure. It is important that realistic guideline figures are set and adhered to. Boreholes with low yields should be drilled to greater depth with respect to DWL (and have longer screened intervals) than those with higher yields, rather than adopting a uniform approach.
- Rainfall intensity during the month of drilling has a direct influence on failure rates. It is essential that where drillers operate throughout the year, they develop compensation strategies for seasonal drilling. This is likely to involve drilling to greater depth in relation to DWL during the wet season, but groundwater levels must be recorded in order to develop appropriate strategies for different geological environments.
- Borehole failure increases with age and is most common at five years old or more, suggesting that most borehole failures are associated with reduction in yields and degradation of well construction over time.
- The siting success rate in a given area does not have a strong affect on the borehole failure rate in that area. It should not, therefore, be assumed that areas of complex hydrogeology will result in higher failure rates.

On the basis of the results obtained it is important that drillers develop field practices which take full account of seasonal groundwater variations and low borehole yields. The people involved in groundwater development must have the skills and knowledge required to be effective, so that they can acquire a real understanding of the environment in which they operate, rather than just follow rigid operational guidelines. The required yield should be matched to forecasted water demand for each specific borehole, based on the population and water usage, rather than using a fixed arbitrary guideline value. Drilling practitioners must pay special attention to low pH water and it is essential that pH values are measured both prior to construction and after development. While there are a range of techniques that can be used for borehole rehabilitation, such as acid treatment, chlorination, and hydrofracturing, the cost and management needs associated with these are often prohibitive. Prevention is better than cure, but this requires appropriate monitoring and information management.

We are now in a situation where many thousands of boreholes have been drilled in sub-Saharan Africa and little knowledge has been gained from them (MacDonald & Davies, 2002). What information we have must be used to its maximum potential, and further information should be collected and managed, in order to ensure sustainable development, on all fronts.

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