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Overseas Geology Series

UNCONSOLIDATED SEDIMENTARY AQUIFERS: REVIEW NO 2 - BOREHOLE PERFORMANCE MAINTENANCE

P HOWSAM

Natural Environment Research Council

International Division
British Geological Survey
Keyworth
Nottingham
United Kingdom NG12 5GG

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Sigatoka River flood plain, Fiji

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Other Reviews available in this Series

1 Design of Boreholes (BGS Technical Report WC/94/27)

UNCONSOLIDATED SEDIMENTARY AQUIFERS (UNSAs)

PREFACE

This Review is one of a set of reports prepared as part of a project entitled 'Groundwater Development in Alluvial Aquifers', Project No R5561 (BGS 93/2), under the ODA/BGS Technology Development and Research (TDR) Programme of aid to the developing countries. The project addresses all unconsolidated sedimentary aquifers (UNSAs) not only alluviums.

This particular review describes the general principles behind borehole performance maintenance. The nature of the cause processes which affect performance are described along with guidelines on how to monitor and diagnose borehole performance, condition and processes. Equal emphasis is given to the need to understand the cure processes applied and to the importance of preventative measures through better design, construction and operation. It is stressed that borehole performance maintenance must be given due consideration at all stages in the development of UNSAs.

This review is a compilation of existing knowledge. It is intended to be updated, as appropriate, following the results of research which will be carried out during the lifetime of the project, which is scheduled to run until 1996.

The project is funded by ODA as part of their research and development programme designed to improve living standards and conditions in the world's developing countries.

Project Manager: Dr R Herbert
Hydrogeological Adviser to ODA
British Geological Survey

Copy this & 4
following sheets (5
total) on yellow
paper.

A GUIDE TO THE SEDIMENTOLOGY OF UNCONSOLIDATED SEDIMENTARY AQUIFERS (UNSAs)

INTRODUCTION

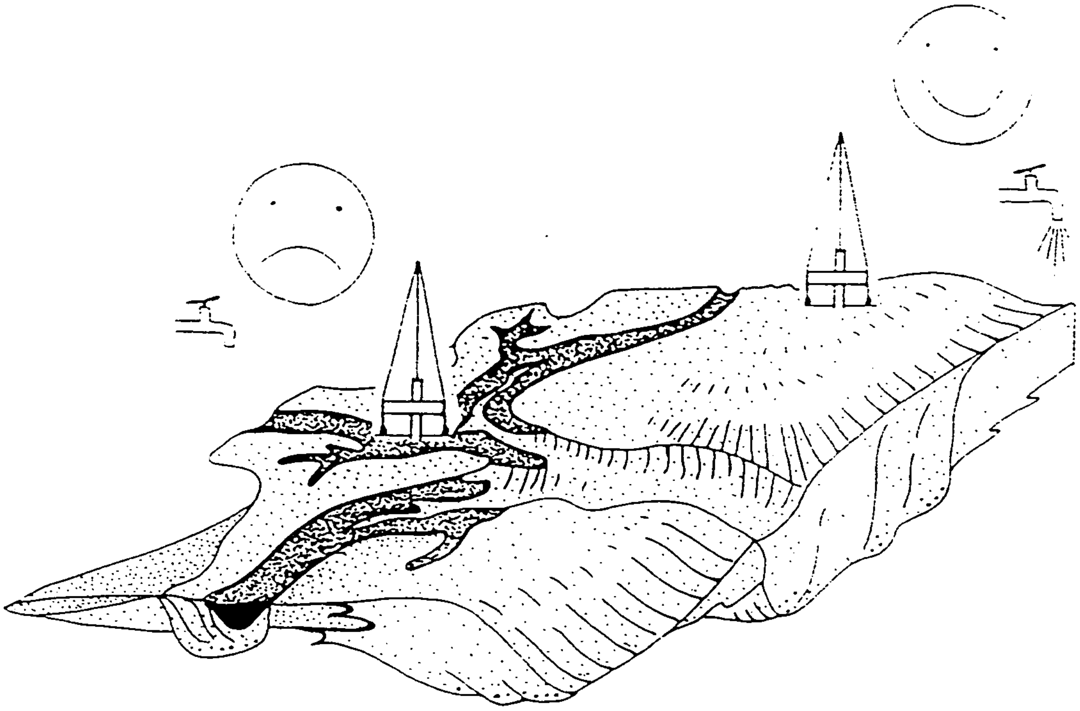
WHAT ARE UNSAs AND WHY IS IT IMPORTANT TO UNDERSTAND THEM?

UNSAs are unconsolidated sedimentary aquifers. These are the water-bearing strata within the swathes of unconsolidated sediment that mantle much of the earth's surface. There is no clear dividing line between UNSAs and aquifers in consolidated rocks, as lithification is a gradational process: deposits a hundred years old can be lithified, while some deposits 500 million years old are still essentially unlithified. However, for most purposes, UNSAs can be understood as deposits which have accumulated over the past few million years, that is during Quaternary and Neogene (late Tertiary) time. They are important sources of water in many parts of the world, and in particular constitute the only major sources of groundwater for vast areas throughout the developing world. In the influential text book ***Hydrogeology*** by Davies and De Weist it says:

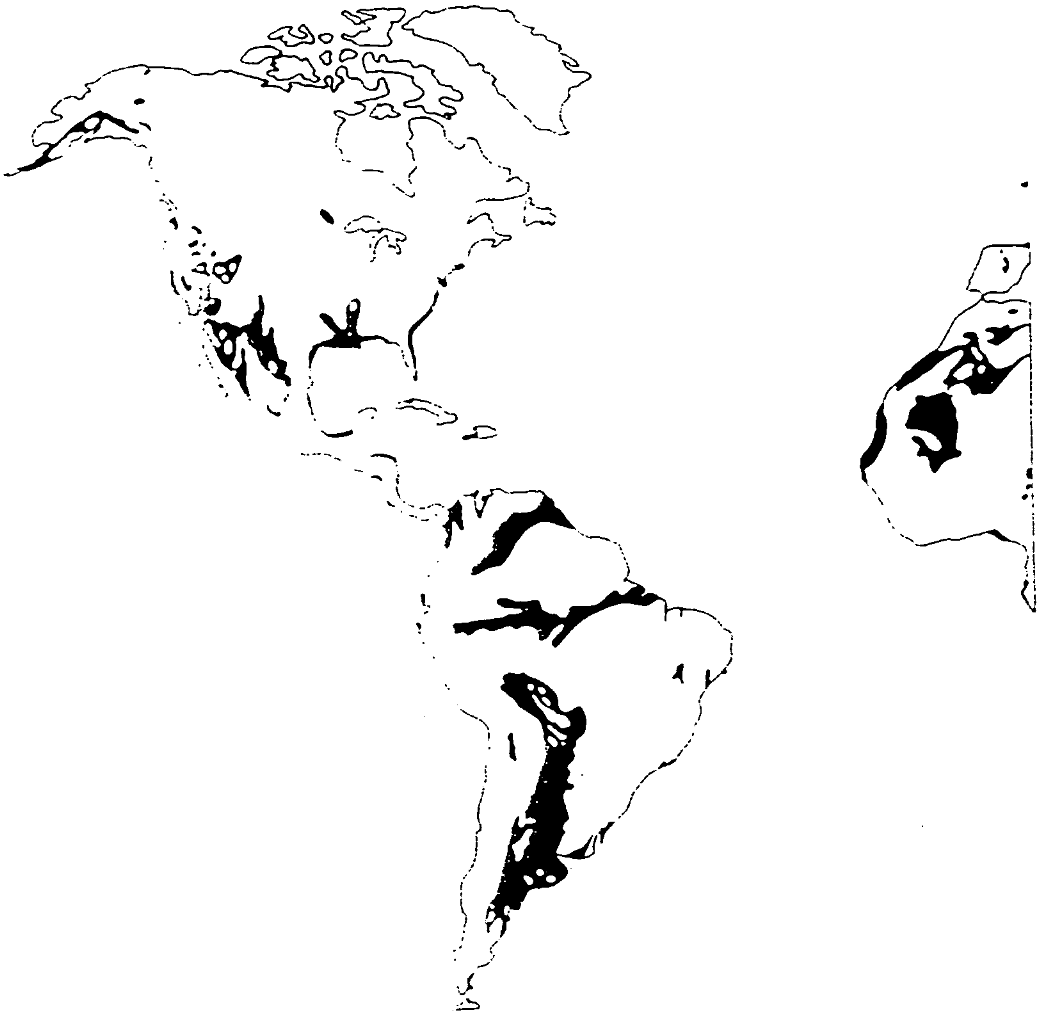
> *"The search for ground water most commonly starts with an investigation of non-indurated sediments. There are sound reasons for this preference. First, the deposits are easy to drill or dig so that exploration is rapid and inexpensive. Second, the deposits are most likely to be found in valleys where ground water levels are close to the surface and where, as a consequence, pumping lifts are small. Third, the deposits are commonly in a favourable location with respect to recharge from lakes and rivers. Fourth, non-indurated sediments have generally higher specific yields than other material. Fifth, and perhaps most important, permeabilities are much higher than other natural materials with the exception of some recent volcanic rocks and carvernous limestones".*

To date, though, few attempts have been made to understand the detailed internal structure of unconsolidated aquifers even though such knowledge may be crucial to the long term success of any water development project. This shortcoming is probably the reason why the operational lives of many water boreholes are frequently much shorter than expected.

Understanding of the internal structure or 'architecture' of many types of sedimentary deposit has, however, advanced greatly over the past couple of decades. Part of this research has been academic, but much has been sponsored by the oil industry, so as to better predict the possible location of oil within sedimentary traps. Oil, like water, is most profitably located within bodies of relatively coarse-grained and porous sediment. Thus, there is obvious scope for applying this recently gained understanding to hydrogeological problems. Advances have also been made in the understanding of the geometry of complex 'soft-rock' deposits by the application of appropriate combinations of investigative techniques, including remote sensing, rapid geophysical methods and new drilling techniques. The combination of these bodies of knowledge can provide a framework for locating and assessing UNSAs.



Sedimentary bodies are characterised by variably complex geometry and internal structure. These properties exert a strong internal control on the location, quantity and quality of groundwater. Diagram adapted from Galloway and Hobday (1983).



MAJOR AREAS OF UNCONSOLIDATED SEDIMENTARY AQUIFERS WORLDWIDE

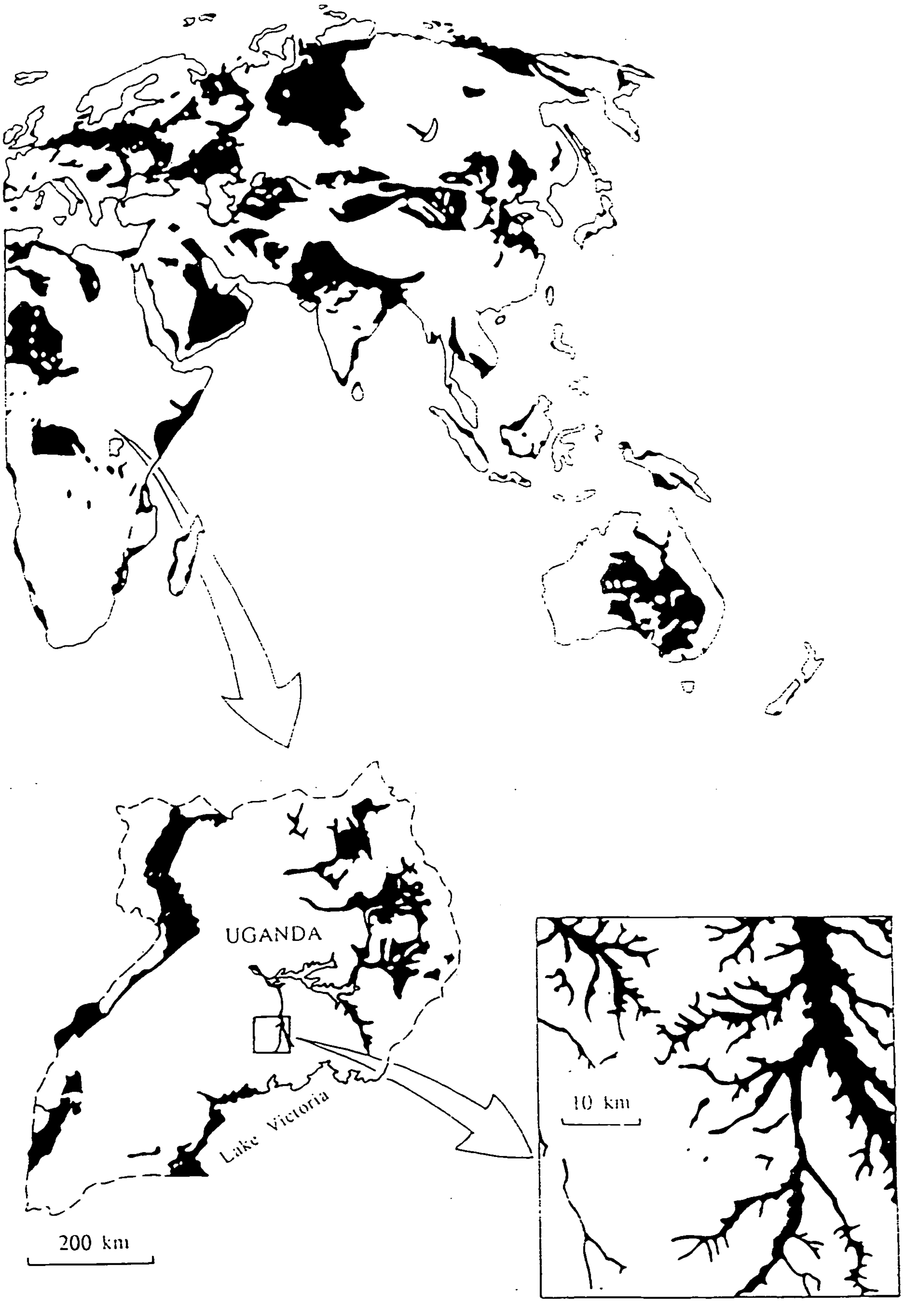
- The map shows the distribution of the thickest and most extensive Quaternary deposits in the world. The great majority of these are unconsolidated, and many include water-bearing deposits (UNSAs).

- A generalised world map such as this, though, severely under-estimates the true extent of UNSAs worldwide. this is because:

  - unconsolidated pre-Quaternary deposits are omitted; these too have a wide distribution, though are difficult to delineate (as they grade into consolidated deposits); they too can include significant UNSAs.

  - the simplification of linework necessary at this scale means that a large proportion of unconsolidated deposits have had to be omitted. The inset map shows the example of Uganda, which seems to have no unconsolidated sedimentats at the global scale, while significant and extensive deposits 'appear' once the country is looked at more closely. At a yet larger scale the unconsolidated sediments appear yet more widespread. The message is clear. *Unconsolidated sediments, and therefore UNSAs, are ubiquitous.*

Diagram data modified from various sources.


UGANDA
Lake Victoria
200 km
10 km

UNCONSOLIDATED SEDIMENTARY AQUIFERS (UNSAs)

Borehole Performance Maintenance section, by P.Howsam

Important acknowledgement

Much of the basic material for this report has come from efforts made in the preparation of a CIRIA (Construction Industry Research and Information Association) report, namely:

Howsam, P., Misstear, B. and Jones, C. (1995)
Monitoring, maintenance and rehabilitation of water supply boreholes
CIRIA Report 137 London

P.Howsam
March 1995

UNCONSOLIDATED SEDIMENTARY AQUIFERS (UNSAs)

Borehole Performance Maintenance - P.Howsam

METHOD SUMMARY SHEETS

1. Borehole performance/maintenance - cause processes
2. Borehole performance/maintenance - monitoring
3. Borehole performance/maintenance - diagnosis
4. Borehole performance/maintenance - cure processes
5. Borehole performance/maintenance - design/construction factors
6. Borehole performance/maintenance - operational factors
7. Borehole performance/maintenance - cost-effectiveness evaluation - case study (BHPM 7)

UNCONSOLIDATED SEDIMENTARY AQUIFERS (UNSAs)

Borehole Performance Maintenance - PH

AIMS

To provide guide-lines on best practice for the maintenance of the performance of boreholes used to abstract groundwater from Unconsolidated Sedimentary Aquifers.

The practical significance of reduced borehole performance is dependent upon the ease with which this can be avoided or rectified. Changes in drilling, completion or operation practice can obviate many problems, whilst various treatments can be used to rehabilitate the boreholes. None of these measures can be implemented in a rational and optimised manner without first identifying the processes which give rise to the problem. Therefore the practical significance of reduced borehole performance is also a function of the difficulty or otherwise of determining the cause.

This section describes the background to the subject, the processes which cause deterioration in borehole performance; how to monitor and diagnose these processes and their consequences; how to avoid or reduce these processes and how to cure the conditions which they cause.

BACKGROUND

GENERAL

Current practices in relation to the monitoring, operation and maintenance of boreholes are highly variable in both policy and action. The reasons are equally variable with the perpetuation of both bad as well as good practices, together with lack of awareness and knowledge aided by a scattering of misconceptions. This situation is typical throughout the world. In very few countries has a policy of planned and systematic monitoring, operation and maintenance been adopted and successfully implemented.

Where rehabilitation has been carried out it has often been on a 'suck-it-and-see' approach. As a result the outcomes have often been disappointing. Part of the problem has been the seeking and offering of standard solutions without due regard to the circumstances of the borehole, the nature and extent of the cause processes and the nature and consequence of the cure process(s) applied. The strategy has typically been one of crisis management, ie responding to events as and when they arise; rather than one of planned maintenance.

It is also well understood amongst practitioners that boreholes which are correctly designed, constructed and operated often need little maintenance. The highly variable nature of Unconsolidated Sedimentary Aquifers means that they require the most care and attention of all aquifers.

However for all aquifers the abstraction system, the borehole or well, is traditionally dealt with by a variety of disciplines, at different stages of development, usually in an uncoordinated manner. For example the hydrogeologist usually investigates the aquifer, selects the site, often designs, and supervises construction of, the borehole. Once the borehole has been completed it is then usually handed over to the user ie the water supply or irrigation engineer. As long as water is delivered at the well-head little attention is given to the below-ground, out-of-sight, out-of-mind system, until a problem occurs.

The consequences of such an approach can now be seen in many cases to be inefficient, with disbenefits with regard to economics, public health, food production and user confidence. This is particularly important in developing countries where weak economies could well do without the added strain of supporting inefficient systems or where failure can simply lead to going without.

An ODA funded international survey and conference held in 1990 addressed the attitude and circumstances relating to borehole monitoring, maintenance and rehabilitation and revealed:

* that monitoring is given a low priority world-wide, because of lack of finance, of organisational and logistical resources, of expertise, of co-ordination between departments involved; and because monitoring is not afforded great prestige, is considered to be unproductive and can lead to a cause of embarrassment when errors in design construction and/or operation are discovered.

* that monitoring is essential for proper maintenance and that all systems require some degree of maintenance.

* that the commonest causes of operational difficulties were sand ingress, fines migration and iron biofouling, followed by encrustation, corrosion, anaerobic clogging, and overpumping

* that borehole operational problems often reflect poor design/construction and operation and that borehole pump problems outweigh those associated with the borehole structure itself. Addressing the problem of the maintenance and rehabilitation of existing wells should feedback to the better design, construction, operation of new wells.

* that whilst estimates of the percentage of boreholes which suffered from impaired performance ranged from 0 - 100%, all available information suggests 40% as a realistic figure for the number of boreholes/tubewells world-wide, with operational problems.

* that experiences of attempts at rehabilitation are commonplace and that a basic awareness of, as opposed to a good understanding of, available rehabilitation technologies exists.

* that approximately 66% of rehabilitation attempts are ultimately unsuccessful; mainly due to a lack of monitoring, resources, expertise and of an understanding of the cause process, a failure to remove the root cause of the problem, the degree of dilapidation of boreholes/tubewells, a lack of will to improve the situation.

* that there were many instances where rehabilitation should have been attempted but had not, because of a lack of finance, equipment and expertise; and because of the attitude that drilling a new borehole would be simpler and be more likely to succeed, leading to avoidance of any attempt at rehabilitation.

* that where there is more than one department involved with a groundwater supply project there is often a reluctance for any one to accept responsibility; and that Governments and water supply departments must be convinced of the value of good management of their underground assets.

* that attitudes are changing and that the need for a greater emphasis on monitoring, maintenance and rehabilitation is receiving greater recognition by international funding agencies. Stimulating the development of a sound institutional framework to support project sustainability has become a priority. Experience has taught donor organisations that merely providing capital for new investment is insufficient to ensure the success of a project. The development of a policy of longer term commitment to projects has been adopted despite the problems of securing funds over a 10-15 year period.

* that groundwater is vital in supporting world food production and improving living standards. The maintenance and rehabilitation of wells is essential if this is to be sustained.

* that water wells are important assets, whose efficiencies need to be monitored and improved, and that as underfunding on operation and maintenance gives poor performance on capital investment, recurrent costs needs to be adequately funded.

STRATEGIES

Borehole performance maintenance needs to be part of an integrated strategy for optimum aquifer management and groundwater supply. In the development of such a strategy it is necessary to consider a wide range of factors and information:

Groundwater engineering :
For each borehole - location; hydrogeology; design; yield-drawdown characteristics; operating schedule; licensed and actual abstraction; abstracted water quality; performance history; equipment history, maintenance history;

Groundwater resources and demand :
Regional hydrogeology (water levels and quality); past current and future water supply demand; groundwater component of demand; total existing licensed and actual abstractions; actual and potential interference from other abstractions; likely restrictions on groundwater resource development;

Management and economics :
Manpower resources and skills; equipment and facilities; costs involved; cost benefit analysis; alternative sources; possible changes in legislation, performance and quality targets; benefits for operation and maintenance

It is clear from the above that many disciplines and departments within an organisation need to be involved in such a strategy:- management, finance, policy, planning, water resources, engineering, operations, control, maintenance, new works, water quality laboratories, treatment, distribution, drilling. Often the institutional and manpower framework will need to be adjusted to allow this to happen.

An integrated strategy for borehole monitoring, maintenance, design and operation is necessary in order to encourage a well managed system involving routine preventative maintenance and to replace a system of crisis management.

An essential component of any successful integrated strategy is a procedure for the proper handling and analysis of data, and the communication and accessibility of information to all concerned.

PRINCIPLES

The principle elements in borehole performance maintenance can be summarised as follows:

The existing elements are the *aquifer* and the *borehole*

Baseline *information* on these are required in order to be able to plan *monitoring* of future condition and performance

Monitoring of the *aquifer, borehole* and its *operation* are required to acquire *data*

Data needs to be *processed and analysed* in order to achieve a *diagnosis*

A *diagnosis* is required in order to identify the *cause*

The *cause* needs to be identified in order to select a *cure* or *preventative* action

A *cure* may involve *maintenance* or *rehabilitation*

The consequences of any *cure* need to be *monitored*

Diagnosis of a cause should be used to select alternative operating schedules in order to prevent/reduce problem recurrence

A *diagnosis of a cause* should be used to amend the *design/construction* of new boreholes in order to avoid/reduce problem recurrence

These elements can be defined as follows:

Water supply borehole: any engineered system constructed in order to abstract groundwater from an aquifer. In most instances this will be a vertical hole drilled and invariably lined, in a water yielding formation. Various terms exist: borehole, bore, well, tubewell. Other systems for abstracting groundwater include adits, hand-dug wells, collector-wells, infiltration galleries, qanat or falaj.

Monitoring: regular, and by implication, planned surveillance over a period of time of the condition and/or performance of a system. Surveillance can include visual observations but usually involves some form of periodic measurement. The principle purpose of monitoring is to provide a warning of a change in performance or condition. The data gained by monitoring needs to be processed and analysed in order for a diagnosis of the situation to be made.

Diagnosis: deduction of the reasons for a change in borehole performance.

Maintenance: the process of causing to continue, to preserve, to keep in good repair. Maintenance is carried out on a regular or periodic basis.

Rehabilitation: the restoration of a system to effectiveness or to its proper condition. Rehabilitation is applied to a system which has not been maintained and whose condition has changed significantly from its original or proper condition.

Design and construction: the formation of a preliminary plan or layout of the components of a system and the putting together of those components to form the whole system, in this case an operational borehole.

Operation: is the action or process of working.

It is clear from these definitions how operation and maintenance fit so well together.

METHODS

MONITORING

Introduction

The purpose of monitoring is to provide information to borehole operators on the performance and condition of their operating boreholes, and on processes which may affect them. Monitoring provides data which when analysed, enables diagnosis of the process to be made. This enables identification of the nature of the problem, which then permits selection of a suitable preventative or curative (maintenance or rehabilitation) procedure.

Monitoring should not be undertaken purely out of historical habit nor because it seems a sensible thing to do. It must be considered as an integral part of any good groundwater supply management strategy. As such it is part of a cycle not an independent exercise with no direction or consequence.

The primary and simplest level of monitoring is aimed at borehole *performance*. However once a decline in operating *performance* has been diagnosed it is then necessary to assess the *condition* of the components of the system to be able to identify the extent and location of the problem(s). Thus a secondary level of monitoring is necessary which relates to the *condition* of the system which has caused the *performance* to deteriorate.

Knowing the *condition* of the components of the system is rarely enough to be able to select the most appropriate curative or preventative action. A tertiary level of monitoring is therefore required to identify the *process(es)* which generated the *condition* which caused a decline in *performance*.

In order to monitor and diagnose correctly it is necessary first to be aware of and understand the nature of the processes involved.

Processes affecting borehole performance

Various processes and factors play a part in adversely affecting borehole performance. The primary processes involved may be categorised as :

- Physical
- Chemical
- Microbial

with important secondary factors being:

- Operational
- Structural & Mechanical

Rarely do these processes act in isolation.

They can occur in all parts of a borehole groundwater abstraction system:

- Aquifer
- Borehole
- Pump
- Well-head works

Physical processes

Clogging
The process of clogging (or reduction in material permeability) is caused by the redistribution of particulate matter in a variety of ways:

- Drilling fluid invasion damage at the time of construction
- Inter-mixing of aquifer horizons as a result of wash-out and caving during drilling and development
- Inter-mixing of aquifer and gravel-pack material due to poor installation procedure and/or over aggressive development
- Migration of fines from the aquifer towards the borehole and into the gravel-pack material during operation
- Migration of aquifer material into the borehole causing it to be infilled

Abrasion
The process involves relatively high velocity particle laden water causing abrasion damage, such as pump impeller wear, screen slot enlargement, holes in rising mains and removal of protective coatings. In the latter case this may lead to further problems such as exposure to corrosion.

Chemical processes

Clogging
In this case the process of clogging is by chemical precipitation. The most commonly reported encrustations are those of iron oxyhydroxides (sometimes associated with manganese deposits) and calcium carbonate. The former occurs when ferrous bearing anaerobic groundwater becomes oxygenated causing the ferrous to ferric conversion and the precipitation of insoluble ferric oxyhydroxides. In groundwater environments the ferrous/ferric balance is influenced by pH and Eh. In some circumstances siderite (iron carbonate) will precipitate out.

The precipitation of calcium carbonate is often quoted but apparently less commonly observed. The process is generally explained by saying that as groundwater approaches and enters a borehole there is a drop in pressure, which causes carbon dioxide to be released, which in turn affects the carbonate/bicarbonate equilibrium, with the result that calcium carbonate is precipitated. For many circumstances in and around a borehole however, the pressure, flow, temperature, time conditions as generally perceived, are not adequate to cause the deposits sometimes observed or predicted. This implies that understanding of flow conditions around a borehole is not always as good as it should be; or that other factors such as microbial metabolic use of carbon dioxide, play a significant part.

Electrochemical Corrosion
This process is well described in the chemical and engineering literature, as are the consequences, such as corrosion of casing or screen joints, leading to sand ingress and possible complete structural failure of the borehole; corrosion and enlargement of screen openings, leading to ingress of formation or gravel-pack material into the borehole; corrosion and failure of pump components and rising main.

Microbial processes

Clogging
Awareness of clogging by microbial processes is a relatively recent development. It is now understood that:

a) Groundwaters and aquifers, which are not obviously polluted, have widely been perceived as being bacteriologically 'pure'. However, while groundwater does contain far fewer microorganisms than surface water, it is by no means sterile. The soil through which much groundwater passes on its way to the aquifer is teeming with microorganisms. Some of these can adapt to conditions in the aquifer and become residents, some can be introduced into the aquifer during drilling (migrants) and some described as ultra-microcells, with extremely slow rates of metabolism and by shedding surplus cellular material, are able to travel long distances through (itinerants) and reside in the aquifer (residents)

b) Biofouling can be enhanced by high velocities and turbulence, and iron biofouling does not necessarily require high levels of iron or oxygen.

c) The consequences of biofouling will in some cases be visually obvious, ie a slimy material can be observed clogging the strainer of a retrieved pump or soft filamentous material can be observed with a down-hole CCTV camera, covering the slots of a borehole screen. In other cases however the appearance of the clogging material, for example brittle encrustation, clay-like sludge, will give no clue that microbial activity is, or has been, involved. Biofilms have the ability to absorb minerals and trap inorganic particles such that composition and therefore appearance can be highly variable. There is growing evidence that many encrustations perceived as chemical in origin , probably in fact involved microbial processes. There are many bacteria (for example *Gallionella*) which can initiate and enhance the formation of commonly encountered iron deposits and others which are associated with precipitation of calcium carbonate in natural environments.

(d) Some natural drilling additives can be broken down to provide nutrients and can therefore contribute to microbial growth.

Microbially Induced Corrosion
This is a process which can occur in any part of the engineered system and relates mainly to a group of anaerobic microorganisms called sulphate-reducing bacteria. These microbes, which attach to and create biofilms on surfaces, are particularly hardy having been found to exist in a wide range of environments. Examination of typical apparently purely electrochemical corrosion-encrustation cell material (for example rust tubercules on a ferrous pipe surface) has revealed the presence of sulphate-reducing bacteria.

Biofilms can also grow in aerobic conditions and can enhance corrosion by causing the depassivation of metal surfaces. Metabolic by-products of biofilms, typically acids, can also be locally very corrosive.

Biocorrosion can occur in macro-environments which would not normally be considered as corrosive. This is because micro-environments can exist within a biofilm, even ones of only a few millimetres thickness. Standard corrosion indices will not therefore always be reliable indicators of localised corrosion risk.

Operational factors

Inappropriate Operating Schedules
This is a factor which can enhance many of the primary processes affecting the aquifer, borehole, the pump and pipework. For example intermittent pumping may lead to increased particle redistribution (sand pumping and fines migration) as a result of the higher velocities generated at start up; and with oscillating water levels may also lead to increased oxygenation of groundwaters in and around the borehole.

Pumping boreholes at too high a rate or pumping a group of boreholes together with high levels of interference, may cause pumping water levels to fall below the top of the screen. This again enhances oxygenation and therefore the potential for iron fouling. It also necessitates placing the pump within the screen, thereby increasing the potential for sand pumping and fines migration where there is intermittent pumping.

Aquifer Over-abstraction
This is likely to affect borehole yield and should be the first factor to check when there is a reduction in performance.

Structural/Mechanical factors

Poor Design and Construction
This is a relatively common factor which can compound problems caused by the primary processes. The most significant design factors are those which create high velocities in any part of the system; For example screen diameter, length, slot size and open area in relation to aquifer properties and pumping rate.

Poor construction may include such cases as:

- insufficient care taken when installing or joining the casing and screen string which may lead to parting at joints

- inappropriate use and improper placement of grouting materials, which may lead to ingress of polluted or oxygenated waters into the borehole

- poor selection and installation of gravel-pack, which may lead to movement of material through the screen causing damage to the screen itself and the pump, or to clogging of the gravel pack by formation material

- poor selection and implementation of drilling method, leading to hole instability, caving and collapse of the borehole.

Inappropriate Selection of Borehole Component Materials
Eg the use of ferrous materials where there is any risk of corrosion. Corrosion can directly contribute to causing:

- sand pumping by enlarging screen slots and creating gaps in casing joints
- pump failure by corrosion of mechanical parts
- clogging by increasing iron concentrations and hence iron fouling

This issue, with the range of suitable non-corrodible materials (particularly the HDPE, uPVC, GRP and GRE) now available, should be a problem of the past, but unfortunately it is not.

Parameters to be monitored

All monitored parameters which must be relevant to diagnosis and to maintenance and rehabilitation action, can be grouped according to the major purpose of the monitoring; ie:

- to check overall *performance* of system
  Eg yield and energy consumption

- to check *condition* of components of the system
  Eg clogged screen slots and worn pump impellers

- to check on existence of adverse *processes* in system
  Eg iron biofouling and particle redistribution

and also related to the different components of the system:

- Aquifer
- Borehole
- Pump
- Well-head Works

These principles are summarised in Fig.1
Many practitioners will know that there is not always a clear distinction between these activities and components. They do however help to provide a systematic basis on which to plan and evaluate a monitoring strategy.

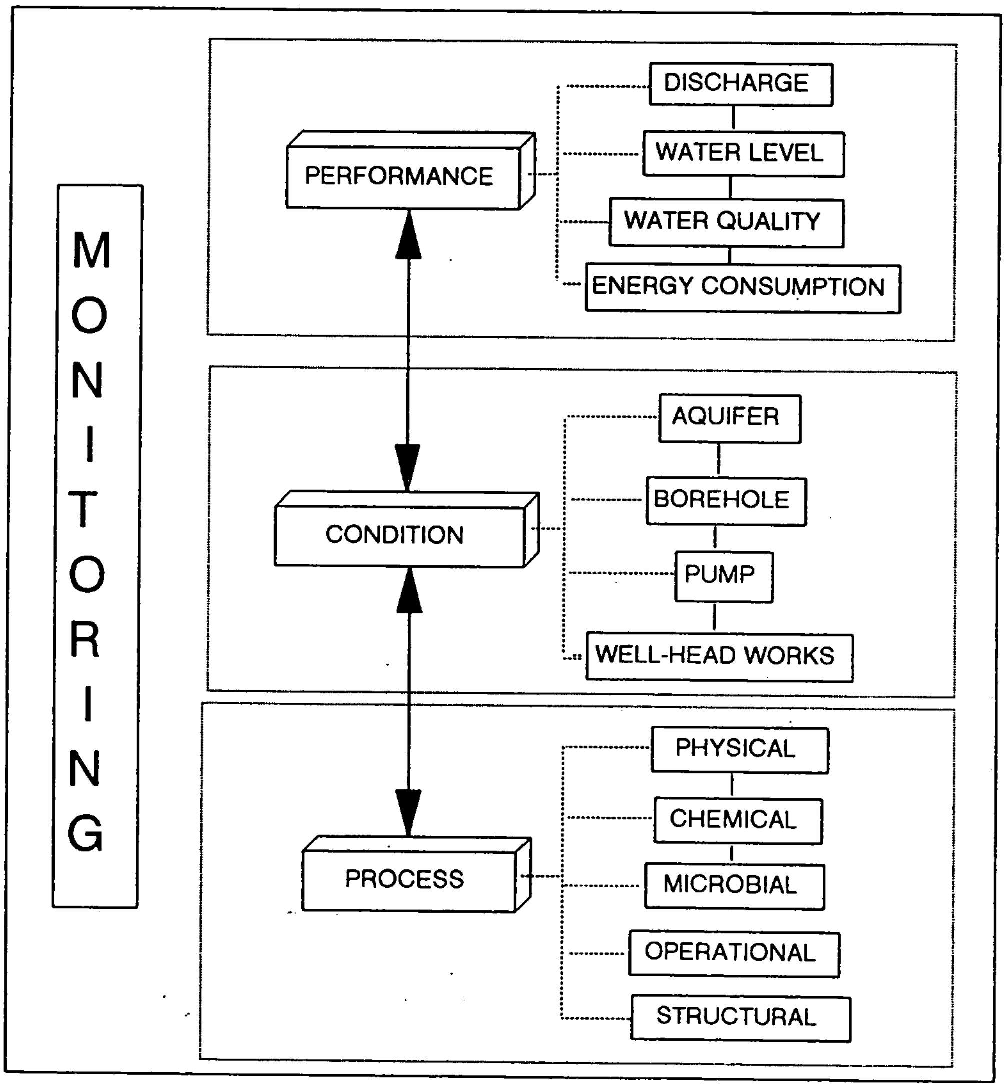
Monitoring of performance is really the primary and minimum level of monitoring that should be carried out and in practice relates largely to the borehole and borehole pump.

Monitoring of condition relates to all components of the system and does itself provide some of the best indicators of the processes prevailing. Performance and condition monitoring form the basis of diagnosis for most practitioners, where the diagnosis is retrospective rather than predictive. To ensure predictive diagnosis and therefore preventative maintenance it is necessary to carry out monitoring of processes.

What parameter to monitor is the key decision to make but then come the questions of *how*, *where* and *when*. As regards to where, ie in the aquifer, in the borehole or at the well-head, the first priority must be to monitor at the point of activity wherever possible. Practical, operational constraints often limit monitoring to the well-head. This can be overcome for new boreholes by designing in features which facilitate downhole monitoring.

When to monitor will depend on many factors such as equipment type and availability and manpower resources as well as on typical process, condition and problem development times. In principle it is advisable to monitor on a frequent basis initially. Periodic reviews of the data and subsequent diagnosis will determine whether each parameter needs to be monitored at a greater or lesser frequency in the future.

Fig.1 Monitoring of performance, condition and process



Source: CIRIA report: Monitoring, maintenance and rehabilitation of water supply boreholes (1995).

Where automatic systems are used (for example in water level monitoring) then there is flexibility in measurement time intervals. Automation is often linked with data logging and telemetry which provides even further flexibility in when measurements are taken, recorded and processed. Automation cannot be applied to all forms of monitoring and in practice are restricted to parameters such as water level, water quality, power consumption and discharge, ie largely performance related. Such systems are excellent when working properly but are very expensive to install and themselves require regular monitoring and maintenance, ie site visits to check equipment and to carry-out measurement calibration. Manual methods may traditionally be regarded as much cheaper options but may involve higher staff and travelling costs, so reducing long term cost benefits.

Monitoring methods
Monitoring methods are summarised in the Table 1.

Data handling and analysis
The important factors in data handling and processing are *how* (by what method), *who* (who handles raw and or processed data) and *when* (when and how often are the data processed and analysed). It is important that once collected, data are analysed and utilised in diagnosis. Diagnosis can be made more or less easy by the way the data are handled and processed.

Data handling may range from storing data on data sheets to be kept in hard-copy files to fully comprehensive computerised databases. The data and analyses must be available or communicated to those who need to know, so that the correct diagnosis can be made and the correct action taken. In this respect a networked computer system is likely to be more efficient than trying to organise a file copy and transfer system especially where different locations are involved. The former system is obviously more appropriate for the larger borehole operators, whereas for smaller organisations with fewer boreholes, staff, disciplines, departments etc., the latter system can be made to work efficiently.

The easiest form of data processing is a graphical representation of the observation with time which provides a rapid visual indicator of changes in the monitored parameter. Such information on its own, whilst being an indicator to stimulate further investigation, will not be sufficient to make a proper diagnosis. It will always need to be evaluated in conjunction with other existing evidence.

Who handles, processes and analyses the data will depend on available resources but can and should involve all relevant disciplines:

- water resource scientists: hydrogeologists, geologists, and hydrologists
- water quality scientists: chemists, geochemists, and microbiologists
- engineers: water supply, water treatment, operation & maintenance, groundwater, pump, drilling
- managers: supply, resources, information technology, and laboratory

Table 1 Monitoring methods

Monitoring aim	**Parameter**	**Method**
PERFORMANCE	discharge rate	• flow rate meter; totalising flow meter + operating period
	pumping water level	• dip-meter; transducer (in operating borehole)
	static water level	• dip-meter; transducer (in operating or observation borehole)
	specific capacity	• continuous processing of discharge and drawdown data • periodic step drawdown tests
	discharge head	• pressure meter or transducer
	energy consumption	• electricity meter; fuel gauge or Yates meter
CONDITION	abstraction/recharge	• analysis of regional water resources information
	regional water level	• periodic dipping of observation boreholes
	regional water quality	• analysis of regional water resources quality information
	appearance - borehole	• down hole CCTV inspection or photos; geophysical logging, eg calliper log for borehole diameter and acoustic or sonic log for grout seal behind casing
	appearance - pump	• retrieval with either dismantling and direct inspection, or indirect inspection using fibre-optic borescope
	appearance - rising main	• retrieval, dismantling and inspection
	appearance - well-head works	• retrieval with either dismantling and direct inspection, or indirect inspection using fibre-optic borescope
PROCESSES	formation PSD	• sieve analysis of formation samples from drilling
	gravel pack PSD	• sieve analysis of installed gravel pack material
	sand content	• use sand-cone on discharge water
	flow-rate/velocity	• calculation from pumping rate, well design, flow log data
	infill depth	• dip-meter; plumb line; CCTV inspection
	collapse depth	• dip-meter; plumb line; CCTV camera inspection
	gravel pack level	• plumb line or dip-meter
	aquifer status	• compare water levels with hydrogeological situation to assess confined or unconfined status
	water chemistry	• well-head analysis of discharge samples, eg pH, EC, DO • laboratory analyses of fixed samples • in situ downhole measurement by ion-electrodes • downhole measurement by geophysical logging (EC and temperature) • downhole sampling and subsequent analysis
	corrosion	• installation, retrieval and inspection of coupons • voltmeter to measure self potentials • analysis of materials and water chemistry
	geochemistry	• analysis of hydrogeology/geochemistry
	materials	• refer to design/construction records; by inspection
	recharge water quality	• water quality analysis of all recharging waters
	nutrient status	• analysis of TOC, nitrogen, phosphorus, etc
	microbial activity	• Bacterial Activity Reaction Test kits (BARTS) • well-head moncell or downhole coupons • microscopic analysis of water/deposit samples

Source: CIRIA report: Monitoring, maintenance and rehabilitation of water supply boreholes (1995).

DIAGNOSIS

Introduction

Diagnosis involves deducing the what, where, when and why of a change in borehole performance. What and where help to define curative action; when and where are linked to monitoring; what and why help to define preventative action; why and when help identify contributory factors.

These basic principles are summarised in Fig.2. They help to set a simple approach to diagnosis, which can so often be complicated by the range of factors involved in each case.

Approach to diagnosis

There are two basic scenarios for diagnosis:

(a) Diagnosis during routine monitoring. Here the performance, condition and processes involved are known and the story evolves with time. Problems are anticipated and curative or preventative action can be taken in a planned manner in order to avert serious consequences to operations and supply. This approach or variations on it are to be encouraged.

(b) Diagnosis for particular events after they have occurred. A retrospective process where the story is unravelled by piecing together bits of any available historical data, combined with new information gained from post-event investigations. Unlikely to be successful if baseline data are not available or are not reliable.

Currently diagnosis for many borehole operators takes the latter form and frequently runs in to difficulties when insufficient information is available. This approach is not recommended.

As with monitoring, diagnosis can be divided into three main phases. Diagnosis of *performance, condition, process(es)*

Diagnosis of performance

The key elements for diagnosis are abstraction rate, volume and pumping water level. At the simplest level an observed reduction in yield is an obvious indicator of reduction in performance of a borehole. But rarely is that observation adequate to diagnose the reason for that change in performance. It will invariably prove of more benefit to observe yield in relation to pumping and non-pumping water level. Combining these sets of data will in turn allow evaluation of general borehole performance or specific capacity.

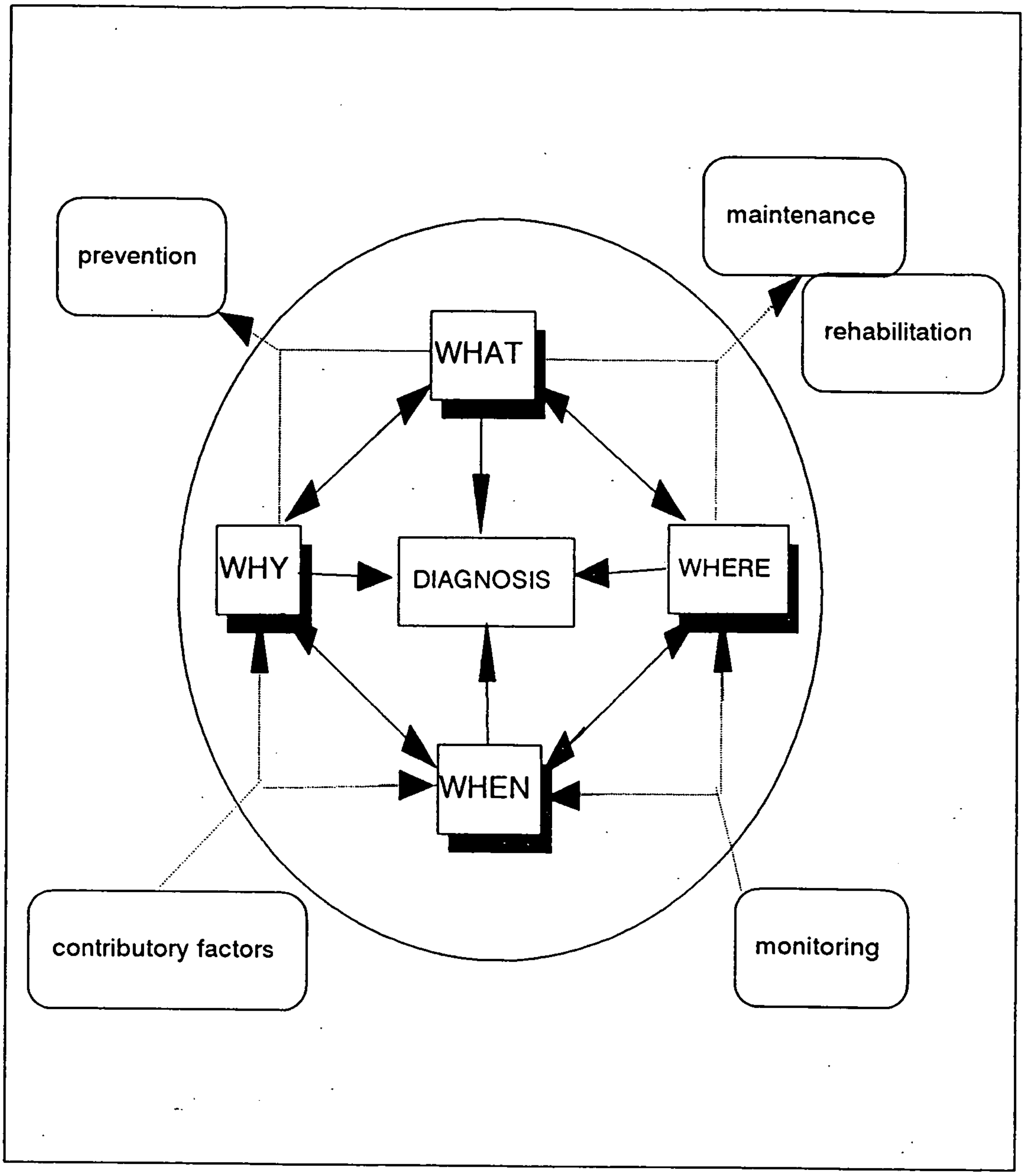
These elements can be recorded continuously or periodically. In either case the data are plotted against time so that any changes can be identified. It should be noted that diagnosis of borehole performance should always be conducted in conjunction with an evaluation of pump performance.

Performance should also be checked by carrying out periodic step pumping tests.

Diagnosis of condition

Diagnosis of condition is usually obtained from direct observation of the component. This applies to equipment on the surface which is directly accessible and to equipment which can be retrieved from the borehole. CCTV cameras and fibre-optic borescopes provide evidence for down-hole components and those which cannot be dismantled.

Fig. 2 Principles of diagnosis



Source: CIRIA report: Monitoring, maintenance and rehabilitation of water supply boreholes (1995).

Diagnosis of process(es)
Whilst a combination of performance and condition diagnosis will often give some good indications of the processes involved, it is always wise to carry out further investigation to fully ascertain the processes involved, ie *why* is the condition as observed?. This knowledge may enable the prediction of conditions beyond those which are directly observable and will allow appropriate preventative measures to be taken.

Water quality, particular chemical parameters, is often considered a key factor in the diagnosis of processes. However they are not always precise or reliable indicators of downhole processes.

This is because:
(a) the parameter value will vary depending on sampling time and location

(b) the various processes occur over a relatively wide range of parameter values

(c) the water chemistry can be affected by localised microbial activity.

MAINTENANCE AND REHABILITATION

Introduction

Maintenance is intended to preserve a level of performance by keeping in good repair both the system and its component parts. Whereas rehabilitation is the process of attempting to restore a system to its original level of performance or its component parts to their proper condition. In applying a cure to a particular problem then in many cases the basic difference between maintenance and rehabilitation is only the degree to which a technique may have to be applied.

For instance, borehole maintenance against recurrent encrustation, if it cannot be avoided, may involve a mild washing with a chemical solution of the screen area; whereas rehabilitation of a badly encrusted screen could involve a suite of treatments procedures such as high pressure jetting followed by repeated treatments of high concentration chemicals, followed by a further hydrodynamical clean-up application. Similarly for an aquifer problem such as dewatering, short term maintenance may involve reduced abstraction during a dry spell when water levels are declining, whereas long term rehabilitation may involve permanent cessation of abstraction or engineered schemes of artificial recharge.

Maintenance and rehabilitation policy

In theory if borehole operators were to adopt a good monitoring, operation and maintenance programme there should never be a need for rehabilitation, as all boreholes would be maintained at peak operational performance and condition. In practice however such a situation would also be dependant on all boreholes having been correctly designed and constructed.

However the number of new boreholes which could be installed under new regimes of improved design, operation and maintenance will be outnumbered by the number of existing ones for many years to come. Rehabilitation will therefore be a higher profile option whilst boreholes are restored to optimum performance and condition and then subsequently maintained by improved monitoring and maintenance strategies.

There may also be some degree of economic restraint on achieving the ideal properly maintained system. In problematic systems it may mean very high maintenance return periods or frequent rehabilitation if the former is not practical from an operational point of view.

Currently most policies lie somewhere between the ideal and the crisis management approach ie:

- a well managed full monitoring and maintenance strategy
- an unpredictable system of responding to events as and when a system fails, which is hardly a strategy at all.

The relationship between borehole performance and maintenance and rehabilitation, as suggested by these two policies is shown schematically in Fig 3. General experience suggests that maintenance is easy and successful if carried out properly on a regular basis at shorter rather than longer intervals.

Boreholes neglected for long periods of time develop to a condition which cannot be fully rehabilitated. With time worsening rates of decline in performance can be expected as various conditions and processes interact to compound or introduce new, problems. It is suggested that where performance has deteriorated by more than 25% full recovery is not practical.

As it is necessary to understand the cause processes relating to borehole performance decline it is equally necessary to understand the cure processes used in recovering performance. It is not therefore considered a good approach to offer standard recipes for a list of known problems.

It is first necessary to think about the what, why, how and where of a problem. By understanding the borehole situation and both cause and cure processes, the engineer has a better chance of matching the correct solution to the problem.

The suggestion of pat recipes for each specific problem has been how the subject has been tackled in the past. This has led to too many disappointing attempts at rehabilitation and maintenance largely because either the cause process has not been fully understood or that the cure process has not been fully understood, or both. In such circumstances any of the following permutations could occur (indeed have occurred):

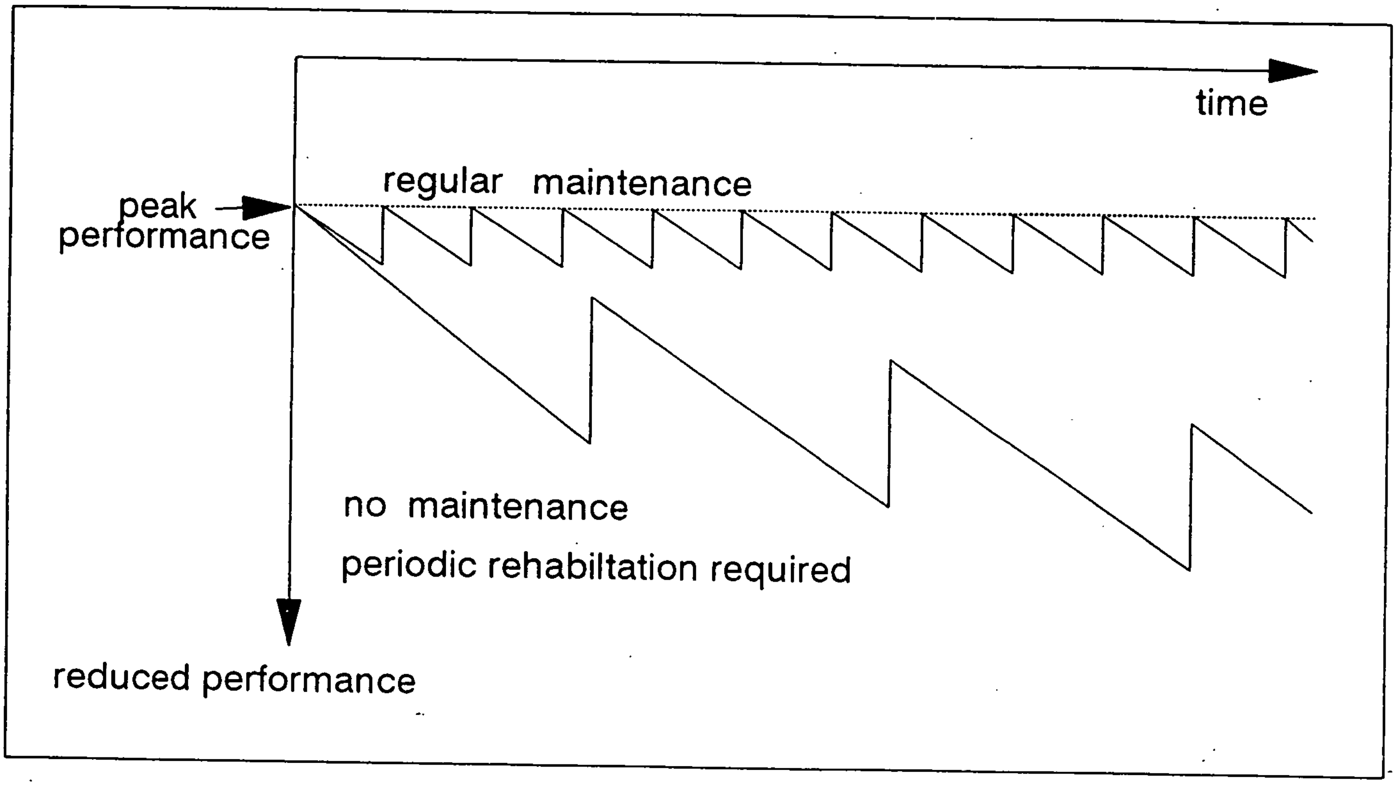
- the correct application of an appropriate method
- the correct application of an inappropriate method
- the incorrect application of an appropriate method
- the incorrect application of an inappropriate method

With only one out of four of these leading to success one can see how a significant proportion of attempts at rehabilitation have in the past met with failure or only partial success.

As with cause processes it is important also to recognise where a process needs to be applied:

- Aquifer
- Borehole
- Pump
- Well-head works

Fig. 3 Borehole performance in relation to maintenance & rehabilitation policy



Source: CIRIA report: Monitoring, maintenance and rehabilitation of water supply boreholes (1995).

For instance applying a process to a pump can be expected to involve some differences in procedure and equipment, compared to when applying the same process to the borehole screen, even though the principles of the process are the same.

Aquifer related processes and methods

Water level recovery

The aim is to induce water level recovery after local or regional dewatering due to over-abstraction. The method involves reduced abstraction by:

- reducing total abstraction from aquifer. This may involve other abstracters in which case will involve negotiation with other operators and the NRA
- reducing abstraction from individual borehole. This may be suitable on short term (seasonal) basis.
- reducing simultaneous abstraction, in order to reduce local dewatering due to interference between neighbouring boreholes.
- induced recharge by utilising seasonally surplus surface water resources. Recharge via boreholes or lagoons is possible but the technology is not yet fully developed to ensure efficiency of process.

Water Quality recovery

The aim is to permit abstraction of groundwater of the original quality prior to deterioration. The method can involve:

- Reduced abstraction: in the cases where brackish or saline water is being induced into a fresh groundwater zone due to pumping, reduced or zero abstraction will slow down or stop but not reverse the process.
- Induced fresh water recharge: to encourage dilution and to reverse groundwater gradient from contaminated zone towards borehole.
- Groundwater flow control: install surface and subsurface barriers to prevent further contamination and to prevent movement of contaminated groundwater into the well. Control can also be achieved by intercepting the contaminated groundwater using specially drilled wells, eg in the case of separating fresh and saline groundwaters special dual level pumping scavenger wells are used.
- Removal of pollution: isolate or remove source of contamination and then remove pollutant from system (ie pump to waste).

Borehole related processes and methods

Removal of infill material

The aim is to remove non-cohesive material from a borehole either before or after another operation or as an operation in its own right; choice of method will depend on the particulate nature and size, and on borehole characteristics; material removed should be regularly examined in order to identify whether its origin is aquifer, gravel-pack or both.

The methods can involve:

- Airlift Pumping: readily available equipment; a flexible process suitable for a wide range of conditions; requires a submergence ratio of 60% which if not naturally permitted can be artificially induced by adding water to borehole; Can apply alternate pumping and surging to loosen-up material if required; airlift pipe should be lowered in stages until borehole cleared to bottom. Process can be stopped once all material has been removed from the hole or once it is apparent that ingress exceeds removal.

- Bailing: using a bailer, can be applied by simple cable tool rig or any rig with a winch system. and is suitable for a wide range of conditions; requires knowledge of internal diameters; can be aggressive and should be applied gently at least initially in order to avoid creation of high pressure or suction forces capable of collapsing casing and screen.

<u>Removal of material clogging casing/screen slots</u>
The aim is to remove material from clogged screen slots, in order to improve flow into the well. The aim will usually also include the cleaning of encrustations attached to the internal surface of the casing and screen, in order to rectify diameter reduction and to remove environments for secondary processes which may occur below the deposit surface at the material-casing contact.

The material may be particulate, of chemical or microbial origin or as is very often the case a combination. The process applied will need to be related to the character and location of the material.

The methods can be:

Physical where the processes basically involve dislodgement (physical breakup and dispersion).

- Brushing:
  Using a wire or stiff nylon brush rotated and oscillated inside the casing and screen string; requires knowledge of diameter of string in all sections; where thick deposits exists may need to be applied in stages using larger diameter brushes. Suitable for all deposits except hard brittle encrustations.

- Jetting:
  A very versatile process if correctly applied; the key variables and the ranges in which they have been applied are given in Table 2 below:

Table 2 Jetting

Variable	Range used	Recommended
Pressure	150 - 8000 psi	1000 psi' for soft deposits 3000 psi' for harder encrustations
(NB these ' pressures are safe in plastic lined boreholes)		
Nozzle diameter	2 - 11 mm	2-3 mm
(NB Pressure and nozzle diameter control flow rate and therefore velocity)		
Flow rate	0.2 - 12 l/s	
Velocity	25 - 500 m/s	>30 m/s
Nozzle - surface distance	25 - 50 mm	25 mm
Head rotation speed	20 - 60 rpm	<30 rpm
Head vertical speed	5 - 30 m/hr	10 m/hr)

Jetting should be applied with simultaneous pumping to remove debris and to create a groundwater gradient into from the aquifer into the borehole rather than vice versa. Results in the field with regard to improvements to borehole yield have been variable because of variable conditions and variable applications. Where CCTV surveys have been carried out it is possible to judge the effectiveness of the cleaning operation on the inside of the casing and screen only.

Laboratory tests have demonstrated that at distances of 20 nozzle diameters from the end of the nozzle (ie 40 mm for a 2 mm nozzle), jet pressure will be only 10% of the exit pressure.

- Explosive treatments:
  Sometimes to break the bond between two different materials (eg a steel casing and an iron encrustation) a shock or series of shocks or vibrations can be effective. A shock can be applied using explosives [a detonator in conjunction with a length of cordex or primacord (a high velocity explosive detonating fuse) set in the borehole in a centralising cage]. There are reports of use of dry ice to generate less controlled shocks by dropping portions of this solid carbon dioxide down boreholes The shock is generated by a rapid change from a solid to a gas phase. Some field trials carried out in the UK suggest that such treatments should never be applied to plastic lined boreholes.

- Ultrasonics:
  This method uses the same process of breaking the bond between two different materials, as aimed for with explosive treatments. The principle of ultrasonic treatments is the generation of very high frequency vibrations. The process is successfully applied in the removal of stubborn scale from laboratory glassware and industrial vessels such as boilers. There are less reports of its use of in boreholes. Applications in oil-industry wells are reported to have caused unwanted effects such as the breaking of cement grout-casing bonding. Laboratory tests suggest method to be ineffective against slimy biofouling deposits.

- Pasteurisation:
  A process commonly applied in other situations for the sterilisation of equipment. The process involves raising the temperature to a level at which most microorganisms cannot survive. It is applicable to boreholes where biofouling is occurring. In such cases it is advocated that temperatures be raised to above 60 °C and held there for 30 minutes. The heat not only kills bacteria but also causes the biofilm to break up and slough off from surfaces to which it is attached. Trials, mainly in Canada, have applied heat in boreholes by the injection of high pressure steam or hot water and by the in situ heating of the water using an electric heating element.

- Irradiation:
  Preliminary trials in the USA suggest that the levels of irradiation necessary would be no greater than those used in food irradiation treatments. The process works by splitting water molecules and generating biocidal hydrogen peroxide rather than by killing bacteria by radiation. There are reports of the use cesium isotopes in boreholes in some Eastern block countries. It is likely that with the public fear of radioactive processes, this process will not become widely used in boreholes.

Chemical - where the processes basically involve dispersing (deflocculating), dissolving and disinfecting. The chemicals used may themselves have other beneficial properties or they may be used in combination with other chemicals with such properties:

- wetting agents are used to improve penetration of chemical solutions.
- sequestering and chelating agents are used to prevent dissolved material re-precipitating.
- inhibitors are used to prevent chemical reactions with certain borehole components and materials

- *Disperse*

The commonest dispersant used in boreholes are polyphosphates (Eg sodium tripolyphosphate or hexametaphosphate, such as Calgon). These surfactants act by surrounding and breaking the bonding between individual particles which make up the clogging material. They are commonly used where clay and fines make up the clogging layer. Recommended application is 20 -40 kg/m^3 of water in the borehole, added as a solution. Phosphate is the limiting bacterial nutrient in groundwater and in order to discourage increased microbial activity care should be taken to remove all the chemical from the borehole after treatment. Practitioners often add a 50-100 ppm hypochlorite solution to the borehole when treating with polyphosphate.

Detergents such as some of the foams used for drilling also have a similar effect as Calgon.

- *Dissolve*

In practice this means acids such as

Hydrochloric - the commonest; in the past people have used industrial grade (muriatic) but now only food-grade should be used because of the traces of impurities in the former; is supplied as 36%; minimum downhole concentration should be 18%. When applying downhole pH should be continuously monitored so that fresh acid can be added to replace that which is spent. When used to remove biochemical iron deposits this is particularly important as it is believed that at a pH above 3, gel-like deposits can form which can reclog the system. As with all chemicals it is important to be aware of the by-products generated by reaction with all down-hole materials. For example carbon dioxide and pressure build-up when acids are used to dissolve calcium carbonate. The other danger is the dissolution of natural cementing material in the formation adjacent to the borehole which may cause fines to be released, which may migrate and themselves cause particulate clogging.

Sulphamic - a slower reacting acid than hydrochloric and is supplied in a granular or pelletized form (It is the main ingredient of Johnson's Nu-well acid).

Phosphoric - sometimes recommended for treating manganese based deposits.

Citric - a mild acid

Hydroxyacetic - a mild acid with biocidal and sequestering properties used against biofouling deposits; supplied at 70% concentration and used downhole at an effective 10% concentration.

- *Disinfect*

The most common disinfectants are the chlorine based compounds - chlorine gas, chlorine dioxide, sodium hypochlorite, calcium hypochlorite ('bleaching powder'). Others include hydrogen peroxide, ozone, and quaternary ammonium compounds (Eg hyamine). It is best not to use calcium hypochlorite in boreholes since most calcium salts are relatively insoluble and reaction products may themselves cause a clogging problem.

When using chlorine it is not the amount of chlorine which is added to the borehole but the free-chlorine residual that exists in the borehole. To be effective chlorine residual should be continuously monitored so that fresh solutions can be added when needed.

Hydrogen peroxide is environmental friendly since the by-products of reaction are heat and water.

Removal of material from gravel-pack/aquifer formation
The aim is to remove material which is clogging the pores of the formation adjacent to the screen and the gravel-pack or formation stabiliser where used. The material may be particulate, of chemical or microbial origin or a combination. The methods can be:

Physical - where the processes basically involve dislodgement (physical breakup and dispersion). If applied from within the borehole then severe energy dissipation must be expected due to transmission through the screen. To be effective it is necessary to generate grain mobilisation. It has to be appreciated that this is difficult especially for instance if the gravel-pack is confined by overburden pressures or if the formation is confined or cemented.

Commonly used physical methods include jetting, mechanical surging, overpumping, airlift-pumping and surging.

Chemical - where as discussed above, the processes basically involve dispersing (deflocculating), dissolving and disinfecting. The methods are those as discussed as above

Pump and headworks related processes and methods

The same processes applied for boreholes can also be applied to pumps, rising mains and headworks.

DESIGN AND OPERATION

Design and construction

The influence of borehole design and construction on performance is primarily geared towards maximising yield. with relatively little consideration given towards performance maintenance. This is not good practice.

The aims of good design and construction practice should be to minimise or avoid problems, to make monitoring easy and effective and to allow scope for maintenance work where it is at all anticipated.

The factors are generally not different from many of the principles of good design and construction practice; ie (a) good hydraulic design (with special attention to entrance velocities - the widely recommended design value of 0.03 m/s will in variable alluvial formations often hide much higher localised values - a general value of 0.01 m/s is recommended particularly in the absence of detailed permeability and flow data); (b) use of the right construction method and material; (c) good supervision and quality control; (d) keeping of accurate records and the establishment of benchmark data.

Operation
The influence of operating schedule on performance should be well understood but is frequently ignored.

Intermittent pumping enhances particle redistribution process such as sand-pumping, due to the high hydraulic gradients and consequent velocities generated at start-up. Frequent movement of the water table through unsaturated or partially saturated cone of depression enhances oxygen dependent processes such as iron precipitation and biofouling which leads to increased rates of clogging.

Pumping at high rates for too long a period can result in regional aquifer depletion and local dewatering. This may lead to pumping water levels dropping below the top of the screen, leading to cascading and again the enhancement of oxygen dependant clogging processes. It also might lead to fines migration and subsequent clogging and/or abrasion of components.

Continuous operation at a moderate discharge is to be preferred to intermittent operation at a higher discharge.

High velocities and turbulence can enhance biofouling and should generally be avoided. Consideration should also be given to the type of velocity distribution in different types of pumps.

Care should always be taken that when introducing new pumps, increased pump speeds or operating hours etc, that the conditions imposed on the system do not conflict with the original design criteria.

IMPORTANT ACKNOWLEDGEMENT

Much of the basic material for this report has come from efforts made in the preparation of a CIRIA (Construction Industry Research and Information Association) report, namely:

Howsam, P., Misstear, B. and Jones, C. (1995)
Monitoring, maintenance and rehabilitation of water supply boreholes
CIRIA Report 137 London

REFERENCES

Key References
This review made extensive use of the two references given below. They are considered to be the two most up to date and comprehensive references on borehole monitoring, maintenance and rehabilitation practice. They both contain extensive reference lists/bibliographies to which the reader is referred.

1. American Water Works Association Research Foundation (1993)
   Borch, M.A., Smith, S.A. & Noble, L.N.
   Evaluation and restoration of water supply wells
   AWWARF (Denver, USA).

2. CIRIA Report 137 (London)
   Howsam, P., Misstear, B. and Jones, C. (1995)
   Monitoring, maintenance and rehabilitation of water supply boreholes.

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METHOD SUMMARY SHEETS
for BoreHole Performance Maintenance section

Method Summary Sheet (BHPM 1):	Borehole performance/maintenance - cause processes
Method Summary Sheet (BHPM 2):	Borehole performance/maintenance - monitoring
Method Summary Sheet (BHPM 3):	Borehole performance/maintenance - diagnosis
Method Summary Sheet (BHPM 4):	Borehole performance/maintenance - cure processes
Method Summary Sheet (BHPM 5):	Borehole performance/maintenance - design/construction factors
Method Summary Sheet (BHPM 6):	Borehole performance/maintenance - operational factors
Method Summary Sheet (BHPM 7):	Borehole performance/maintenance - cost-effectiveness evaluation - case study (BHPM 7)

Method Summary Sheet (BHPM 1)

Title: Borehole performance/maintenance - cause processes

Scope and use of method:
A check-list of the processes which cause reduction in borehole performance.

Recommendation
A full understanding of the range. nature and location of cause processes is necessary in order to be able to select appropriate preventative or curative measures.

Method:
Use check-list to help consider all appropriate options relating to borehole design, construction and operation as well as to maintenance and rehabilitation. Remember these processes can occur in the aquifer, the borehole, the pump and the well-head works/distribution.

PHYSiCAL:	
particle redistribution:	- clogging - abrasion
CHEMICAL	
encrustation	- clogging
corrosion	- component failure
	- water loss
MICROBIAL	
biofouling	- clogging
biocorrosion	- component failure
	- water loss
OPERATIONAL:	- enhanced physical/chemical/microbial processes
aquifer over-abstraction	
inappropriate operating schedules	
STRUCTURAL:	- enhanced physical/chemical/microbial processes
poor design and construction	
inappropriate component materials	

Key References

1. American Water Works Association Research Foundation (1993)
   Borch, M.A., Smith, S.A. & Noble, L.N.
   Evaluation and restoration of water supply wells
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   CIRIA (London, UK)

Method Summary Sheet (BHPM 2)

Title: Borehole performance/maintenance - monitoring

Scope and use of method:
In the development of monitoring and maintenance strategies - selection of monitoring parameter/frequency/method

Recommendation

Primary (minimum) level of monitoring:	Performance
Secondary level of monitoring:	Condition
Tertiary level of monitoring:	Process(es)

Collate, analyse and communicate monitoring data

Method:
Use check-list along with other relevant factors to help identify appropriate monitoring parameters, methods and frequencies.

PERFORMANCE MONITORING

Parameter	Method	Frequency
discharge rate	flow-meter	High
operating hours	clock/meter	High
pumping water level	dip-meter	High
rest water level	dip-meter	High
specific capacity	calculation	High
efficiency	step pumping test	Low

CONDITION MONITORING

Parameter	Method	Frequency
component appearance	CCTV/geophysical logging	Low
	retrieve and inspect	Low
pump efficiency	power/temperature meter	Medium
pump vibration	observation	High

PROCESS MONITORING

Parameter	Method	Frequency
Physical:		
sand content	sand cone	Medium
flow velocities	calculation	Low
infill or collapse depth	plumb-line/dip-meter	Low
Chemical:		
water chemistry	well-head analysis	Medium
	down-hole ion-electrodes	Medium
	down-hole coupons	Medium
	laboratory analysis	Medium
Microbial:		
microbial activity	field kit or lab analysis	Medium
	well-head moncell	High
	down-hole coupons	Medium
nutrient status/water chem.	well-head or lab analysis	Low
flow velocities	calculation	Low

High: Daily to monthly
Medium: Monthly to every 6 months
Low: 6 monthly to every 5 years

Key References

1. American Water Works Association Research Foundation (1993)
Borch, M.A., Smith, S.A. & Noble, L.N.
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2. CIRIA Report 137 (London)
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CIRIA (London, UK)

Method Summary Sheet (BHPM 3)

Title: Borehole performance/maintenance - diagnosis

Scope and use of method:
In the development of monitoring and diagnosis, operation and maintenance strategies - check-list of factors for consideration

Recommendation
Ensure adequate information is available before trying to make a diagnosis.

Undertake diagnosis during routine monitoring. The picture evolves with time and therefore problems can be anticipated, curative or preventative measures can be taken in a planned manner and serious consequences to operations and supply can be averted. Retrospective diagnosis after failure is rarely satisfactory.

Method:
PERFORMANCE
- Plotting of discharge, pumping/rest water levels, drawdown and specific capacity against time to see trends.
- Comparison of periodic step pumping test results.

CONDITION
- Usually by direct or indirect observation.

PROCESS
- By combining information on chemical, physical and microbial quality of water with information from condition monitoring.

Key References
1. American Water Works Association Research Foundation (1993)
   Borch, M.A., Smith, S.A. & Noble, L.N.
   Evaluation and restoration of water supply wells
   AWWARF (Denver, USA)

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Method Summary Sheet (BHPM 4)

Title: Borehole performance/maintenance - cure processes

Scope and use of method:
For the understanding and use of cure processes for borehole maintenance and rehabilitation.

The purpose of maintenance or rehabilitation can be one or more of the following

Process control
Condition rectification
Performance recovery

Maintenance is aimed at process control in order to prevent condition and performance deterioration. Rehabilitation is aimed at condition rectification and performance recovery.

Recommendation
Ensure that the nature and location of the problem is fully understood before selecting a cure process.

Ensure that the nature of the cure process is also fully understood before applying it.

This will help to ensure that the correct remedy is applied and that it is applied correctly.

In all cases take action to prevent or reduce problem recurrence.

Method:

AQUIFER

Aim	Method
Water level recovery	reduce local or regional abstraction induce additional recharge
Water quality recovery	reduce abstraction induce fresh-water recharge prevent further pollution remove contaminant from aquifer blend with other sources

BOREHOLE

Aim	Method
Removal of infilling deposits	airlift pumping bailing
Removal of deposits from internal surface of casing/screen	high pressure jetting brushing or swabbing explosive or ultrasonic treatment chemical dissolution or dispersion

Removal of deposits from screen slots	high pressure jetting + pumping surging + pumping chemical dissolution or dispersion combined physical/chemical process explosive or ultrasonic treatment
Removal of deposits from external surface of casing/screen	chemical dissolution or dispersion combined physical/chemical process explosive or ultrasonic treatment
Removal of deposits from gravel-pack and adjacent formation	surge-block surging + pumping airlift surging + pumping high pressure jetting + pumping chemical dissolution or dispersion combined physical/chemical process
Repair of ruptured or perforated casing /screen	reline in situ repair retrieve + replace seal off section of borehole
Correction to faulty design and construction	reline in situ modification seal off section of borehole
Corrosion reduction	coatings cathodic protection reline replace component
Biofouling reduction	apply chemical disinfectants/biocides pasteurisation

PUMP (after retrieval)

Aim	Method
Removal of deposits from external surfaces of pump + rising main	high pressure jetting brushing or swabbing chemical dissolution/dispersion
Removal of deposits from internal surfaces of pump + rising main	dismantle + high pressure jetting dismantle + brushing or swabbing chemical dissolution/dispersion
Rectify electrical. or mechanical fault	dismantle and replace part
Corrosion reduction	coatings replace with alternative material
Biofouling reduction	apply chemical disinfectants/biocides pasteurisation

WELL-HEAD WORKS

Aim	Method
Removal of deposits from internal surfaces of well-head pipes and fittings	dismantle + high pressure jetting dismantle + chemical dissolution

Repair of non-functioning part	dismantle + repair or replace
Repair of rupture /perforation to prevent leakage	dismantle + repair or replace reseal or patch
Biofouling reduction	apply chemical disinfectants/biocides pasteurisation

Key References

1. American Water Works Association Research Foundation (1993)
Borch, M.A., Smith, S.A. & Noble, L.N.
Evaluation and restoration of water supply wells
AWWARF (Denver, USA)

2. CIRIA Report 137 (London)
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Monitoring, maintenance and rehabilitation of water supply boreholes.
CIRIA (London, UK)

Method Summary Sheet (RHPM 5)

Title: Borehole performance/maintenance - design/construction factors

Scope and use of method:
For recognition of cause process(es) in performance deterioration in existing boreholes and for consideration in the selection of design and construction specifications for new boreholes.

Recommendation
Ensure an integrated long term approach to borehole design and operation by taking into consideration all factors - available groundwater resources and quality; demand; engineering and material options; economics; policy, legislation and planning.

Method:
Use check-list in conjunction with other factors relevant to borehole design and performance, to maximise performance over time.

1. select optimum drilling method for conditions at each site.
2. select materials for construction appropriate to hydrogeology.
3. carry out post construction well development and testing with care and attention.
4. ensure good supervision and quality control during all stages of construction.
5. ensure casing and screen diameters are adequate for the passage not only of pumps but also for monitoring and inspection equipment. (ideally install dip or inspection tubes: 18-50 mm for water level probes; 80-100 mm for CCTV).
6. ensure that level of top of screen is well below any anticipated maximum pumping water level, particularly where iron fouling is anticipated
7. adopt a maximum effective average entrance velocity of 0 01 m/s for screen design (assume a 50% screen blockage). Check also that approach velocities at the formation/filter interface are not high.
8. design not for maximum yield but for optimum and sustainable performance This may involve incorporating features in the design to facilitate monitoring and maintenance.

Key References

1. American Water Works Association Research Foundation (1993)
Borch, M.A . Smith, S A. & Noble. L N
Evaluation and restoration of water supply wells
AWWARF (Denver. USA)

2. CIRIA Report 137 (London)
Howsam, P., Misstear, B.D. and Jones, C. (1995)
Monitoring, maintenance and rehabilitation of water supply boreholes.
CIRIA (London, UK)

Method Summary Sheet (BHPM 6)

Title: Borehole performance/maintenance - operational factors

Scope and use of method:
For recognition of cause process(es) in borehole performance deterioration and for consideration in the selection of borehole operating schedules and in the design of new boreholes.

Recommendation
Ensure an integrated long term approach to borehole design and operation and maintenance by taking into consideration all factors - available groundwater resources and quality; demand; engineering and material options; economics; policy. Legislation and planning.

Method:
Use check-list in conjunction with other factors relevant to borehole design and performance, to maximise performance over time.

1. Do not operate boreholes at their maximum physical capacity
2. Operate a borehole continuously at a lower rate rather than intermittently at a higher rate for a given demand.
3. Do not allow pumping water level to fall below the top of the screen.
4. Operate borehole within any limitations imposed by periodic declines in aquifer capacity.
5. Monitor and record performance and operating schedule.

Key References

1. American Water Works Association Research Foundation (1993)
Borch, M A., Smith, S.A. & Noble. L N
Evaluation and restoration of water supply wells
AWWARF (Denver, USA)

2. CIRIA Report 137 (London)
Howsam, P., Misstear, B. and Jones, C. (1995)
Monitoring, maintenance and rehabilitation of water supply boreholes.
CIRIA (London, UK)

Method Summary Sheet (BHPM 7)

Title: Borehole performance/maintenance - cost-effectiveness evaluation

Scope and use of method:
For evaluating the cost-effectiveness of various monitoring and maintenance options. The spreadsheet based method is:
(i) relatively simple and easy to apply by a range of professional disciplines.
(ii) flexible in relation to the wide range of hydrogeological and groundwater engineering circumstances likely to be encountered.
(iii) flexible in relation to the amount and quality of data available.
(iv) flexible in relation to the users needs and circumstances.

In all cases the user goes through a three stage process: guided data input to a structured spreadsheet file, selected data analysis and a choice of result presentation.

Recommendation

The consequence of maintaining or not maintaining borehole performance can be far reaching with significant cost implications. A cost-benefit analysis, taking into account all the factors involved, enables the selection and adoption of a cost-effective strategy.

The method is appropriate for people who are closely involved with the day-to-day management of groundwater abstraction systems, for people who are involved in the planning and implementation of water supply systems and for those who are involved at the project feasibility and financing level. It can be used as either a stand-alone tool or as part of an integrated water management system.

Method:
The assessment of cost-effectiveness can be carried out in two ways. One is to take into account only the anticipated costs 'with' and 'without' m & m (or for different levels of m & m), in order to show simply whether it is more or less expensive to monitor and maintain than not to (or which is the cheaper of two different m & m strategies). Another way is to relate the costs of well management to well performance for 'with' and 'without' m & m (or for different levels of maintenance).

The method makes two basic assumptions: (I) that there are three main components which are important in the assessment of cost effectiveness - these are costs of management options, frequencies with which costs are incurred and well performance over time; (ii) that effective m & m fulfils its objective of the maintenance of a standard of service and that the costs are incurred in doing so.

There are two main steps in the assessment of the cost-effectiveness of m & m. These are an internal technical/monetary assessment, concerning the management of the groundwater abstraction system itself, and external factors relating to water use, water users and the environment in which water abstraction is taking place.

An external assessment is included, which reflects the environment in which the groundwater system operates. This assessment recognises that agents (users or suppliers) may derive benefits (and costs) over and above those which can be measured in monetary values, and that these agents may be willing to commit extra capital and recurrent expenditure in order to secure these non-monetary, less tangible, benefits. The external assessment is compatible with the principle of a 'predefined standard of service'.

The broad structure and content of the method developed are shown in Figure 1.

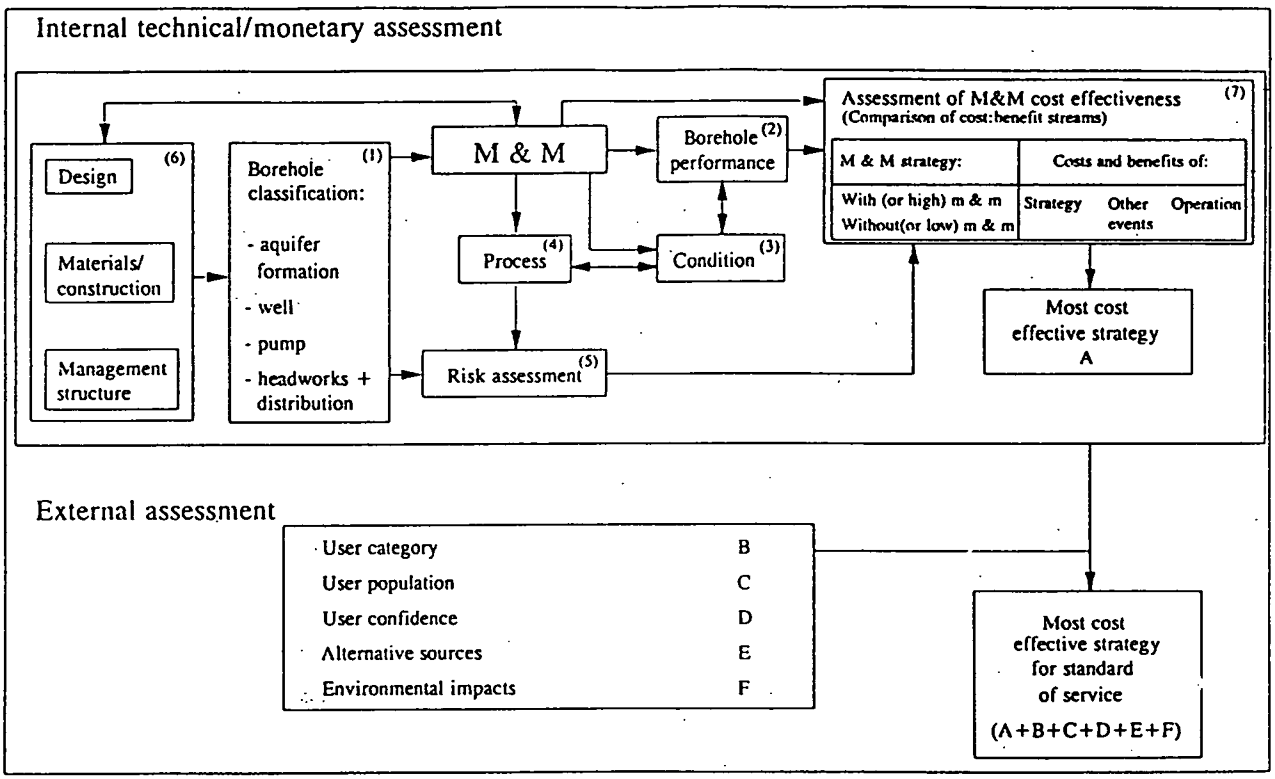

Figure 1: Cost effectiveness assessment of monitoring and maintenance

Key Reference

1. CIRIA Report 137
   Howsam, P., Misstear, B.D. & Jones, C.R. (1995)
   Monitoring, maintenance and rehabilitation of water supply boreholes.
   CIRIA (London, UK)

2. ODA Project 5478A Report
   Sutherland, D.C., Howsam, P. & Morris J. (1993)
   The Cost-effectiveness of Monitoring and Maintenance Strategies associated with Groundwater Abstraction
   Silsoe College (Cranfield University)

COST-EFFECTIVENESS EVALUATION METHOD
CASE STUDY - publicly owned deep tubewells for irrigation in Pakistan

This case-study has been prepared with data supplied by engineers during a recent BGS/ODA sponsored visit to Pakistan. The data for publicly owned deep tubewells (DTWs) was supplied by staff of the International Waterlogging and Salinity Research Institute IWASRI) and the Irrigation Research Institute (IRI) in Lahore. Some of the staff have close contacts with, or have previously worked for, the various monitoring organisations of the Water and Power Development Authority (WAPDA).

The data supplied is typical for the conditions with which the engineers are familiar and therefore represent an average case. Only costs associated with well management and the frequency with which they are incurred, have been considered. The brief nature of the visits precluded detailed investigation of well performance data. However, as a typical example it provides a very useful indicator of the order of magnitude of the costs/benefits of an effective monitoring and maintenance (m&m) strategy. This example also indicates, because of the way in which the method is formatted, that well performance data (which may be lacking in many evaluation situations) is not always necessary in order to make some preliminary general evaluation. It would be important, however, when considering boreholes in detail.

The exchange rate for the example below is £1 = 50 Pakistan Rupees. The discount rate used for this analysis is 10%.

The costs associated with borehole management are as follows:

Monitoring:	Recurring costs (annual)	20,000 Rupees (R)
Maintenance:	Recurring costs (annual)	25,000 R
New well:		1,000,000 R
Rehabilitation:		25,000 R
Pump replacement:		200,000 R
Operating costs:	(Average annual with m&m)	70,000 R
	(Average annual without m&m)	77,000 R

The frequency with which well management costs are incurred are as follows:

	With m&m	Without m&m
New well	20 years	15 years
Rehabilitation	10 years	10 years
Pump replacement	12 years	4 years

The above data was input to the spreadsheet model and produced the following results:

The net present costs, over twenty years:	
With monitoring and maintenance	1,150.000 Rupees
Without monitoring and maintenance	1,400,000 Rupees

The results are also summarised in Figure A. In this, there would appear to be a financial argument in favour of looking at routine m&m as a strategy.

Sensitivity analysis shows that the use of different discount rates would not affect this conclusion. In this case where operating costs do not make up so large a percentage of total costs, the costs associated with infrequent events, such as new well construction are particularly significant. For example, if the without m&m pump life was 8 years rather than the 4 years, then there would be little to choose between with and without m&m strategies regarding long term costs.

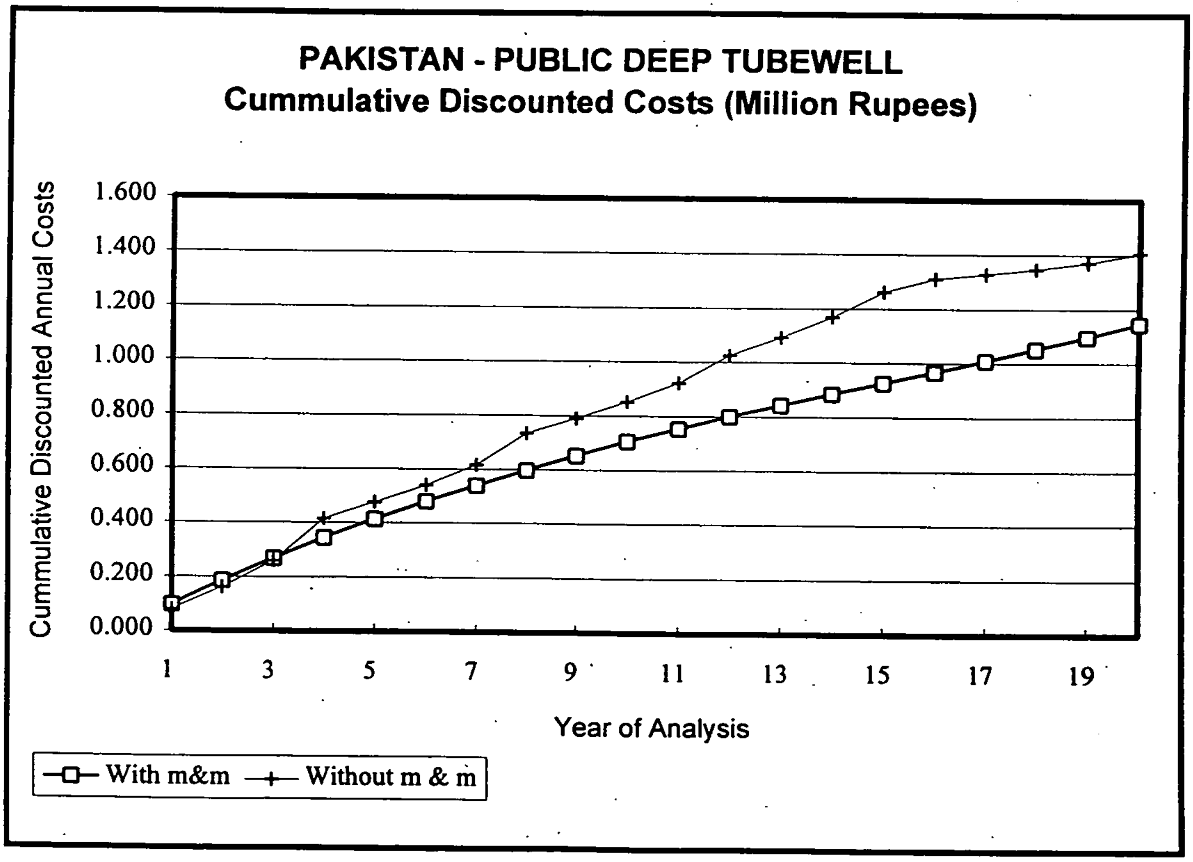

Figure A: Case Study - Public deep tubewells for irrigation, Pakistan