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Overseas Geology Series

UNCONSOLIDATED SEDIMENTARY AQUIFERS: REVIEW NO 1 - DESIGN OF BOREHOLES

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Sigatoka River flood plain, Fiji

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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 issues involved in the design of boreholes, which are the prime means of exploiting thick (>20 m) UNSAs. All the accepted criteria used to design boreholes are presented. The review presents a logical design procedure incorporating new methods which will enhance the design process. In particular, the usual method for the selection of gravel packs is improved and a technique is described which allows the performances of different borehole designs to be compared, prior to construction.

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

INTRODUCTION

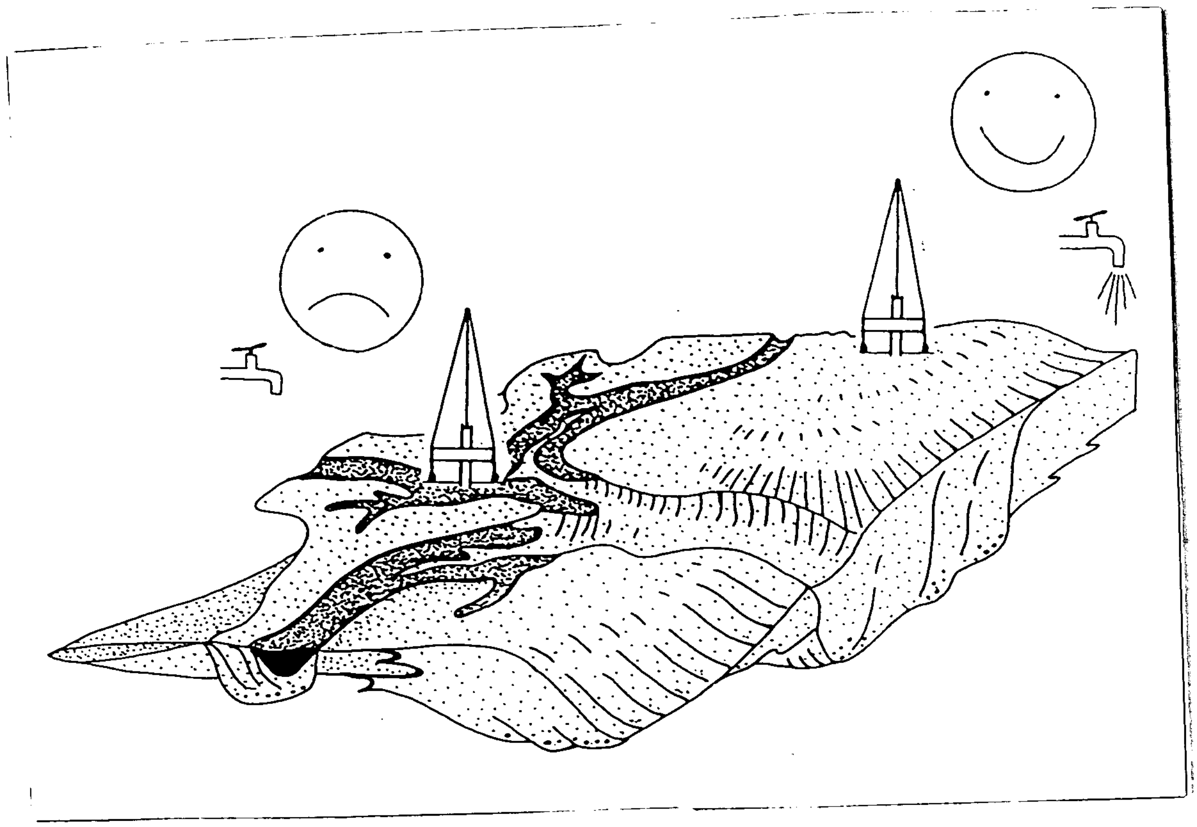
WHAT ARE UNSAs AND WHY IS IT IMPORTANT TO UNDERSTAND THEM?

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:

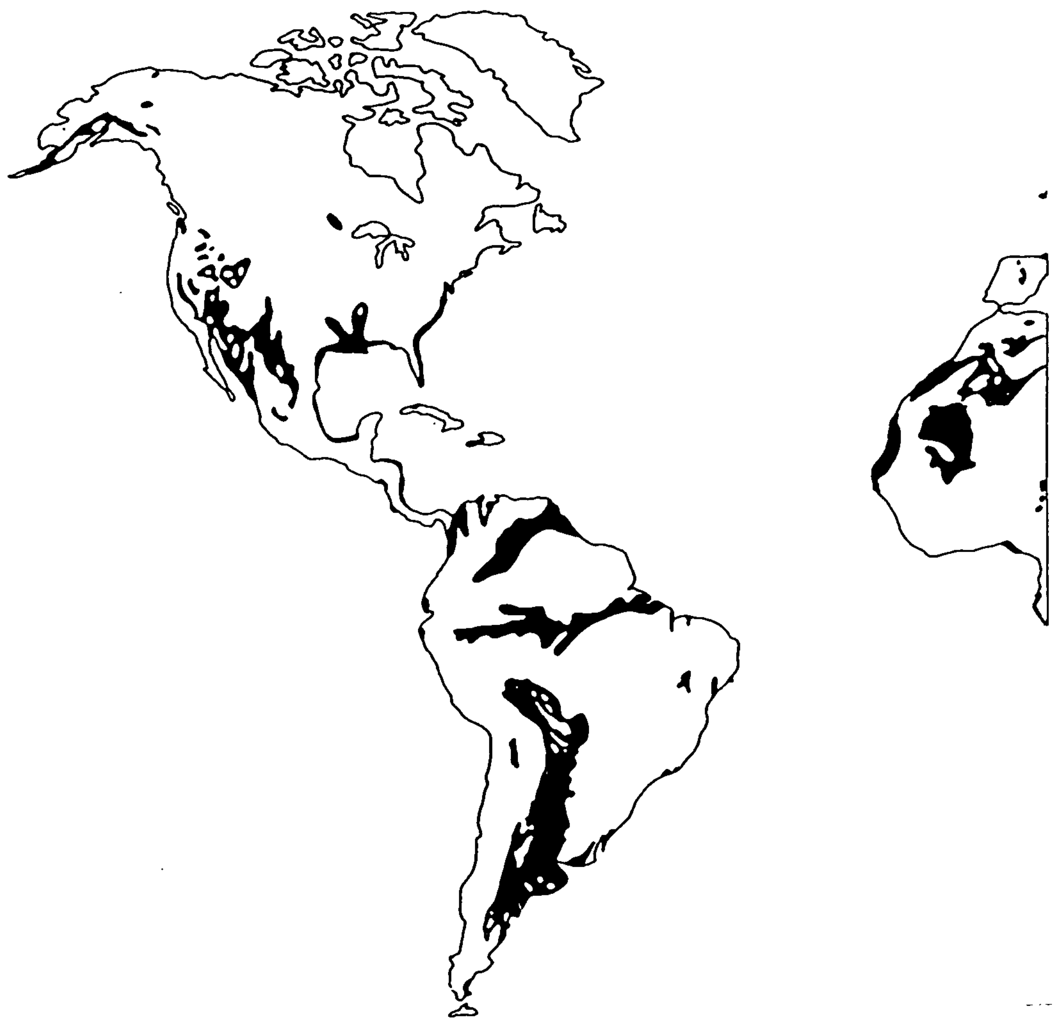
> *"The search for ground water most commonly starts with an investigation of non-indurated sediments. There are sound reasons for this preference. First, the deposits are easy to drill or dig so that exploration is rapid and inexpensive. Second, the deposits are most likely to be found in valleys where 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

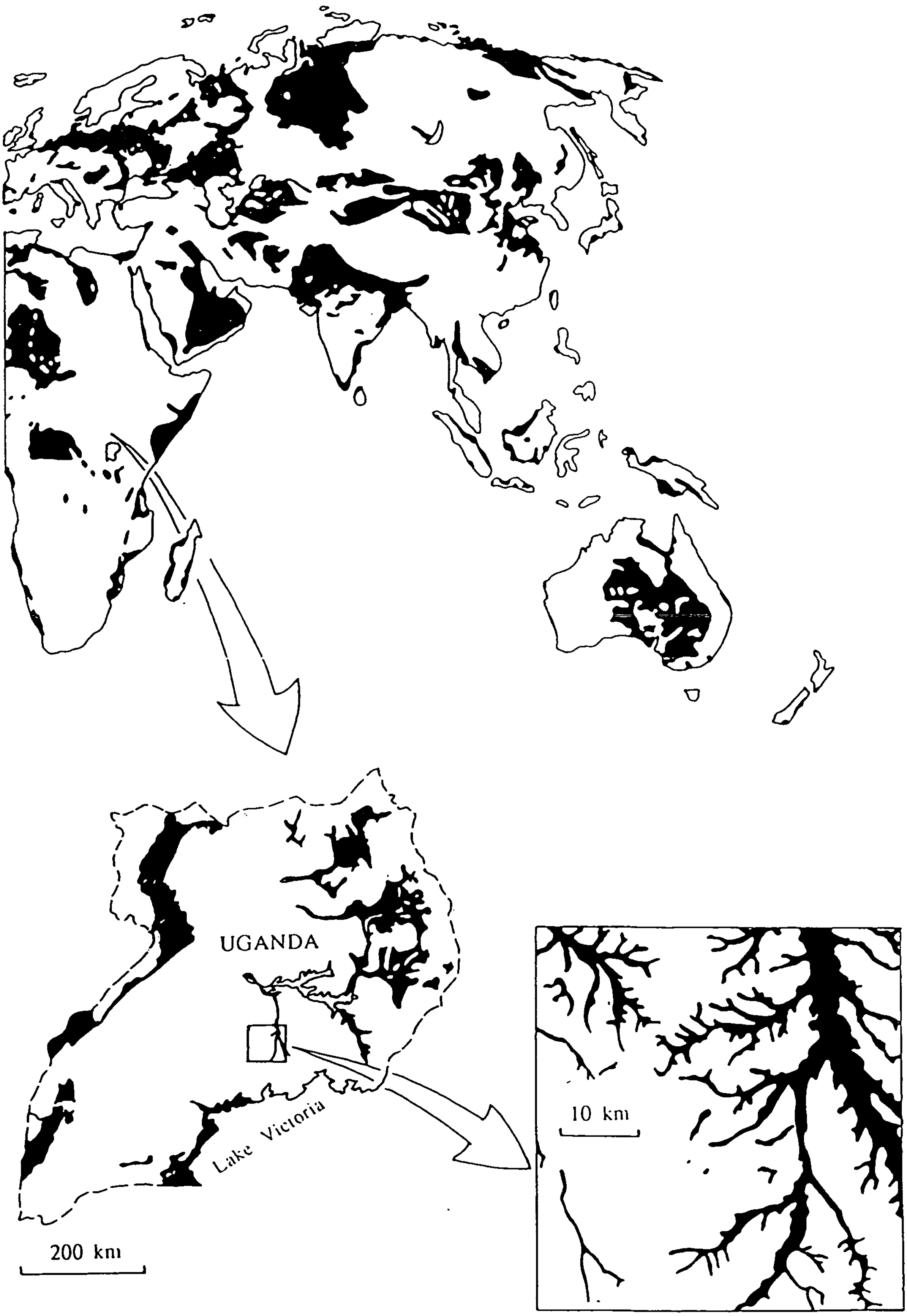
- The map shows the distribution of the thickest and most extensive Quaternary deposits in the world. The great majority of these are unconsolidated, and many include water-bearing deposits (UNSAs).

- 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 sediments 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

DESIGN OF BOREHOLES

1. AIMS

2. BACKGROUND

3. THE METHOD: THE DESIGN OF BOREHOLES

3.1 Definition of Borehole

3.2 General Criteria to be met in Borehole Design

3.3 Design Sequence

Step 1: Data collection
Step 2: Select sustainable yield
Step 3: Select screen and lower casing external dimensions
Step 4: Predicting borehole drawdown resulting from flow through the aquifer
Step 5: Selection of material for casing and screen
Step 6: Selecting pump casing dimensions
Step 7: Select lower casing dimensions
Step 8: Gravel pack and screen slot size
Step 9: Sanitary protection
Step 9a: Predict borehole losses (s_{bhi})
Step 10: Comparison of different designs
Step 11: Select optimum borehole design

REFERENCES

Method Summary Sheet (bhd1):	Borehole Design Sequence
Method Summary Sheet (bhd2):	Determining the Ryznar Stability Index
Method Summary Sheet (bhd3):	Selecting Gravel Pack and Screen Slot Size
Method Summary Sheet (bhd4):	Predicting Head Losses Inside Boreholes

1. AIMS

The following is a review of accepted and new procedures used for preparing the specifications for boreholes to be drilled in UNSAs.

2. BACKGROUND

The procedures in general use for borehole design are largely empirical but have proved to be satisfactory. These procedures are included in the following chapters. Until recently, no theoretically correct method existed for predicting the relationship between drawdown and yield for a borehole. A method is presented which allows this to be done. Thus, for the first time the costs of different designs can be prepared and an optimum design can be selected. It is this new procedure which is also presented in this review and which enhances the existing procedures.

An important feature of borehole design is the selection of the gravel pack and screen slot size. Recent work in Eastern Europe has shown that the frequent premature failure of boreholes in UNSAs is probably explained by the aquifer material being ill-sorted. Terzaghi's well-proven techniques for the design of gravel packs have been adapted to meet the problems posed by this ill-sortedness. This improved technique is also included in the following chapters.

3. THE METHOD: THE DESIGN OF BOREHOLES

A method is presented for the design of boreholes in UNSAs. The method is appropriate to reasonably homogeneous, thick, permeable deposits. In multi-layered strata, or where complex designs using, for example, telescoped screens or pumps below the screens, more exotic techniques must be used for design. The key references give sufficient information to allow such design methods to be developed.

Summary Method Sheet (bhd1) consists of four pages and is a précis of the entire design process. Summary Method Sheets (bhd2), (bhd3) and (bhd4) describe procedures used in the design process namely, the calculation of the Ryznar stability index (is environment encrusting or corrosive?), the selection of gravel pack and screen slot size and the calculation of borehole head losses (what is the CQ^2 term of step drawdown tests $s_w = BQ + CQ^2$).

3.1 Definition of Borehole

For the purposes of this Review a borehole is either too narrow or too deep to be constructed by hand, in contrast a well is not. In UNSAs, boreholes in general, comprise of a casing to house the pump and a screen to allow entry of the water to the well. The screen is a pipe with perforations, usually referred to as slots. Water enters the slots and rises up inside the screen towards and into the blank walled casing en route to the pump intake. A gravel pack will usually be used surrounding the screen but occasionally the aquifer material itself is adequate. Fig 1 shows a typical borehole.

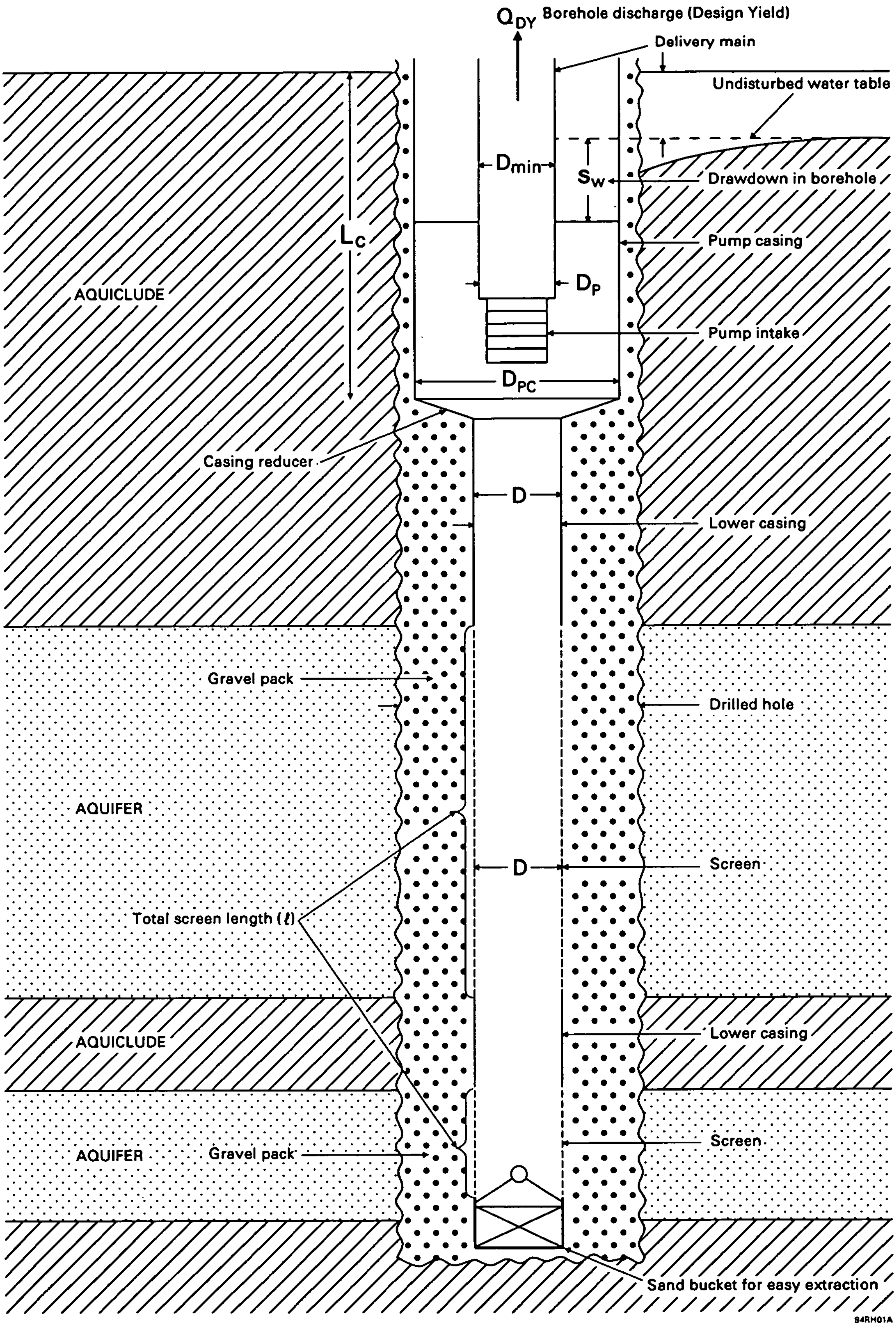


Fig 1. A typical borehole and notation used

NOTATION:

		Units
Q_{DY}, Q_w	Design yield of borehole	m3/second
$D_{(min)}$	(minimum) diameter of screen and lower casing	m
ℓ	Total length of screen	m
s_w	Drawdown in borehole	m
s_a	Drawdown in aquifer	m
s_{bhi}	Drawdown (head loss) incurred in borehole	m
s_{skin}	Drawdown ( ) due to borehole wall damage	m
L_c	Length of pump casing below ground level	m
D_{PC}	Diameter of pump casing	m
D_p	Maximum diameter of pump intake or delivery main	m
P_c	Collapse strength of casing or screen	psi
d_n	n% of sieved material is finer than grain size d (mm)	mm
d_{np}	d_n for gravel pack	mm
d_{nA}	d_n for aquifer material	mm
S	Slot size	mm
d_{nAC}	d_{nA} for coarse component of illsorted portion	mm
d_{nAF}	d_{nF} for fine component of illsorted portion	mm
CQ^2_w	Equals s_{bhi}, C is a constant calculated using Eqn 14	sec^2/m^5
α,β	Constants allowing calculation of friction and momentum losses (see Table)	sec^2/m^5
g	Acceleration due to gravity	m/sec^2
f_s	Friction factor of individual lengths of casing in borehole	(-)
ℓ_s	Length of individual lengths of casing in borehole	m
D_s	Diameter of individual lengths of casing in borehole	m
k'	A dimensionless constant associated with casing reducer hydraulics ($\approx$ 0.2 for cone angles <15°)	(-)

3.2 General Criteria to be Met in Borehole Design

Borehole design must ensure the following:

[1] Good quality water with proper protection from contamination.

[2] Water that remains sand free.

[3] A maximum well life.

[4] The design that is most appropriate to any one country should give strong consideration to including as much locally constructed material as possible. The design must also take into account the drilling rigs that are available.

[5] The construction materials used must be strong enough to withstand pressures met in the ground during construction as well as when pumping.

[6] The minimum cost of water delivered is achieved. In practice this means the sum of capital cost of construction (the larger the diameter of borehole casing the more costly) and the pumping costs (the smaller the diameter the larger the borehole head losses and the higher the pumping costs) should be a minimum.

[7] Most importantly, the borehole yield required must be appropriate to the aquifer hydraulic properties but equally must be suitable to ensure sustainable use by the users. This latter point is particularly important when introducing groundwater development to new users. A companion Review is written which addresses sustainability issues.

[8] The well must be able to be developed after construction, its performance should be able to be monitored (access to measure water levels and for downhole logging tools) and it must be amenable to maintenance (rehabilitation). A Review is written describing these issues in more detail.

3.3 The Design Sequence

Fig 2 shows one sequence of events that can be followed if the optimum design of a borehole is to be achieved. The sequence is iterative because a borehole is designed to provide a chosen yield and yet a boreholes performance cannot be predicted accurately until the design is complete.

The sequence given is more complex than that in common usage to date. this is because only recently has it become possible to predict borehole losses with any accuracy. Put another way, it is now common practice for the design process to end at the *'selection of gravel pack and slot size'* step 8 of Fig 2. Thus, there would be no investigation of different screen dimensions and the subsequent selection of the low-cost option design would not be possible. The different steps in the design sequence are described below.

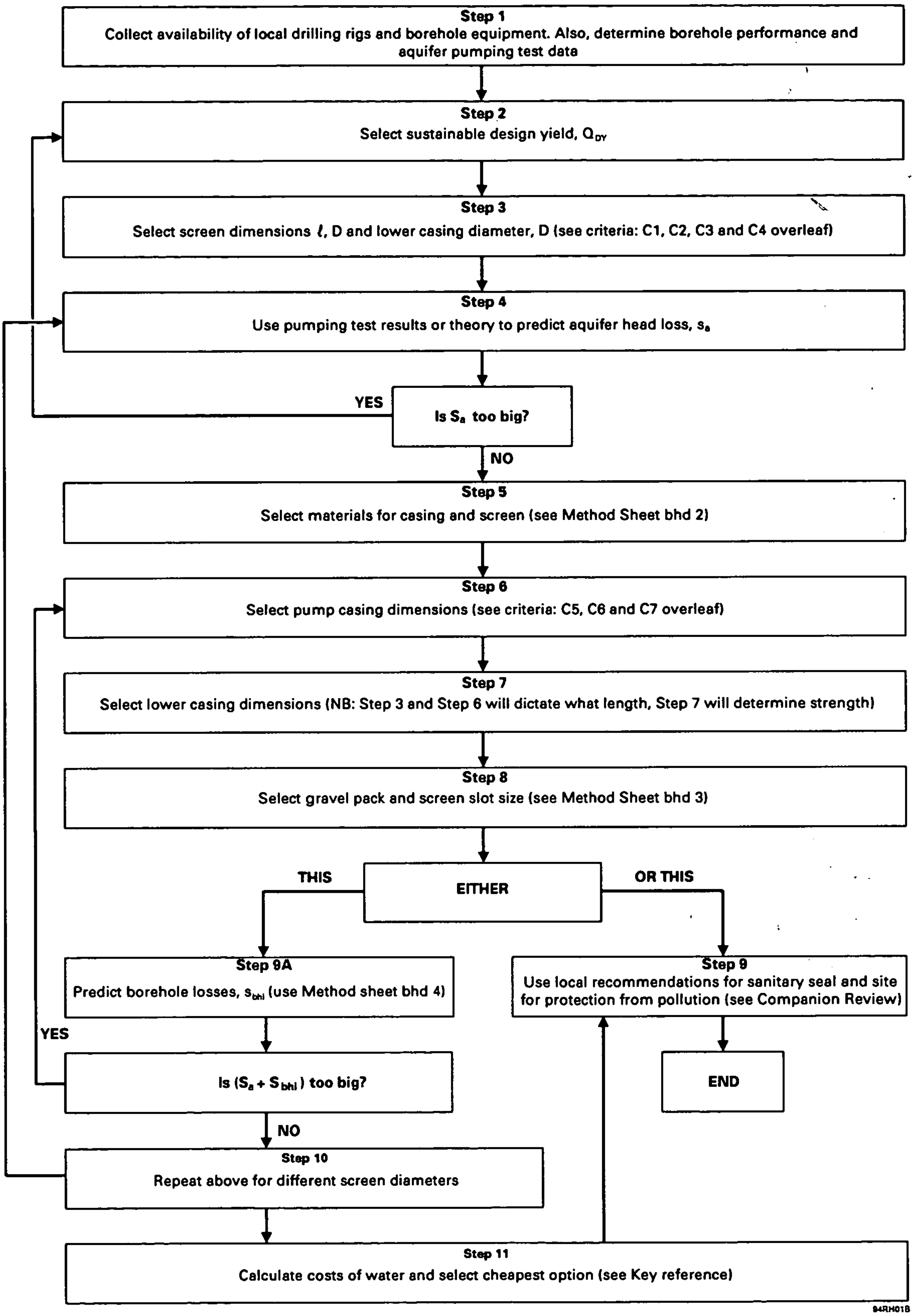


Fig 2. Borehole design sequence

Finally, it should be remembered that no borehole design is possible if assumptions about the aquifers geometry and hydraulic properties are not made. Thus, it is essential a pumping test or well yield test has been made in the aquifer. Even so, every borehole drilled is to a degree exploratory, i.e. the geology cannot be predicted with certainty. For this reason the 'optimum' design adopted must be adapted to the geology found at the drilling site. Under no circumstances should a standard design be adhered to rigorously at the expense of data gained during drilling.

Step 1: Data Collection

Data is collected on the local availability of drilling rigs and locally manufactured casing, screen and pumps. It is likely the most economic and sustainable design of borehole will utilise as much of these local resources as possible. Existing borehole construction details and their yield-drawdown performance are collected. There must be estimates of aquifer properties at the site of the borehole. These data are essential if a prediction of the new borehole performance is to be made. If no such data exist, an investigation programme must be carried out which will include construction of exploratory boreholes and carrying out of step-drawdown and pumping tests.

Step 2: Select Sustainable Yield

Having regard to existing well performance data a sustainable yield of the well is selected that is technically possible and appropriate to the intended users. Great care must be taken in making this decision. The yield must be such that it can be most efficiently used, and society and institutions must be able to monitor and maintain borehole performance. Socio-economic and Institutional studies are now considered to be a part of any borehole scheme. Environmental issues are equally important and if the borehole is to be used for water supply inputs must be provided to ensure healthy use of the water.

These complex issues are discussed elsewhere in this Family of Reports. For the purposes of this Review it is assumed an appropriate sustainable yield has been selected before next steps are undertaken.

Step 3: Select Screen and Lower Casing External Dimensions

<u>Location of the Screen</u>

The screen should be sited opposite the highest yielding stable strata. Its exact location can be determined during drilling by careful borehole logging of drilling samples.

<u>Screen and Lower Casing Minimum Diameter</u>

The uphole velocity in the lower casing or screen must not be greater than 1.5 m/sec to minimise friction losses of upward flow to pump. This criteria will be met by the dimensions and discharges of boreholes given in Table A.

Table A. **Maximum Discharge Rates for Certain Diameters of Standard-Weight Casing, based on an Uphole Velocity of 5 ft/sec (1.5 m/sec)**

Casing Size		Maximum Discharge			
in	mm*	gpm	m^3/day	l/sec	m^3/sec
4	102	200	1,090	12.7	0.013
5	127	310	1,690	19.6	0.020
6	152	450	2,450	28.4	0.028
8	203	780	4,250	49.3	0.049
10	254	1,230	6,700	77.7	0.078
12	305	1,760	9,590	111.2	0.111
14	337	2,150	11,700	135.7	0.136
16	387	2,850	15,500	179.8	0.180
18	438	3,640	19,800	229.7	0.230
20	489	4,540	24,700	286.5	0.290
24	591	6,620	36,100	418.8	0.419

* Actual inside diameter

$$D_{min}\,(m) \geq 0.92\,\sqrt{Q_{DY}}\,(m^3/sec) \qquad (C1)$$

Where: D is diameter of screen and lower casing in metres
Q_{DY} is required borehole yield in m^3/sec.

NB: the nearest nominal size of available screen and casing is chosen.

Selection of Percentage Open Area, Screen Diameter and Length

Criterion C1 gives a minimum diameter for screen and lower casing if friction head losses are to be small. The actual selection of dimensions will depend on the aquifer thickness available and percentage open area required. the procedure is as follows.

Percentage Open Area of Screen

$$\text{The \% open area of screen} \geq 7 \text{ to } 10. \qquad (C2)$$

Many authors have shown that an open area of screen greater than 10% will ensure screen entry losses will be negligible. Barker and Herbert (1989) allows calculation of likely slot losses. A large slot area is also desirable if borehole development and rehabilitation is to succeed. It is for this reason the above criterion should be rigorously enforced.

Screen entry losses are here defined to be the head loss that occurs as a result of constricting the essentially radial flow towards the screen so that it passes through the slots and not through the entire surface of the screen.

Screen Dimensions

The screen dimensions, diameter and length appropriate to aquifer thickness available, can be determined by ensuring the following criterion is met:

$$\text{Screen slot entry} \leq 0.1\ ft/sec \text{ or } 0.03\ m/sec \qquad (C3)$$

Meeting this criterion will ensure:

(i) the rates of corrosion and encrustation of slots will be minimised, and

(ii) the frictional losses in the slots will be small.

Rewriting (C3) the length ℓ and diameter D of a screen should satisfy the following:

$$\ell(m)D(m) \geq 100.Q_{DY}(m^3/\text{sec})/\%\ (\text{open area of screen})/0.03/\Pi$$

and as % open area is selected to be 10% (see C2),

$$\ell(m)D(m) \geq 106\ Q_{DY}\ (m^3/\text{sec}) \qquad \text{(C4)}$$

Using C4: D_{min} from C1 is substituted in C4 to give ℓ. If the aquifer is thick enough this is accepted. If the aquifer is too thin and of thickness ℓ' this is substituted into C4 to give D. If D is significantly too large for practical purposes, select the maximum practical size or reconsider selection of sustainable yield.

Step 4: Predicting Borehole Drawdown Resulting from Flow Through the Aquifer

Why

It is important to know the water level in the borehole caused by pumping at the design yield because of the need to set the pump intake below maximum drawdown (see criterion for pump casing depth) and to estimate pumping costs (see later section on borehole economics) so that a minimum cost borehole can be constructed.

Definition of Borehole Drawdown

The drawdown in a borehole, s_w, can be expressed as follows:

$$s_w = s_a + s_{bhi} + s_{skin}$$

where s_a is the drawdown in the aquifer resulting from flow towards the borehole (including effects of partial penetration), s_{bhi} is the head loss incurred inside the borehole from screen entry momentum change and frictional losses within the screen and casing, and s_{skin} is head loss from damage to the aquifer resulting from drilling or subsequent blocking or encrustation of the gravel pack or screen.

s_{skin} cannot be predicted until the borehole design is complete. Also, application of criterion C1 has ensured S_{bhi} will be minimised, thus s_a will give a good first approximation to s_w.

Predicting s_a

Borehole screen diameter and length have been selected in Step 3. The aquifer dimensions and hydraulic properties are understood from data collected in Step 1. Thus, s_a can be estimated from theoretical relationships derived for pumping test analysis. These are described in a companion Review and relate the change in s_a to borehole yield and time of pumping.

The maximum value of s_a that can be experienced by a borehole might include contributions from a gradual recession of groundwater levels, interference from other pumped boreholes as well as its own self-induced drawdown. Predictions for all the above effects can be made by careful use of the analytical relationships developed for pumping test analysis.

Having said this, this is probably the least accurate of all the calculations that are made in the design process and heavy reliance should be put on experience of existing well performance.

Finally, if the predicted value for s_a can be reasonably sustained by the aquifer dimensions, more detailed design can proceed. If the drawdown is too large, the selection of a technically sustainable yield must be re-addressed.

Step 5: Selection of Material for Casing and Screen

General

Types of material available include steel, thermoplastic, fibreglass and concrete. Steel or cast iron is widely used but thermoplastic and fibreglass are gaining in popularity especially for corrosive situations for boreholes less than 300 m deep. Plastic casing is more flexible than steel and its collapse strength, thickness for thickness, is much less. Fibreglass casing is equal in strength to steel. Plastics are variable in properties. They can be designed to be heat or cold resistant. Care must be taken that the properties are well understood. Some plastics would need very careful storage with much support to avoid 'sagging' especially in hot climates. Some plastics however, are easy to use when constructing the borehole. They have roughly the same density as water and so float and cannot easily be dropped and lost down the borehole.

Table B compares the properties of typical well casing materials. In reality material specifications vary from country to country and developments are being made constantly. The properties of all the casings available must be obtained in each situation.

Corrosion Resistant Casing and Screen

Borehole casing and screen must be of corrosion resistant material - stainless steel, plastic or fibreglass - if the water quality to be pumped is prone to encrustation or bacterial clogging, or corrosion. Corrosion resistant casing is necessary in the first two

Table B. Comparison of Well Casing Materials

Material	Specific Gravity	Tensile Strength psi	Tensile Modulus 10^5 psi	Impact Strength ft-lb/in	Upper Temperature Limits, °F	Thermal Expansion 10^{-6} in/in °F	Heat Transfer BTu-in/ hr-ft^2 °F	Water Absorption wt %/24 hrs
ABS	1.04	4,500	3.0	6.0	180	5.5	1.35	0.30
PVC	1.40	8,000	4.1	1.0	150	3.0	1.10	0.05
Styrene Rubber	1.06	3,800	3.2	0.8	140	6.8	0.80	0.15
Fibreglass Epoxy	1.89	16,750	23.0	20.0	300	8.5	2.30	0.20
Asbestos Cement	1.85	3,000	30.0	1.0	250	1.7	0.56	2.0
Low-Carbon Steel	7.85	35,000 (yield)* 60,000 (ultimate)	300.0	†	800-1,000	6.6	333.0	Nil
Type 304 Stainless Steel	8.0	30,000 (yield)* 80,000 (ultimate)	290.0	†	800-1,000	10.1	96.0	Nil

* Yield strength is the tensile stress required to produce a total elongation of 0.5 percent of the gauge lenth as determined by an extensiometer. Expressed in psi.

† Because testing methods for steel and other materials are not the same and the results are not comparable, the impact strength values for steel are not shown. In any event, the actual impact strength is so high relative to the demand of water well work that it can be ignored in design considerations.

(Purdin, 1980)

cases so as to resist the damaging effects of likely subsequent chemical treatments for rehabilitation and maintenance of yield. Driscoll (1986) describes how different quality waters can reduce well life.

Case History: Thousands of irrigation boreholes were installed in Pakistan in the 1950s. They were constructed largely in mild steel. The boreholes became blocked and their life expectancy was typically seven years. It was concluded that the waters were corrosive and the pitting itself gave a good base on which encrustation could occur. All subsequent boreholes drilled (tens of thousands) were constructed in non-corrosive materials.

Indicators of Corrosive Conditions

[1] Low pH. If the pH value is less than 7, the water is acidic, and corrosive conditions are indicated. Similarly, a Ryznar Stability Index value greater than 7 indicates corrosive conditions (see below).

[2] Dissolved oxygen. If dissolved oxygen exceeds 2 mg/l, corrosive water is indicated. Dissolved oxygen may be found in shallow wells in unconfined aquifers.

[3] Hydrogen sulphide. Hydrogen sulphide in groundwater can be detected readily by its characteristically rotten-egg odour. Less than 1 mg/l can cause severe corrosion, and this amount can be detected by odour and taste.

[4] Total dissolved solids. If total dissolved solids exceed 1,000 mg/l, electrical conductivity of the water is great enough to cause serious electrolytic corrosion. To avoid electrolytic corrosion, metal well screens must be made of a single, corrosion-resistant metal.

[5] Carbon dioxide. If the amount of this gas exceeds 50 mg/l, corrosive water is indicated.

[6] Chlorides. If the chloride content of the water exceeds 500 mg/l, corrosion can be expected.

The presence of two or more corrosive agents appears to intensify the corrosive attack on metals, compared with the effect caused by individual agents.

Indicators of Encrusting Conditions

[1] High pH. If the pH value is above 7.5, the water will tend to be encrusting. A Ryznar Stability Index of less than 7 also indicates encrusting conditions (see below).

[2] Carbonate hardness. If the carbonate hardness of the groundwater exceed 300 mg/l, encrustation of calcium carbonate (limescale) is likely.

[3] Iron. If the iron content of the water exceeds 0.5 mg/l, precipitation of iron is likely, although some precipitation may begin at concentrations as low as 0.25 mg/l.

[4] Manganese. If the manganese content of the water exceeds 0.2 mg/l and the pH value is high, precipitation of manganese is likely if oxygen is present.

Calculating the Ryznar Stability Index

The Ryznar Stability Index for a water sample can be calculated from the following equation:

$$I = S - C - pH$$

where I is the Ryznar Stability Index and S and C are factors derived from Figures 3a and 3b, based on total dissolved solids, methyl orange alkalinity, and calcium ion concentration (0.4 x calcium hardness). The steps to determine S and C are:

[1] Obtain a value for S using the known total dissolved solids and Figure 3a.

[2] Obtain a value for C using the methyl orange alkalinity, the calcium ion concentration, and Figure 3b.

For example, assume that a water analysis produces the following data:

pH = 7
Total dissolved solids = 400 mg/l
Methyl orange alkalinity = 200 mg/l
Calcium hardness = 125 mg/l

Note that the calcium ion concentration for the Ryznar Stability Index equation is 0.4 x 125 = 50 mg/l.

[1] The value of S from Figure 3a is 23.12.

[2] The value of C from Figure 3b is 8.0

[3] The Ryznar Stability Index I, is 23.12 - 8.0 - 7.0 = 8.12.

Recommendation: It is recommended that non-corrosive material is used for borehole screens. this is because, even in encrusting conditions the recommended method for blocked screens is acidisation. It is common practice to use mild steel for pump casing in encrusting waters.

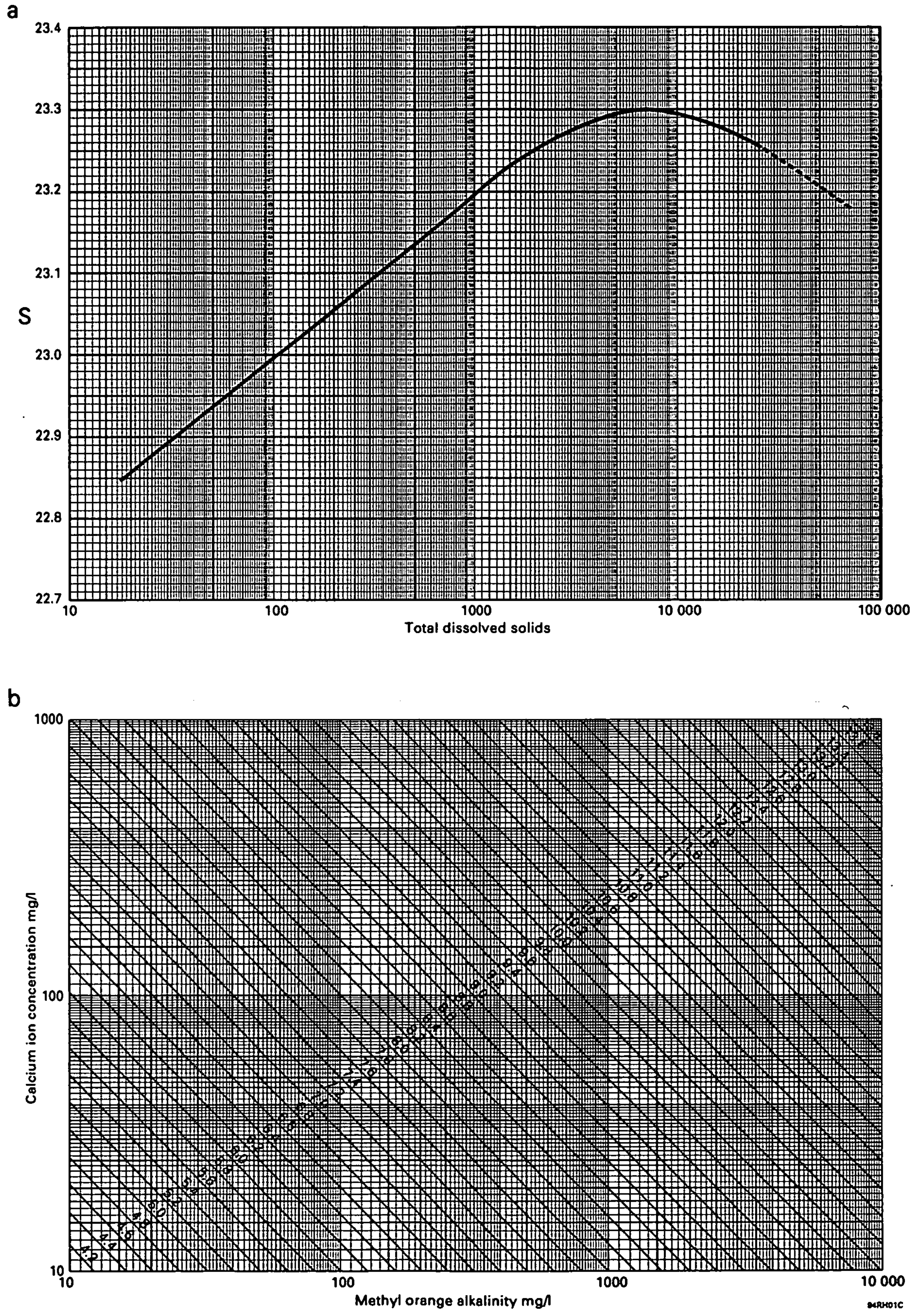


Fig 3. Aid to calculation of Ryznar Stability Index

Step 6: Selecting Pump Casing Dimensions

Pump Casing Depth

Ideally the pump is housed inside the blank pump casing. The pump intake must be below the maximum expected drawdown in water level within the borehole (see Step 4).

$$L_c > s_a + \textit{depth to undisturbed water table} \quad \text{(C5)}$$

Pump Casing Diameter

The casing must be large enough to accommodate the pump. Ideally the casing should be at least one nominal size greater than the max diameter of the pump.

$$D_{pc} > D_p \quad \text{(C6)}$$

Casing Thickness

Casing thickness must be sufficient to withstand full hydraulic loading. The collapse strength must exceed lpsi (6.9 kPa) for every 2.31 ft (0.7 m) of depth beneath the top of the aquifer. This criterion allows for the extreme condition met when the water is outside the borehole but it is completely empty. This can occur during construction particularly when developing the boreholes.

$$\textit{Collapse strength } (P_c) \geq [\textit{depth below surface (ft)}/2.31]\ \textit{psi} \quad \text{(C7)}$$

Calculating the collapse strength of casing

The collapse strength of casing is usually specified by the manufacturer. Campbell and Lehr (1973) show how the collapse pressure, P_c (psi) of a pipe can be estimated:

$$P_c = \frac{2E}{1-U^2} \frac{1}{\left(\frac{d}{t}\right)\left(\frac{d}{t}-1\right)^2} \quad (1)$$

where: P_c = critical collapse pressure (psi)
E = modulus of elasticity of pipe material
U = Poisson's ratio of pipe material
d = O.D. of the pipe (inches)
t = wall thickness of the pipe (inches)

Axial tension and bending reduce and axial compression increases collapse resistance. Poor welding of joints may reduce the tensile strength at these points to 40 percent. Because of these factors and the assumed average value of soil pressure, Equation 1 is used with a design factor of three for wells in unconsolidated formations.

Step 7: Select Lower Casing Dimensions

The diameter D of lower casing and screen and screen length, ℓ, was determined in Step 3. The depth of pump casing has been determined in Step 6, thus, the aquifer geometry will determine the required length of lower casing.

(a) As for upper pump casing, the lower casing thickness and the screen chosen must be sufficient to withstand 1 pound per square inch (p.s.i.) for every 2.31 ft of depth beneath the top of the aquifer. See criterion C7.

(b) The screen must withstand the axial compression of the complete borehole string (casing and string) in the unsupported state.

Manufacturers of the screen must be approached for the above screen capabilities.

Step 8: Gravel Pack and Screen Slot Size

Definitions

Figure 1 shows a typical borehole construction, this section is concerned with the design of the gravel pack, which is often used to surround the screen, and the screen slot size, which is dependent on the gravel pack size.

Requirements of a Gravel Pack Slot Size Design

The gravel pack-screen component of the borehole should ensure:

(a) structural stability of the borehole

(b) cleaning of the drilled hole is possible after emplacement of gravel pack [development of borehole]

(c) passage of some fine aquifer material (if possible) immediately after emplacement [development of borehole]

(d) fines-free pumping after development

(e) no blocking of gravel pack by fines

(f) periodic maintenance is possible.

Given the above criteria, and noting some aquifer material is self-filtering thus ensuring (c) to (e) are guaranteed, a gravel pack is sometimes used simply to ensure that the largest screen slot size possible can be adopted, thus helping with (b) and (f) and reducing the likelihood of encrustation or corrosion of the screen slots.

Aquifer Grain Size Determination

It is essential to determine the screened layers' grain size distribution curves if the requirements (a) to (f) above are to be achieved.

Representative samples of the aquifer are obtained and dried during drilling. (It should be noted that whilst it is not commonly accepted, recent work suggests accurate samples can be obtained directly from boreholes drilled by the rotary method. A bucket is required to divert the circulating fluid, preferably water, at frequent depths during drilling (Davies and Herbert, 1993).

A set of standard testing sieves, and an accurate balance or scale for weighing sample material are required. The coarsest sieve should not retain more than 20% of the sample. Sieve openings are designated by size in thousandths of an inch, millimetres, or by mesh number of the wire cloth. The sieves are stacked with the finest one resting on the bottom pan and the coarsest at the top. The dried sample is weighed and put onto the top sieve. If possible, samples should be shaken mechanically for at least 5 minutes. The weight of the material retained on each sieve is recorded.

The Grain Size Distribution Curve

The grain size distribution curve plots the cumulative weight retained against sieve size. Figure 4 shows plots for several samples taken from a braided steam deposit. Superimposed on this is a hypothetical plot for a more typical well-sorted sand.

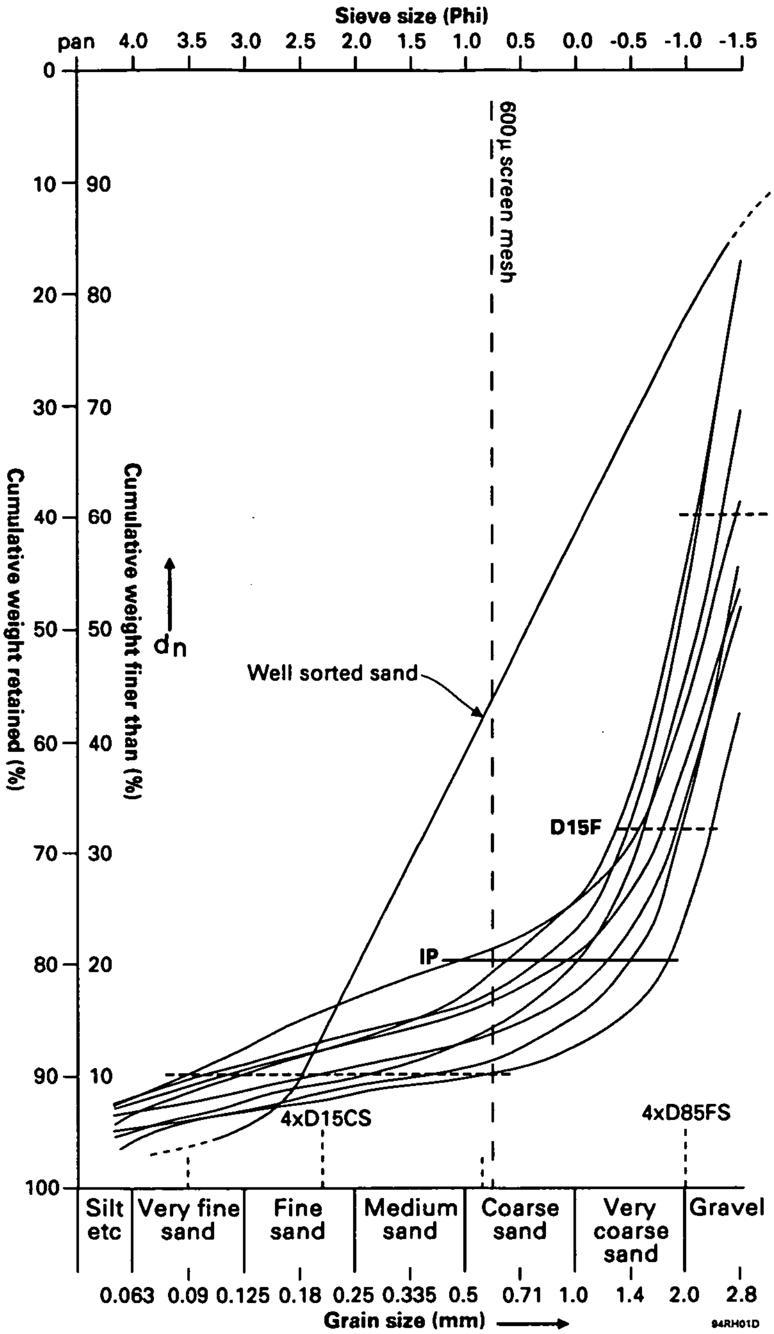


Fig 4. A set of grain size distribution curves

Standard Design Criteria

Notation for grain size specification

d_n means there is n% of the sieved material which is finer than grain size d (mm). In Figure 4, d_{40} is about 1.6 mm.

Background

It is usual to treat the aquifer to be screened/gravel packed as being a well-sorted, relatively homogeneous, medium. This subsection gives criteria which are perfectly adequate when this is so.

Hunter-Blair (1970) reviewed the many criteria which exist for the selection of gravel pack grading required in a borehole. Almost all are based on Terzaghi's Rule for design of drainage filters (Terzaghi, 1943). His criteria have proved to be successful in practice and are recommended here.

Terzaghi's Criteria

If subscripts A and P mean aquifer and gravel pack respectively, then:

$$d_{15P} \geq 4d_{15A} \textit{ for coarsest layer in screened material,} \\ \textit{and } d_{15P} \leq 4d_{85A} \textit{ for finest layer in screened material.} \qquad \text{(C8)}$$

In addition, for boreholes, experience shows the slot size S (mm) of the screen in a borehole is selected as follows:

$$S \approx d_{85P} \qquad \text{(C9)}$$

Design Criteria for Poorly-sorted Material

Notation for distinguishing between different fractions of the ill-sorted aquifer material

It is thought many aquifers are comprised of distinctly different fine and coarse fractions. Also, it is possible that individual layers in unconsolidated aquifers can be so thin that screening/gravel packing must occur across several layers each having different gradings. Here both these conditions are referred to as ill-sorted aquifers. Figure 4 gives a series of grading curves which are typical of such material, i.e. they have distinguishably different coarse and fine fractions.

In this section d_{nAC} and d_{nAF} mean that n% of the coarse, C, or fine, F, fraction of the aquifer material is finer than d(mm).

Background

Davies and Herbert (1993) examined the hypothesis that many of the borehole failures experienced in UNSAs were due to the misapplication of Terzaghi's criteria to ill-sorted aquifer material. Through experimentation in the field they demonstrated that the theories of Kojacs and Ujfaludi (1983) could explain borehole performance in ill-sorted aquifers.

Kedzi (1969) showed how the aquifer material can be separated into two parts, a coarse and fine portion.

Testing for poor sorting

The grain size distribution curve is split into two parts by a diameter d_N chosen arbitrarily. In very ill-sorted sands there is an easily identifiable d_N which separates the fine and coarse fractions. If this cannot be done the following is done at several values for d_N.

Using these fractions it can be investigated whether the coarser fraction can act as a filter and protect the mass of the smaller particles. Put another way, the coarse fraction should have all the attributes of a gravel pack in relation to the fine fraction. Thus Terzaghi's criteria given earlier can be used to see if this is so:

$$\begin{aligned} &d_{15AC} \geq 4d_{15AF} \textit{ for coarsest layer in screened material,} \\ &\textit{and } d_{15AC} \leq 4d_{85AF} \textit{ for finest layer in screened material} \end{aligned} \qquad \text{(C10)}$$

If the above criteria are met the material is self-filtering and stable.

Testing for aquifer collapse

If the aquifer is ill-sorted then suffusion is likely to occur and fine matrix material can be removed. This could result in coarse sediment framework collapse. Kovacs (1981) attempts to determine if the coarse sediment framework will stand up after removal of fine matrix material and at what velocities removal of fine matrix material occurs. We suggest that as a simple rule of thumb if $4d_{50AF} \leq d_{50AC}$ then the coarse sediment framework will not collapse.

$$4d_{50AF} \leq d_{50AC} \qquad \text{(C11)}$$

Summary Design Criteria for All Conditions

Three alternative material states are recognised:

(a) Material is self-filtering. In this case the aquifer is considered to be well-sorted and standard design criteria, C8 and C9, for boreholes given earlier apply.

(b) Material is non-self-filtering and collapsing - no attempt should be made to screen this material.

(c) Material is non-self-filtering and non-collapsing. In this case, an appropriate size of gravel pack and screen should be selected using the grain-size distribution of the coarse grained fraction. Thus, Terzaghi's criteria for packs in well-sorted material should be adopted as follows:

$$d_{15P} \geq 4d_{15AC}$$
$$d_{15P} \leq 4d_{85AC} \text{ and} \qquad \text{(C12)}$$
$$S \simeq d_{85P}$$

It should be noted that when this condition pertains, it follows that a coarser gravel pack and larger slots than those required for self-filtering material, are essential.

Thickness of Gravel Pack

EPA (1976) state: Generally, the thinner the pack the better ..... but the mechanical difficulties of satisfactorily placing a ½ inch thick pack preclude its use. From a practical standpoint, packs are usually 4 to 8 inches (10 to 20 cm thick). Care must be taken to avoid bridging and segregation during installation. Frequently it is placed via a tremie pipe.

Note: Apart from design for sanitary protection of the borehole it is common practice to cease the design sequence at this step. However, we strongly recommend the subsequent stages are completed now that it is possible to predict well head losses, s_{bhi}, accurately for most aquifer situations.

Step 9: Sanitary Protection

Background

A survey carried out in Georgia, US in 1969 of water quality in boreholes drilled for domestic supply showed 40% were contaminated with coliform bacteria. Deficiencies identified included (i) insufficient and sub-standard casing, (ii) inadequate 'formation seal' between casing and borehole wall, (iii) poor welding of casing joints and (iv) lack of sanitary cover. Standards of borehole construction for domestic supply in 1969 in the USA, were probably similar to, or better than, those now routinely used in much of the developing world for rural water supply.

Sanitary Seals

Contaminated water from surface drainage or low quality water high in the borehole should not be allowed to move downward through the annulus around the casing. A cement grout seal is generally used to ensure this and it is often placed by tremie pipe.

Each country has its own criteria for minimum length of seal required; also, placing of the seal is a skilled operation. Driscoll (1986) summarises the procedures required. In addition it is obvious that the borehole must have adequate protection on the surface.

Siting for Pollution Protection

A companion Review discusses this subject in more detail. In general, a borehole and its screen should be sited upstream of or sufficiently far downstream of a potential source of pollution to provide reasonable assurance that pollutants in the subsurface flow will not reach the borehole in significant quantities.

Step 9A: Predict Borehole Losses (s_{bhl})

Earlier, Step 4 showed how drawdown to the borehole, s_w, is made up of a head loss in the aquifer to borehole screen, s_a, head losses incurred within the borehole, s_{bhi}, and occasionally, head losses incurred at the screen or gravel pack due to encrustation or blocking of screen or mud invasions of the borehole wall by drilling mud, s_{skin}, (skin losses).

$$s_w = s_a + s_{bhl} + s_{skin}$$

If the borehole is adequately designed and borehole development is complete, then at the time of completion, skin losses will be negligible.

Calculating s_{bhi}

Barker and Herbert (1989) describe hydraulic tests carried out on a specially designed test rig to define the head losses incurred when flow occurs through and up a given length of well screen.

The use of digital models for complex aquifers: Barker et al (1989) shows how a digital model can be constructed of a multilayered aquifer which incorporates borehole screen losses, s_{bhi}, and can predict borehole losses, $s_a + s_{bhi}$. Specific models may need to be built for each complex aquifer or borehole design met. This work should be delegated to aquifer modelling specialists.

Predicting s_{bhi} in simple aquifers and boreholes: Herbert and Barker (1990) show how s_{bhi} can be calculated for a typical borehole design.

Consider the steady-state flow system shown in Figure 5. The quantity of interest is the total head loss between the outer aquifer boundary and the head in the casing just below the pump. For a given discharge rate, head losses between this point and the discharge end of the surface pipe do not depend on the well design and, although not unimportant, are not addressed here.

The approach adopted here is to break the total head-loss problem down into a number of simpler head-loss problems (Figure 5). The total head loss can be split up as follows

$$
\begin{aligned}
\text{Total head loss } (\bar{h}_e - h_w) = \; & \text{Aquifer loss } (\bar{h}_e - \bar{h}_p) \\
& + \text{'Penetration' loss } (\bar{h}_p - \bar{h}_{ps}) \\
& + \text{Gravel-pack loss } (\bar{h}_{ps} - \bar{h}_{se}) \\
& + \text{Slot losses } (\bar{h}_{se} - \bar{h}_s) \\
& + \text{Well-screen loss } (\bar{h}_s - h_{st}) \\
& + \text{Losses above screen } (h_{st} - h_w) \qquad (2)
\end{aligned}
$$

where:

- $\bar{h}_e$ is the average vertical head over the exterior boundary,
- $\bar{h}_p$ is the average vertical head over the whole aquifer depth at the radius of the gravel pack,
- $\bar{h}_{ps}$ is the average vertical head over the screened interval of the well at the radius of the gravel pack,
- $\bar{h}_{se}$ is the average vertical head over the screened interval of the well on the outside of the screen,
- $\bar{h}_s$ is the average vertical head over the screened interval of the well on the inside of the screen,
- h_{st} is the head at the top of the screen inside the well, and
- h_w is the head indicated by the water level in the well.

s_a is the sum $\bar{h}_e - \bar{h}_{ps}$ of Figure 5 and as stated earlier can be estimated using standard analytical methods for a number of different aquifer situations. In addition, $\bar{h}_{ps} - \bar{h}_{se}$ the head across the gravel pack can be calculated as described immediately below. s_{bhi} can be considered to be the sum of the remaining terms in (1) above.

The head loss across the gravel pack is

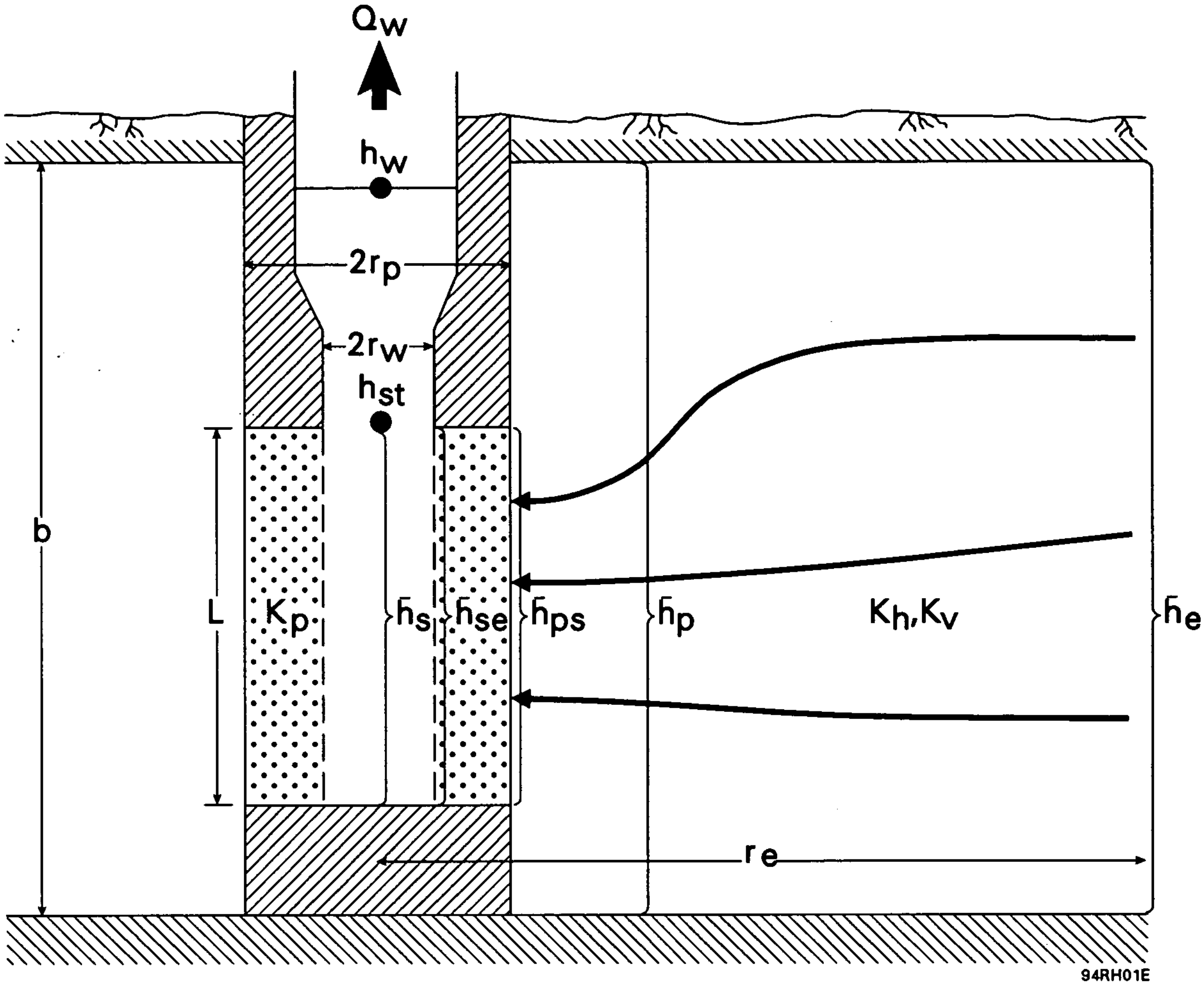


Fig 5. Simple model of a borehole showing intervals over which average heads, $\bar{h}_p$, apply

$$\bar{h}_{ps} - \bar{h}_{se} = \frac{Qw}{2\pi \ell K_p} \ln \frac{r_p}{r_s} \qquad (3)$$

where ℓ is the length of the screen and K_p is the horizontal hydraulic conductivity of the gravel pack.

Note the implicit assumption that no water flows vertically through the gravel pack opposite the casing or in the region beneath the gravel pack and well (Figure 5).

The head, $\bar{h}_{se}$, in (3) is the average over the outside of the screen. In reality, the flow in the gravel pack must converge to the slots, and this introduces an extra component of head loss. This loss will depend on: the slot design, the percentage open area, the slot spacing, and the gravel-pack, however, simple calculations indicate that this loss is small in relation to other losses provided total open area is greater than 7 to 10%, see criterion 2 developed earlier for different reasons for screen design.

<u>Slot Losses ($\bar{h}_{se}$-$\bar{h}_s$)</u>

There is some head loss as water flows through a slot. This loss is normally assumed to be given by the **orifice law**, which relates the head loss to the square of the inflow velocity. For uniform flow to a screen of length ℓ, this law takes the form

$$\bar{h}_{se} - \bar{h}_s = \left[\frac{Q_w}{2\pi \ell r_w C_v C_c A_s}\right]^2 \frac{1}{2g} \qquad (4)$$

where: C_v is the velocity coefficient (a value of about 0.97 is appropriate for a slot); C_c is the contraction coefficient (typically 0.63); and A_s is the fractional open area through which flow occurs (normally taken as either half the fractional slot area or the production of the gravel-pack porosity and the fractional slot area).

If slot entrance velocity is kept to less than 0.1 ft/sec these losses will be minimised. See the criterion developed earlier for different reasons for screen design.

<u>Well-Screen Loss ($\bar{h}_s$-h_{st})</u>

Barker and Herbert (1989b) show that the hydraulic characteristics of a wide variety of well screens can be described in terms of the following equation for the rate of head loss with depth, z, inside the screen.

$$\frac{dh_s}{dz} = \alpha Q^2 - \frac{\beta Q dQ}{dz} \qquad (5)$$

The two parameters α and ß are empirical constants which vary from one screen to another (although ß can be closely estimated from the screen radius alone). Table C lists values for α and ß determined from hydraulic tests on a wide range of screens. In order to evaluate the screen-loss term from this equation, it is necessary to make an assumption about the variation of Q with vertical distance along the screen. The simplest assumption is that the inflow to the well is uniform so Q is linear with depth. With this assumption integration of (5) gives the average head:

$$\bar{h} - h_{st} = Q_w^2 \left[\frac{\alpha \ell}{4} + \frac{\beta}{3} \right] \qquad (6)$$

which is the required screen-loss formula.

Equation (6) has appeared previously in the work of Chen (1975, 1985), although its derivation and form are quite different here. Sixteen wells of different design were constructed in Bangladesh and their performance was closely monitored over a wide range of discharges. In only one case was significantly non-uniform inflow observed to the screen (Davies et al., 1988).

Losses Above the Top of the Screen (h_{st}-h_w)

Head losses above the top of the screen must also be taken into consideration in well design. There will be frictional head loss inside the casings, and extra losses at the joints. Head losses across the joints would require special study, and are probably not very significant. The total head loss in all sections of (unperforated) casing can be calculated from a formula of the form:

$$\Delta h_{casing} = \frac{8 Q_w^2}{\pi^2 g} \sum_s \frac{f_s L_s}{D_s^5} \qquad (7)$$

where the summation is taken over all casing sections, and section s has friction factor f_s, length L_s and diameter D_s.

**Table C	Values of α and β for a number of screens**

Test No.	Make*	Material+	Nominal Diameter (in)	I.D. (m)	α (s^2/m^5)	β (s^2/m^5)
1	Jo	SS	6	0.158	26.0	540.0
2	BC	GRP	6	0.153	18.50	652.0
3	Jo	SS	6	0.158	31.00	523.0
4	No	SS	6	0.150	31.20	637.0
5	No	SS	6	0.151	23.20	662.0
6	Du	P	6	0.147	18.80	732.0
7	Du	P	6	0.148	16.00	746.0
8	Du	P	6	0.148	17.70	730.0
9	Hy	P	6	0.147	23.70	759.0
10	Pr	P	6	0.148	15.80	712.0
11	Pr	P	6	0.151	11.80	686.0
12	De	P	6	0.149	17.00	813.0
13	De	P	6	0.147	20.30	738.0
14	De	GRP	6	0.168	20.00	492.0
15	Jo	SS	4	0.112	138.00	2240.0
16	No	SS	4	0.101	76.40	3610.0
18	Du	P	4	0.102	72.90	3490.0
19	Du	P	4	0.102	123.00	3530.0
20	Hy	P	4	0.101	156.00	3750.0
21	Jo	SS	8	0.201	6.14	173.0
22	BC	GRP	8	0.203	3.49	201.0
23	Du	P	8	0.197	3.47	220.0
24	Hy	P	8	0.200	3.25	229.0
25	Jo	SS	10	0.259	2.46	78.3
26	No	SS	12	0.298	0.81	41.6
27	Du	P	12	0.301	0.71	42.8
28	Hy	P	12	0.300	0.71	43.7
29	BC	GRP	6	0.152	13.10	646.0

\+ SS - Stainless steel
P - Plastic
GRP - Glass-reinforced plastic

* Jo - Johnson
BC - Bristol Composite
No - Nold
Du - Durapipe
Hy - Hydrotech
Pr - Preussag
De - Demco

NB: To calculate s_{bhi} in meters use table values as shown and Q_w in m^3/sec.

There will often be at least one reducer (at the bottom of the pump casing). There will be a head increase across the reducer (from Bernoulli's equation), but also frictional and turbulent head loss. An estimate of the net loss in pressure head can be made using:

$$\Delta h_{reducer} = \frac{8Q_w^2}{\pi^2 g}\left[\left(\frac{1}{D_{pc}^4}-\frac{1}{D^4}\right) - k'\left(\frac{1}{D_{pc}^2}-\frac{1}{D^2}\right)^2\right] \tag{8}$$

where D and D_{pc} are the internal diameters at the lower (upstream) and upper (downstream) ends of the reducer, respectively (e.g. Daugherty and Franzini (1977). For a well-designed reducer - one with a cone angle less than about 15° - the value of k' should be about 0.2.

There must be a further significant head loss as water enters the pump intake. This will be roughly proportional to the square of the well discharge rate and must also depend on the diameter of the casing in which the pump is housed. However, for a given discharge rate the loss will not depend on the design of the well below the pump casing.

As a first estimate of this additional loss in head, it has been assumed that it will be roughly equal and opposite in sign to that induced by the expansion term of equation (8). This would be exact if the pump intake were of diameter D_1 and were connected directly to a reducer of the same but inversed geometry of the expansion joint.

Use of this approximation reduces the right-hand side of equation (8) to

$$\Delta h_{reducer} = \frac{8Q_w^2 k'}{\pi^2 g}\left(\frac{1}{D^2}-\frac{1}{D_{pc}^2}\right)^2 \tag{9}$$

The drawdown in the well, s_w, can then be usefully thought of as recording the piezometric level of the water at the pump intake.

Some field results: If equations (4), (6), (7) and (9) are summed, a general expression for s_{bhi} is obtained which is appropriate for a well pumping at a steady-state and for which uniform inflow occurs along the length of the screen. This expression can be simplified to the form:

$$s_{bhl} = CQ_w^2 \qquad (10)$$

where C is a constant. Using the simple theory presented earlier, the theoretical value of C is given by equation (11) for a single reducer and where slot losses have been ignored.

$$C = \left(\frac{\alpha\ell}{4}+\frac{\beta}{3}\right)+\frac{8}{\pi^2 g}\left[\sum_{s}\frac{f_s L_s}{D_s^5}+k'\left(\frac{1}{D^2}-\frac{1}{D_{pc}^2}\right)^2\right] \qquad (11)$$

Seventeen step-drawdown tests were carried out in Bangladesh on wells with varying screen materials, design and geometry (Davies et al., 1988). The results of these tests are summarised in Table D where comparisons are made between the values derived graphically from the field data and from the theory presented earlier. The average contribution to C from the three terms in equation (11) were: 67% (screen loss), 30% (casing loss), and 3% (reducer loss).

Figure 6 is a plot of C values derived from theory and field tests. It can be seen that an unexpectedly good agreement is obtained, suggesting the theory presented is reasonably accurate.

Calculating s_{skin}

s_{skin} cannot be calculated independently with any certainty. The thickness and permeability of the 'skin' of low permeability cannot be measured. s_{skin} must therefore be deduced by difference between observed values of s_w and the calculated values for $s_a + s_{bhi}$. Regular monitoring of borehole performance will allow changes in s_{skin} to be assessed. Herbert and Barker (1990) show how step drawdown tests can be interpreted to give an estimate of s_{skin} values. Step-drawdown tests are described in a companion Review.

Borehole Performance in Conventional Design

Conventional design methods have not included methods for calculation of s_{bhi}, borehole losses. These have been lumped together with s_{skin}, skin losses and called well losses. It has been wrongly assumed that if a well were perfectly designed and constructed losses of the type (Const.Q^2) would be zero. The recent work described above shows this to be incorrect.

Table D **Comparison of the Step Test Results and Values (of C) Predicted by the Theory.**

Well	Material*	Diameter (nominal)	Length (feet)	C (field) (s^2/m^5)	C (theory) (s^2/m^5)	Error in theory C (%)
1c	SS	10	90	240	73	70
2	SS	6	80	920	958	-4
3	SS	6	60	960	857	11
4	SS	8	80	264	187	29
5	SS	8	120	238	185	22
6	SS	6	100	360	554	-54
7	Gtex.	6	80	1000	487	51
8	Gtex.	6	120	586	655	-12
9	Gtex.	8	90	168	127	25
10/4	Gtex.	4	120	1600	2521	-58
10/6	SS	6	80	740	700	5
11	GRP	6	120	328	550	-68
12	GRP	6	80	540	584	-8
13	GRP	8	80	184	105	43
14	GRP	10	80	56	52	8
15	GRP	8	120	126	125	1
16	GRP	6	60	380	510	-34

* SS - Stainless steel, wire wound
Gtex. - Mesh-wrapped plastic
GRP - Glass-reinforced plastic

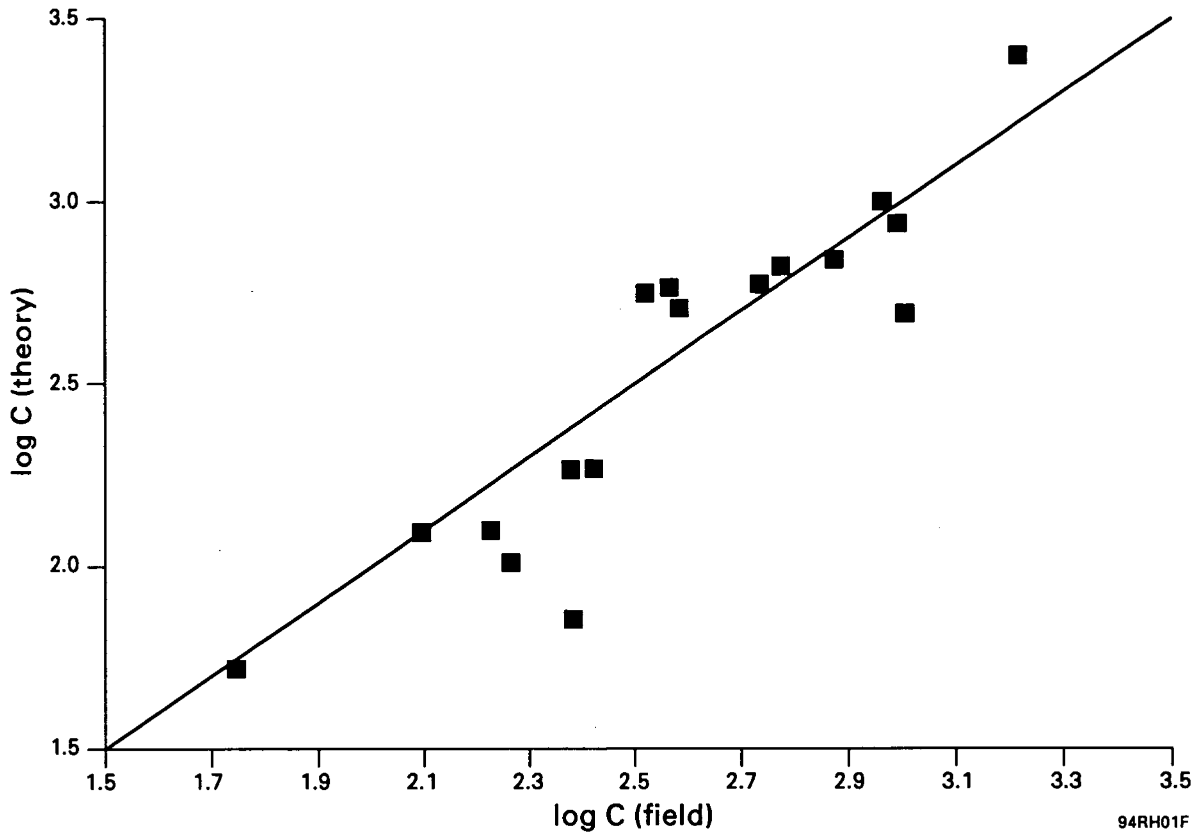


Fig 6. Comparison of theoretical and experimental (step-test) values for the coefficient of non linear head loss, C

Conventional design has worked well in practice, the criteria which minimise up-hole flow velocity and screen slot entry velocity, criteria (C1, C4) have ensured s_{bh_i} is small. However, if the minimum cost borehole is to be designed, comparisons between the performance of different designs must be made and the new method described in this section must be employed. Similarly, accurate predictions of borehole performance are necessary if monitoring of borehole performance is to be correctly diagnosed.

Step 10: Comparison of Different Designs

The performance of different borehole designs is now compared. HINT: Experience shows that the cost of water delivered is primarily affected by the chosen screen radius and cost of screen material. Thus, the cheapest satisfactory screen material should be used and investigation should be centred on determining the optimum screen radius.

Steps 4 to 9A are repeated for at least the two nearest available nominal screen radii and predictions made of total expected drawdown in the borehole.

Step 11: Select Optimum Borehole Design

The cost of water pumped includes the costs of drilling, construction materials, pumping costs and maintenance. Each country has different ways of meeting these costs so no general method is presented here. Herbert et al. (1988) describe how this was done using a simple spreadsheet to rapidly compare costs of different designs for Bangladesh.

The Final Step (Step 9 Fig 2)

The selected optimum well design must include measures to protect its water quality. Step 9 has already been described, which ensures this will be done.

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Kovacs G and Ujfaludu L (1981). Movement of Fine Grains in the Vicinity of Well Screens. Hydrological Sciences Journal, Vol. 28, Part 2, pp 247-260.

Terzaghi K and Peck R (1948). Soil Mechanics in Engineering Practice. John Wiley & Sons, London, pp 49-51.

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Method Summary Sheet (bhd 1)

Title: ***Borehole Design Sequence***

Scope and Use of Method:

This set of summary sheets give the steps to follow to produce the specifications of a borehole design having components like that in Fig bhd 1/2. Present-day design usually misses out steps 9a, 10 and 11, but for simple aquifer geometries, including multi-layered aquifers having similar permeabilities, steps 9a, 10 and 11 are all possible and are strongly recommended.

For more complex boreholes with telescoped screens or boreholes with pumps inside the screen or in aquifers having contributing layers with different permeabilities, digital modelling studies will be necessary to determine the distribution of inflow to the screen and the borehole losses associated with that distribution. See Key References for an example of such complex studies.

To use the Design Method the following related sheets have been prepared:

Method sheet bhd 1:	gives scope and use of method with key references
Fig bhd 1/1:	gives the design flow chart
Fig bhd 1/2:	shows a typical borehole with all required notation
Method sheet bhd 2:	determination of Ryznar Index
Method sheet bhd 3:	selection of gravel pack and slot size
Method sheet bhd 4:	calculation of borehole head loss, s_{bhi}

Method:

Fig bhd 1/1 is a flow chart which lists the steps that must be followed to design a borehole. Many of the steps refer to criteria which must be satisfied. These are listed below and use the same notation as that on Fig bhd 1/2

<u>Criteria Used in Design Sequence</u>

Step 3:

- $D_{min}(m) \geq 0.92 \sqrt{Q_{DY}}\ (m^3/sec)$ - C1
- % open area of screen ≥ 7 to 10 - C2
- Screen slot entry ≤ 0.03 (m/sec) - C3

If C2, C3 satisfied: $\ell\ (m)\ D\ (m) \geq 106\ Q_{DY}\ (m^3/sec)$ - C4

NB: Substitute D_{min} from C1 into C4 to give ℓ.

Step 6:

- $L_c\ (m) > s_a$ (maximum expected drawdown) + depth to undisturbed water table (m) - C5
- $D_{PC} > D_P$ - C6
- P_c, collapse strength of casing (psi) ≥ [depth below surface (ft)/2.31] - C7

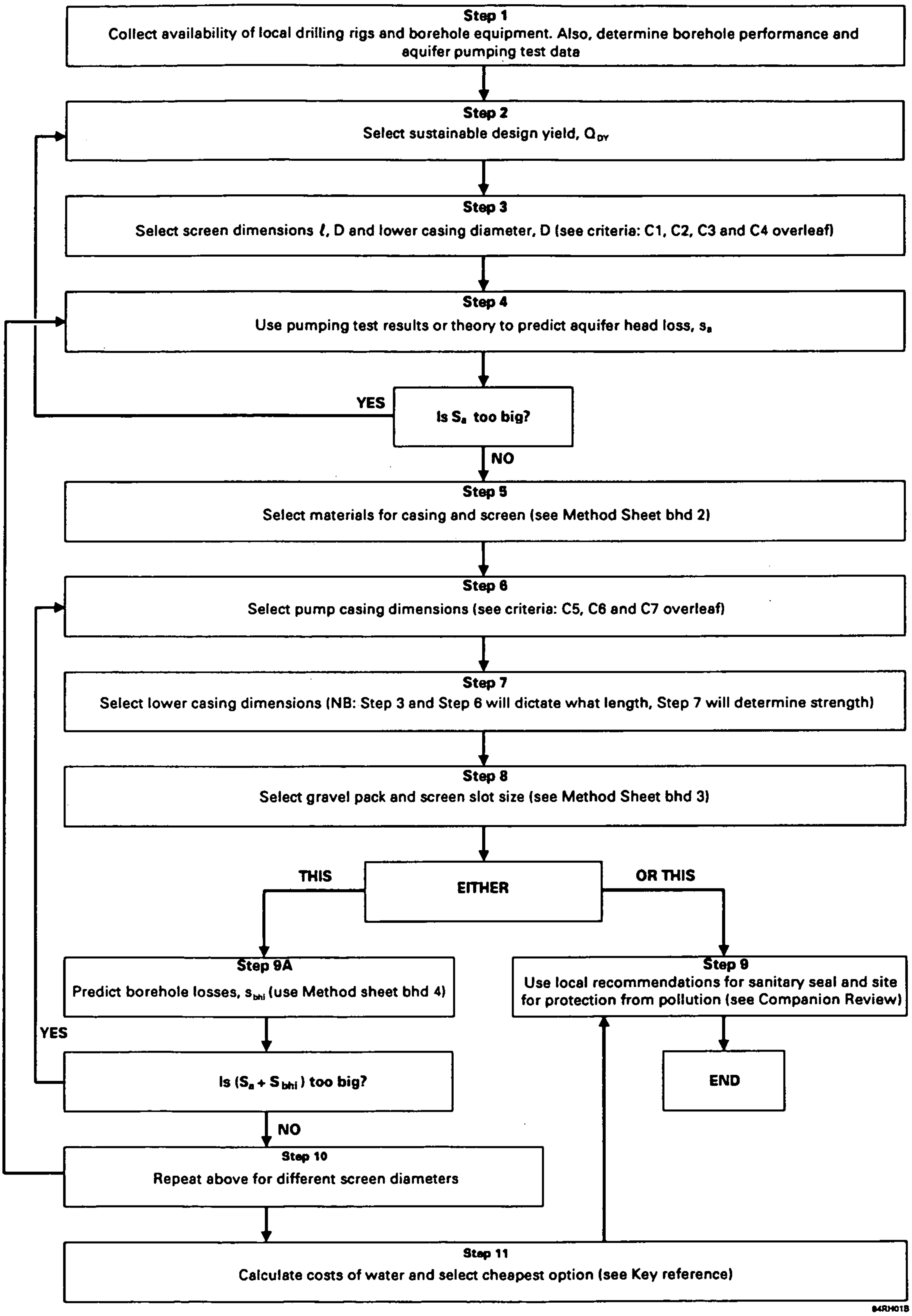


Fig bhd 1/1. Borehole design sequence

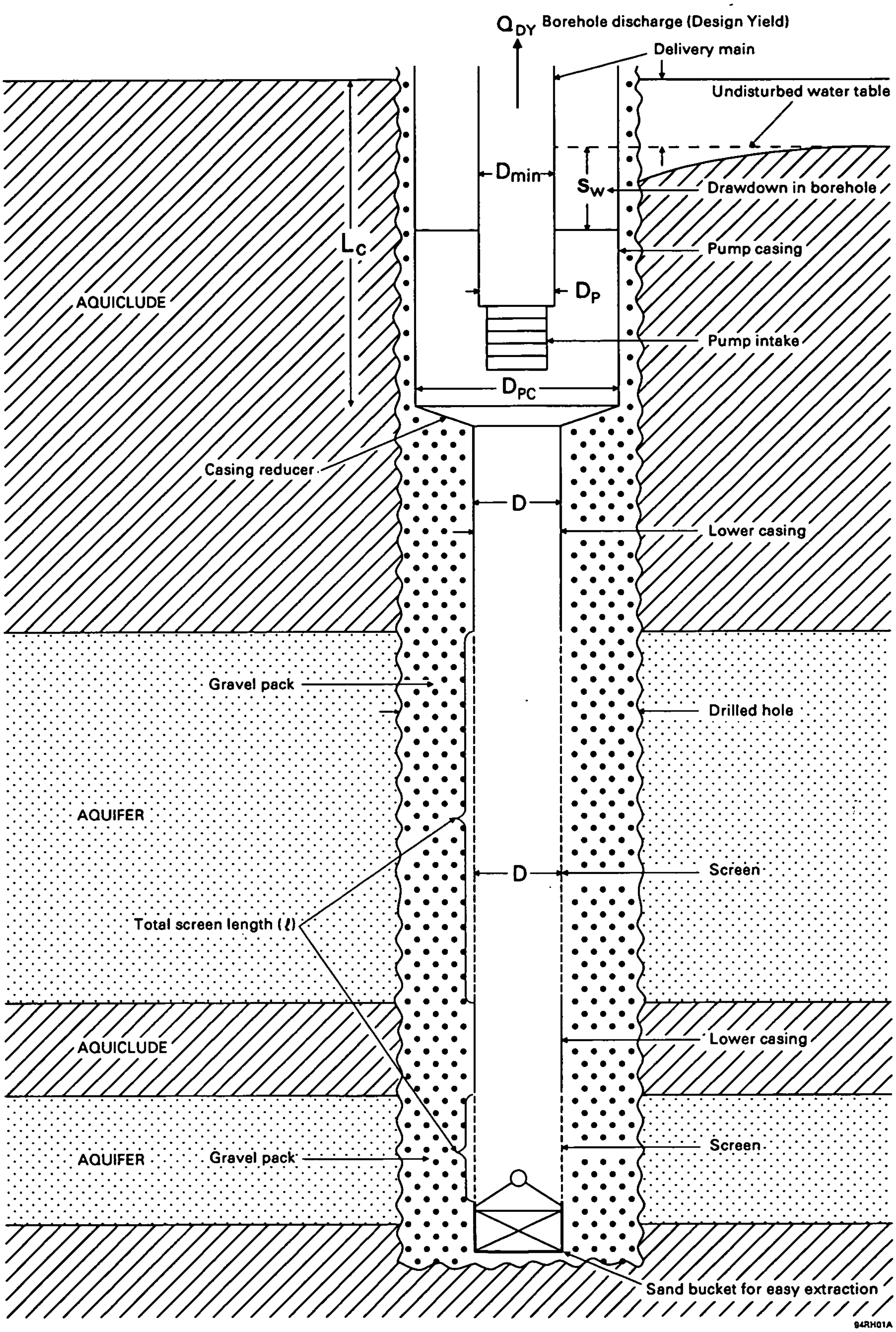


Fig bhd 1/2. A typical borehole and notation used

NOTATION:

		Units
Q_{DY}, Q_w	Design yield of borehole	m3/second
$D_{(min)}$	(minimum) diameter of screen and lower casing	m
ℓ	Total length of screen	m
s_w	Drawdown in borehole	m
s_a	Drawdown in aquifer	m
s_{bhi}	Drawdown (head loss) incurred in borehole	m
s_{skin}	Drawdown ( ) due to borehole wall damage	m
L_c	Length of pump casing below ground level	m
D_{PC}	Diameter of pump casing	m
D_p	Maximum diameter of pump intake or delivery main	m
P_c	Collapse strength of casing or screen	psi
d_n	n% of sieved material is finer than grain size d (mm)	mm
d_{np}	d_n for gravel pack	mm
d_{nA}	d_n for aquifer material	mm
S	Slot size	mm
d_{nAC}	d_{nA} for coarse component of illsorted portion	mm
d_{nAF}	d_{nF} for fine component of illsorted portion	mm
CQ^2_w	Equals s_{bhi}, C is a constant calculated using Eqn 14	sec^2/m^5
α,β	Constants allowing calculation of friction and momentum losses (see Table)	sec^2/m^5
g	Acceleration due to gravity	m/sec^2
f_s	Friction factor of individual lengths of casing in borehole	(-)
ℓ_s	Length of individual lengths of casing in borehole	m
D_s	Diameter of individual lengths of casing in borehole	m
k'	A dimensionless constant associated with casing reducer hydraulics ($\approx$ 0.2 for cone angles <15°)	(-)

Key References:

Driscoll F (1986) Groundwater and Wells. Johnson Division, St Paul, Minnesota 55112.

Barker J and Herbert R (1989a). The Pilot Study into Optimum Well Design, IDA 4000 Tubewell II Project, Bangladesh. Volume 4: Well and Aquifer Modelling, Part II - A simple theory for approximating well losses. BGS Technical Report No. WD/89/12.

Barker J and Herbert R (1989b). The Pilot Study into Optimum Well Design, IDA 4000 Tubewell II Project, Bangladesh. Volume 3: Hydraulic Tests on Well Screens. BGS Technical Report No. WD/89/10.

Herbert R, Barker J, Davies J and Nuruzzaman N (1988). The Pilot Study into Optimum Well Design, IDA 4000 Tubewell II Project, Bangladesh. Volume 5: Calculating and Comparing Costs and Selection of the Optimum 2-Cusec Irrigation Well. BGS Technical Report No. WD/88/33.

Method Summary Sheet (bhd 2)

Title: ***Determining the Ryznar Stability Index*** (The Selection of Material for Casing and Screen)

Scope and Use of Method:

The Ryznar Stability Index, RSI, is one of many indicators that can be used to see if groundwater is corrosive or encrusting. The appropriate Review, which includes borehole design, should be read in conjunction with this summary sheet if further details are required.

Recommendation

All screens, except for temporary boreholes for dewatering etc, should be made of non-corrosive material. This is necessary because acidisation is the recommended method for rehabilitating encrusted wells and the acid used would otherwise attack the screen. As regards casing, it is common practice to use mild steel for pump casing in encrusting waters.

Method:

The RSI is calculated using values for total dissolved solids, TDS, methyl orange alkalinity and calcium ion concentration (0.4 x calcium hardness). ***An RSI of less than 7 is indicative of encrusting conditions and an RSI of greater than 7 is indicative of corrosive conditions.***

$$RSI = S - C - pH$$

S is obtained from Fig 1 using TDS; C is obtained from Fig 2 using methyl orange alkalinity (mg/l) and calcium ion concentration mg/l.

Fig 1

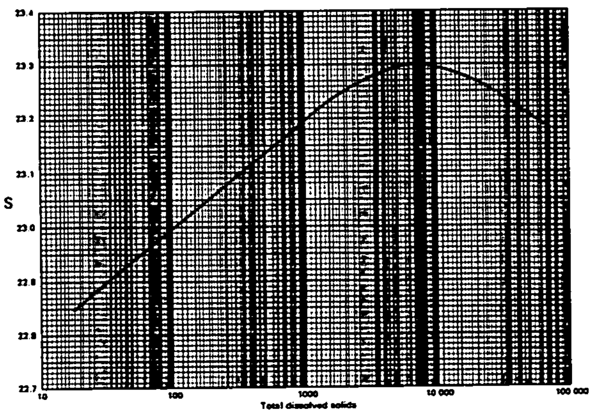
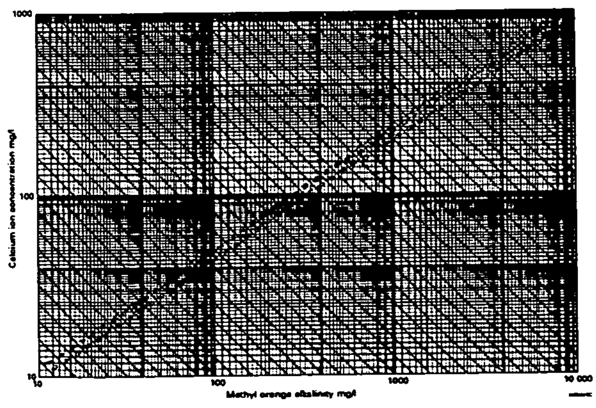


Fig 2



Key References:

Driscoll F (1986). Groundwater and Wells. Johnson Division, St Paul, Minnesota 55112.

Method Summary Sheet (bhd 3)

Title: ***Selecting Gravel Pack and Screen Slot Size***

Scope and Use of Method:

It is recommended gravel packs are used in all boreholes in UNSAs because regardless of any other issue the largest slot size possible can then be used. This will reduce the likelihood of encrustation or corrosion and will better assist rehabilitation by surging or jetting. The procedure given allows for the aquifer material being ill-sorted (a mixture of two materials). The full procedure recommended is not in universal use but there is growing evidence that ill-sorted sands are common (braided-river systems) and that these are one possible cause of short well life (see Davies & Herbert). If present day common practice must be adhered to and/or the aquifer is considered not to be ill-sorted, then Steps 1, 4 and 7 below are sufficient for gravel pack and slot size design.

Method:

Step 1: Determine the grain size distributions (gsds) of the aquifer layers to be screened, by sieve analysis. Fig 1 shows a family of gsds for sand samples taken from a river alluvium in Fiji.

Notation: d_n means there is n% finer than grain size d (mm) in the sample. In Fig 1 d_{40} is about 2.0 mm. Also, d_{nAC} and d_{nAF} means n% of the coarse, C, and fine, F, fraction of the aquifer, A, is finer than d (mm).

Step2: Test for ill-sortedness. Split the gsd curve into two parts. In very ill-sorted sands there is an easily identifiable break in slope. For several splits check the following:

$d_{15AC} \geq 4d_{15AF}$ for coarsest layer and $d_{15AC} \leq 4d_{85AF}$ for finest layer (Criterion C10)

If above criteria are met the material is self-filtering and not ill-sorted.

Step 3: Test for screened material collapse. If aquifer is ill-sorted, C10 do not apply, the fine material will move through the coarse and collapse could occur.

If $d_{50AF} \leq d_{50AC}/4$ (Criterion C11), collapse will not occur.

Step 4: If material is self-filtering, C10 applies, *then if subscripts A and P mean aquifer and gravel pack* then choose pack gsd as follows:

$d_{15P} \geq 4d_{15A}$ for coarsest layer and $d_{15P} \leq 4d_{85A}$ for finest layer (Criterion C8)

Step 5: If material is ill-sorted and collapsing, neither C10 nor C11 apply, no attempt should be made to screen this material.

Step 6: If material is ill-sorted but not collapsing, C11 applies but C10 does not then the pack gsd should satisfy Criteria C12:

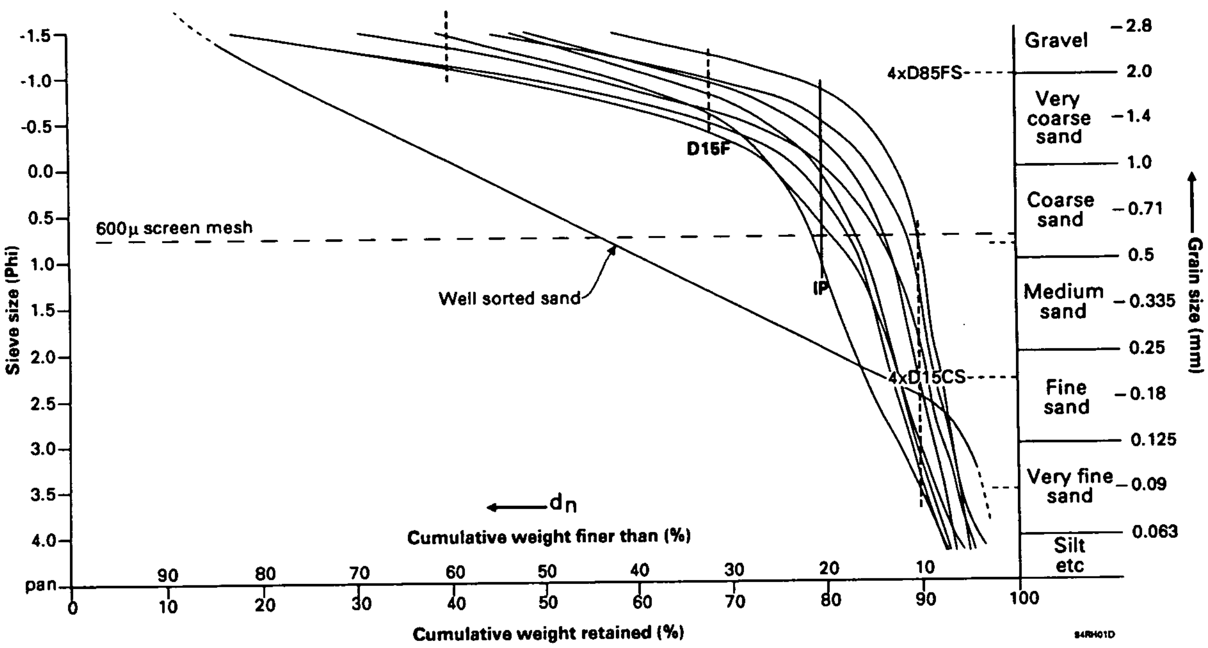
$d_{15P} \geq 4d_{15AC}$)
)   Criteria 12
$d_{15P} \leq 4d_{85AC}$)

Step 7: A slot size S (mm) is chosen using Criteria 13:

$$S(mm) = d_{85P}$$

NB: If material is ill-sorted, then a coarser gravel pack and bigger slot size than usual will be required by above criteria.

Fig 1



Typical Grading Size Curve for Samples taken from Braided River Deposits in Fiji.

Key References:

Davies J, Herbert R & Kumar P (1993). Shallow Aquifers Characterised by Poor Sediment Sorting and Tixed Textures: Final Report. BGS Technical Report No. WD/93/17.

Kovacs G and Ujfaludu L (1981). Movement of Fine Grains in the Vicinity of Well Screens. Hydrological Sciences Journal, Vol. 28, Part 2, pp 247-260.

Terzaghi K and Peck R (1948). Soil Mechanics in Engineering Practice. John Wiley & Sons, London, pp 49-51.

Method Summary Sheet (bhd 4)

Title: ***Predicting Head Losses Inside Boreholes, s_{bhi}***

Scope and Use of Method:

The drawdown in a borehole, s_w, can have three components: s_a, a head loss in the aquifer to the screen; s_{bhi}, head losses inside the borehole and s_{skin}, head loss incurred at the screen or gravel pack due to encrustation or blocking of screen. At the time of drilling, if the borehole is fully developed, s_{skin}, will be negligible. The method described below can be used to calculate, s_{bhi}. This is useful in interpretation of borehole performance and pumping test results. This method will be accurate for well-designed screens, where Equation 1 applies:

$$D_{minSCREEN} \geq 0.92 \sqrt{Q_{DY}} \ (m^3/sec) \qquad (1)$$

The Review gives a detailed derivation of Equation 3 below. The Key Reference by Barker et al gives more details and experimental field tests, which verify the accuracy of the technique.

Method:

s_{bhi} can be calculated using Equations 2 and 3:

$$s_{bhi} = CQ_w^2 \qquad (2)$$

$$C = (\alpha\ell/4 + \beta/3) + 8/\pi^2 g \left[\sum_s f_s \ell_s / D_s^5 + k' (1/D^2 - 1/D_{pc}^2)^2\right] \qquad (3)$$

Where α and β come from Table 1.

NB: All notation is the same as that used in Fig bhd 1/2 of Method Summary Sheet (bhd 1).

<u>Check:</u>

If step drawdown tests are run correctly and each step is run long enough to ensure the same quasi-steady state is achieved in the vicinity of the borehole, CQ_w^2 can be determined from the usual plot of s/Q_w.vs.Q_w. The slope of the curve will equal C.

Key Reference:

Barker J and Herbert R (1989a). The Pilot Study into Optimum Well Design, IDA 4000 Tubewell II Project, Bangladesh. Volume 4: Well and Aquifer Modelling, Part II - A simple theory for approximating well losses. BGS Technical Report No. WD/89/12.

Table 1 **Values of α and β for a wide range of borehole screens**

Test No.	Make*	Material+	Nominal Diameter (in)	I.D. (m)	α (s^2/m^5)	β (s^2/m^5)
1	Jo	SS	6	0.158	26.0	540.0
2	BC	GRP	6	0.153	18.50	652.0
3	Jo	SS	6	0.158	31.00	523.0
4	No	SS	6	0.150	31.20	637.0
5	No	SS	6	0.151	23.20	662.0
6	Du	P	6	0.147	18.80	732.0
7	Du	P	6	0.148	16.00	746.0
8	Du	P	6	0.148	17.70	730.0
9	Hy	P	6	0.147	23.70	759.0
10	Pr	P	6	0.148	15.80	712.0
11	Pr	P	6	0.151	11.80	686.0
12	De	P	6	0.149	17.00	813.0
13	De	P	6	0.147	20.30	738.0
14	De	GRP	6	0.168	20.00	492.0
15	Jo	SS	4	0.112	138.00	2240.0
16	No	SS	4	0.101	76.40	3610.0
18	Du	P	4	0.102	72.90	3490.0
19	Du	P	4	0.102	123.00	3530.0
20	Hy	P	4	0.101	156.00	3750.0
21	Jo	SS	8	0.201	6.14	173.0
22	BC	GRP	8	0.203	3.49	201.0
23	Du	P	8	0.197	3.47	220.0
24	Hy	P	8	0.200	3.25	229.0
25	Jo	SS	10	0.259	2.46	78.3
26	No	SS	12	0.298	0.81	41.6
27	Du	P	12	0.301	0.71	42.8
28	Hy	P	12	0.300	0.71	43.7
29	BC	GRP	6	0.152	13.10	646.0

\+ SS - Stainless steel
P - Plastic
GRP - Glass-reinforced plastic

* Jo - Johnson
BC - Bristol Composite
No - Nold
Du - Durapipe
Hy - Hydrotech
Pr - Preussag
De - Demco

NB: To calculate s_{bhi} in meters use table values as shown and Q_w in m^3/sec.