BRITISH STANDARD

BS 6316 : 1992

Code of practice for

Test pumping of water wells

Essai de pompage de l'eau des puits — Code de bonne pratique

Leitfaden für Pumpversuche an Brunnen

BSI STANDARDS

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Foreword

This British Standard code of practice has been prepared under the direction of the Industrial-process Measurement and Control Standards Policy Committee. It supersedes BS 6316 : 1983 which is withdrawn.

The increasing demand for water makes it vital for water resources to be used efficiently, and this in turn adds great importance to reliable quantitative estimates of groundwater resources. The pumping test is, for the present, the most reliable way of evaluating the hydraulic behaviour of wells and aquifers. Development of groundwater resources without adequate pumping test data is a speculative operation which may have unforeseen consequences.

It has been assumed in the drafting of this British Standard that the execution of its provisions is entrusted to appropriately qualified and experienced people, for whose guidance it has been prepared.

Compliance with a British Standard does not of itself confer immunity from legal obligations.

Section 1. General

0 Introduction

Pumping tests are normally carried out to obtain data with which to:

(a) assess the hydraulic behaviour of a well and so determine its ability to yield water, predict its performance under different pumping regimes, select the most suitable pumping plant for long term use and give some estimate of probable pumping costs;

(b) determine the hydraulic properties of the aquifer or aquifers which yield water to the well; these properties include the transmissivity and related hydraulic conductivities, storage coefficient and the presence, type and distance of any hydraulic boundaries;

(c) determine the effects of pumping upon neighbouring wells, watercourses, or spring discharges.

A pumping test also provides a good opportunity to obtain information on water quality and its variation with time and perhaps with discharge rate.

When water is pumped from a well, the head in the well is lowered, creating a drawdown or head loss and setting up a localized hydraulic gradient which causes water to flow to the well from the surrounding aquifer. The head in the aquifer is also reduced and the effect spreads outwards from the well. A cone of depression of the potentiometric surface is thus formed around the well and the shape and the manner of expansion of this cone depend on the pumping rate and on the hydraulic properties of the aquifer. By recording the changes in the position of the potentiometric surface in observation wells located around the pumping well it is possible to monitor the growth of the cone of depression and determine these hydraulic characteristics. The form of the cone of depression immediately around the well will generally be modified because additional head losses are incurred as the water crosses the well face. The drawdown may be considered to consist of two components:

(1) head loss through the aquifer;

(2) head loss in the well.

Consequently, there are two test objectives: an understanding of the characteristics of the well and those of the aquifer.

A test may be performed to serve any or all of the main objectives. If they are satisfied it may be said that the hydraulic regime of the well and aquifer has been evaluated. However it needs to be understood that other information, particularly about other factors affecting recharge, will be required to predict the long term effects of abstraction.

It needs to be recognized that there are inherent difficulties involved in carrying out a pumping test, e.g. making many physical measurements. In part these arise from the tendency of the measuring process or equipment to change the quantity being measured. For example, the drilling of boreholes to investigate the hydraulic regime of an aquifer may disturb that hydraulic regime by providing vertical communication between aquifer levels containing water at different heads. A second difficulty involves sampling. Only rarely will a cone of depression be circular and symmetrical; the relatively few observation boreholes which are usually available in effect provide a limited number of sampling points with which to determine the form of the cone. It is important that these limitations and difficulties are kept clearly in mind when designing and analysing a pumping test and, in particular, when using the results.

Figure 1 indicates the normal sequence of events in a pumping test.

1 Scope

This code of practice describes the factors which need to be considered and the measurements which need to be made when designing and performing a pumping test. However, there can be no such thing as a 'standard' pumping test because of the great diversity of objectives, aquifers, groundwater conditions, available technology and legal contexts. This code therefore provides a set of guidelines for field practice, with an indication of how they may be varied to take account of particular local conditions. It deals with the usual types of pumping tests carried out for water supply purposes, in which water is abstracted from the entire screened, perforated, or unlined interval(s) of a well. Some guidance is also provided on slug tests and packer tests. Specialized tests, such as drill-stem tests, and tests of strata for engineering purposes, are not considered in detail. Guidance on some of these specialized tests is given in BS 5930.

Interpretation of the data collected during a pumping test is referred to in this code only in a general way. For full details of the analysis and interpretation of test data, e.g. with regard to stream flow depletion, reference should be made to specialized texts. Examples of such texts are included in a selected bibliography.

NOTE. The titles of the publications referred to in this code of practice are listed on the inside back cover.

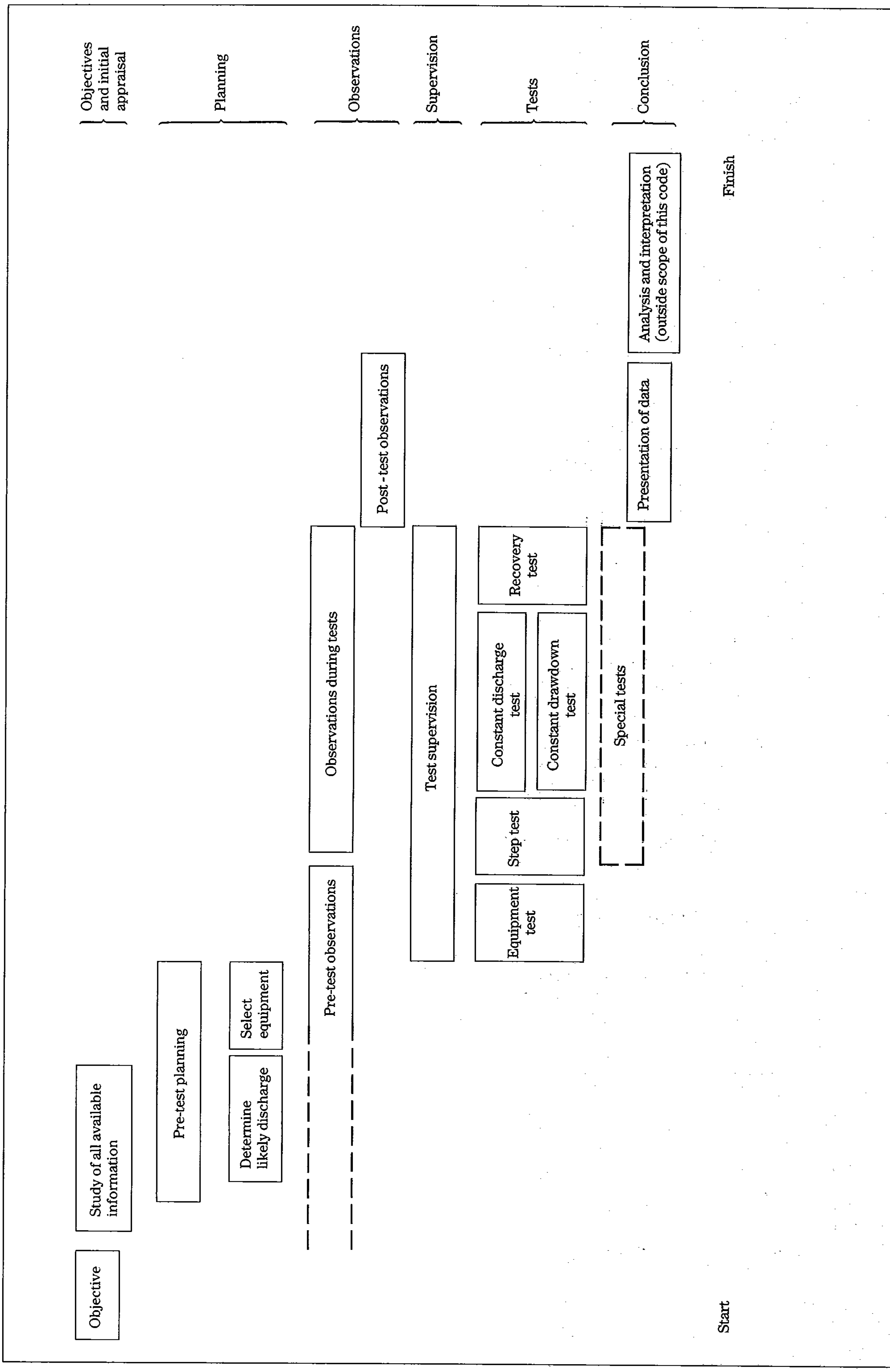


Figure 1. Typical pumping test procedure

2 Definitions

For the purposes of this British Standard the following definitions apply.

2.1 abstraction

The removal of water from any source, either permanently or temporarily.

2.2 access tube

A pipe inserted into a well to permit installation of instruments, and safeguarding them from touching or becoming entangled with the pump or other equipment in the well.

2.3 aquifer

A lithological unit, group of lithological units, or part of a lithological unit containing sufficient saturated permeable material to yield significant quantities of water to wells or springs.

NOTE. It may contain unsaturated permeable material.

2.4 aquifer loss

The head loss at a pumped or overflowing well associated with groundwater flow through the aquifer to the well face.

2.5 aquifer properties

The properties of an aquifer that determine its hydraulic behaviour and its response to abstraction.

2.6 borehole

A hole, usually vertical, bored to determine ground conditions, for extraction of water or measurement of groundwater level.

2.7 casing

A tube used as temporary or permanent lining for a well.

2.8 column pipe

That part of the rising main within the well.

2.9 cone of depression

That portion of the potentiometric surface that is perceptibly lowered as a result of abstraction of groundwater from a well.

2.10 confining bed

A bed or body of impermeable material stratigraphically adjacent to an aquifer and restricting or reducing natural flow of groundwater to or from the aquifer.

2.11 discharge

Volumetric flow rate.

2.12 drawdown

The reduction in static head within the aquifer resulting from abstraction.

NOTE. See also appendix A.

2.13 filter pack

Granular material introduced into a well between the aquifer and a screen or perforated lining to prevent or control the movement of particles from the aquifer into the well.

2.14 steady flow

Flow in which parameters such as velocity, pressure, density, and temperature do not vary sufficiently with time to affect the required accuracy of measurement.

2.15 uniform flow

Flow in which the magnitude and direction of flow at a given moment are constant with respect to distance.

2.16 foot valve

A non-return valve fitted at the bottom of a suction pipe of a pump.

2.17 groundwater

Water within saturation zone.

2.18 hydraulic conductivity

The volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured perpendicular to the direction of flow.

NOTE 1. See also appendix A.

NOTE 2. This definition assumes an isotropic medium in which the pores are completely filled with water.

2.19 hydraulic gradient

The change in static head per unit of distance in a given direction.

2.20 hydrogeology

The study of subsurface water in its geological context.

2.21 impermeable material

Material that does not permit water to move through it at perceptible rates under the hydraulic gradients normally present.

2.22 incompetent stratum

A stratum unable to stand without support.

2.23 isotropic

Having the same properties in all directions.

2.24 lining

A tube or wall used to support the sides of a well, and sometimes to prevent the entry of water.

2.25 lining tube

A preformed tube used as the lining for a well.

NOTE. See also casing (defined in **2.7**) and screen (defined in **2.38**).

2.26 lithology

The physical character and mineralogical composition that gives rise to the appearance and properties of a rock.

2.27 observation well

A well used for observing groundwater head or quality.

2.28 overflowing well

A well from which groundwater is discharged at the ground surface without the aid of pumping.

NOTE. A deprecated term for this definition is an artesian well.

2.29 permeability

The characteristic of a material that determines the rate at which fluids pass through it under the influence of differential pressure.

2.30 permeable material

Material that permits water to move through it at perceptible rates under the hydraulic gradients normally present.

2.31 phreatic surface

The upper boundary of an unconfined groundwater body, at which the water pressure is equal to atmospheric.

2.32 potentiometric surface

The surface that represents the static head of groundwater.

2.33 radius of influence

The radius of the cone of depression.

2.34 rising main

The pipe carrying water from within a well to a point of discharge.

2.35 rock

A natural mass of one or more minerals that may be consolidated or loose (excluding top soil).

2.36 running plot

A graph of a variable against elapsed time continually updated as measurements are taken.

2.37 saturated zone

That part of an aquifer, normally beneath the deepest water table, in which ideally all voids are filled with water under pressure greater than atmospheric.

2.38 screen

A type of lining tube, with apertures designed to permit the flow of water into a well while preventing the entry of aquifer or filter pack material.

2.39 slurry

The mixture of fluid and rock fragments formed when drilling or developing a borehole.

2.40 specific capacity

The rate of discharge of water from the well divided by the drawdown within the well.

2.41 specific yield

The ratio of the volume of water yielded by unit volume of permeable rock or soil when drained by gravity under specified conditions after being saturated to unit volume.

2.42 static head

The height, relative to an arbitrary reference level, of a column of water that can be supported by the static pressure at a given point.

2.43 storage coefficient

The ratio of the volume of water that a vertical column of an aquifer of unit cross-sectional area releases from storage as the head within the column declines unit distance to unit volume.

2.44 transmissivity

The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the saturated aquifer under a unit hydraulic gradient.

2.45 unconsolidated rock

Rock that lacks natural cementation.

2.46 unsaturated zone

That part of an aquifer between the land surface and the deepest water table.

2.47 viscosity

The property of a fluid whereby it tends, within itself, to resist relative motion.

NOTE. See also appendix A.

2.48 water table

The surface of a groundwater body at which the water pressure is atmospheric.

2.49 well

A hole sunk into the ground for abstraction of water or for observation purposes.

NOTE. See also appendix B.

2.50 well development

The physical and chemical treatment of a well to achieve minimum resistance to movement of water between well and aquifer.

2.51 well efficiency

A measure of the performance of a production well.

2.52 well loss

The head loss resulting from flow of groundwater across the well face, including any part of the aquifer affected by drilling, and any filter pack or lining tube, into the well and up or down the well to the pump.

Section 2. Hydrogeological considerations

3 General

Before a pumping test is planned a full assessment of the hydrogeological conditions at and around the test site should be carried out. Relevant information can be obtained from the regional offices of the responsible statutory bodies, such as the National Rivers Authority or the River Purification Boards in Scotland, or from the National Well record collection of the British Geological Survey. A survey of existing wells is necessary and, in areas where the hydrogeological data are inadequate, it may be desirable to expand these by a field survey.

Because of the wide range of circumstances in which pumping tests might be contemplated, and the probability that the aquifer will be partly and perhaps nearly fully developed already, a search for and analysis of existing borehole operational and test data and associated surface water levels and flows should be considered as prerequisites to such tests.

4 Aquifer response characteristics

Two parameters define the quantitative hydrogeological properties of an aquifer, namely permeability and storage. Permeability is concerned with the ability of an aquifer to permit groundwater flow under a hydraulic gradient. Storage concerns the volume of water available within the aquifer and subsequently released when water levels are depressed around a discharging well. Together these two parameters can be taken to control the response time for pumping effects in an aquifer. With a low permeability and a large storage coefficient, the radius of influence will increase slowly. An aquifer with a high permeability and a small storage coefficient would exhibit a rapid increase in the growth of the radius of influence.

A consideration of the aquifer response time is necessary when locating sites for observation wells.

5 Groundwater conditions (see also appendix C)

The storage coefficient in a confined aquifer may be at least 100 times less than in the same aquifer in an unconfined state. This reduction is reflected in a much more rapid aquifer response time.

When the confining bed is not wholly impermeable the storage coefficient varies between the totally unconfined and the totally confined values and the aquifer response time will vary accordingly.

The presence of overlying impermeable strata does not necessarily imply a confined aquifer. The presence of an unsaturated zone beneath an impermeable stratum may permit the aquifer to demonstrate an unconfined response.

It is possible for confined and unconfined conditions to occur in different parts of the same aquifer, or in the same part of the aquifer, as a result of seasonal or other movements of the potentiometric surface.

6 Multi-layered aquifers

Most aquifers comprise sedimentary strata and these are deposited as a series of superimposed layers. Successive layers could have different lithological characteristics from the adjacent layers and consequently the hydraulic conductivity in the horizontal plane tends to be greater than that in the vertical plane. In extreme cases intervening layers may be impermeable resulting in a multi-layered aquifer. Wells penetrating such an aquifer may intersect an unconfined layer near the surface and one or more confined layers at depth. Failure to recognize this possibility may lead to inadequate monitoring of groundwater levels and to misleading data being obtained in a pumping test.

7 Boundary conditions

Barrier boundaries are normally presented by geological discontinuities caused by faulting-out of the aquifer or by the aquifer itself having a rapid diminution in thickness or saturated thickness. Occasionally aquifers show a rapid, lateral, lithological change with a consequent severe reduction in the aquifer properties. Deep channels scoured in an aquifer and later filled with impermeable deposits may also form barriers. Barrier boundaries have the effect of increasing the drawdown. The pumping of another well in the same aquifer will have the same effect as a boundary if the cones of influence of the two wells intersect.

Recharge boundaries occur when water other than from groundwater storage effectively contributes to an aquifer drawn on by a pumping well. Such boundaries may be provided by surface watercourses, by lakes, or by the sea when these lie within the radius of influence of the well.

All these may be regarded as discrete recharge boundaries and often are definable as point or line recharge sources for the purpose of analysis. Recharge boundaries have the effect of decreasing the rate of drawdown, or checking the drawdown altogether. Downward leakage from overlying strata or the interception of natural flow through the aquifer may simulate a recharge boundary by decelerating the drawdown, but the effects cannot necessarily be identified with a localized source.

8 Other hydrogeological factors

There are several factors which may significantly affect the analysis of pumping test data although they may not affect the test itself.

The thickness of the aquifer should be ascertained, at least approximately. Corrections are necessary in the analysis for partial penetration by the pumping wells. The degree of penetration of the observation wells is also important to ensure the measurement of realistic water levels.

Unconfined aquifers may demonstrate the phenomenon of delayed yield from storage. The rate of drawdown during the early stages of the test may be temporarily reduced for a period ranging from an hour to several weeks before turning to a more normal rate of drawdown. It may be necessary in these circumstances to prolong the pumping test to obtain sufficient drawdown data after the effects of the delayed yield have ceased.

During the period of a pumping test in a confined aquifer water levels in the pumping well, and possibly in the observation wells, may fall below the confining bed. If this possibility exists, the depth of the base of the confining bed needs to be determined in all the wells to permit proper analysis of the test data.

Section 3. Pre-test planning

9 Statutory requirements

Attention is drawn to Acts, Byelaws, Regulations and any other statutory requirements relating to matters dealt with in this code of practice. Work should be carried out in accordance with, and the equipment in use should comply with, the appropriate regulations. Amongst others particular attention is drawn to the following provisions current in the United Kingdom at the date of publication of this code of practice:

(a) Public Utilities Street Works Act 1950;

(b) Rivers (Prevention of Pollution) (Scotland) Act 1951;

(c) The Construction (General Provisions) Regulations 1961;

(d) The Construction (Lifting Operations) Regulations 1961;

(e) The Construction (Working Places) Regulations 1966;

(f) The Construction (Health and Welfare) Regulations 1966;

(g) Health and Safety at Work etc. Act 1974;

(h) Control of Pollution Act 1974;

(i) Water (Scotland) Act 1980;

(j) Water Act 1989;

(k) Environmental Protection Act 1990;

(l) Water Resources Act 1991;

(m) National Heritage (Scotland) Act 1991.

Sites within designated areas such as national parks, areas of outstanding natural beauty, areas of special scientific interest, etc., or those close to or within residential areas may have special constraints imposed on test operations, and these should be ascertained before any drilling or test pumping operations commence.

Persons planning to sink and/or test pump a well are advised to discuss their proposals in advance with appropriate regulatory authorities. Unless specifically exempted by the regulations, it is essential that they ensure that procedures for obtaining permissions or consents are followed before any works are carried out.

10 Site facilities and organization

10.1 General

Guidance is given on general matters which affect the organization and activities of the test pumping site. The actual details will vary from site to site and may include matters not described in this clause which therefore should not be assumed to be exhaustive in its coverage. As well as the recommendations for site facilities and organization, and the requirements of the provisions listed in clause **9**, the following publications offer guidance pertinent to test pumping activities:

(a) *Code of safe drilling practice*: Part 1 *Surface drilling*[1];

(b) National Joint Council Health and Safety Commission for the Water Industry Guidance Note *Health and safety at work*[2];

(c) *Safety in wells and boreholes* (1972)[3];

(d) BS 5573.

Before any drilling or test pumping commences a preliminary survey should be carried out bearing in mind these recommendations for site facilities and organization.

10.2 Space and headroom

At the outset it is necessary to ensure that sufficient space is available for any test equipment and pumping plant required on the site as well as lagoons for disposal of acid sludge, etc., where necessary. Parking space for vehicles should be designated, and overhead obstructions such as power cables, guy lines, trees and so forth should be noted and clearly marked if necessary.

10.3 Safety of personnel on site

Every care should be taken to reduce the risks to personnel working at the test pumping site. First aid kits should be provided on site as a part of the normal safety arrangements and should be additionally equipped with soda for the neuralization of acid when the acid is to be handled during the development of a well; an adequate supply of flowing fresh water should be available for washing acid from the eyes or sluicing it from the skin or clothing.

Paths between the site hut, the test well, the observation wells, etc. should be clearly marked, as should hazards such as fences, cables, mud pits and spoil heaps. Sites which on initial inspection appear to be firm and dry often degenerate to a slippery morass around the well head. The nature of the ground therefore should be carefully inspected beforehand and if necessary arrangements made to provide duckboards and walkways for the working team.

If the test is prolonged through the hours of darkness adequate lighting should be provided.

The site inspection should have revealed the presence of any overhead electric cables likely to be a hazard. Unless details are already available a check should be made for the presence of any underground electric cables or other services under

[1] Available from the British Drilling Association, PO Box 113, Brentwood, Essex CM15 9OS.
[2] Available from National Water Council Publications, Queen Anne's Gate, London.
[3] Available from the Institution of Civil Engineers, Great George Street, London W1.

the site, such as gas mains, telecommunication cables, etc., and the route of these should be temporarily marked. In the case of overhead cables a vehicle route beneath them should be established and clearly marked giving also the minimum overhead clearance.

NOTE 1. Additional safety advice on the danger from overhead electricity lines and underground cables is given in Guidance Note GS6 *Avoidance of danger from overhead electric lines* published by the Health and Safety Executive[1] and in the booklet *Recommendations on the avoidance of danger from underground electricity cables* published by the National Joint Utilities Group of British Telecom, the Electricity Council, British Gas and the National Water Council.

NOTE 2. The presence of either overhead or underground power lines may also affect certain types of electronic equipment, notably pH and ion-selective meters and down-hole logging equipment.

10.4 Utility services

If electrically powered equipment is to be used, the possibility of making available a supply from the mains will need to be investigated. This should be done well ahead of mobilization to site since a temporary incoming switchboard and metering point will be required and the precise requirements for this are likely to vary between different electricity supply authorities. At the same time earthing arrangements should be settled. In many cases the supply authorities will be able to provide an earth terminal either from a continuous earth wire system or from a protective multiple earthing system. It is important to ascertain which form of earthing any electricity supply authority will provide as the requirements imposed on the customer are different (see the IEE Regulations for Electrical Installations)[2]. If there is any doubt about the mains earthing arrangements it is essential to provide an earth leakage circuit breaker of suitable capacity.

If a mains supply is not available it will be necessary to supply a generator of suitable capacity (see **13.3**). In this case electrical earthing requirements can be met by cross bonding the lifting rig, pump pipework and generator and providing an earth probe. The earth loop impedance of the complete system should not be greater than 2 Ω.

All electrical installations on the site should comply with the requirements and recommendations of the IEE Regulations for Electrical Installations and CP 1017 as appropriate. Surface power cables between generator and well head should be armoured. Flexible braid armoured cable is more suitable and easier to handle in this application than single wire armoured cable. Single wire armored cable should comply with BS 6346. A watertight emergency stop lock-out button should be mounted within easy reach.

Special tests, such as certain types of packer test, will require a water supply. Constraints may be applied on the type of water to be used; tankers may be required, and possibly storage on site arranged. If the site is residential it will be necessary to provide a supply of potable water as well as water for general use. Where this is provided in containers these should be marked to distinguish potable from non-potable water.

If a telephone is required, it should be installed prior to the test commencing.

10.5 Site accommodation

A suitable hut or shelter should be erected upon the site, adequately lit and, if necessary, heated. Such accommodation should include tables and seating for the partaking of meals and facilities for boiling water and heating food.

The accommodation should be sufficiently secure to store first aid and fire-fighting equipment, test equipment, records, etc. If the test is to continue for one or more nights, sleeping accommodation should be arranged for off-duty personnel.

Latrines and washing facilities should be made available on site; if the operation is of a long term nature, consideration should be given to the provision of shower facilities.

10.6 Site communications

Signalling between the observation and pumping wells during the test can be carried out by visual or audible means, appropriate to the circumstances, e.g. by radio. Under some conditions visual signals may be inadequate.

10.7 Avoidance of pollution and disposal of wastes

Care should be taken to dispose of liquid or solid wastes carefully and safely and in a manner that will not pollute the wells or the surrounding area. If it is not possible to dispose of contaminated waste water directly into the sewerage system it should be collected and removed from site for treatment and disposal. Disposal of contaminated waste waters to a soakaway, albeit remote from the well head, ditches and watercourses, should not be undertaken without the consent of the regulatory authority. Solid wastes should be removed from the site for disposal at a licensed waste facility.

If an internal combustion engine is to be employed, either for power supply or direct drive, precautions should be taken to ensure that any oil or fuel spillages are contained. This point needs particular attention when an internal combustion engine is connected through a right angle gearbox to a long shaft turbine pump at the well head. The engine should be mounted on a firm platform with means

[1] Available from HMSO.
[2] Available from the Institution of Electrical Engineers, Savoy Place, London WC2R 0BL.

to ensure that any fuel or oil spillage can be contained. Adequate storage of fuel will also need to be provided with suitable precautions taken against leakage and fire.

In addition to the prevention of pollution by oil and fuel, precautions should be taken to prevent the well being infected by pathogenic and non-pathogenic organisms. The most likely source of pathogenic organisms is from latrine accommodation which should therefore be sited as far as possible from the well. Sterilization of any equipment to be placed in the well will reduce the risk of introducing infections from other sources (see **10.10**).

10.8 Disposal of pumped discharge

Arrangements should be made for the disposal of the pumped discharge, including any pipelines required. Ideally, the discharge point should be such as to exclude any possibility of recharge occurring of the abstracted water into the aquifer. The location of the discharge point should be cleared with the local authorities, landowners, and the National Rivers Authority (NRA). In many cases, discharge of turbid water into water courses will not be permitted so early advice should be sought from the regional NRA office. It should be noted that in wooded or forested areas, particularly with regard to coniferous trees, soakway disposal is undesirable because weakening of the root structure and consequent possible wind damage may result. In some cases the quantities of pumped discharge involved may make it impractical to use lagoons or soakway disposal for anything but the first small quantities of slurry or acid residue from the borehole. Discharges into watercourses should be so directed that scouring of the bed and banks does not occur.

10.9 Noise

Continuous noise can be exhausting and have a deadening effect on the reactions of personnel. This therefore is an important consideration in the location and silencing of any internal combustion engine employed. There is added significance when the site is located near permanent habitation where noise nuisance during the night may be unacceptable. Special arrangements should therefore be made for damping engine noise by the use of sound deadening enclosures around internal combustion engines, by using 'super-silenced' plant or by the use of baffle screens, e.g. a wall of straw bales. Additional general guidance on the avoidance of problems associated with noise from surface sites may be found in BS 5228 and in the Health and Safety Executive publication *Code of practice for reducing the exposure of employed persons to noise*[1)].

10.10 Maintenance and storage of equipment

Structures, plant, machinery and test and measuring equipment should be inspected at regular intervals in accordance with the manufacturer's recommendations. In the case of plant which is subject to corrosion, steps should be taken to effect repairs before corrosion reaches dangerous limits.

Electrically operated hand tools and lamps, together with leads and earth wires, should be inspected at regular intervals to ensure that they have been maintained in good order and such inspections should be recorded. Trailing cables, except for hand lamps and small portable tools, should comply with BS 6708. Pliable armoured cables are preferred.

It is recommended that equipment is sterilized before installation in the well, in order to avoid introducing any infection resulting from the previous use of the pump and column pipe in an infected well. The simplest method is immersion in a 1 % solution of sodium hypochlorite by volume. Phenolic agents should not be used to sterilize pumping equipment. Subsequent storage and handling of the pumping equipment should be such as to avoid the introduction of any polluting material into the wells.

11 Design of the test

11.1 General considerations

The pumping test should be designed keeping in mind the objectives stated in the introduction and taking into account also the hydrogeological conditions of the site and the methods by which the results are to be analysed. A systematic approach ensures that the maximum information will be learned about both the well and the aquifer. Such an approach requires close control of the design and running of the test, but this can be achieved with little or no additional expense. It should be appreciated that the test is a scientific exercise providing a good database both for the aquifer and the abstraction of water therefrom.

Five types of pumping test may be considered as applicable. These are the equipment test, the step test, the constant discharge test, the constant drawdown test and the recovery test. The equipment test is carried out to check that the equipment is fully functional and to guide the operator with regard to obtaining suitable valve settings for the tests. In the main the step test provides information on the well hydraulics. The constant discharge and constant drawdown tests provide information on the aquifer properties.

[1)] Available from HMSO, 49 High Holborn, London WC1 for personal callers, or by post from HMSO, PO Box 276, London SW8 5DT.

11.2 Equipment test

The equipment test provides a check that the pumping equipment, discharge measuring devices and water level measuring instruments are functioning satisfactorily, and that all the equipment is in a safe condition with all safety devices fully functional. It will also give sufficient data for planning the tests in **11.3** to **11.5**, including data with which to determine appropriate values for valve settings for subsequent pumping tests.

11.3 Step test

The purpose of a step test is to establish short term yield-drawdown relationships and thereby define those elements of head loss attributable to laminar flow and those attributable to turbulent flow. The step test comprises pumping the well in a series of steps, each of which is at a different discharge rate. At least four steps are advisable, and the final discharge rate should approach the estimated maximum yield of the well. If the latter cannot be attained then the maximum capacity of the pump should be substituted. Care should be taken to avoid excessive drawdown as this could result in the pump running dry and so being damaged.

The steps may be taken consecutively, the pumping rate being changed at the end of each step, or intermittently, pumping being stopped after each step to permit groundwater levels to recover before commencing the next step. In consecutive steps the pumping rate should be either increased in equal increments from the first to the last step, or decreased in equal decrements from the first to the last step. The latter is less usual. In intermittent steps the pumping rate may be changed at random, the resultant data being analysed as a series of discrete tests.

Normally each of the steps should be of equal duration. It is rarely necessary for each step to last for more than 2 h but it is often convenient, both operationally and for plotting graphs, etc. for each step to last 100 min.

Where observation wells are present groundwater level measurements should be taken in them in addition to the pumping well. Observation wells are not necessary in the analysis of well performance but some indication will be given of the range of groundwater level fluctuation that will be produced in a test of longer duration.

11.4 Constant discharge test

Constant discharge tests are carried out by pumping at a constant rate for a period of time dictated by the discharge rate and the local hydrogeological conditions. The purpose of a constant discharge test is to obtain data on the hydraulic characteristics of an aquifer within the radius of influence of the pumped well. Observation wells are necessary in order to determine fully the aquifer properties. Table 1 gives the minimum durations that should be allowed for constant discharge tests. In certain situations, such as those described in this subclause, in clause **8** and in **11.7**, increases or decreases to these periods will be appropriate.

Table 1. Minimum duration of constant discharge tests

Discharge rate	Minimum duration of constant discharge
m^3/day	days (of 24 h constant discharge)
Up to 500	1
500 to 1000	2
1000 to 3000	4
3000 to 5000	7
Over 5000	10

The effect of a recharge boundary (see clause **7**) is a deceleration in the rate of drawdown. Where the recharge source is a specific feature, such as a watercourse or a lake, the elapsed time before the onset of this deceleration will increase in proportion to the square of the distance between the pumping well and the recharge source. Eventually drawdown will stabilize for the remainder of the test.

If a delayed yield effect (see clause **8**) occurs the development of the time-drawdown relationship will be delayed. It is not possible to estimate accurately in advance the length of this delay unless it has occurred in nearby wells previously tested in the same aquifer. If a delayed yield is expected an extension of the duration of the test should be considered.

Barrier boundaries (see clause **7**) have the effect of accelerating the rate of drawdown and present a serious constraint on the yield of the well. The shorter periods given in table 1 may therefore require extending by one or two days to observe the effects adequately, particularly if they appear towards the end of the period as initially specified.

11.5 Constant drawdown test

A constant drawdown test[1)] may have the same purpose as a constant discharge test. In theory constant drawdown tests can be performed upon any aquifer, providing that a pump with a variable discharge rate can be controlled in such a manner as to keep the drawdown to a particular constant amount. If the groundwater rest level is not expected to vary during the test period then the constant drawdown is at a constant level,

[1)] This is also known as a constant head test.

otherwise it is essential that the levels in control observation wells be used to estimate the pumping level needed to maintain constant drawdown.

Constant drawdown tests are used for tests with suction pumps, for design of dewatering schemes, for overflowing wells, for tests in piezometers and for tests using over capacity pumps.

In a well which is not overflowing the test should be carried out in the same manner as a constant discharge test, except that the discharge rate should be controlled so as to keep the drawdown constant. Particularly accurate measurement of the discharge rate is necessary.

In a well which is overflowing no pumping is necessary. The procedure is to shut off the flow at the well head, and then to measure the head of water thus contained. The well is then uncapped as near instantaneously as possible, thus reducing the head to near well head level. The discharge rate is then measured at the frequency recommended for a constant discharge rate. The advantage of this type of test is that no pumping plant is required. Estimates for transmissivity, and crude estimates of the storage coefficient, can be made without use of observation wells but such estimates are no more valid than similar estimates made without observation wells during conventional pumping tests.

The minimum duration of the test should be sufficient for the discharge to reduce to about 1 % of the initial rate.

NOTE. The minimum duration cannot be the same as for a constant discharge test (see table 1).

11.6 Recovery test

The recovery test can be carried out upon any aquifer after a constant discharge test or a variable discharge test.

The recovery test requires careful measurement of the duration and rate of pumped discharge prior to the discharge ceasing. The recovery test can form a useful check on values of transmissivity derived from a discharge test. The specific yield or storage coefficient may be determined less accurately by this means. This is largely due to the incomplete resaturation of the interstices within the aquifer dewatered during the test.

A recovery test dependent upon water levels measured in the test well should only be performed if a foot valve has been fitted to the rising main. This is because, in the absence of such a valve, there tends to be a rapid rise in water level as water surges in from the rising main and perhaps also from the weir tank if used. A recovery test may be performed using only water level data obtained from observation wells if the rising main in the test well is not fitted with a foot valve.

11.7 Surface water flow

Abstraction of groundwater will have an effect upon the natural discharge of water at the surface. Spring and stream flow depletion is often a major factor to consider during a programme of test pumping groundwater, particularly if the proposed discharge is high. The feasibility of a study of this kind will depend upon the accuracy of estimating the difference between the flow measured during the test and the flow that would have occurred if the abstraction had not taken place. This in turn will depend upon a number of factors including the scale of the abstraction relative to the surface flow, the distance between the test well and the surface flow, the point of discharge of the abstracted water and the accuracy and frequency of the surface flow measurement. In favourable conditions the effects may be observable within a few days. This is not commonly the case; it is more usual for the test to have to last at least 2 weeks and in some cases 12 weeks or more in order to permit satisfactory analysis of the surface water flows. This is particularly the case when recirculation occurs with groundwater being discharged to a river and induced recharge taking place from the same river into the pumped aquifer. It will be necessary also to consider the timing of the test in relation to the normal seasonal variations in surface water flow and the impact of climatic changes.

12 Observation wells

12.1 Purpose and characteristics of observation wells

In a constant discharge test observation wells are necessary for the accurate determination of the properties of transmissivity and storage coefficient of the aquifer. The value of the transmissivity is obtained by a study of the shape of the cone of depression which is indicated by water levels in the observation wells surrounding the pumping well. Existing wells should be used if their dimensions and locations are suitable. In other cases observation wells may need to be constructed before the test takes place. Additionally, as part of the test pumping consent requirements, existing wells within a specified distance of the test well may need to be monitored.

The time taken for the drawdown to affect the observation wells is proportional to their distance from the pumped well. Once drawdown commences at any point it may be rapid, irrespective of the radial distance from the test well. The magnitude of the drawdown is attenuated in proportion to the square of the distance from the pumped well.

12.2 Number and location of purpose-drilled observation wells

Preliminary calculations using estimated transmissivities, e.g. estimated from existing borehole data, should be made to indicate the likely response in observation wells to pumping and hence to determine their spacing from the test well and the timing of the observations.

Ideally the minimum number of observation wells is four, arranged in two rows at right angles to each other, but in most instances one to two observation wells will suffice. When a number of observation wells is required their distances from the test well should approximate to a geometrical series. Based simply on the response and the state of the aquifer the spacings in table 2 are a guide to the most favourable spacing of the closest of the observation wells. A spacing of less than 10 m from the test well is undesirable, the data obtained from closer distances presenting difficulty in analysis.

Attention should be paid to boundary conditions which may affect the location (see clause 7). The distance from the test well may need to be reduced if the boundary is in close proximity.

12.3 Depth of observation wells

Ideally observation wells should be constructed to the same stratigraphic level as the test well. In certain cases however, in order to investigate particular localized phenomena, they may be drilled to a shallower depth than the test well.

In multi-layered aquifers inaccuracies will arise where observation wells penetrate only the uppermost layer or layers. The options available in this case are to drill one of the following:

(a) a single observation well to the full depth of the test well and to install piezometers against each aquifer level;

(b) a number of observation wells to different levels, lining out all levels except one in each well;

(c) a single observation well open to the same stratigraphic levels as in the production well.

Unless an extensive analysis is to be performed, **12.3**(c) should give reasonable results.

12.4 Observation well design

Where observation wells are not to be fitted with instruments using floats or transducers, and water sampling is not to be undertaken, a large internal diameter is not necessary. A sufficient guide is for the internal diameter of the completed well to be three times the diameter of the probe on the dipper.

Sensitive continuous recording equipment is needed to discriminate between drawdown and other effects on water level in distant observation wells. The justification for automatic equipment in observation wells relatively close to the pumping well is reduced if the test is of only a few days' duration. In this case manual or visual water level recording should be adequate.

Where a means of automatic water level measurement is used the installation and operation should be in accordance with the instructions of the manufacturer in every respect.

The usual size of recorder float used in observation wells is between 75 mm and 115 mm. Where steel lining tubes are used, and the depth to water level does not exceed 30 m (at full drawdown), an internal diameter of 150 mm is sufficient. Where the depth to water level is greater than 30 m, an internal diameter of 200 mm is advisable since this reduces the possibility of the float and cable catching on the lining wall and producing steps or 'jumps' on the time-drawdown curve. If internally smooth thermoplastics or glass reinforced plastics lining tubes are used, a minimum internal diameter of 200 mm should be used. This is because there may be difficulty in maintaining sufficient verticality in a narrower lining tube to avoid fouling the float cable. Transducers can be of smaller diameter than floats and, since they do not travel continuously up and down the well, the diameter of the well need be sufficient only to contain the instrument.

Lining tubes should be carried down, if possible, to 2 m below the maximum expected depression of the water level. Floats tend to catch on the bare aquifer walls and may be lost if they catch on the end of the lining tubes when being withdrawn.

Table 2. Location of observation wells

Aquifer state	Transmissivity	Measurable response	Typical lithology	Spacing from test well
	m^2/day			m
Unconfined	50 to 500	Slow	Unfissured sandstone	25 to 35
Unconfined	over 500	Fast	Fissured limestone	45 to 60
Confined	50 to 500	Slow	Unfissured sandstone	60 to 100
Confined	over 500	Fast	Fissured limestone	10 to 200

If screens are fitted a minimum of 5 % open area should be ensured to minimize lag between change of water level in the aquifer and that in the observation well. The type of screen is relatively unimportant.

If instruments are being inserted into an existing well these recommendations and those in appendix D should be taken into account.

12.5 Drilling methods

The method by which an observation well is drilled should be recorded. The use of non-degradable drilling fluids such as bentonite mud should be avoided and development of the completed well should be undertaken to ensure the maximum hydraulic continuity between the well and the aquifer (see appendix E). This is particularly important in wells penetrating clay or chalk where the slurry may make an effective seal. When existing wells are used for observation purposes, the drilling method used for their construction should be considered and appropriate development undertaken.

13 Test well

13.1 General

The four basic objectives in correctly designing a test well are to facilitate the entry of groundwater into the well and the operation of pumping equipment, the collection of data from within the well and the measurement of pumped discharge.

13.2 Groundwater entry into the well

The design of the well should enable free entry of water from the aquifer but preclude entry of aquifer particles, and also needs to ensure that the well does not collapse and that the yield does not decrease over the long term.

The depth of the well needs to be adequate to penetrate sufficient saturated aquifer to provide the required yield without the drawdown becoming excessive. In the analysis and reporting of the test pumping it should be recognized that the measured transmissivity will probably relate only to that thickness of the aquifer which is screened or open in the test and observation wells.

The well construction should be such as to contain the pump and column pipe and any additional equipment required in the well. The diameter should also be sufficient to prevent restriction of flow to the pump.

In all wells it is essential that a sufficient length of plain lining tube is emplaced to prevent the ingress of surface water and soil water as well as to guard against collapse of the well in the zone of loose, weathered strata usually present close to the ground surface. The casing should be carried to greater depth if certain aquifers are to be excluded or if incompetent strata, such as soft clay, are penetrated.

In unconsolidated intergranular aquifers, screens are necessary to prevent collapse of the well and to permit groundwater entry. Filter packs around the screen are usually essential and may be either artificial packs of a uniform or graded type, or natural packs developed in situ from the aquifer.

13.3 Pumping equipment

One objective of the pumping test is to determine the type of pump suitable for permanent use in the well. The test pump may require a wide range of operative yields although some indication of the probable range required should be available from other wells in the same locality. The fact that a test pump is operating at less than the optimum efficiency is of little significance except in very prolonged tests.

It is advisable to avoid using the pump destined for permanent duty in the well since test pumping is a demanding and often abrasive duty. If the test programme calls for a wide range of discharge volume there is a possibility that an electrically driven submersible pump may overload at the extremes of the range. There is also excessive end thrust under 'nearly closed' valve conditions (see **23.2**) which may give rise to thrust bearing failure if the condition is prolonged. This would be minimized by using a variable speed drive. It is recommended that the pump capacity is sufficient to allow a discharge of up to 25 % more than the required yield of the well for normal duty. The selection of a suitable capacity pump is discussed further in appendix F. The pump should be installed as low as possible, so that maximum drawdown of water level is available to determine well capacity, but sufficient space should be left underneath the pump to allow the settlement of any sediment and so avoid any risk of blockage of the pump. To protect the pump from dry running the pumping water level should always be kept a few metres above the pump suction level.

Wherever possible the pump should be positioned within the lined section of the well. In all cases the pump should be so placed as to avoid damage to the well screen or the collapse of an open well during the pump's installation or operation.

The rising main needs to be of sufficient diameter to enable the maximum yield required to pass without undue head loss.

It is recommended that the rising main is fitted with a non-return valve (see figure 2). This may be either positioned at the bottom of the column pipe or mounted on the surface. The first is the recommended arrangement, the foot valve being located in the discharge of a submersible pump or on the suction of a spindle pump, and if recovery levels are to be measured in the test well after completion of pumping, a non-return valve at the foot of the column pipe is essential.

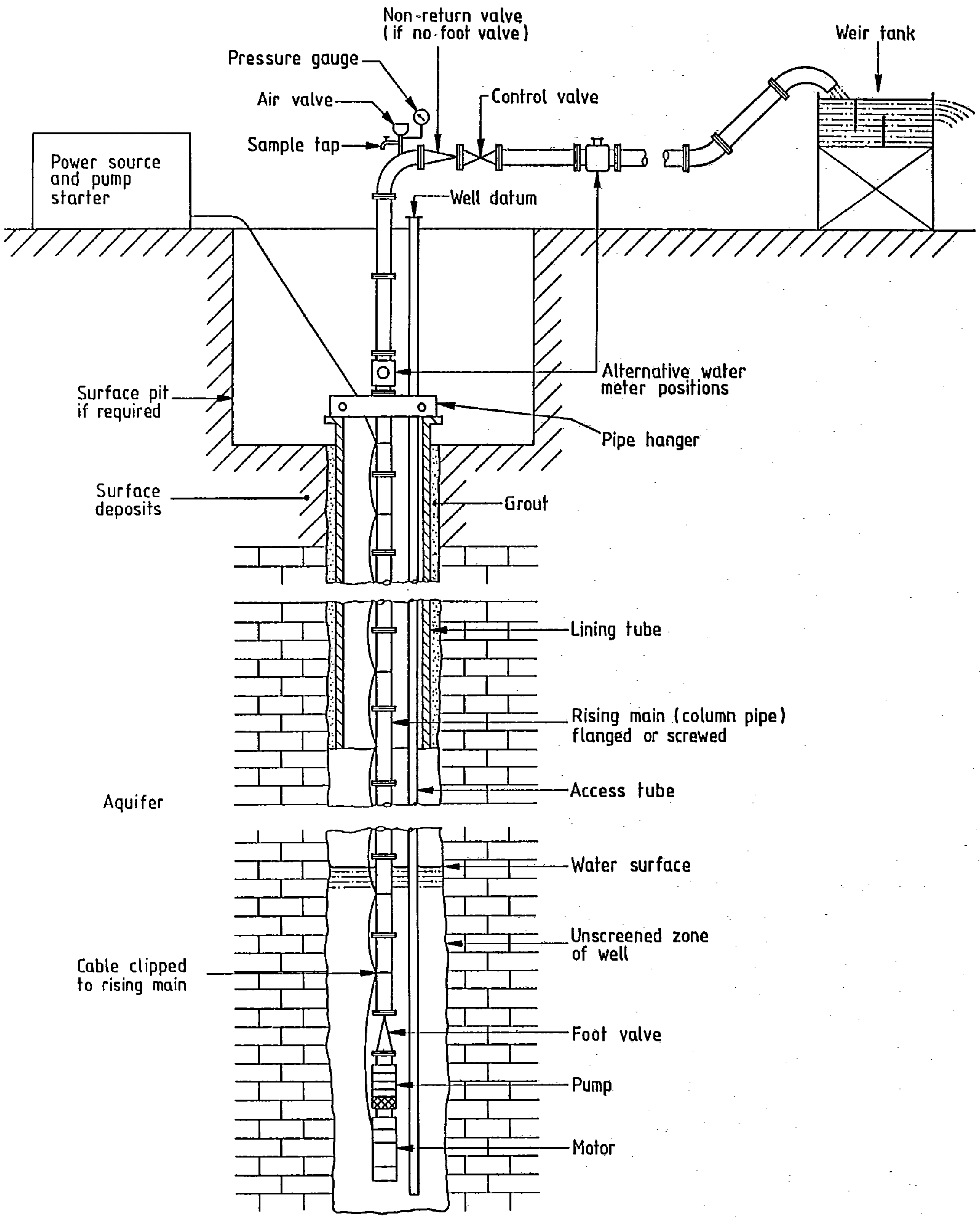


Figure 2. Typical arrangement of equipment in an unscreened test well

There are however two reasons for mounting the non-return valve on the surface, the first being that the column pipe is empty when the pump is not running and therefore lighter to lift and the second being that if the well is dirty, i.e. prone to periodic entry of solids from an incompetent stratum, the backflushing action of an emptying column pipe after the pump stops will tend to clear the pump of ingested solids. This procedure is not recommended however if the column pipe is long, say over about 100 m, as the backflushing water is likely to cause the pump to rotate at high speed in the reverse direction and so loosen impeller lock nuts and bushes. It will also interfere with water level recording. (See **11.6**.)

A valve capable of drip-tight closure should be fitted to the head of the column pipe to control the discharge rate. In the absence of variable pump speed control equipment this valve is normally operated manually. An airvalve preceding the control valve is useful in some circumstances for blowing off air at the beginning of a test. A stopcock is useful for taking water samples for analysis during the test. A discharge pipe or channel should connect the control valve to the flow measuring device (see **13.5**).

When a generator is required to power the pump and any other ancillary equipment, the power output should be approximately twice the power requirement of the pump so that high momentary starting currents can be accommodated without excessive slowing of the generator.

When a well has been drilled through incompetent strata a settling tank or stilling pit should be provided at a convenient point in the discharge path.

13.4 Measurements in the test well

Any instruments used in the test well during the test should be lowered through a specially inserted tube which extends at least 2 m below the pump intake level. For water level measurement this tube need only be three times the diameter of the probe of the dipper (see appendix D). If a vertical flow meter is to be used an additional tube of larger diameter sufficient to accommodate this is required.

Vertical flow meters, temperature and electrical conductivity probes can be used to detect inflow horizons. The different types of geophysical log are discussed in appendix G. Television cameras are sometimes used to supplement this information. Geophysical logs can be used before test pumping commences.

13.5 Measurement of pumped discharge

The most reliable method of measuring pumped discharge is to use a weir tank with the pumped water discharging over a V-notch or a rectangular notch. A full description of the method of measurement and the equipment required is given in appendix D and BS 3680 : Part 4A.

Weir tanks and similar devices are only accurate if they are properly installed, correctly levelled, used with great care, and if the notches or orifices are accurately machined and kept perfectly clean. In many cases a modern meter can be at least as accurate as a weir device if correctly installed and recently calibrated.

A less accurate alternative to the weir tank is a sharp-edged orifice plate attached to the end of a horizontal pipe at least 2 m in length. This method has some disadvantages because it is not as flexible in range or accuracy as the weir tank. For further information see BS 1042.

An individual meter is accurate only within a strictly specified range of flows. Within this flow range, a meter can be as accurate as a weir tank.

Some meters are equipped with a flow rate indicator as well as the more normal accumulative counter. It is rarely possible to obtain direct readings from such an indicator with sufficient accuracy for subsequent analysis. The counter values should be used. Nevertheless a flow rate indicator may be useful for setting the discharge rate.

Further information on methods of measurement and equipment for measuring pumped discharge are given in appendix D.

13.6 Frequency of discharge measurements

The discharge rate should be measured and recorded at the same frequency as water level measurements (see **14.2**). If continuous recorders are being used it may still be necessary to make manual measurements where instrument resolution is inadequate.

14 Groundwater level measurement

14.1 Methods of measuring groundwater levels

The resolution of measurement in the test well should be 10 mm or better. Normally groundwater levels in the test well should be measured using either a dipper or a pressure transducer. In the case of the latter, it is essential to give careful consideration to the choice of equipment since it has to be capable of measuring over the whole of the anticipated range of drawdown at the required resolution. The measurement datum should be clearly marked on each well.

The resolution of measurement in the observation wells should be 5 mm or better. Unless data loggers are used here, manual measurements are usually necessary during the initial period of a test since few mechanical recorders are capable of providing effective level values at time intervals of less than 5 min. Some mechanical recorders can be read directly, either from graduated tapes or from a digital counter, thus saving the necessity of having a separate dipper. Measurement of groundwater levels at intervals of 15 min or longer can usually be accomplished satisfactorily by continuous mechanical recorders.

Recent developments in proprietary data logger systems provide a means of monitoring both the test and observation wells with the potential for generating data in a format ready for rapid computer analysis and presentation. However, it is essential that careful attention be paid to the resolution and accuracy of the equipment (see **F.1.3**) and calibration by manual dipping will still be necessary.

14.2 Frequency of water level measurements

Analysis of the data is considerably simplified if measurements taken in two or more observation wells are made simultaneously, particularly during the first hour of the test. Some form of signal that can be heard or seen by all staff making measurements is therefore desirable.

During analysis, a time-drawdown or time-discharge graph (as appropriate) and a time-recovery graph will be used, the time being plotted on a logarithmic scale. In practice, where data is being collected manually the following intervals can be used as a satisfactory compromise:

NOTE 1. The intervals listed in (a) to (j) relate only to the collection of data and are not recommendations for the actual length of the test (see clause **11**).

(a) immediately before discharge is started, stopped or changed;

(b) every 30 s for the first 10 min, if practicable, or else every minute for the first 10 min;

NOTE 2. Measurements of water level in observation wells are desirable when possible at 30 s intervals during the first 10 min of a test. Where a digital readout of water level is possible, or when one person measures water levels manually while a second person records them, measurements may be made at 30 s intervals. Where only one person is available, and measurements are taken manually, it is advisable for 1 min intervals to be used during this period.

In the pumped well, it is difficult to measure water levels at close time intervals at the beginning of the test because of the rapid drawdown. The intervals between measurements should be as short as possible during the first 10 min, providing that the measurements are accurate.

(c) every 5 min thereafter until the completion of 1 h of pumping;

(d) every 15 min thereafter until the completion of 4 h of pumping;

(e) every 30 min thereafter until the completion of 8 h of pumping;

(f) every hour thereafter until the completion of 18 h of pumping;

(g) every 2 h thereafter until the completion of 48 h of pumping;

(h) every 4 h thereafter until the completion of 96 h of pumping;

(i) every 8 h thereafter until the completion of 168 h of pumping;

(j) every 12 h thereafter until completion of the test, unless other influences warrant more frequent measurement.

There are loggers available which can be set to operate at the above frequencies. This is undesirable since a pump failure after say 48 h of pumping may result in a large number of recovery readings being missed as the specified interval is then 4 h. Setting a timed interval of 15 s would ensure that this occurrence is adequately monitored but would produce enormous quantities of data. The preferred option would be event based logging with a sampling interval of 15 s which will accurately record all the necessary information.

15 Measurement of time

The means used to measure time should be capable of measuring to the nearest second. During the first 10 min of the test, an error in timekeeping greater than 5 s should be avoided. For the sake of general accuracy, time should be recorded to within 30 s thereafter until 1 h of pumping is completed, and to within 1 min from then until the completion of the test. Timing devices should be synchronized prior to the start of the test. The start and completion of events should be recorded in local time; it is often convenient to start a test on the stroke of the hour.

Section 4. Pre-test observations

16 General considerations

Hydrological, hydrogeological and climatological factors may influence the hydraulic behaviour of an aquifer during a pumping test. It is necessary to assess the significance of these variables before test pumping takes place so that their effects can be allowed for in subsequent analyses. Some variables will be independent of the pumping test, e.g. rainfall and barometric pressure. Others will be directly affected by the test, e.g. groundwater levels and spring discharges. Many of these items may require measurement throughout the test and some may also be continued as post-test observations. Some observations may be required outside the area immediately affected by the test (see section 2).

The duration and frequency of observation will depend on the rapidity of change likely in any given parameter. Where changes are cyclic, observations should cover several cycles. Where changes are in the form of a long term trend, observations should be made for a pre-test period at least twice as long as the proposed duration of the test.

17 Surface waters

17.1 Tidal water

Tidal levels, where these may affect the test, should be observed over a period of at least two full tidal cycles preferably during a period of a spring tide. If possible, groundwater levels should be measured in two wells adjacent to the shoreline and the observations compared with the tide levels on the shoreline to obtain the tidal efficiency and tidal lag times at different distances from the shoreline. Measurements of level should preferably be made with a continuous water level recorder. If taken manually measurements should be at intervals not exceeding 15 min.

Chemical analyses of groundwater from different depths in coastal wells and of sea water should be made to establish the characteristics of the waters. Repeated sampling of the well water or measurements of electrical conductivity during one or more full tidal cycles will give an indication of any saline interface that the well intersects.

17.2 Non-tidal waters

17.2.1 ***Still water***

Stage measurements should be made of surface waters, such as lakes or ponds, that may be affected by the test. If levels are not measured continuously, manual measurements should be made at specified intervals. The period over which observations are made should be sufficient to identify any natural trend which may occur during the test.

17.2.2 ***Stream flow***

Discharge rates from wells are frequently very small in relation to natural stream flows. In many circumstances, it is unlikely that any significant change in stream flow in response to pumping from a well will be measurable. Nevertheless, measurements of stream flow should be made where possible on watercourses which may be affected by the test. Such measurements should be made at existing flow gauging weirs or at specially constructed sites. Temporary weirs or current meter sites may be necessary. Observations should be made where possible on a continuous recorder and should start at least 2 weeks in advance of the test.

17.2.3 ***Chemical analysis***

Samples of water from the sites listed in **17.2.1** and **17.2.2** should be taken and analysed. If natural variation in quality is considered probable, systematic sampling may be necessary.

On-site measurements may be made for pH, electrical conductivity, temperature, redox potential, total alkalinity, dissolved oxygen and specific ions. Laboratory determinations should be made for all major and minor ions, and bacteriological analyses should be made also (see also appendix H).

17.2.4 ***Radioisotopes***

Radioisotope determinations are occasionally made when there is a possibility of determining the relative ages of groundwaters, i.e. with a view to assessing whether recharge is occurring.

18 Groundwaters

18.1 Groundwater levels

Groundwater levels should be measured in specified observation wells and pumped wells within the area likely to be affected by the test. Levels may also be measured at sites beyond this area for control purposes.

Levels may be measured continuously or at specified intervals. Normally, they should be taken for a period of the order of twice the duration of the test, subject to a minimum of 2 days, prior to the start of pumping.

18.2 Groundwater quality

Groundwater samples should be taken from pumped wells and from specified observation wells in the vicinity of the test site. The analyses to be carried out should be similar to those in **17.2.3** (see appendix H) and **17.2.4**.

19 Meteorological parameters

19.1 Barometric pressure

Barometric pressure should be recorded in conjunction with the groundwater levels for a period sufficient to determine the barometric efficiency of the aquifer prior to the start of the test.

19.2 Rainfall

In the vicinity of the test site rainfall and other precipitation such as snow should be recorded in conjunction with the groundwater level measurements for a period sufficient to determine the response of groundwater levels to such events. It may prove possible to make use of existing raingauge networks.

20 Abstractions and discharges

All pumped wells, spring discharges or recharge operations in the vicinity of the test well should be monitored so that their effects on groundwater levels and quality may be taken into account during analysis of the test results.

Pumped wells in the vicinity of the test site should not necessarily cease pumping during the test. They should be held as nearly as possible to a constant rate, however, both during the pre-test observations and during the test. If pumping is stopped then groundwater levels should be permitted to recover fully before the start of the test.

Section 5. Pumping test

21 General considerations

21.1 Test programme

Normally, the sequence of events for a comprehensive test of both well and aquifer should be as follows:

(a) equipment test (see clause **22**);

(b) step test (see clause **23**);

(c) constant discharge test (see clause **24**) or constant drawdown test (see clause **25**);

(d) recovery test (see clause **26**).

21.2 Test supervision

One person should be appointed to supervise the various tests. All decisions regarding the collection and recording of data before, during and after the test should be referred to the supervisor.

21.3 Staffing

The supervisor should ensure that all staff are familiar with the tasks they are to perform during the test and with any instruments that they may be required to use. All staff should be aware of the frequency of water level measurements to be taken (see **14.2**) and the accuracy of measurement required. Staff need to be advised of any safety regulations in force.

21.4 Equipment

The supervisor should ensure that all equipment is on site and in working order and that spare equipment or spare parts, including batteries for dippers, are readily available. Figure 2 shows a typical arrangement of equipment in an unscreened test well.

21.5 Timing

The supervisor should be responsible for determining the actual time at which the test starts and stops, and the times at which individual parts of the test start. The supervisor should also ensure that the moments when measurements are to be taken are clearly signalled to the staff involved.

21.6 Records of measurements

The supervisor should be responsible for issuing suitable forms for recording measurements and collecting and collating the completed forms. Some examples of data recording sheets are shown in appendix J.

The supervisor should also keep a record of progress of the test with details of all operations carried out, including running plots of drawdown levels against time in the case of a constant discharge test or discharge rate against time in the case of a constant drawdown test, so that an indication can be gained of the type of aquifer response (see clause **28**). Appendix K describes some typical 'time-drawdown' curves (see also clauses **14** and **28**).

21.7 Record of well dimensions and distances

Depth, diameter, level above ordnance datum and other details of the test well and the observation wells should be recorded. These records should be attached to the records of measurements taken during the test. The records should include the distances, centre to centre, of the observation wells from the test well. A plan showing the relative positions of the observation wells and the test well should be prepared.

22 Equipment test

The well should be pumped for a short period at discharge rates which need to be measured only approximately and with the drawdowns for each rate also measured. A check on the effectiveness of a well's development also should be made.

Groundwater level should be measured in the test well and any observation wells prior to the start of pumping and in the observation wells just before the end of the equipment test. These measurements serve to indicate the range of water level depressions that may be expected during the following tests.

When pumping is stopped at the end of the test, the water level should be allowed to recover in both the abstraction well and the observation wells before any further testing is done. This recovery will occur normally within a few hours, during which time a record of the water level related to time should be made.

In the case of an overflowing well the head above the measuring point should be recorded before pumping or free discharge commences.

In an overflowing well where no pumping is to be undertaken, the equipment test is much simpler and comprises the measurement of flow from the open well. The well should be capped off on completion of the test and the static head monitored.

Stream flow gauging equipment should be checked.

The control valve settings should be recorded during the equipment test so that in subsequent tests it is possible to set the valve approximately to the pumping rate required without necessitating further adjustment. If a pressure gauge is fitted, this is also useful for determining settings for flow discharge rates.

23 Step test

23.1 Discharge rates, duration and number of steps

The discharge rate, duration of each step and number of steps will have been determined in advance (see **11.3**). Any yield-drawdown curve obtained in the equipment test may be used as a guide.

In the case of an overflowing well, where it is considered that a constant drawdown test will be adequate, the step test is usually omitted since adjustment to provide different heads is technically difficult.

23.2 Start of test

Ideally, pumping should start instantaneously at the prescribed rate and be held at that rate until a change is desired. In practice this is not generally possible but the following procedures are quite adequate.

(a) If a foot valve is not fitted, the pump should be started against an empty rising main and with the control valve open to the first test setting.

(b) If a foot valve is fitted (see figure 2), the pump should be started against a full rising main with the control valve fully closed or very slightly open or opened up to the first test setting.

When it is proposed to start the pump against a closed valve, care should be taken that the pump is suitable for such an application (see clause **10**). The pump should be started, allowed to run for a few moments and, at the specified moment, the valve should be opened rapidly to the setting determined to obtain the first discharge rate (using information obtained during the equipment test).

The control valve should not be adjusted again until either an increase in rate is required or until after the pump is stopped. No attempt should be made to obtain an exact discharge rate but the actual rate should be carefully measured.

Rest water levels should be measured in the test well and in any observation wells prior to the start of pumping.

23.3 Test procedure

23.3.1 *Consecutive step test*

It is convenient to start at a low rate of pumping, and to increase in steps to a high rate. The reverse may be adopted if preferred.

When changing from one discharge rate to the next, at the moment designated by the test supervisor, the control valve should be adjusted rapidly to the setting for the next required pumping rate.

23.3.2 *Intermittent step test*

The amount of change in the pumping rate between steps may be progressive or intermittent (see **11.3**). Each step should be considered as a discrete test and should start under the procedure described in **23.2**. At the end of each step the pump should be stopped and groundwater levels allowed to recover before commencing the next step.

23.4 Measurement of groundwater levels

For each step in the test groundwater levels should be measured in the pumped well and observation wells at the relevant intervals recommended in **14.2**. If a constant discharge test is later to be performed, groundwater levels during the step test need to be measured in one or two observation wells close to the test well, since more distant wells may not show significant drawdowns during the relatively short duration of the step test. If a constant discharge test is not to be performed, the water levels in all available observation wells should be measured during the step test.

23.5 Analysis of step test

Full analysis of the step test is beyond the scope of this standard but a limited analysis is needed to estimate a maximum safe yield for the borehole. This is necessary for the design of the constant discharge rate test to maintain water levels above the pump. The usual method is to plot the specific drawdown (drawdown divided by discharge rate) against the discharge rate for each step. The drawdown is determined by extrapolation of the water level trend of each step to the end of the next step (Clark 1977). The points on the specific drawdown–discharge plot should fall in a straight line. If the later points diverge from this trend by an increase in specific drawdown then the point of divergence is the safe yield. If no divergence occurs, then the greatest step discharge rate is the safe yield.

24 Constant discharge test

24.1 Discharge rate

The design discharge rate has to be determined prior to the start of the test from the results of the equipment test and the step test and should approximate the likely operational discharge rate of the well in production. It is essential that the instantaneous discharge rate during the test does not exceed either the maximum step test rate or the safe yield (as defined in **23.5**).

24.2 Start of test

The procedure as recommended for step tests should be used (see **23.2**).

24.3 Measurement of pumped discharge

The pumped discharge should be measured as described in **13.5**.

24.4 Measurement of groundwater levels

Groundwater levels should be measured in the test well and in all observation wells at the intervals recommended in **14.2**.

After 4 h of pumping measurements need no longer be made precisely at the specified intervals. It may be sufficient for one person to make the rounds of the manual dipping sites noting the time at which each measurement is made.

24.5 Duration of test

The duration of the test should be as recommended in **11.4**.

25 Constant drawdown test

25.1 General

This test applies mainly to tests with suction pumps, dewatering schemes and flowing wells.

25.2 Start of test

If the well is to be pumped, the start procedure is similar to that of the constant discharge test differing only in that the discharge rate is carefully and frequently reduced in order to maintain a constant drawdown.

When the test is made on an overflowing well, the well should be uncapped or otherwise rapidly opened at a preselected moment so as to produce as nearly as possible an instantaneous fall in head. No further adjustments should be made.

25.3 Measurement of discharge

The discharge should be measured continuously as described in **13.5**.

When the discharge becomes very small, containers of known size can be used and measurements of the time taken to fill the container are recorded in seconds and tenths of seconds.

25.4 Measurements of groundwater levels and static heads

The groundwater level or static head should be measured in the test well prior to commencing the test at the intervals recommended in **14.2**. For overflowing wells the height of the overflow above the casing rim should be estimated and recorded at intervals.

Groundwater levels or static heads in observation wells, where present, should be measured at the intervals recommended in **14.2**. Where static heads are too great for standpipes to be used, they should be measured with manometers. Pressure gauges or pressure transducers may be used if they are sufficiently accurate.

25.5 Duration of test

The minimum duration of the test should be sufficient for the discharge to reduce to about 1 % of the initial rate.

NOTE. The minimum duration cannot be the same as for a constant discharge test (see table 1).

25.6 Constant drawdown test with variable head

It is possible to determine aquifer properties from a test where the static head and the discharge rate both vary, although the analysis is complex. Continuous monitoring of both the static head and the discharge is necessary, but otherwise procedures are the same as for a well with a constant static head.

26 Recovery test

26.1 General

Recovery tests in the test well should only be performed if a non-return valve is fitted to the foot of the rising main. Recovery tests carried out after step tests are difficult to analyse but they can give a further check.

26.2 Start of test

The recovery test normally follows immediately upon the end of a constant discharge or a constant drawdown test. The discharge should be stopped at the designated moment by stopping the pump or by capping the well as appropriate.

26.3 Measurement of discharge

There should be no discharge from the well. The discharge rate, whether pumped or free flow, will have been measured during the period of the preceding pumping. These measurements are required for the analysis of the recovery test.

26.4 Measurement of groundwater levels

Groundwater levels should be measured in the test well and in the observation wells at the intervals recommended in **14.2** commencing at the time discharge ceases.

26.5 Duration of test

The test should be continued until a stable level has been achieved.

27 Interruptions of tests

27.1 Breakdowns

Normally, pumping plant should have been serviced prior to commencing pumping. If it breaks down to the extent of stopping the discharge at any time during a step test, or during the first 24 h of a constant discharge or drawdown test, groundwater levels should be allowed to recover and the test started again. In the case of a step test, pumping may be resumed at the rate taken for the previous step and the results from previous test steps may still be valid. Once a constant discharge or drawdown test has been in progress for 24 h, there may be breaks in pumping of up to 1 h although provision may need to be made for unbroken abstraction in the case of specialized tests.

Measuring devices can malfunction and it is advisable to have standbys available, especially in the case of dippers, in order to avoid breaks in the collection of data.

27.2 Falling groundwater levels

If the groundwater level in the test well is approaching the pump suction level, and the indication is that this level will soon be reached, pumping should be stopped. A further test may be carried out at a lesser discharge rate. A recovery test, carried out when pumping has stopped, may provide useful data upon which to decide whether further testing is feasible or necessary.

27.3 Developing wells

Test wells which have been inadequately developed may show some development during the test. In these circumstances a constant discharge or drawdown test is not compromised necessarily. The effects of the lack of development are confined to the test well and will have no effect upon the observation wells. However, if lack of development is indicated during the step test, the latter should be stopped immediately and the well properly developed before recommencing testing (see appendix E).

Failure of an observation well to show drawdowns may be due to inadequate development. Complete or partial hydraulic isolation of the well water from the aquifer should be considered as unacceptable and the observation well should be developed before testing.

27.4 Other interruptions

Once a well test has started it should be completed if possible. That a particular well proves to have an inadequate yield for its proposed operational requirement should not be sufficient reason for automatically considering abandoning a test.

28 Measurement of aquifer response during constant discharge and drawdown tests

During a discharge test time-drawdown or time-discharge graphs (as appropriate) should be kept for the test well and the observation wells. These graphs should be constructed both on linear-log and log-log paper, in both cases with time plotted on a log scale. 'Theis' type curves for $W(u)$ against u and $1/u$ should be made available on log-log paper of the same scale.

NOTE. $W(u)$ is a non-dimensional exponential function referred to as the well function and u is a parameter (see **26.3.2.2** of BS 5930 : 1981).

Comparison of the observed curves with the Theis curve will indicate departures from the ideal case. Similarly, flexures in the normal straight line on the linear-log plot may also indicate departures.

If such a departure is observed immediate steps should be taken to check that the measurements have been correctly taken, that pumping plant is functioning properly, and that the discharge rate is being maintained. If these factors are not at fault, it can be assumed that the departure is due to an aquifer condition; some departures due to well losses may be found in the pumped well.

Appendix K refers to data from which the Theis curve should be drawn up, and gives further information on type curves together with illustrations of curves which depart from the infinite aquifer condition specified by Theis.

29 Quality of groundwater from the test well

Samples of water should be taken from the test well to determine the groundwater quality and whether there is any variation. The analyses may include those in **17.2.3** (see also appendix H). Geophysical logging may be of assistance in determining the position of suitable sampling points when these are in the well itself.

30 Stream flow depletion

Stream flow measurements may be made during constant discharge or drawdown tests by structures or by current meter gauging (**17.2.2**). Weirs should be fitted with continuous recorders. Where current meters are used it may not be possible to make frequent measurements of flow. Abstractions of groundwater and surface water and discharge into the watercourses of industrial and domestic effluents, all of which are likely to be variable, need to be considered as well as runoff from precipitation.

Section 6. Special tests

31 General

Tests can be carried out using a single borehole in order to study the characteristics of an aquifer along the open section of the borehole. Such tests may comprise normal pumping with concurrent observations of water level within the borehole although the value may be limited in the absence of observation boreholes. Alternatively, injection tests may be performed, either into the open borehole in the case of slug tests, or into sections of the borehole in the case of packer tests. In both cases, free access to the borehole, a supply of water and apparatus to lower the necessary equipment into the borehole are required.

The slug test and the packer test are also useful where pumps cannot be installed or where insufficient depth of water is available for normal pumping.

Slug tests and packer tests are specialized procedures and should be undertaken only with specialist advice. The main features are summarized in clause **32** and clause **33**.

32 Slug test

32.1 Introduction

The slug test involves relatively small displacements of water levels in a borehole by the rapid injection of a 'slug' of water with a bailer, or by the introduction of a mechanical displacer.

Whichever process is used, speed is essential. The reliability of the data depends upon the availability of numerous observations over a short period of time. The nearest approach to an instantaneous change in water level is obtained by the use of a displacer. The use of rapid water injection depends upon the availability of a suitable supply and an efficient apparatus for introducing it into the borehole.

Analysis of slug test data can provide information on the transmissivity of the formation which is open or screened in the well being tested. Given some knowledge of the transmissivity a slug test in an observation well can indicate whether the well has been developed effectively and so is in good hydraulic continuity with the aquifer, or if further development is necessary. Slug tests may also be carried out in sections of the well isolated between packers (see clause **33**).

32.2 Displacer

The normal displacer comprises a hollow, sealed tube, heavily weighted internally, and of known volume. The size should be sufficient to raise the water level in the borehole by at least 2 m upon total immersion. In boreholes of small diameter, drill rods with a closed end may be adequate.

32.3 Water level measuring device

The usual float-operated recorder is not usually satisfactory in this situation, and the electrical contact type dipper cannot measure changes in the water level sufficiently quickly. The ideal instrument is the pressure transducer, sensitive over a few metres' range. The transducer should be located 1 m to 2 m beneath the displacer or bailer when this is at its lowest point. The cable connecting the transducer to the well head may require protection within an access tube. When water injection is being used, the transducer should be located 1 m to 2 m beneath the rest water level.

32.4 Recording apparatus

Either a chart recorder capable of reading rapid input changes or an electronic system incorporating a data logger is required. It is necessary also for time intervals to be recorded automatically.

32.5 Procedure

When the displacer is used, first it should be lowered into the borehole until its base is resting within the water surface. When the recording instruments are running, the displacer should be lowered rapidly until 95 % submerged. When the water levels have stabilized the displacer should be raised rapidly until it is clear of the water and the water levels again allowed to stabilize. The test should be repeated several times. Adjustments in recording speed may be required to obtain usefully spaced data, depending upon the speed with which the water levels recover.

When using water injection, the process is analagous to the insertion of the displacer, but cannot simulate its withdrawal. The injection should comprise a volume of water equivalent to 2 m to 3 m depth of the borehole.

When a bailer is used it should be lowered until approximately 80 % submerged, and the water levels allowed to stabilize. The bailer then should be lifted rapidly until clear of the water surface, thus simulating the withdrawal of the displacer.

The tests should be repeated until at least five comparable cycles have been completed.

32.6 Safety precautions

Slug tests cause rapid movements of water level in the borehole. They should not be carried out where the resultant rapid pressure changes could cause collapse of the borehole wall, or where serious particle rearrangement would be caused in a filter pack.

32.7 Screened boreholes

When a borehole has been fitted with a screen with a limited open area per unit length, a slug test may provide little useful information upon the aquifer characteristics but can provide information on the degree of development of an observation well. An open area of at least 10 % should be considered as the limiting value.

33 Packer test

33.1 Introduction

In layered or fissured aquifers it is sometimes necessary to have quantitative knowledge of the variation of hydraulic conductivity with depth, and hence the contributions which the various layers make to the total transmissivity of the strata through which the well has been drilled. In these circumstances the use of packer tests, in which the chosen section of the well is isolated by one or more packers, may provide a cheaper alternative to sinking several pumping and observation wells to various depths.

A packer is a cylinder of slightly less than borehole diameter and fitted with an inflatable jacket. On being located at a particular level within the borehole the jacket is inflated by gas pressure, fluid pressure or mechanical means and the packer forms a watertight plug in the borehole. The packer may be blind or access to the borehole beneath the packer may be provided by a tube leading from the well head through the base of the packer.

The use of packers in boreholes fitted with screens requires special care as borehole fluids may otherwise bypass the packer. The same applies where large fissures are present in the aquifer and similarly prevent a watertight seal. No attempt should be made to seat packers in strata that will not stand without support, or within broken rock which the packer may displace.

Borehole testing using packers can be undertaken by:

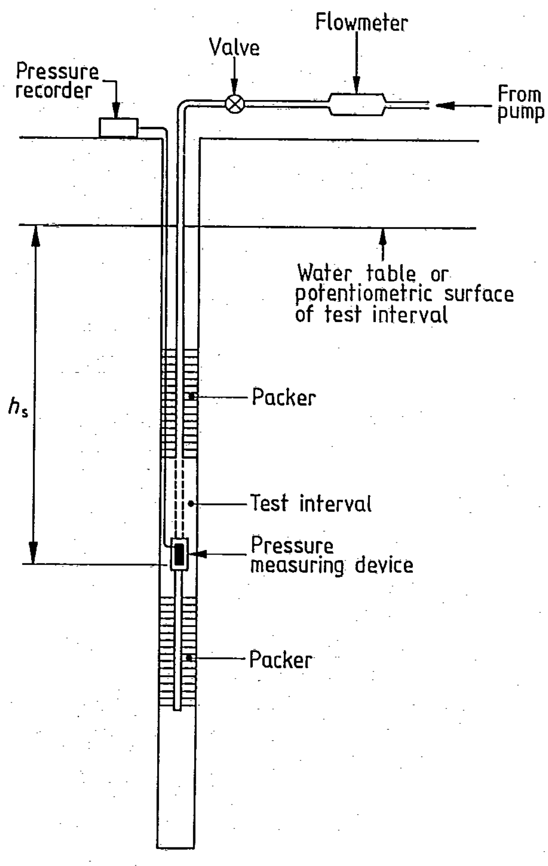
(a) pumping water out of a well;

(b) injecting water into a well, often at pressures exceeding those afforded by gravity alone.

In the first case, the permeability of the strata within the section of the borehole under test is evaluated from the relation developed between the drawdown and abstraction rate; in the second, the permeability is evaluated from the pressure head and injection rate.

Pump-out packer tests are used where the aquifer has a moderate or high permeability, and they require a well of sufficient diameter to allow the passage of pumps and water level measuring apparatus. A water supply is not needed. Samples of water should be taken for chemical analysis (see clause **29**).

Injection tests can be used in aquifers with either a low permeability or a high permeability. The technique is used frequently for site investigation (see BS 5930). Large amounts of water are likely to be required (see **10.4**). Figure 3 shows the typical arrangement of equipment for a double packer injection test.



NOTE. h_s is the head on the pressure measuring device under static conditions.

Figure 3. Typical arrangement of equipment for a double packer injection test

33.2 Types of packer test

A test using a single packer simply divides the borehole into two sections. The advantage of this arrangement is that it can be used during pauses in drilling operations, testing successive sections as the borehole is advanced. However, there is a disadvantage in that the test section is undeveloped and the permeability of the borehole walls, and hence the apparent permeability of the aquifer, is likely to be reduced by the wall-cake produced in the drilling process (see **D.1**).

The more usual arrangement (the double packer system) uses two packers, a known distance apart, isolating a test section of the borehole at a specified depth (see figure 3). Prior to the test, the borehole is developed in the normal manner. After each test, the packer system may be relocated to isolate a different test section. Where a continuous profile is required, each test section should overlap the previous section slightly.

33.3 Equipment

The equipment comprises the packer units, inflators, a pump for abstracting or injecting water, and apparatus for measuring pressures and flow rates. The equipment is specialized, and experienced operators are essential. Attention should be drawn to the dangers inherent in using gas-inflated packers where high pressures are involved.

The standard sizes of packers in use at present are suitable for boreholes of 75 mm to 200 mm diameter, although diameters up to 300 mm are available. Above this size, the packers may have to be manufactured to order.

When the double packer system is used, the distance between the packers is usually fixed, and varies from 3 m to 6 m, depending upon the test requirements.

33.4 Test schedule

A test cycle should normally consist of five steps during each of which water is abstracted from or injected into the test section of the borehole at a constant rate or pressure. When carrying out an injection test, care should be taken that the injection pressure is not so great that it causes fracturing of the overlying rock. In each step, the pressure should be held constant for 15 min with the total injected volume of water recorded at intervals of 5 min. Changes of pressure between steps should be made as quickly as possible; the pressures need not be adjusted exactly to the target levels, providing that the precise values are recorded.

33.5 Recording results

For each test section, specified by depth below surface, the applied drawdown or pressure should be tabulated against the abstraction or injection rate, as appropriate. When measuring pressure, unless transducers or the like are used to measure the pressure in the tested section directly, the length, diameter and material of the pipework also need to be recorded since the applied pressure needs to be corrected for pipe friction loss. The interpretation of the results involves the calculation of permeability from simple formulae and, with care, an accuracy within an order of magnitude is attainable.

33.6 Overflowing wells

Although packer tests can be used in overflowing wells, it is possible also to use the same techniques described in **11.5**. Allowances should be made for partial penetration effects during the analysis of the results.

Section 7. Post-test observations

34 Post-test observations

The measurement of significant variables during recovery from pumping until the return of pre-test conditions forms an integral part of the test.

Monitoring of the variables described in section 4 should continue for a period after recovery to establish trends prevalent during the test pumping period.

Section 8. Presentation of information

35 Presentation of information

Clear and consistent presentation of the test sampling data and results can improve significantly the quality of decisions to be made when the test pumping programme has been completed. All the original data sheets and recording charts from automatic measuring devices, etc. should be retained for subsequent analysis and to support any charts, etc. prepared for the final presentation of data.

Two types of chart should be prepared, both relating to the period of the test pumping and a sufficient period beforehand to establish a rainfall-aquifer replenishment correlation, e.g. 3 months to 6 months for the chalk, for which purposes all levels should be reduced to Ordnance datum. (That is, it would take 3 months to 6 months for the aquifier to be recharged by rainfall in the upper chalk.)

The first chart should be a vertical section through the test well, extending to about 5 km on either side of it and showing existing wells and ground levels plotted at their radius from the test well, with simultaneous test and observation well water levels and surface water levels shown before, during, e.g. at significant steps of step tests or discharge tests, and after test pumping. Where boreholes are not actually on the chosen line of section they may be projected onto the chosen line, or the section may be varied in order to take in additional boreholes (see figure 4).

The second chart should comprise continuous plots of precipitation, barometric pressure, groundwater level in the test well and pumping rate against the corresponding time scale, and should particularize test pumping operational procedures, e.g. surging operations, and their results (see figure 5).

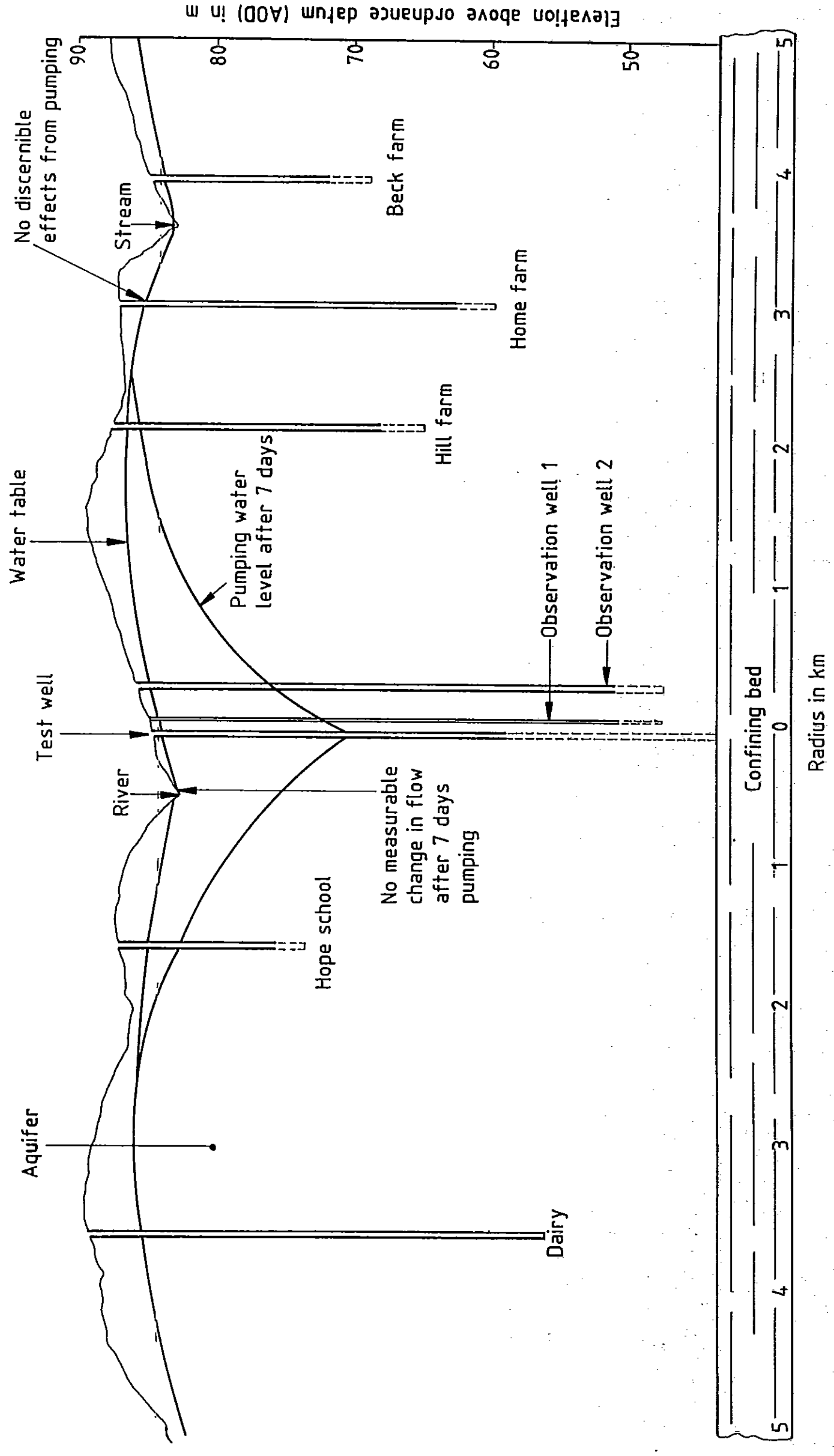


Figure 4. Typical vertical section through test well and environs

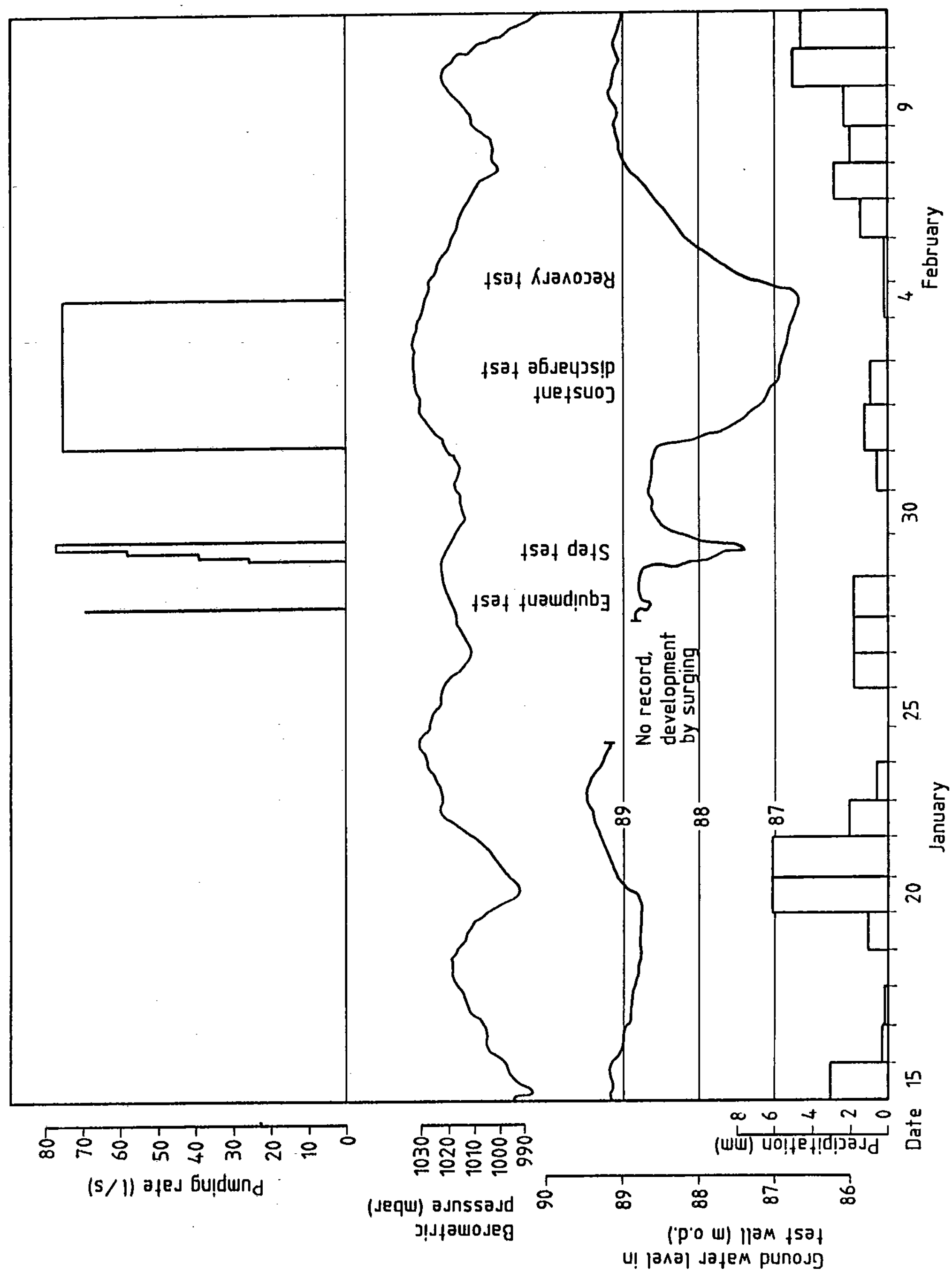


Figure 5. Continuous plot of pumping test data

Appendices

Appendix A. Groundwater flow

The steady flow of groundwater through the saturated zone of an aquifer is described by Darcy's law. In simplified form, this can be written as:

$$Q = KA\frac{h_1 - h_2}{l} \quad (1)$$

where

Q	is the rate of flow of water (in m^3/day);
A	is the cross-sectional area through which flow is taking place (in m^2);
h_1 and h_2	are the static heads (in mH_2O) at the two points between which flow is occurring;
l	is the distance between these two points (in m);
K	is the hydraulic conductivity of the aquifer (in m/day).

The static head at any point is the height, above some reference level, to which the water would rise in an open-topped tube or manometer inserted into the aquifer at that point. Static head is thus a measure of the potential energy of the water; groundwater flows from places where it has high energy to places where it has low energy, i.e. from high heads to low heads.

Laboratory test apparatus for a simple demonstration of Darcy's law is shown in figure 6. In the case of an aquifer, observation wells give an indication of the head in the aquifer at that location (see figures 7 and 8). Only exceptionally, such as in deep wells where temperature changes occur, or in coastal aquifers with salinity variations, will the density of the water column not be constant. Figure 9 demonstrates that in such exceptional cases it is important to measure head changes in terms of head of liquid in the aquifer rather than in terms of changes of level of the liquid in the well. It may be preferable to measure head changes, such as drawdown, by means of a pressure transducer suspended in the well opposite the aquifer. There may also be differences in

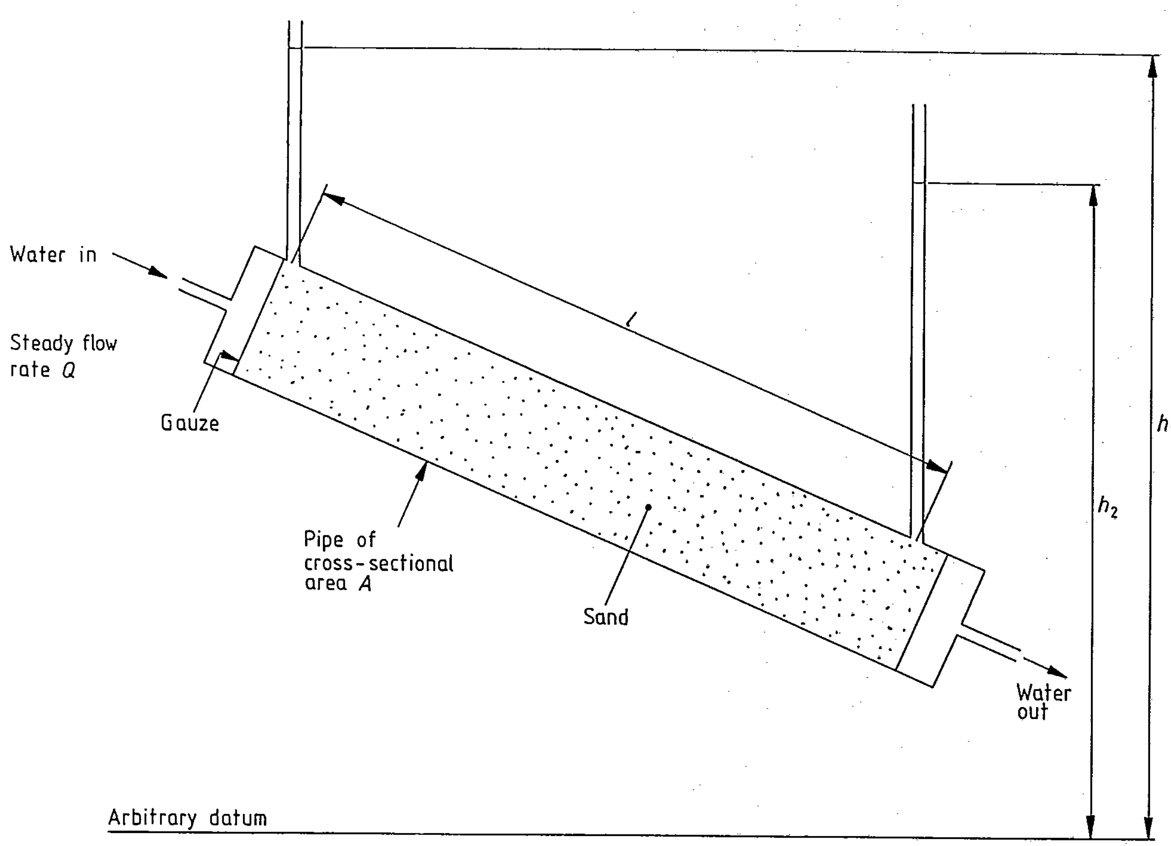


Figure 6. Test apparatus for a demonstration of Darcy's law

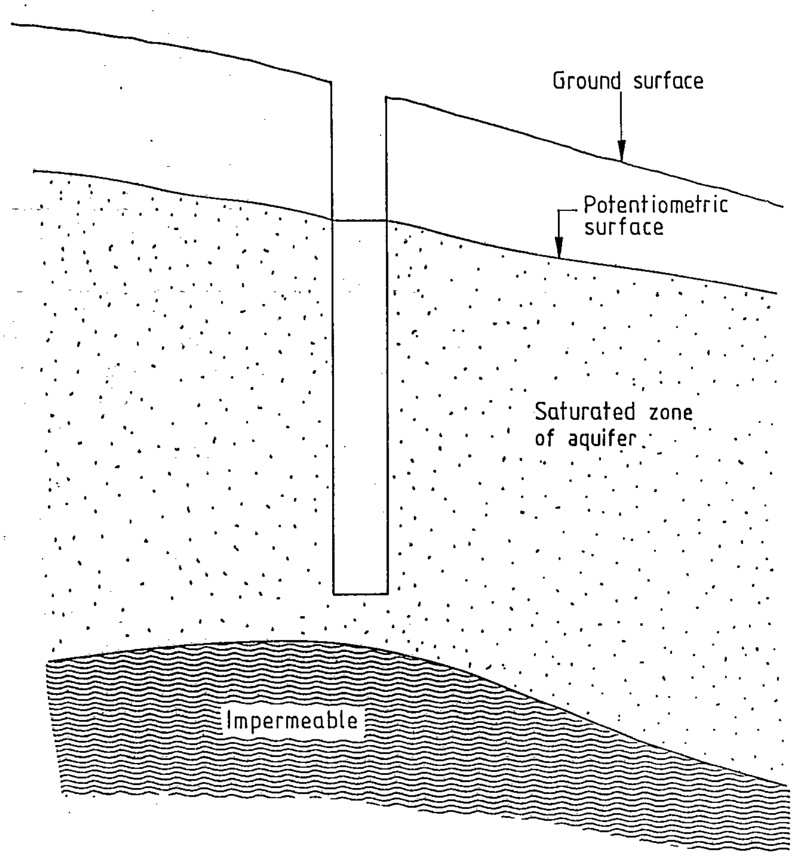


Figure 7. Observation well in an unconfined acquifer

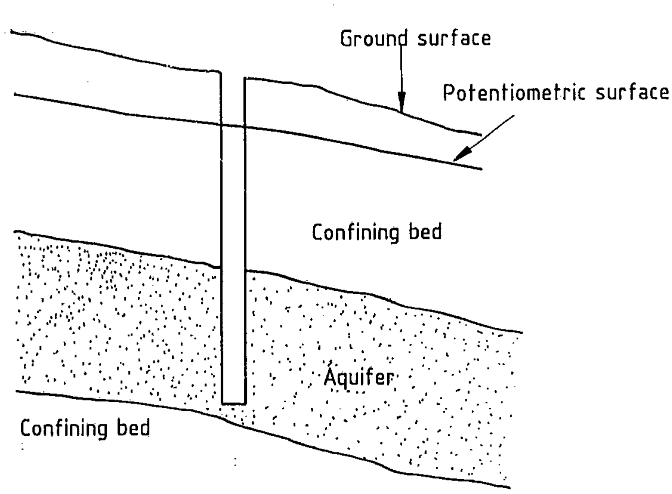


Figure 8. Observation well in a confined acquifer

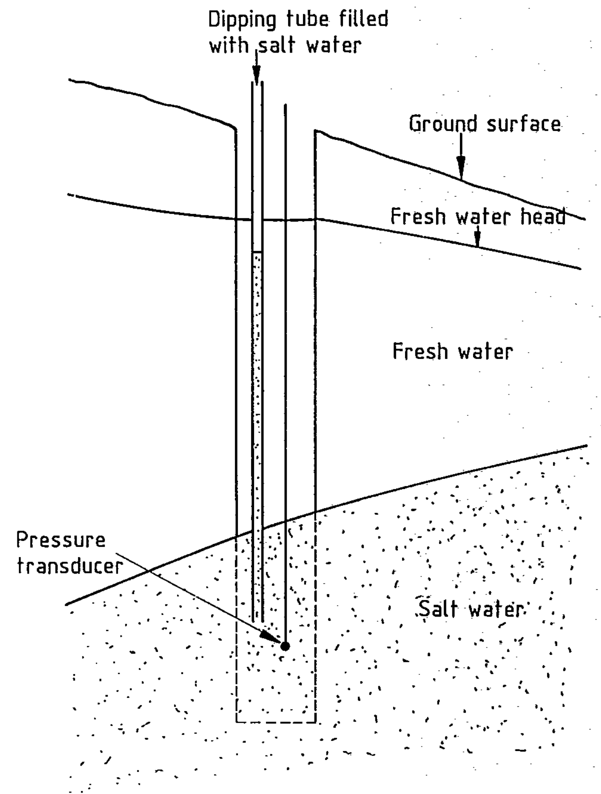


Figure 9. Observation well penetrating salt water

layered aquifers, where water may be at slightly different heads in the various layers, and a well open at all these layers will cause complications by permitting vertical flow of water between the various layers in an attempt to equalize the heads. In the majority of cases, however, the term static head or head as used in this code of practice can be regarded as synonymous with water level in a well.

In equation (1) $\frac{h_1 - h_2}{l}$ represents the average rate of change of head or water level with distance and is thus the average hydraulic gradient.

The other term in equation (1), the hydraulic conductivity K, is a measure of the ease with which water can flow through unit cross-sectional area of the aquifer under a given hydraulic gradient. It depends on the pores or other openings in the aquifer and on the viscosity of the water; warm pure water is less viscous than cold or saline water and will therefore flow more easily.

Another term sometimes used in groundwater tests is specific discharge, q (in m/day). This is defined simply as:

$$q = \frac{Q}{A} \qquad (2)$$

where Q and A are as in equation (1).

The factors that decide whether a rock unit will be economic as an aquifer include not only the hydraulic conductivity but also the thickness. The transmissivity expresses the combination of effective thickness and hydraulic conductivity; in a homogeneous aquifer, it is the product of the hydraulic conductivity and the saturated thickness. In aquifers consisting of layers of material with different hydraulic conductivities, the transmissivity of the aquifer is the sum of the transmissivity contributions of the individual layers, and it may be misleading in such a case to divide the total transmissivity by the saturated thickness to derive an 'average' hydraulic conductivity. It should also be remembered that most pumping test interpretation formulae assume that the aquifer is homogeneous and isotropic, or that simple layering or anisotropy are present; the application of such formulae to the more complicated situations present in most aquifers, although common, is not strictly valid.

The first non-equilibrium pumping test formula was developed by C.V. Theis in 1935 for use in confined aquifers which are always fully saturated and in which the water is at a pressure greater than atmospheric. Removing water from a confined aquifer is rather like removing air from a motor car tyre; the pressure drops, but the aquifer is still filled with water, in the same way that the tyre is still filled with air. In an unconfined aquifer, or in a confined aquifer which becomes unconfined as a result of the potentiometric surface being drawn down below the top of the aquifer, the saturated thickness (and therefore the transmissivity) decreases as the drawdown increases. A second complication that occurs in unconfined aquifers is the phenomenon of delayed yield. After an initial period during which the cone of depression expands rapidly, there follows an interval where the rate of expansion decreases, on occasion approaching an apparently steady state. This interval may be as short as 1 h, or may extend to several weeks. Thereafter, the cone of depression resumes its previous rate of expansion. As illustrated by a time-drawdown plot, the curve initially follows the normal Theis prediction, then tends to level out, and finally moves upward again to approach the Theis curve although the latter is now displaced some distance along the time axis (typical time-drawdown curves are described in appendix K). Several explanations of delayed yield have been offered, but none has full general acceptance at the present time.

Appendix B. Well construction

In the United Kingdom, new supplies of water are frequently obtained by drilling a borehole down to the water-bearing strata, using a surface operated rotary drilling rig. Such 'wells' have a relatively narrow diameter. In some instances a shaft may be dug to reach the water table; shafts are of larger diameter than boreholes and are excavated from within, either by hand or by using powered tools. Shafts are still used in many developing countries, especially to provide shallow wells. A near horizontal tunnel, known as a heading or drift, may be driven into the saturated zone of an aquifer from a shaft or borehole with the intention of improving its performance.

Whilst a borehole is being sunk a drilling fluid may be used to seal off porous zones, to counterbalance subsurface hydrostatic pressures, to lubricate and cool the drilling bit and stem and to enable drill cuttings (in the form of a slurry) to be raised to the surface. The fluid is circulated down the borehole while drilling is in operation by pumping down the drill stem (direct circulation) or up the drill stem (reverse circulation), and consists of a suspension of certain additives in water. There are numerous drilling fluid additives now available but the ones most commonly used are bentonite clay (to increase fluid viscosity and seal off porous zones), organic polymers (similar in action to bentonite but with the ability to be broken down to a low viscosity fluid to aid subsequent removal in well development), barytes and other minerals (to add mass to a fluid to counteract hydrostatic pressures) and foaming agents (used to seal off highly porous zones in karstic limestones).

The process of drilling results frequently in the wall of the borehole becoming partially or even completely sealed by material caked onto or forced into the wall. This usually needs to be cleared before test pumping by developing the well (see appendix D). Occasionally, however, it may be necessary deliberately to close crevices, for instance to seal off cavernous zones while drilling karstic rocks or to consolidate the wall of the borehole. In such cases a special grout will be used. This is a liquid cementitious mixture, different formulations of which may contain ordinary Portland cement, sulfate-resisting cement, cement-bentonite mixture, cement-pfa (pulverized fuel ash) and binding polymers. A common application of grouting is to fill the annulus in boreholes between the permanent casing and the surrounding rock in order to fix the casing and protect it from external corrosion and to prevent movement of groundwater behind the casing.

Once the borehole has been drilled to the required stratigraphic level, the drill stem and drilling bit are removed. Any casing or filters or other structures are then added and if necessary the well is developed. The required instrumentation and pumping equipment is then inserted and the test pumping can commence.

Appendix C. Groundwater conditions and aquifer states

This appendix is intended to clarify certain terms in general use beyond the definitions contained in clause **2**. Figure 10 illustrates many of the terms considered.

An aquifer is defined as a lithological unit containing sufficient saturated, permeable material to yield significant amounts of water to wells and springs.

When water falls onto the ground within an aquifer outcrop, or seeps into the outcrop from streams or lakes, a portion infiltrates downwards under the influence of gravity, moving through voids in the strata that do not become wholly saturated. This part of the aquifer is called the unsaturated zone, and all the water is at or less than atmospheric pressure.

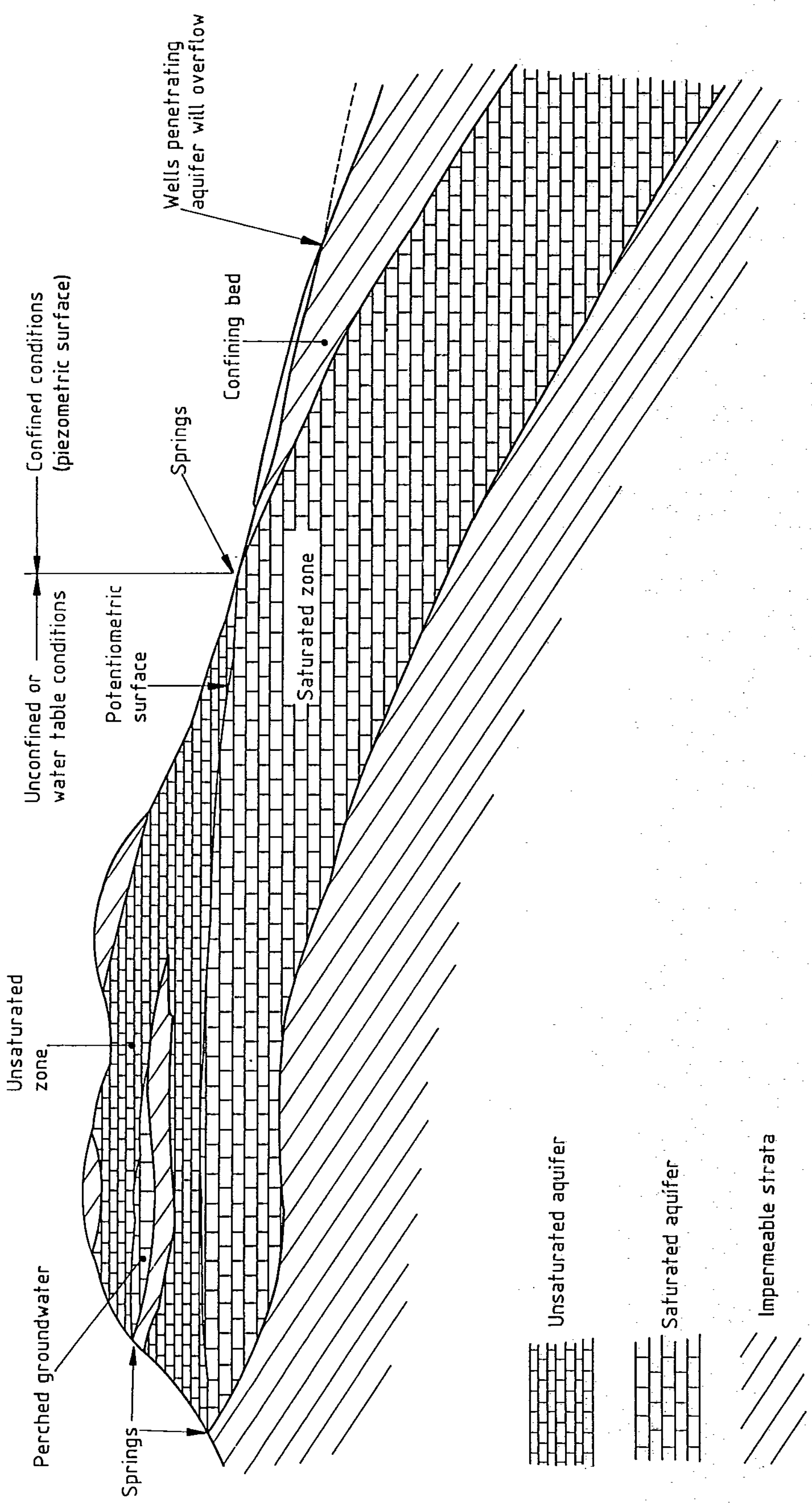


Figure 10. Groundwater conditions and aquifer states

Eventually, the infiltrating water cannot move downward any further, and all the voids become fully saturated. This part of the aquifer is called the saturated zone, and the water contained within this zone is at greater than atmospheric pressure.

The top of the saturated zone is defined as that surface where the water is under atmospheric pressure, and the voids are fully saturated. This surface is called the water table. In practical terms, the water table is considered as that surface joining all the static (or rest) water levels observed in wells penetrating the saturated zone. An aquifer in which a water table is present is said to be unconfined.

Occasionally there exist in an aquifer impersistent layers of impermeable material which support small saturated zones. These are termed perched aquifers, with perched groundwater and perched water tables. Perched groundwater is usually considered to be within the unsaturated zone.

When groundwater is contained within an aquifer under pressure and beneath an impermeable confining bed, there is no water table and no unsaturated zone, and the aquifer is said to be confined. When a well is constructed penetrating a confined aquifer, the water rises above the base of the confining bed to a level dictated by the static head. The surface formed by joining all the water levels observed in such wells is the piezometric surface.

An aquifer can be confined in one area and unconfined in another. In this case, the piezometric surface continues into the water table. In modern practice, the water table and the piezometric surface are called the potentiometric surface; the use of the term piezometric surface is declining, but when the potentiometric surface is within an unconfined aquifer the term water table is often used.

When the potentiometric surface in relation to a confined aquifer is above the ground surface, water will be discharged without pumping from a well penetrating below the confining bed. This is called an overflowing well (it is often called an artesian well, but this term has a number of meanings and is best avoided).

Aquifers may be classified according to the manner in which groundwater passes through them, and by the way in which groundwater is stored within them. In an intergranular aquifer, groundwater moves through the interstices between the constituent grains and is stored within these same voids. In a fissure-flow aquifer, the matrix of the rock is relatively impermeable, and the water moves through fissures. In the latter case, it is not unusual for a significant amount of intergranular storage to be present and the term mixed or dual-porosity aquifer has been used.

Appendix D. Water level and discharge measuring devices

D.1 Measurement of water level

D.1.1 *Continuous water level recorders*

This appendix describes methods of measurement and gives practical guidance in the use of conventional water level recorders. These operate by the movement of a float within the borehole or stilling well of a weir tank. BS 3680 : Part 9B specifies the functional requirements for float operated recorders. It contains a description of the working environment, instrument construction, chart records, digital records, timing, measurement of height or water level, power source and marking.

Pumping tests are often short, and temporary installations of water level recorders are frequently required. The manufacturer's operating manual should give full instructions, illustrated by diagrams where necessary, on the following:

(a) setting up and chart or tape changing procedures;

(b) calibration;

(c) normal maintenance and servicing;

(d) faults and repairs;

(e) spares list;

(f) dismantling and transport.

Levels in a borehole are required to the nearest 0.01 m. Those in a stilling well of a weir tank are required to the nearest 1 mm.

The range of operation can be increased by the use of different gearing systems in both the level measurement and timing. The choice depends upon the requirements for each individual pumping test or well or borehole. There are obvious difficulties in using floats and counterweights in a borehole that contains a rising main, an electric cable to the pump, and access tubes. Special care should be taken to clamp these together and allow as much room as possible for the recorder float in its own tube.

The initial rapid drawdown and turbulence set up in a pumped well may cause difficulties in the use of float operated recorders (see **12.4**). If there is insufficient room in the existing borehole for a float, then other methods should be investigated; these include pressure transducers and pneumatic methods.

Chart recorders produce a continuous line upon a paper or plasticized chart. The chart itself is graduated or pre-printed to facilitate the reading of times and levels. For further details refer to BS 3680 : Part 9B.

Punched tape recorders produce a set of point readings at regular intervals by punching a series of holes in a paper or plasticized tape. Normally, readings are at 15 min intervals; it is possible to record at 5 min intervals but shorter periods are not available on current instruments.

All recorders require charts or tapes to be changed periodically and batteries may need replacing also. The chart or tape should be clearly marked at the start and finish with the time, data and water level. In addition, the location of the observation and the test should also be marked.

The check water levels should be obtained using a borehole dipper or a hook gauge on the stilling well of a weir tank.

If the chart drive rate or interval time is changed during a test, then a new chart or tape should be used, otherwise this could lead to confusion in subsequent interpretation.

The punched tape recorder is not as suitable for on-site operational records as the chart recorder. Level values from the weir tank should be available at intervals similar to those recommended in **14.2** with a resolution of 1 min. The advantage of a punched tape recorder is the ease of subsequent analysis which has to be undertaken by computer.

D.1.2 ***Manual water level measuring devices***

The normal 'dipper' instrument relies upon an electrical circuit being completed when a slim electrode makes contact with the water. Modern dippers employ a twin cable in the form of flat tape with the cables embedded in the tape edges. Flat tapes are usually graduated at 1 cm or 0.5 cm intervals, but care should be taken in case the tape has been shortened after being repaired or lengthened over time due to stretching.

Electrical dippers are invariably battery powered, and provide a surface signal visually by a light or a meter needle, or audibly by a buzzer. On a noisy site, the buzzer may be difficult to hear.

D.1.3 ***Shaft encoders***

Shaft encoders are available which produce a digital output from a float and counterweight system similar to that in a chart recorder. Modestly priced encoders are available with an accuracy of 1 mm and are in use in river level stilling wells.

D.1.4 ***Transducers***

Instead of float operated recorders, strain gauge transducers can be used. The disadvantage of most tranducers which work on the strain gauge principle is that they are currently available at sufficient accuracy over only a limited range. Since pumping tests may involve changes in water level of 25 m, and occasionally more, the attainable accuracy of the order of 0.25 % is inadequate.

However, where the expected depressions in water level are small, the transducer can provide a useful, continuous record. Tranducers require calibration prior to the start of the test and special electronic recording equipment needs to be made available.

Transducers using quartz crystals are available which are sufficiently accurate for many purposes over a wide range of pressures, but they are too expensive for most applications. Strain gauge transducers measure pressure relative to a reference value. Usually this is either atmospheric pressure, i.e. the transducer measures gauge pressure, or it is an evacuated chamber, i.e. the transducer measures absolute pressure. The type in use should be ascertained. Transducers reading gauge pressure are vented to the atmosphere, usually through the cable. Kinking or trapping of the cable, or exposure of a length of cable to temperature changes, e.g. by coiling in sunlight, can cause a back pressure to develop on the transducer diaphragm which is likely to affect the measurement. If in doubt, and especially where measurement is to be carried out over lengthy periods, non-vented transducers have been shown to be generally reliable but these require correction for barometric pressure which must be recorded separately.

D.1.5 ***Recording digital information***

Data loggers are now available for recording digital information from either shaft encoders or transducers. These are sealed solid state units requiring battery changes every few years and interrogated by hand held units, e.g. laptop computers, ruggedized handheld computers or organizers.

Information can be logged at different time intervals or according to a variable scheme. A better alternative is event based logging where a reading is sampled at e.g. 15 s intervals and only stored in memory if it differs from the previous stored value by more than a set amount.

D.1.6 ***Measurements in overflowing wells***

Heads in overflowing wells can be measured by a manometer fitted to the well head, or, if the pressure head reaches to a short distance only above ground level, a standpipe can be attached. It is important to allow sufficient time for levels in standpipes to stabilize, and to recognize their sensitivity to the opening and closing of adjacent overflowing wells and to fluctuations in barometric pressure. For high pressures or for continuous recording of pressure the use of transducers and chart recorders or recording pressure gauges may be necessary.

D.2 Measurement of discharge

D.2.1 *Weir tanks*

The accuracy of discharge measurements is of prime importance in the subsequent calculations of borehole and aquifer performance.

The most common method of measuring pump discharge is to use a weir tank, with the water discharging over a V-notch or a rectangular notch (see figures 11 and 12). BS 3680 : Part 4A describes methods for the measurement of water flow using such thin plate weirs.

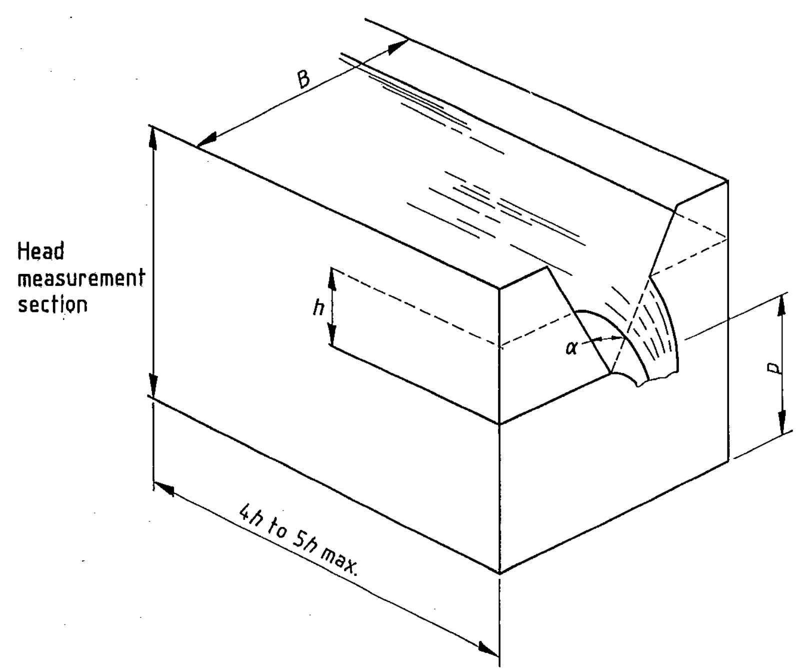
The discharge over thin plate weirs is a function of the head of the weir, the size and shape of the discharge area, and an experimentally determined coefficient which takes into account the head on the weir, the geometrical properties of the weir and the approach channel (or weir tank) and the dynamic properties of water.

BS 3680 : Part 4A should be used in the design and construction of weir tanks and their installation and operation.

The accuracy of discharge measurements depends primarily on the accuracy of the head and notch-angle measurements, and on the applicability of the discharge formula coefficients used. If great care is exercised in meeting the construction, installation, and operational conditions described in BS 3680 : Part 4A, uncertainties attributable to the coefficient of discharge will be not greater than 1 %.

The experimental results in BS 3680 : Part 4A have been developed using a rectangular approach channel. The conditions applying to a weir tank are different. Certain precautions should be taken to minimize errors.

The tank should be constructed of a rigid material. It should be placed on a crib of timbers, jacked and wedged in a horizontal position, and firmly supported so that it is stable throughout the test.



Key

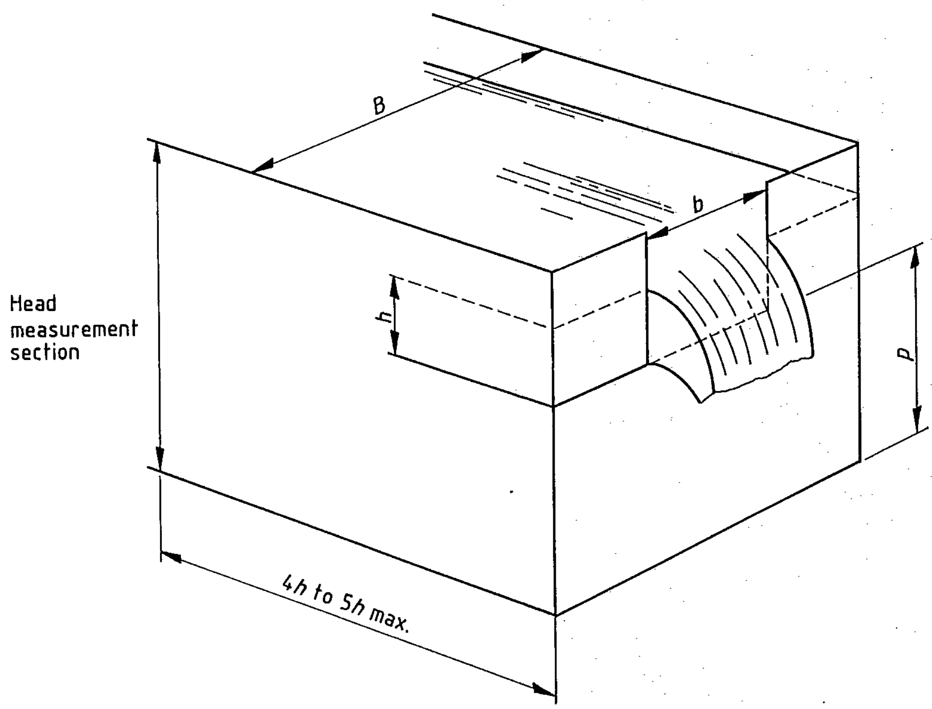
α is the notch angle, i.e. the angle included between the sides of the notch;

B is the width of the approach channel;

h is the measured head;

p is the height of the vertex of the notch with respect to the floor of the approach channel.

Figure 11. V-notch thin-plate weir



Key

b is the measured width of the notch;

B is the width of the approach channel;

h is the measured head;

p is the height of the crest relative to the floor.

Figure 12. Rectangular notch thin-plate weir

The notch should be truly horizontal as required in BS 3680 : Part 4A. Regular measurements of the horizontal position of the notch should be taken before and after the test.

The details of notch design and construction are found in BS 3680 : Part 4A. When test pumping water wells it is common practice to have a removable notch. The notch edge should be protected by timber at all times when not required for measurement.

The tank itself should be rectangular in shape with provision for an inlet at one end and a notch outlet at the far end. Normally the maximum size of tank is about 2 m wide by 4 m long by 1.5 m deep. The tank should be fitted with lifting eyes so that it can be positioned exactly on site.

For small discharges (less than 20 l/s) one tank may be sufficient. Baffle plates are essential to smooth out turbulence due to water entry. These baffles may be of a vertical slat type of wooden section 20 mm across by 100 mm in the direction of flow with gaps 20 mm wide. Other baffle designs should have the same objective of producing a uniform laminar flow towards the notch.

For discharges greater than 20 l/s two tanks may be required. This also applies to pumping tests carried out using airlift techniques where errors may result from vibration, fluctuating discharge rates and entrained air. The tanks preferably should be connected by several pipes 200 mm to 300 mm diameter positioned halfway between the notch level and the base of the tank.

Water levels above the notch are measured most accurately with a hook gauge and a float-operated recorder capable of measuring water levels with a resolution of 1 mm. The hook gauge and recorder float should be positioned in a stilling well because variations in water level in the weir tank can occur due to wind eddies. Level values should be available from the recorder at intervals similar to those recommended in **14.2** although readings just after a change of discharge, at 1 min intervals, are not usually practicable from present recorders. These readings should be noted manually.

The effects of wind on the water surface can be minimized by placing a covering over the tank. In any case a stilling well is required to eliminate short period changes (less than 30 s) in the water surface level resulting from turbulence and other hydraulic phenomena.

The stilling well should be separate from the weir tank. It should not protrude into the approach channel to the notch. The well can be constructed from any suitable rigid material and should be watertight, permitting water to enter or leave only through the intake. The height of the well should be such that it remains effective throughout the full range of water level. Its inner walls should be smooth and free from irregularities and should be substantially vertical such that no moving part of equipment located in the well is closer than 75 mm to any wall at any point throughout its full range of movement. The bottom of the well should be at least 300 mm below the invert level of the notch, to provide space for sediment storage and to avoid the danger of the float grounding. The well should be large enough to allow safe entry for cleaning. In cold weather the well should be protected from the formation of ice. In particular, the connection pipe to the weir tank should be as short as possible and lagged during cold weather. In order to control the short period oscillations a 50 mm valve is useful within the connection pipe. The inlet pipe should be set 100 mm below crest level and at 4 times to 5 times h_{max} back from the notch, where h_{max} is the maximum value of the head measured at the notch. (See figures 11 and 12.)

Means of cleaning the weir tank should be provided, because the internal baffles will also act as a trap for suspended solids. Accumulations of sand during a test can alter the approach depth, p, and the rating calibration.

Prior to the test a zero level should be obtained as described in BS 3680 : Part 4A, and the tank should be filled. It takes a finite volume to bring the water level from the bottom of the notch to the stage indicating the flow. This may be important with a large weir tank and it is therefore advisable to record the size of weir tank and to check if this phenomenon might occur.

The zero level should be checked again at the end of the test.

As stated previously, whenever possible weir tanks conforming to BS 3680 : Part 4A should be used to measure flow in the field. When the highest accuracy is not required or where site conditions make it difficult to install or operate large tanks satisfactorily, smaller tanks may be used.

There is a limited amount of data on how the discharge coefficients of weirs are affected by the size of the tank, as well as by non-standard headmeasuring positions, asymmetric and unsteady flow conditions at entry, and sediment deposits. Further information can be obtained from *The performance of weir tanks fitted with V-notch and rectangular thin plate weirs*[1].

In order to give some guide to the effect that a reduction in the size of the weir tank will have, values of the discharge coefficient have been tabulated for seven different sizes of weir tank. Table 3 gives values of C_D in the equation for a 90° V-notch and of C_e in the Kindsvater and Carter equation for a contracted rectangular notch, specified in BS 3680 : Part 4A.

Some indication of the influence of sediment deposits is given in table 4, which show values of C_e for a tank with dimensions conforming to BS 3680 : Part 4A but with differing amounts of sediment deposited against the weir plate. The uncertainty of these coefficients is approximately 1 %.

Within the range of tank sizes and heads covered in table 3, the location of the head measuring device is relatively unimportant. Positions between 100 mm and 720 mm upstream of the weir produce discharge coefficients which vary by less than 0.5 %. Heads should not be measured, however, near the inlet baffle or in the downstream corner of a narrow tank.

Tests have shown that non-uniform flow at entry and surface disturbances in the tank are the largest potential sources of error in flow measurement. If delivery is through a flexible pipe placed behind a slotted baffle as described above, random errors of between 5 % and 10 % in the discharge coefficient can occur unless particular care is taken. In order to minimize these errors, supplementary baffling in the form of perforated or permeable screens should be used whenever possible, with the aim of producing uniform velocity profiles on both horizontal and vertical axes of the tank. Some improvement with a slotted baffle alone can be achieved by arranging the delivery pipe to discharge under water and upstream against the closed end of the tank along its long axis. The coefficients in table 3 can then be applied but the uncertainty attached to them has to be increased to 2.5 % at higher flow rates.

D.2.2 *Other methods*

Other means of measuring pump discharge are available and reference should be made to BS 1042 : Parts 1 and 3. Further details are not given in this code of practice because these methods are less common in test pumping water wells.

[1] Available from Hydraulics Research Limited, Wallingford, England, Report No. EX1243.

Table 3. Discharge coefficients for a 90° V-notch (C_D) and for a rectangular notch (C_e) fitted in small tanks

Tank size[1]	90° V-notches[2]			Rectangular notches[3]		
	Head (h)			Head (h)		
	115 mm	150 mm	180 mm	65 mm	100 mm	135 mm
1	0.593	0.590	0.587	0.609	0.592	0.588
2	0.603	0.592	0.587	0.604	0.592	0.585
3	0.603	0.592	0.587	0.600	0.590	0.585
4	0.597	0.592	0.590	0.606	0.593	0.588
5	0.605	0.596	0.595	0.611	0.598	0.598
6	0.600	0.590	0.586	0.606	0.592	0.588
7	0.602	0.597	0.593	0.613	0.598	0.595

[1] The tank dimensions (length × width × height) are as follows:
(a) size 1 is 2.62 m × 0.92 m × 0.45m;
(b) size 2 is 1.5 m × 0.92 m × 0.45 m;
(c) size 3 is 1.0 m × 0.92 m × 0.45 m;
(d) size 4 is 2.62 m × 0.75 m × 0.45 m;
(e) size 5 is 2.62 m × 0.5 m × 0.45 m;
(f) size 6 is 2.62 m × 0.92 m × 0.3 m;
(g) size 7 is 2.62 m × 0.92 m × 0.3 m.

[2] Where

$$Q = C_D \frac{8}{15} \sqrt{(2g)}\, h^{5/2}$$

(See also BS 3680 : Part 4A.)

[3] Where

$$Q = C_e \frac{2}{3} \sqrt{(2g)}\, b_e h_e^{3/2}$$

(See the Kindsvater-Carter equation in BS 4380 : Part 4A.)

Table 4. Discharge coefficients (C_e) for rectangular notches with sediment deposits

Tank size (length × width × height)	Max. level of deposits at weir crest	C_e values for rectangular notches[1]		
		Head (h) mm		
		65	100	135
m	mm			
2.62 × 0.92 × 0.45	−150	0.605	0.591	0.588
	−40	0.606	0.597	0.590
	−40 (+100 at sides)	0.613	0.601	0.595

[1] Where $Q = C\frac{2}{3} \sqrt{(2g)}\, b_e h_e^{3/2}$
(See the Kindsvater-Carter equation in BS 4380 : Part 4A.)

D.3 Reference data for discharge over thin-plate weirs

As noted in F.2.1 it is very imporant that data collected for the purpose of analysing the performance of a water well and the aquifer is accurate, within known practical tolerances. BS 3680 : Part 4A gives details of all those factors affecting the performance of thin-plate weirs and reference should be made to that standard for guidance on converting the measured head at the notch, h, to an accurate rate of discharge, Q.

However, the accuracy of measurements provided by the tables in BS 3680 : Part 4A is not vital when setting the control valve on the rising main to its initial setting prior to commencing a test.

Figures 13 and 14 provide data with which the appropriate discharge can be estimated. They are derived from general formulae giving reasonable accuracy but do not take into account the depth, width or length of the weir tank. It is stressed that the data are only approximate and should not be used to convert heads to discharge values for use in analysis.

Appendix E. Well development

E.1 General considerations

The correct development of a well results in improved yield as a result of the removal of material that would otherwise hinder the inflow of water. The process of drilling wells by methods currently in use breaks down all or part of the strata into discrete particles which have to be removed. When drilling fluids are employed these particles are circulated in suspension. As the fluid passes over the wall of the well the particles tend to adhere to, or to pass into, the wall, a process that is enhanced by the hydrostatic pressure exerted by the drilling fluid. The result is a facing of slurry on the wall, commonly called a wall-cake. In the case of fissures or large intergranular interstices the slurry may penetrate some distance into the aquifer. The first purpose of development is to disperse and to remove this slurry together with any loose aquifer material. The test pumping of an undeveloped well is highly undesirable since the well efficiency can be greatly impaired by failure to remove the slurry. It is possible for the yield to be so low and the drawdown so great that the aquifer is wrongly discounted as a groundwater resource.

Wells constructed in hard rocks such as granite, indurated sandstones or massive crystalline limestones generally stand without support and are left open through the water yielding section. Development is usually confined to physical methods.

In soft limestones, such as chalk, wells will commonly stand without support. However, surging can cause spalling of rock from the wall, and the aquifer is usually too soft to shatter readily under the shock of explosives. The normal method of development in such strata is treatment with hydrochloric acid.

Wells in fissured rock often present special problems. Frequently the aquifer consists largely of impervious rock relying for its storage on fissures. These fissures may contain deposits of mineral salts, sand, clay and the like. Care therefore needs to be taken to avoid overpumping such aquifers, particularly during the development of a well, as flow velocities through the fissures may otherwise be so high as to result in an undesirably high rate of removal of solids from fissures, so giving rise to a high level of suspended solids or dissolved solids in the pumped water. However, development pumping rates should normally exceed the test pumping rate in order to remove as much of the loose aquifer material as is practical in order to ensure clean water when test pumping commences.

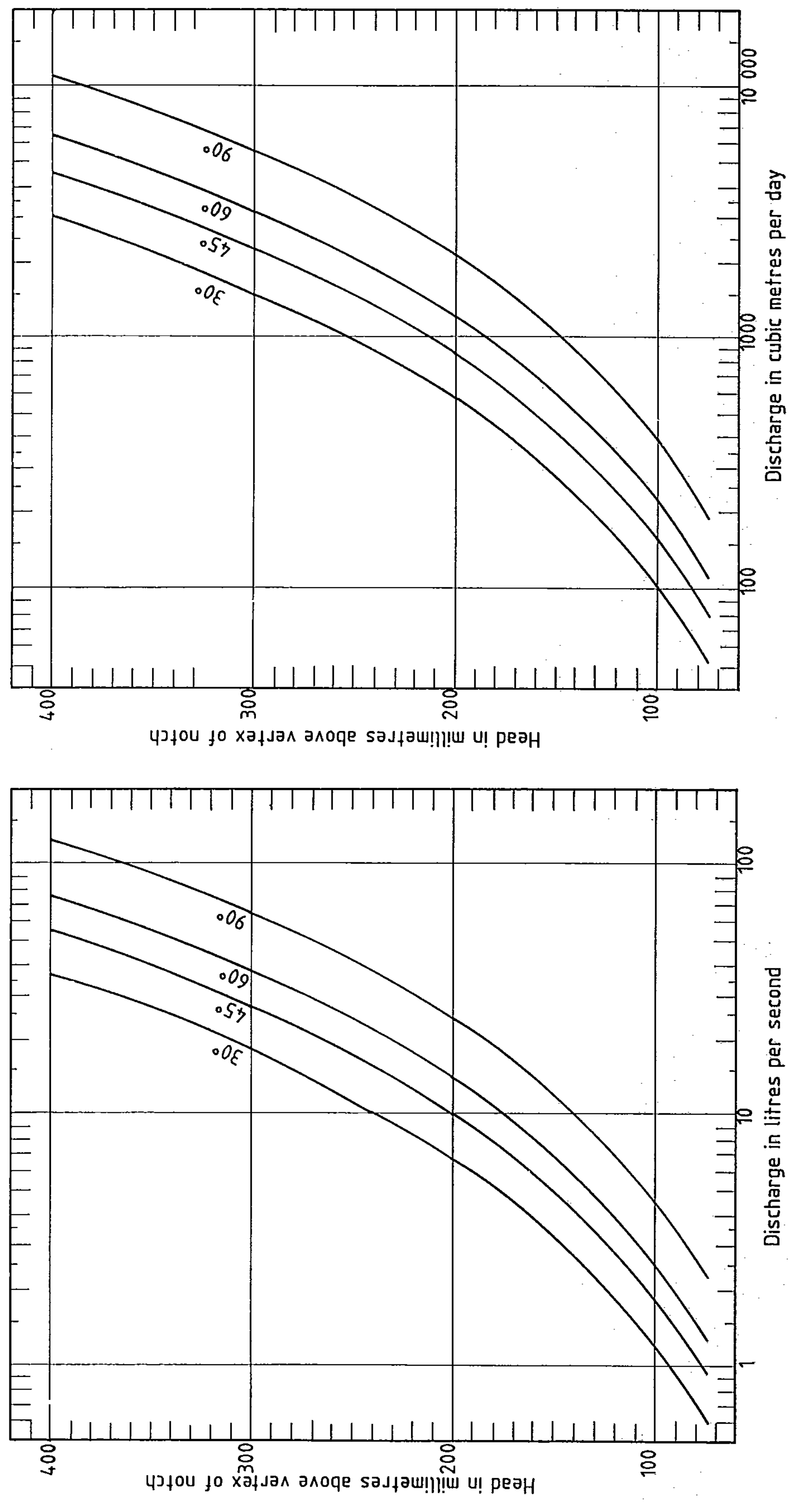
In unconsolidated intergranular aquifers the rock or soil consists of a number of grains of varying size. The development of the well causes the finer of these grains to be drawn into the well, and so the aquifer is left with an improved hydraulic conductivity in the immediate vicinity of the well.

Wells in unconsolidated sand or gravel are normally fitted with screens and filter packs. Development is physical, often with the addition of deflocculants to assist in breaking down the wall-cake.

E.2 Equipment for well development

Owing to the necessity of pumping water with a high content of suspended solids, together with the possibility of initial large drawdowns, the choice of pumps for well developments is limited. In practice two types are generally used.

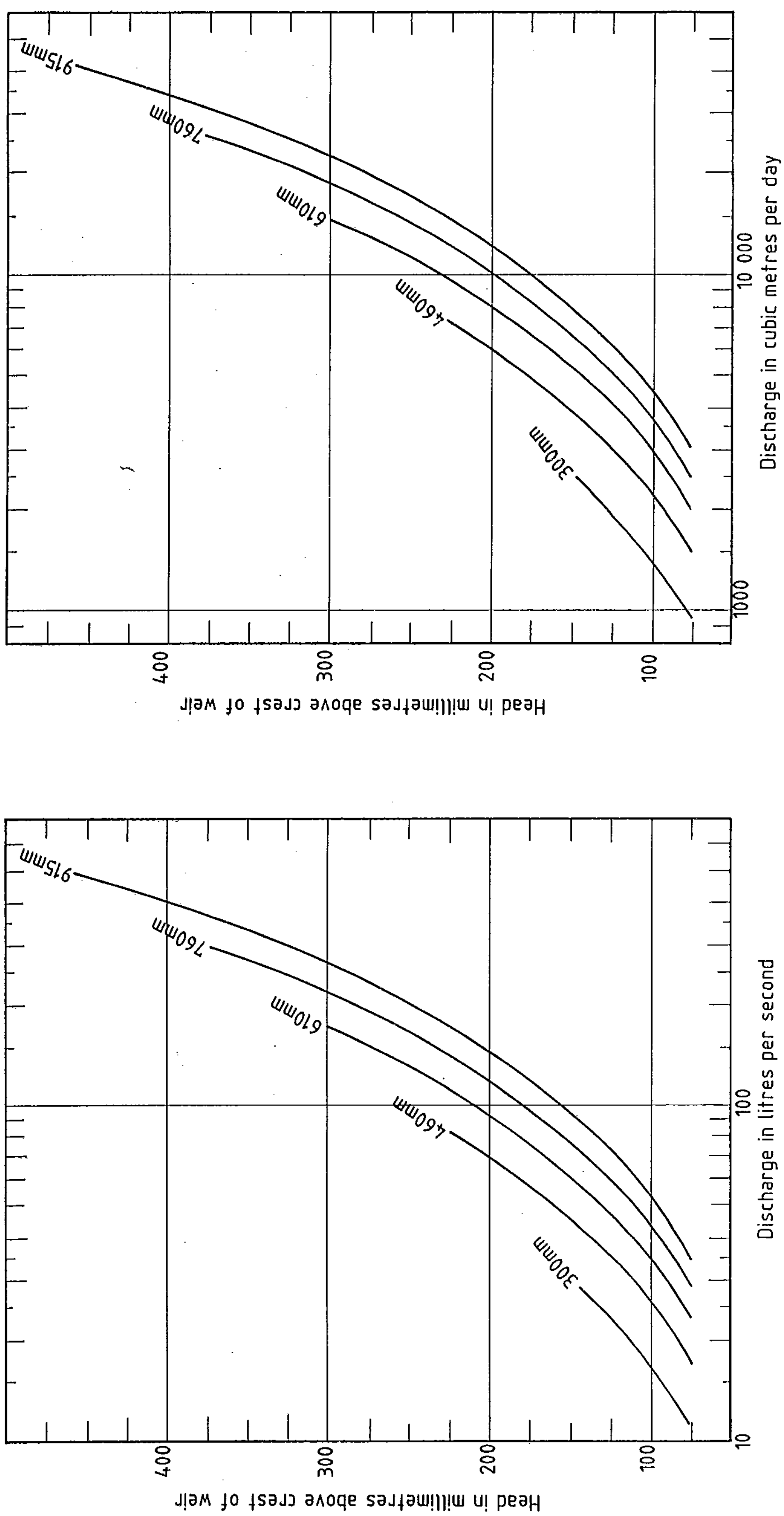
The first type is the centrifugal or turbine pump, driven either by a submersible electric motor or by a surface mounted engine rotating a long drive shaft passing through the rising main (a spindle pump). In either case it is possible to control the discharge rate, either by a valve on the rising main or by varying the power supplied to the engine. It is generally inadvisable to develop a well with the pump intended for operational use since the inevitable passage of suspended solids can damage the pump impellers with subsequent deterioration of performance. Multistage submersible turbine pumps generally rely on 'payload liquid' lubrication for the interstage bearings, so care needs to be taken to avoid loss of pump priming otherwise the pump may be seriously damaged.



(a) Relationship of discharge in litres per second against head in millimetres

(b) Relationship of discharge in cubic metres per day against head in millimetres

Figure 13. Approximate flow over V-notch thin-plate weirs of notch angles α, 30°, 45°, 60° and 90°

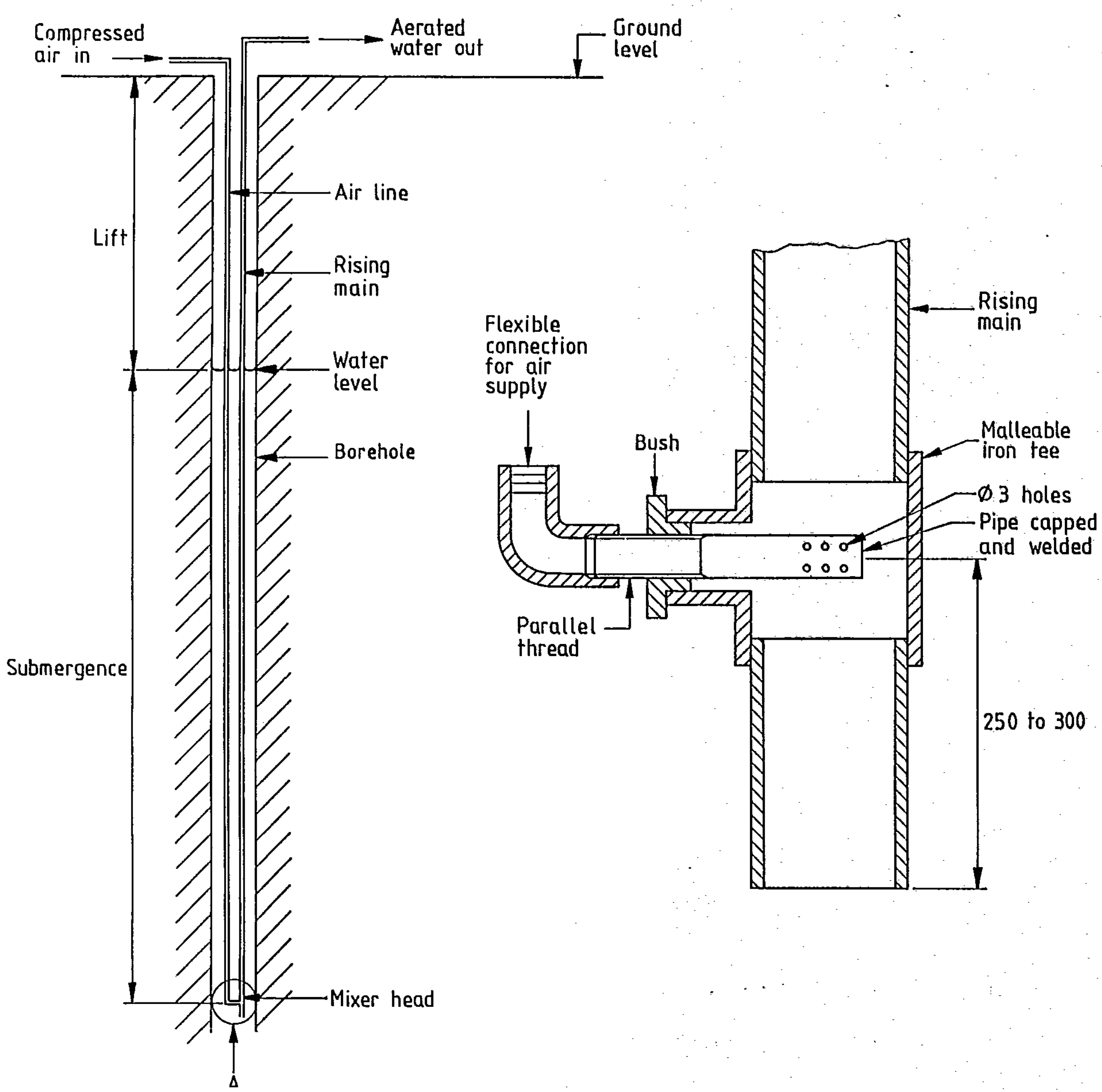


(a) Relationship of discharge in litres per second against head in millimetres

(b) Relationship of discharge in cubic metres per day against head in millimetres

Figure 14. Approximate flow over rectangular notch thin-plate weirs of notch widths, *b*, 300 mm, 460 mm, 610 mm, 760 mm and 915 mm

The second type of pump is the airlift. With this, compressed air is forced down an air pipe from the surface and aerates water within the bottom of the rising main. The aerated water is forced up the rising main by the pressure of the surrounding unaerated water. Figure 15 shows the typical detail of such an arrangement. The depth of submergence of the air pipe, and thus the depth of the well, is critical. The submergence is defined as the depth of the foot of the air pipe beneath the water surface, and the total lift desired is measured upwards from the same surface.

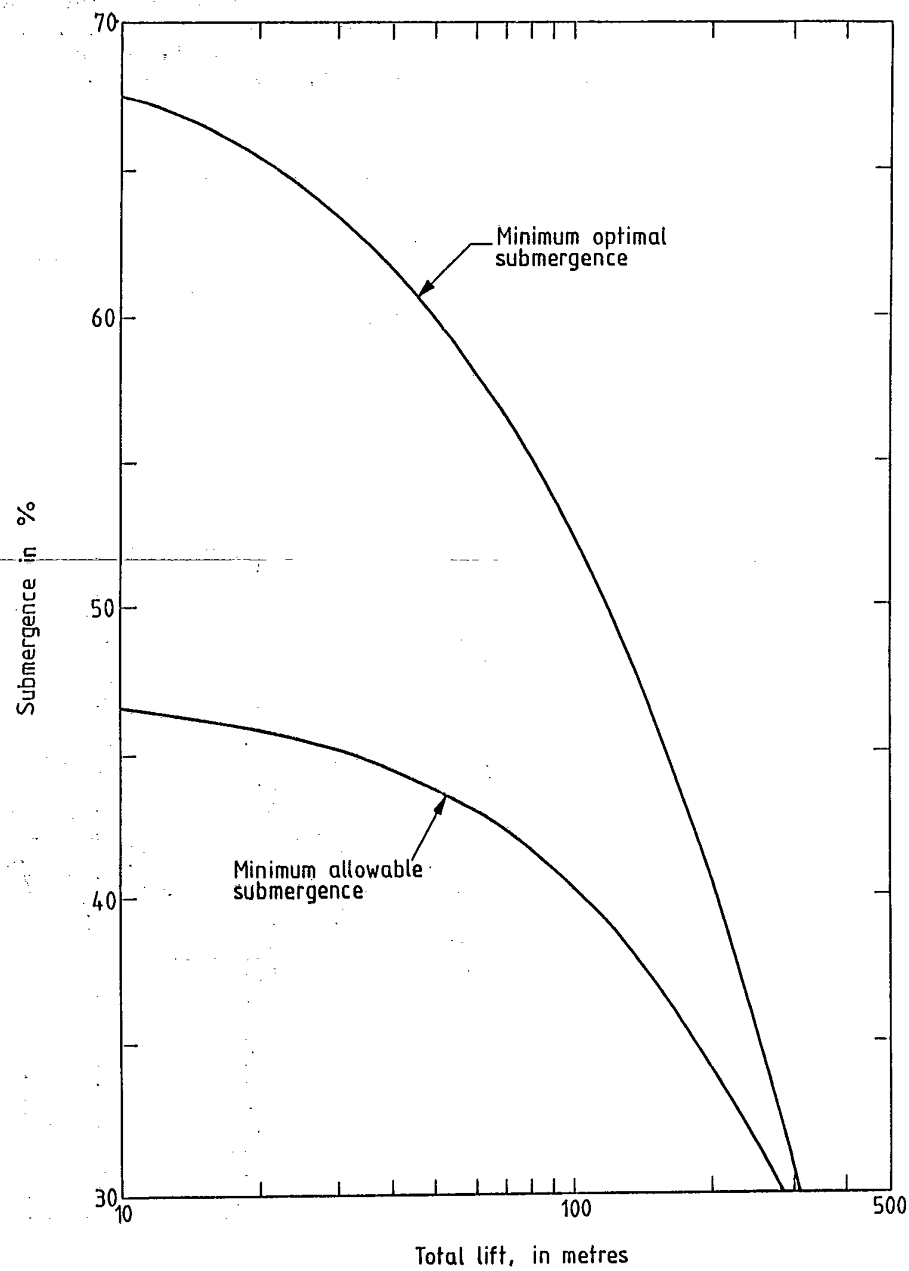


(a) General arrangement

(b) Typical detail of mixer head, A

NOTE. All dimensions are in millimetres.

Figure 15. Configuration of airlift pump in borehole



NOTE. Adapted from CAMPBELL and LEHR, 1973.

Figure 16. Degree of submergence required for airlift pumps.

The required percentage of submergence is calculated from the equation

$$\text{Percentage submergence} = \frac{\text{submergence}}{\text{submergence + total lift}} \times 100$$

Values for percentage of submergence may be determined from figure 16. Where possible, the values dictated by the curve for minimum optimal submergence should be used. Where a skillful operator is available, reasonable results during development may be obtained with values between the two curves. Where chemical analysis of the pump water is important, an airlift should not be used since aeration causes changes in some chemical characteristics.

E.3 Development methods

E.3.1 ***General***

There are many ways in which a well can be developed, and new methods are being sought. **D.3.2** to **D.3.5** summarize those methods commonly used at present in the United Kingdom.

E.3.2 ***Surging***

The principle of surging is to cause water to flow repeatedly into and out of the well, thus causing the finer grains within the aquifer, or the material clogging the fissures, to be worked into the well from which they can be removed. This water movement may need to be vigorous to be successful. Simple pumping of the well for a period of time produces little turbulence and causes the water to flow in only one direction. Although development may take place, it is likely to do so only very slowly.

The use of a bailer is limited by the low rate at which water can be discharged, although considerable turbulence can be induced. Where yields exceeding 0.5 l/s are required, the use of a bailer for development is not recommended.

Intermittent pumping, with water washing back through the rising main when the pump is stopped, is sufficiently effective for many low-yield wells. In favourable circumstances, as when the wall-cake is less cohesive, wells can be developed readily up to 10 l/s by this method. However, caution needs to be used when employing electric submersible pumps because the number of starts in a given time could exceed that for which the switchgear is designed. Where an airlift pump can be used, it has considerable advantages in this respect.

Where more vigorous surging is required, surge blocks or plungers should be used and worked as pistons within the lining tubes; they should not be operated within an open hole or a screen. An alternative to surge blocks, where the well can be sealed, is to use compressed air to depress the water level, and then to release the pressure to allow a rapid and powerful inflow to the well.

The effects of surging can be enhanced by introducing a solution of sodium polyphosphate into the well as a deflocculant. To make the solution, one part dry mass dissolved into 100 parts to 200 parts water is suggested, sufficient solution being used to displace all the water in the well.

E.3.3 ***Jetting***

Jetting employs the use of fine water jets directed radially at a minimum velocity of some 30 m/s. The use of jetting in open holes should be undertaken with caution as the action is very vigorous. Where the jets can gain free passage through the slots, this method can be very successful in screened wells. The disadvantages are that a substantial source of clean water is necessary and that considerable pumping power is required to obtain adequate jet velocities.

E.3.4 ***The use of explosives***

In hard rocks, failure to intersect fissures may result in little or no yield. In order to attempt to establish a hydraulic connection with any nearby fissures, an explosive charge, or charges, can be detonated in the lower part of the well so as to shatter the rock. This method of development is relatively inexpensive, can be effective, and when properly used should not seriously damage the well. Soft rocks (such as chalk) tend to cushion the shock wave; little shattering occurs, and the method is less successful. Expert assistance is essential when using explosives.

E.3.5 ***Acid treatment***

Acid treatment is most useful in soft limestones such as chalk, where the slurry consists mainly of calcium carbonate and where numerous small fissures are present which allow the acid to penetrate under pressure. The well casing should reach below the water surface in the well, and be firmly secured with grout. A safety valve needs to be fitted at the well head to release excess pressure. All pressure lines and related connections should be pressure tested before operations commence. Pumps, pipelines, etc. through which acid is handled should be thoroughly washed out with water upon completion of operations. It may be advisable to cap temporarily nearby observation wells during acid treatment.

Hydrochloric acid is used, normally in a strength of 30° Twaddell (29.4 % hydrogen chloride by mass). The recommended maximum quantity of acid is 200 kg per square metre of rock exposed in the well; smaller quantities may be appropriate for the treatment of small wells. It should be injected as a single charge, and the well capped off to build up pressure. The safety valve should be set to a value not exceeding 40 t/m^2, depending upon the condition of the well lining, the grout seal and the well cap. A pressure gauge, fitted to the well cap, will indicate when pressure is lost, for example, as the fissures are cleared.

After acid treatment is completed, the well should be cleared by either pumping or bailing, and the discharged liquor deposited in a nearby ponded area for final neutralization, where necessary, with slaked lime.

Acid treatment can be hazardous if improperly performed, and should only be carried out by experienced operators.

Personnel handling acids should be equipped with protective clothing including hoods, boots, gloves and goggles. When acid is in use, no person other than the crew directly employed should be allowed in the vicinity. In the event of an accident with acid, first aid treatment should be carried out immediately.

The contents of carboys and other containers should be clearly indicated by proper labelling. A quantity of lime should be made available and utilized to neutralize any acid spilled.

Smoking during acid handling operations should be strictly prohibited. No naked light or other source of ignition should be allowed in the vicinity. Notices to this effect should be prominently displayed.

E.4 Procedure

Development of boreholes by physical means should always commence with caution. Pumping should commence at a low rate, and the drawdown in the well should be measured at frequent intervals as the water level drops. A large drawdown at the start of development may result in an excessive amount of solids being drawn into the well and, particularly in chalk boreholes, may cause serious spalling of the well wall if it is unlined. In unlined wells, pumping and surging should initially be gentle until the stability of the well wall is established. In screened wells, gentle surging results in the deliberate collapse of the aquifer onto the filter pack (if present) and the screen. If this collapse occurs too suddenly and too violently, the screen can be badly damaged. Continuous sounding should be undertaken to ensure that the well does not fill with debris. This is particularly important in the case of screened wells. If surging continues after the screened length is filled with debris, damage to the screen, the lining tubes and the surging equipment can be extensive. It is not possible to be precise about what constitutes a large initial drawdown for well development. It is recommended that the initial pumping rate should be regulated to limit the drawdown to between 2 m and 3 m.

As development continues, the surging can become more vigorous and the pumping rates higher. If the well is developing satisfactorily, the drawdown will decrease gradually for the same pumping rate. When this is observed, and the chemical properties are not significantly changing, the pumping rate can be increased. At this stage a larger drawdown can be accepted. In this manner the well may be developed in stages to its full intended output. Development should be continued until the water is clean, and either no further yield can be obtained or until a yield at least 25 % above the expected operating rate is attained.

Where wells have been treated with acid, and the well has been cleaned by bailing, a short period of pumping should ensue until all trace of the acid residue has been cleared. This would be indicated by a simple well head titration for chlorides which should not exceed background counts by more than 50 mg/l.

E.5 Monitoring of well development

E.5.1 ***General***

During development of a well a number of changes will occur in the pumped water. If these changes are carefully monitored they will provide useful information on the effectiveness of the development of the well and on the suitability of the pumping site.

E.5.2 ***Changes in groundwater quality***

The fluid contained in the well at the start of development will be a mixture of groundwater and drilling fluid. As development proceeds, and water is pumped from the well, the quality of the discharged water may be expected to change. Simple monitoring, such as periodical measurements of fluid conductivity, is recommended. Should the mineral content of the groundwater rise significantly and remain at a high level, a decision may be necessary as to the future potential of the well as a source of useful groundwater.

E.5.3 ***Changes in content of suspended solids***

Physical appearance and suspended solids content can be important indicators of the suitability of pumping rate. The content of suspended solids normally decreases during the development process. However, there are occasions when the concentration does not decrease, but rather increases, e.g. when fine, running sands are encountered. If continued ingress of sand is experienced, the quantity should be measured against time. If the volume of sand remains constant or increases, there may be an attendant risk of collapse of the aquifer. In these circumstances, a decision may need to be taken either to develop the well to a lesser yield or to abandon the site.

Wells in chalk will tend to give a milky discharge on commencement of pumping, and pumping rate should not be increased until the discharge runs clear. Gradual increase of pumping rate may cause the discharge to become milky again. If this occurs, the increase in pumping rate should be stopped until the discharge again runs clear.

Mineral salts will often form a precipitate on contact with air, so that the discharge, initially clear, becomes clouded with suspended matter. The amount of precipitate forming is a useful indicator of change in the mineral salt content. A discharge that is immediately cloudy when pumped from a fissure-flow aquifer is an immediate warning to monitor the pumping rate.

When pumping from sedimentary rock, the sudden appearance of organic matter in suspension, often coupled with a sudden change in pH, will indicate that a lens of organic deposit is present. It is undesirable that such a lens should leach out at a high rate as this can seriously derogate the water quality. Increase in pumping rate should be stopped, and thenceforward the organic content should be monitored at frequent intervals.

Appendix F. Selection of pumping equipment

The total head to be developed by the pump for a specified maximum drawdown (static lift) and discharge can be calculated from the following equation:

$$\Delta h_p = S_{max} - (P + w) + h_f$$

where

Δh_p	is the total pump head (in m);
S_{max}	is the maximum surface elevation level (in m);
P	is the pump suction level (in m);
w	is the minimum water depth above pump suction (in m);
h_f	is the internal head loss from pump to point of discharge (in m).

For the calculation of internal head losses in the discharge side of the pump, reference should be made to D.S. Millar, *Internal flow systems*.

Having calculated the total head, Δh_p, and knowing the required discharge rate Q, reference should be made to the pump manufacturer's charts of pump performance showing discharge against total head (the 'pump curve'). The maximum values of Δh_p and Q should be plotted as a point superimposed upon the appropriate 'pump curve'. If the curve is above the point then the pump capacity is adequate, but if it is below the point the pump capacity could be too low. A graphical solution is then needed to determine what discharge could be achieved at maximum drawdown. The discharge is shown at the intersection of the pump curve and the discharge head curve obtained by plotting the internal head loss for increasing discharge. If this discharge is below the duty yield of the well a larger pump is necessary. Notwithstanding the above, the tendency in practice is to select the nearest commercially available size of pump rather than attempting to design a new, ideal capacity pump.

Appendix G. Geophysical logging

G.1 General

The test pumping of a water well presents an opportunity to carry out geophysical logging which often provides information of assistance to the interpretation of test results.

Formation and construction logs (see table 5) may be run in a borehole almost at any time but test pumping provides a convenient opportunity to run fluid logs both prior to commencement of pumping and again during the testing for comparative purposes. Table 5 lists various types of geophysical log typically used in water wells and their various applications and some limitations.

G.2 Formation and construction logging

Formation and construction logging carried out in conjunction with a test pumping assists in the geological and hydrogeological interpretation of a site and will also provide information on the physical features of the borehole.

The basic suite of logs commonly used includes electrical resistivity and natural gamma. These will provide some assessment of the properties of the formation and the porewaters contained in them. Also, a caliper log can, in addition to describing the dimensions of a well, provide information useful for the interpretation of the fluid logging and may be essential if other logs being run require diameter correction.

Formation logging should be carried out before installation of any pumping equipment and before introduction of any substances to clean or develop the borehole (most commonly hydrochloric acid).

Caliper logs should also be run prior to the test but there may be a need in some instances to repeat this log afterwards to examine such effects as collapse or erosion.

G.3 Fluid logging

Fluid logging is carried out to investigate the flow regime in the well in relation to the immediately surrounding aquifer. The logs normally available are fluid temperature, differential temperature, fluid conductivity, differential conductivity and flowmeter.

The logging cable and sensors should not pass a working pump unguarded. Therefore, where logging below a pump is necessary, an access tube terminating just below the pump needs to be installed. Logging above the pump is carried out in the annular space between the pump rising main and the wall of the well through a separate opening in the well head. Care is needed to avoid entangling with the power cable and the rising

Table 5. Application and limitation of geophysical logs

Application	Fluid properties		Formation and construction features															Limitations								Sonde features			
	Borehole fluid quality	Fluid movement	Formation fluid quality	Water level	Lithology	Bed thickness	Bed boundaries	Correlation	Permeable zones	Porosity	Density	Casing features	Casing location	Cement bonding	Cement location	Collapses	Caving behind lining	Diameter	Fissures	Air filled	Mud filled	Water filled	Lined (steel)	Lined (plastics)	Open hole	Quality reduces with borehole diameter	Borehole diameters	Centralized	Free	Sidewalled	Typical logging speeds
																											mm				m/min
Resistivity (normal, lateral, focussed)			*	*	*	*	*	*		*			*						*		*	*			*	*	> 50		*		5 to 15
Single point resistance				*	*	*	*	*					*						*		*	*			*	*	> 50		*		5 to 15
Self potential			*	*	*	*	*	*	*												*	*			*	*	> 50		*		5 to 15
Induction			*	*	*	*	*	*		*			*						*	*	*	*		*	*	*	> 50		*		3 to 10
Natural gamma					*	*	*	*												*	*	*	*	*	*	*	50 to 300		*	*	3 to 6
Neutron-neutron				*	*	*	*	*		*									*		*	*	*		*	*	50 to 300			*	3 to 6
Gamma-gamma				*	*	*	*	*		*	*		*		*		*		*	*	*	*	*	*	*	*	50 to 300			*	3 to 6
Sonic				*	*	*	*	*		*									*		*	*			*	*	100 to 300	*			5 to 10
Temperature	*	*													*				*			*	*	*	*		> 50		*		3 to 10
Conductivity	*	*																	*			*	*	*	*		> 50		*		3 to 10
Flowmeter		*																	*			*	*	*	*	*	> 50	*			0 to 10
Casing collar locator													*							*	*	*	*			*	> 50		*		3 to 10
Caliper												*	*			*		*	*	*	*	*	*	*	*		50 to 1200		*		5 to 10
Cement bond														*	*						*	*	*			*	100 to 300	*			5 to 10
CCTV	*	*			*							*	*			*			*	*		*	*	*	*	*	> 50	*	*	*	1 to 3

main or other obstructions. A screwed rising main results in more room for access and less risk of cable fouling, compared to a flanged rising main, and is therefore preferred. The power cable to the pump should be clipped to the rising main at frequent intervals to prevent looping (flanged main is at a disadvantage in this respect also).

G.4 Reference

A more detailed consideration of geophysical logging is given in BS 7022.

Appendix H. Well head chemistry

H.1 General

This appendix summarizes the typical tests that are carried out at the well head. Particular pumping programmes may require additional tests to be carried out, e.g. for iron. Sample collection techniques (particularly rinsing) should be followed rigorously, especially in connection with stable and radioactive isotopes for which specialist advice should be sought. Certain chemical parameters may change during the period between sampling at the well head and analysis in the laboratory and should be determined preferably at the well head. Those which are considered here are temperature, pH (hydrogen-ion activity), E_H (redox potential), dissolved oxygen and total alkalinity. When these parameters are to be determined, airlift pumping should not be used since aeration causes significant changes.

It is common practice to monitor changes in groundwater quality by taking periodical measurements of the electrical conductivity at the well head. These measurements are particularly useful as an indication of changing salinity.

Well head determinations of chemical or physical parameters of groundwater are not usually within the work expected of a drilling contractor. Nevertheless, the provision of a suitable sampling tap on the rising main may need to be arranged in advance.

Further information on the assessment of water quality is given in BS 6068 : Section 6.1.

H.2 Isolated flowing samples

It is necessary to determine some parameters of flowing samples that are isolated from the atmosphere. To achieve this, an airtight container, usually made of transparent or translucent plastics, is fitted with inlet and outlet points. The inlet point is connected to the sampling tap on the rising main (plastics tubing of about 12 mm bore is adequate) and the outlet fitting discharges to waste. The top of the container has openings into which the measuring electrodes can be placed and sealed.

To operate the device, the relevant electrodes are fitted, and the sampling tap adjusted to provide a through flow of 1.5 l/min to 2.0 l/min. The container itself should be gently rocked and tapped until all the contained air is displaced.

H.3 Free flowing samples

When it is unnecessary to isolate the samples from the atmosphere, electrodes can be immersed in water flowing through a simple plastics trough (a half section of plastics drainpipe would suffice). The water can be taken either from the sampling tap or directly from the pumped discharge outlet. Every care should be taken to keep aeration to a minimum.

H.4 Static samples

Static samples are normally collected in a glass or plastics open-topped container. This should be thoroughly rinsed with the discharged water before the sample is taken, and aeration of the sample should be avoided as far as possible.

H.5 Tests

H.5.1 ***Redox potential E_H (isolated flowing sample procedure)***

The response of the platinum electrode used for the determination should be checked using Zobell's solution, the formal potential (E_H) of which is +430 mV at 25 °C. The readings will vary depending upon temperature and the reference electrode employed. After checking, the electrode is fitted to the container as described in **H.2**. After the air within the container has been displaced, at least 30 min should be allowed for the reading to stabilize.

H.5.2 ***Dissolved oxygen (isolated flowing sample procedure)***

A temperature compensated meter is required. The electrode should be calibrated to read 100 % in water saturated with air and less than 1 % in a 10 % sodium sulfite (Na_2SO_3) solution by mass. At least 10 min should be allowed for the reading to stabilize.

H.5.3 ***Temperature (free flowing sample or isolated flowing sample procedure)***

The most convenient method is to use a normal mercury-in-glass thermometer. After immersion, the thermometer should be left for 3 min to 4 min for the reading to stabilize.

H.5.4 ***Hydrogen-ion activity pH (free flowing sample or isolated flowing sample procedure)***

Standard pH electrodes should be used, calibrated on site with suitable buffer solutions. Some electrodes require to be shielded in the presence of electrical apparatus such as pumping plant or power cables. The temperature of the electrode and of the buffer solutions should be within 5 °C of that of the groundwater.

When it is not possible to measure the pH in flowing samples, a reasonable measurement can be made in a static sample. In such a case, the measurement should be made as quickly as possible, repeated several times, and the mean taken of the different determinations.

H.5.5 ***Total alkalinity (static sample procedure)***

The recommended method is to use titration against standard sulfuric acid. The sample should be collected with the minimum of aeration and processed as quickly as possible. The mean should be taken of several determinations.

H.5.6 ***Electrical conductivity (static sample procedure)***

An electrical conductivity meter is usually employed. The cell should be rinsed four or five times with the sample before making a measurement. If the cell incorporates temperature compensation, 5 min should be allowed for stirring the sample to permit equilibration. If the cell does not incorporate such compensation, the temperature should be measured with a mercury-in-glass thermometer before the measurement is made.

Appendix J. Examples of forms for data collection (see 21.6)

Figure 17 is an example of a reference form for the recording of the site details (based on an Institute of Geological Sciences form).

Figure 18 is an example of a comprehensive data form for completion on site.

Aquifer test : site details

Country ....
Nat. grid ref. or coordinates [ ] of pump well

Locality ....

Site ....
Ref no. [ ]

Single [ ] or multiple [ ] pumping well test

Aquifer(s)

Time [ ] Date [ ] of start of main [ ] or preliminary [ ] test

Depths and other details for each well are measured from the permanent datum. Datum elevations are relative to

sea level [ ] or to site datum [ ] at ....

.... which is [ ] above sea level

Pump details: electric submersible from mains [ ] from generator [ ] vertical turbine [ ]

airlift [ ] surface [ ] piston force [ ] piston lift [ ] other ....

.... Pump suction at [ ] below well datum

Foot valve fitted [Yes/No] Non-return valve on discharge main [Yes/No]

Nominal discharge rate(s): [ ] [ ] [ ] [ ]

Was maximum discharge rate limited by capacity of pump? [Yes/No]

Any problems with pump? ....

Discharge measurements by: flowmeter(s) (state how many) [ ] orifice or venturi meter [ ]

weir tank [ ] volume tank [ ] other [ ]

Any problems with measuring devices? ....

Aquifer details: known or suspected influences:

barometric [ ] tidal [ ] river [ ] other loading [ ] other pumping [ ]

barrier boundary [ ] recharge boundary [ ] other influence ....

Aquifer believed to be: confined [ ] semi-confined [ ] unconfined [ ]

Pumping well fully [ ] partly [ ] penetrates aquifer. Aquifer base at [ ]

Aquifer top at [ ]

No. of samples taken for chemical analysis [ ] for radioisotope analysis [ ]

Geophysical logging carried out of formations [ ]

Fluid logging carried out at test [ ] while pumping [ ] TV inspection [ ]

Record meter readings and water levels before start of pumping

Check that weir tank is level: before test [ ] after test [ ]

[Turn over] and enter details of pumping well(s) and observation well(s)

Completed by .... Date ....

Figure 17. Example of reference form for recording of site details (based on an Institute of Geological Sciences form)

Well name	From test well		Well datum elevation	Depth	Diameter	Cased intervals	Perforations, screen or open interval:			Rest water level			Remarks
	Distance *	Bearing	*	*	*	*	from *	to *	opposite (formation)	Water level above datum *	time	date	

* State units.

Figure 17. Example of reference form for recording of site details (based on an Institute of Geological Sciences Form) *(concluded)*

Aquifer test : Observations

Variable measured ....

Observations in [   ] well

during [   ] (test name)

Country ....

Type of test [   ] (drawdown, recovery, etc.)

Locality ....

Sheet .... of

Drawdown phase no. [   ] Recovery phase [   ] Preliminary test [   ]

Main test [   ]

This phase commenced [Day] [Month] [Year] Time [   ]

Measurement by: auto recorder [   ] electric probe [   ] other [   ]

Permanent datum description .... Permanent datum elevation

Factor for converting recorded measurement [   ]

Date	Time	Elapsed time since pumping started or stopped		Water level below datum	Drawdown (s)	Discharge (Q)	Notes
		Days	Minutes	*	*	*	

* State units

Figure 18. Example of comprehensive data form for completion on site

Appendix K. Types of drawdown trend exhibited by field data

Analysis of drawdown data from pumping tests is a specialized subject and is carried out with most profit by someone with a thorough knowledge of groundwater hydraulics. Some introduction is given in BS 5930.

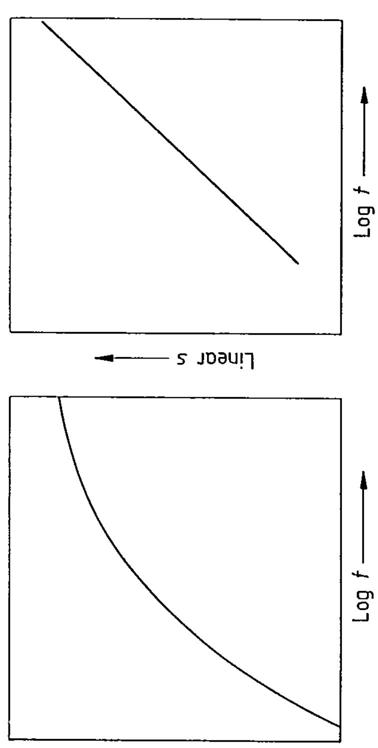
During a pumping test it is useful, however, to plot the trend of drawdown data with time, e.g. in order to decide when to stop pumping. However, if field plotting is used, the true drawdown trend is not necessarily the same as that of apparent drawdown (relative to the water level at the start of the test) as exhibited in such a field plot.

It is usual to refer the variation of drawdown with time (and distance) to a theorectical Theis curve. The latter is derived from the most idealized description of non-steady state groundwater flow near a pumping well. All field data exhibit deviations from this ideal curve to some extent because no field situation is exactly so described. These trends are sometimes very marked and can be identified with certain 'non-ideal' features of the groundwater flow. Some are shown for illustration in diagrammatic form in figure 19. It should be noted that these figures are greatly simplified and are not suitable for detailed analyses of data.

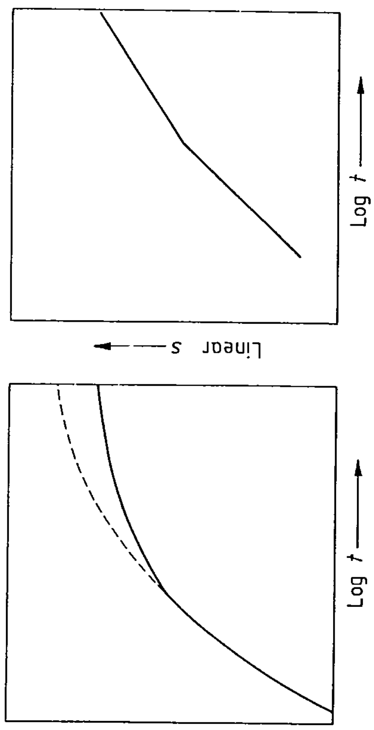
Table 6 gives values of $W(u)$ for values of u for the purpose of plotting a theoretical Theis curve (see clause **28**).

Table 6. Values of $W(u)$ for values of u

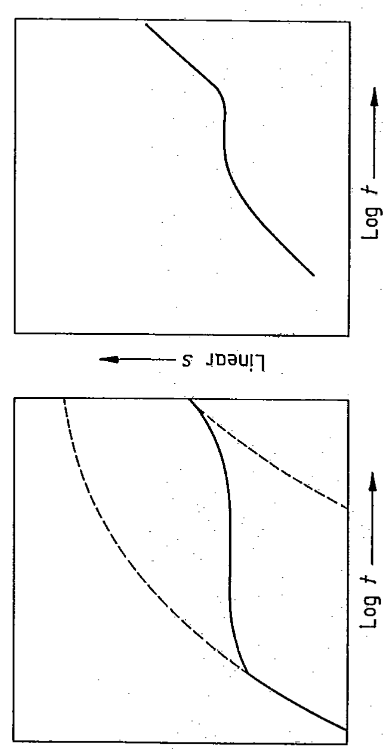
u	$W(u)$								
	1.0	**2.0**	**3.0**	**4.0**	**5.0**	**6.0**	**7.0**	**8.0**	**9.0**
$\times 1$	0.219	0.049	0.013	0.0038	0.0011	0.00036	0.00012	0.000038	0.000012
$\times 10^{-1}$	1.82	1.22	0.91	0.70	0.56	0.45	0.37	0.31	0.25
$\times 10^{-2}$	4.04	3.35	2.96	2.68	2.47	2.30	2.15	2.03	1.92
$\times 10^{-3}$	6.33	5.64	5.23	4.95	4.73	4.54	4.39	4.26	4.14
$\times 10^{-4}$	8.63	7.94	7.53	7.25	7.02	6.84	6.69	6.55	6.44
$\times 10^{-5}$	10.94	10.24	9.84	9.55	9.33	9.14	8.99	8.86	8.74
$\times 10^{-6}$	13.24	12.55	12.14	11.85	11.63	11.45	11.29	11.16	11.04
$\times 10^{-7}$	15.54	14.85	14.44	14.15	13.93	13.75	13.60	13.46	13.34
$\times 10^{-8}$	17.84	17.15	16.74	16.46	16.23	16.05	15.90	15.76	15.65
$\times 10^{-9}$	20.15	19.45	19.05	18.76	18.54	18.35	18.20	18.07	17.95
$\times 10^{-10}$	22.45	21.76	21.35	21.06	20.84	20.66	20.50	20.37	20.25
$\times 10^{-11}$	24.75	24.06	23.65	23.36	23.14	22.96	22.81	22.67	22.55
$\times 10^{-12}$	27.05	26.36	25.96	25.67	25.44	25.26	25.11	24.97	24.86
$\times 10^{-13}$	29.36	28.66	28.26	27.97	27.75	27.56	27.41	27.28	27.16
$\times 10^{-14}$	31.66	30.97	30.56	30.27	30.05	29.87	29.71	29.58	29.46
$\times 10^{-15}$	33.96	33.27	32.86	32.58	32.35	32.17	32.02	31.88	31.76



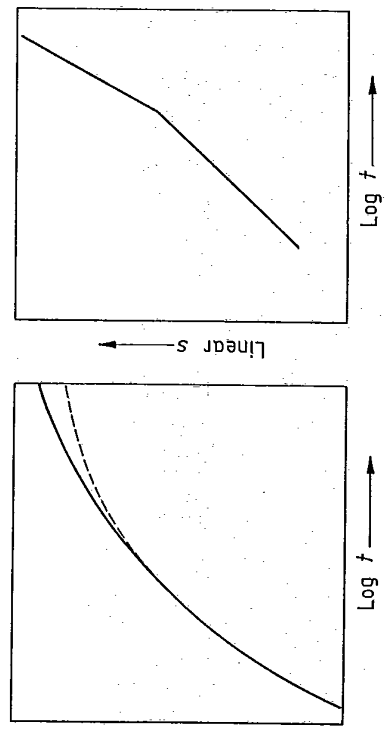
(a) Confined or unconfined aquifer without delayed yield



(c) Confined or unconfined aquifer showing recharge boundary effect



(b) Confined or unconfined aquifer with delayed yield



(d) Confined or unconfined aquifer showing physical barrier effect or effect of start of pumping at a second well, in the vicinity of the test well

NOTE 1. s = drawdown, t = time.

NOTE 2. Theis curves are shown dashed.

Figure 19. Theoretical time-drawdown trends

Bibliography

The following bibliography lists further sources of information on various aspects of test pumping described in this code of practice. It also includes details of general references on groundwater hydraulics and of texts offering guidance on analysis of the data that will be obtained as a result of successfully carrying out a pumping test. It is not exhaustive but it is hoped that users of this code will nevertheless find it useful.

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[4] Available from National Water Council Publications, Queen Anne's Gate, London.

[5] Available from the National Joint Utilities Group of British Telecom, the Electricity Council, British Gas and the National Water Council.

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