BRITISH STANDARD

BS ISO 14686:2003

Incorporating Amendment No. 1

Hydrometric determinations — Pumping tests for water wells — Considerations and guidelines for design, performance and use

ICS 07.060

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The UK participation in its preparation was entrusted by Technical Committee CPI/113, Hydrometry, to Subcommittee CPI/113/8, Wells and boreholes, which has the responsibility to:

— aid enquirers to understand the text;

— present to the responsible international/European committee any enquiries on the interpretation, or proposals for change, and keep the UK interests informed;

— monitor related international and European developments and promulgate them in the UK.

A list of organizations represented on this subcommittee can be obtained on request to its secretary.

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Summary of pages

This document comprises a front cover, an inside front cover, the ISO title page, pages ii to vi, pages 1 to 58, an inside back cover and a back cover.

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Amendments issued since publication

Amd. No.	Date	Comments
16220	March 2006	Addition of supersession details

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 24 July 2003

© BSI 15 March 2006

ISBN 0 580 42314 X

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INTERNATIONAL STANDARD

ISO 14686

First edition
2003-07-15

Hydrometric determinations — Pumping tests for water wells — Considerations and guidelines for design, performance and use

Déterminations hydrométriques — Essais de pompage pour puits d'eau — Considérations et lignes directrices pour la conception, l'exécution et l'utilisation

Reference number
ISO 14686:2003(E)

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Foreword

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International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 14686 was prepared by Technical Committee ISO/TC 113, *Hydrometric determinations*, Subcommittee SC 8, *Ground water*.

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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 pump 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; and

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. These matters are not dealt with in detail in this International Standard.

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 that 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:

a) head loss through the aquifer; and

b) 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 either of these two 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 measurement 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 that 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.

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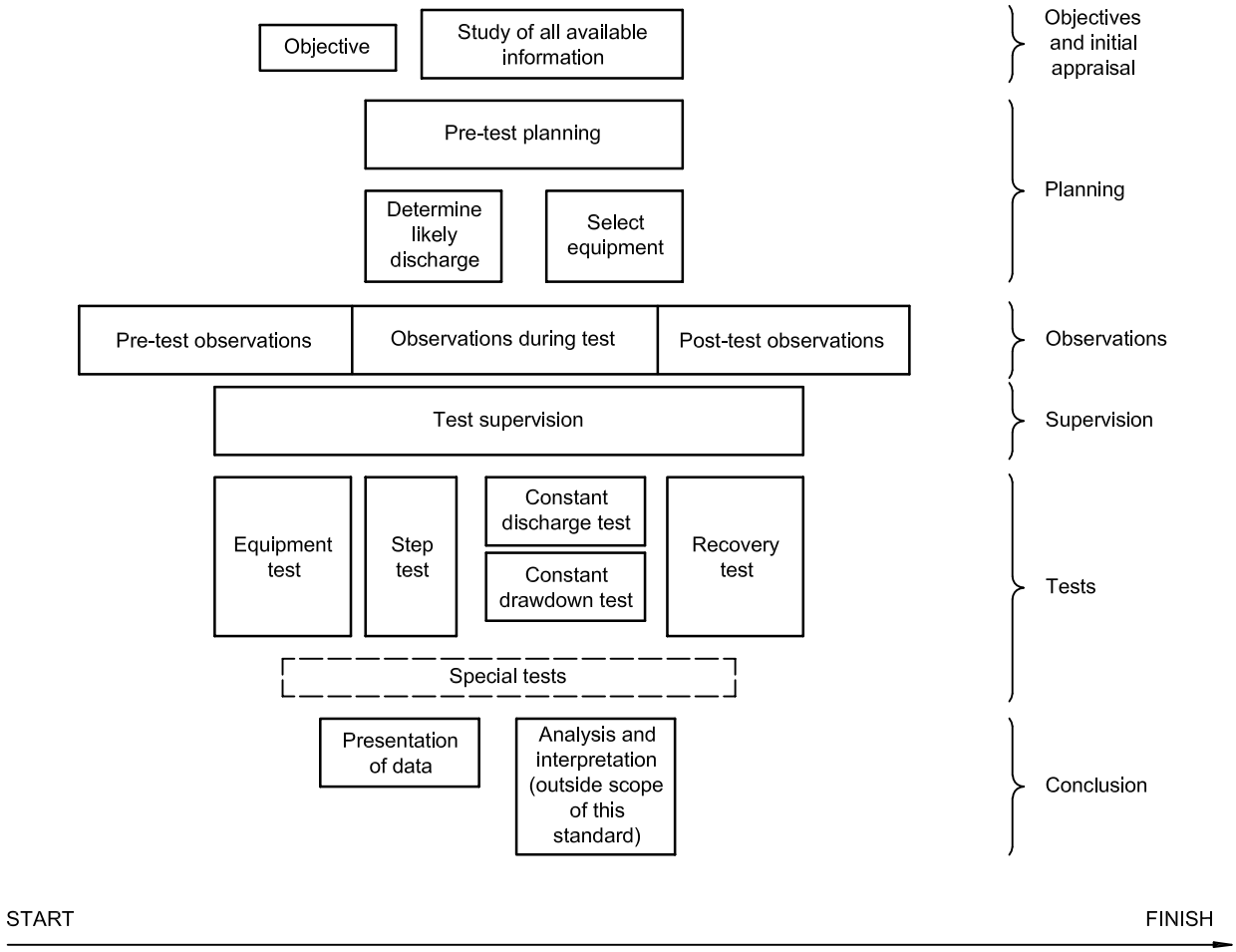

Figure 1 — Typical pumping-test procedure

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Hydrometric determinations — Pumping tests for water wells — Considerations and guidelines for design, performance and use

1 Scope

This International Standard describes the factors to be considered and the measurements to be made when designing and performing a pumping test, in addition to a set of guidelines for field practice to take account of the diversity of objectives, aquifers, groundwater conditions, available technology and legal contexts. The standard specifies the fundamental components required of any pumping test. It also indicates how they may be varied to take account of particular local conditions. It deals with the usual types of pumping test carried out for water-supply purposes, in which water is abstracted from the entire screened, perforated or unlined interval(s) of a well.

Interpretation of the data collected during a pumping test is referred to in this International Standard only in a general way. For full details of the analysis and interpretation of test data, reference should be made to specialized texts. Examples of such texts are included in a selected bibliography.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

2.1
abstraction
removal of water from a borehole or well

2.2
access tube
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
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, boreholes or springs

2.4
aquifer loss
head loss at a pumped or overflowing well associated with groundwater flow through the aquifer to the well face

2.5
aquifer properties
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

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2.7
casing
tubular retaining structure, which is installed in a drilled borehole or excavated well, to maintain the borehole opening

NOTE Plain casing prevents the entry of water.

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
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
reduction in static head within the aquifer resulting from abstraction

2.13
filter pack
granular material introduced into a borehole 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
flow, steady
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
flow, uniform
flow in which the magnitude and direction of flow at a given moment are constant with respect to distance

2.16
foot valve
non-return valve fitted at the bottom of a suction pipe of a pump

2.17
groundwater
water within the saturated zone

2.18
hydraulic conductivity
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 This definition assumes an isotropic medium in which the pores are completely filled with water.

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2.19
hydraulic gradient
change in static head per unit of distance in a given direction

2.20
hydrogeology
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
stratum unable to stand without support

2.23
isotropic
having the same properties in all directions

2.24
lining
tube or wall used to support the sides of a well, and sometimes to prevent the entry of water

2.25
lining tube
preformed tube used as the lining for a well

NOTE See also casing (2.7) and screen (2.39)

2.26
lithology
physical character and mineralogical composition that give rise to the appearance and properties of a rock

2.27
observation well
well used for observing groundwater head or quality

2.28
overflowing well
well from which groundwater is discharged at the ground surface without the aid of pumping

NOTE A deprecated term for this type of well is an artesian well.

2.29
permeability
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
upper boundary of an unconfined groundwater body, at which the water pressure is equal to atmospheric

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2.32
potentiometric surface
surface that represents the static head of groundwater

2.33
radius of influence
radius of the cone of depression

2.34
rest water level
water level in the pumped well observed under equilibrium conditions when the pump is off

2.35
rising main
pipe carrying water from within a well to a point of discharge

2.36
rock
natural mass of one or more minerals that may be consolidated or loose (excluding top soil)

2.37
running plot
graph of a variable against elapsed time continually updated as measurements are taken

2.38
saturated zone
that part of the earthen material, normally beneath the water table, in which all voids are filled with water

2.39
screen
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

2.40
slurry
mixture of fluid and rock fragments formed when drilling or developing a borehole

2.41
specific capacity
rate of discharge of water from a well divided by the drawdown within the well

2.42
specific yield
ratio of the volume of water which can be drained by gravity from an initially saturated porous medium to the total volume of the porous medium

2.43
static head
height, relative to an arbitrary reference level, of a column of water that can be supported by the static pressure at a given point

2.44
storage coefficient
volume of water an aquifer releases from storage or takes into storage per unit surface area of the aquifer per unit change of head

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2.45
transmissivity
rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the saturated aquifer under a unit hydraulic gradient

2.46
unconsolidated rock
rock that lacks natural cementation

2.47
unsaturated zone
that part of the earthen material between the land surface and the water table

2.48
water table
surface of the saturated zone at which the water pressure is atmospheric

2.49
well
hole sunk into the ground for abstraction of water or for observation purposes

NOTE See also Annex A.

2.50
well bore storage
volume of water released from within the well itself during a decline in head

2.51
well development
physical and chemical treatment of a well to achieve minimum resistance to movement of water between well and aquifer

2.52
well efficiency
measure of the performance of a production well

2.53
well loss
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

3 Hydrogeological considerations

3.1 General

Before a pumping test is planned, a full assessment of the hydrogeological conditions at and around the test site should be carried out. 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.

Pumping tests might be contemplated in a wide range of circumstances. There is also the probability that the aquifer will be partly and perhaps nearly fully developed already. Therefore 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.

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

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 that 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 hour, 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. Several explanations of delayed yield have been offered, but none has full general acceptance at the present time.

3.3 Groundwater conditions (see also Annex B)

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.

3.4 Multi-layered aquifers

Many 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. The analysis of data from fractured-rock aquifers may be particularly difficult. The response to pumping may be asymmetric, depending on the number, location, orientation and size of fractures encountered by the well. Some fractured-rock groundwater systems may be acceptably represented as an equivalent porous media conceptual model, and standard analysis methods would then apply. However, certain advanced analysis techniques may dictate pumping and observation well placement.

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3.5 Boundary conditions

Barrier boundaries are normally presented by geological discontinuities caused by faulting 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. Surface watercourses, by lakes, or by the sea, may provide such boundaries 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.

3.6 Other hydrogeological factors

There are several factors that 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, including spatial trends. 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 again increasing. 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.

4 Pre-test planning

4.1 Statutory requirements

Attention is drawn to local acts, byelaws, regulations and any other statutory requirements relating to matters dealt with in this International Standard. Work should be carried out in accordance with, and the equipment in use should comply with, the appropriate regulations.

Sites within designated areas such as national parks, areas of outstanding natural beauty, areas of special scientific interest, 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 and may be required 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.

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4.2 Site facilities and organization

4.2.1 General

Guidance is given on general matters that 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 that therefore should not be assumed to be exhaustive in its coverage.

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

4.2.2 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.

4.2.3 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 neutralization of acid when 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 that on initial inspection appear to be firm and dry often degenerate to a slippery morass around the wellhead. 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 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 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.

4.2.4 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. 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 4.5.3). 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 W.

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All electrical installations on the site should comply with the requirements and recommendations, as appropriate. Surface power cables between generator and wellhead should be armoured. Flexible-braid-armoured cable is more suitable and easier to handle in this application than single-wire-armoured cable. Single-wire-armoured cable should comply with local standards. A watertight emergency stop lockout button should be mounted within easy reach.

Special tests, such as certain types of packer test, will require a water supply. There may be constraints on the type of water which can be used; tankers may be required, and possibly storage on site need to be 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.

4.2.5 Site accommodation

A suitable hut or shelter should be erected on 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.

4.2.6 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.

4.2.7 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 and is consistent with environmental regulations. 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 soakway, 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. Requirements to treat the pumped water or to tanker it for disposal may constrain pumping rate and duration.

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 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 4.2.10).

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4.2.8 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 local authorities and landowners. In many cases, discharge of turbid water into watercourses will not be permitted, so early advice should be sought. It should be noted that in wooded or forested areas, particularly with regard to coniferous trees, soakaway disposal is undesirable because weakening of the root structure and possible consequent wind damage may result. In some cases, the quantities of pumped discharge involved may make it impractical to use lagoons or soakaway 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.

4.2.9 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.

4.2.10 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 that is subject to corrosion, steps should be taken to effect repairs before corrosion reaches dangerous limits.

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 % (by volume) solution of sodium hypochlorite. 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.

4.3 Design of the test

4.3.1 General considerations

The pumping test should be designed keeping in mind the objectives stated in the introduction and also taking into account the hydrogeological conditions of the site, the influence of neighbouring wells 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 for both the properties and productivity of the aquifer.

An estimate of expected drawdown using the expected range of aquifer characteristics is desirable. This estimate will help identify suitable observation well locations, the duration of test necessary to identify possible boundaries, delayed-yield behaviour, etc. The estimation of drawdown will help identify whether the proposed test is able to supply data that might distinguish between competing hypotheses.

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. It is essential that, prior to any test, the well be developed to clear the borehole and screen sediment and thus minimize the resistance between the well and the aquifer.

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Consideration should also be given as to what, if any, chemical determinations will be required on site during the test. Electrical conductivity is often monitored using a simple cell, but redox potential, pH and other determinants may require a “flow-through cell” which must be installed before the start of the test. Electrical conductivity can be used as a general indicator of water chemistry and will give early warning of, for example, saline water being drawn into the well.

4.3.2 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 4.3.3 to 4.3.5, including data with which to determine appropriate values for valve settings for subsequent pumping tests.

4.3.3 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 (Darcian conditions) and other components of head loss such as 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 at least 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.

4.3.4 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 and aquitard within the radius of influence of the pumped well. Observation wells are necessary in order to determine fully the aquifer properties. Table 1 gives guidance on the minimum durations that should be allowed for constant-discharge tests. In certain situations, such as those described in this subclause, in 3.6 and in 4.3.7, increases or decreases in these periods will be appropriate. Longer tests would be required for example to adequately assess the influence of boundaries.

Table 1 — Minimum duration of constant-discharge tests

Discharge rate m^3/day	**Minimum duration of constant discharge** days (of constant 24 h discharge)
Up to 500	1
500 to 1 000	2
1 000 to 3 000	4
3 000 to 5 000	7
Over 5 000	10

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The effect of a recharge boundary (see 3.5) is a deceleration in the rate of drawdown. Where the recharge source is a specific feature, such as a watercourse or a lake, the time that elapses 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 3.6) 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 3.5) 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 initially specified.

4.3.5 Constant-drawdown test

A constant-drawdown test 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, 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 the design of dewatering schemes, for overflowing wells, for tests in piezometers and for tests using over-capacity pumps.

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

In a well that is overflowing, no pumping is necessary. The procedure is to shut off the flow at the wellhead, 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 wellhead 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.

4.3.6 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. In the case of an unconfined aquifer, this is largely due to the incomplete resaturation of the interstices within the unconfined aquifer dewatered during the test.

A recovery test dependent upon water levels measured in the test well may 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. Observations should be made for a period at least as long as the pumping test itself.

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4.3.7 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 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 precipitation, including heavy rainfall and snowmelt (Freeze and Cherry, pp. 360-370).

4.4 Observation wells

4.4.1 Purpose and characteristics of observation wells

In a constant-discharge test, observation wells are necessary for the accurate determination of aquifer properties such as transmissivity, storage coefficient and the influence of boundaries. The values of transmissivity and storage coefficient are 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. At least one observation well is required for determination of the storage coefficient. Furthermore, the effective boundary conditions can also be determined from the shape of the cone of depression and from differences between the responses measured in observation wells. Existing wells should be used if their dimensions and locations are suitable. In other cases, observations 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.

4.4.2 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 or two observation wells will suffice. This guidance assumes idealized aquifer conditions (i.e isotropic and homogeneous aquifers). More complex conditions may require significantly greater numbers of wells. 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 for several example aquifers. Estimates of spacings in other lithologies can be made from an indication of their transmissivity and type curve. A spacing of less than 10 m from the test well is undesirable, the data obtained from closer distances presenting difficulties in analysis.

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