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)

ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.org
Web www.iso.org

Published in Switzerland

Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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*.

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.

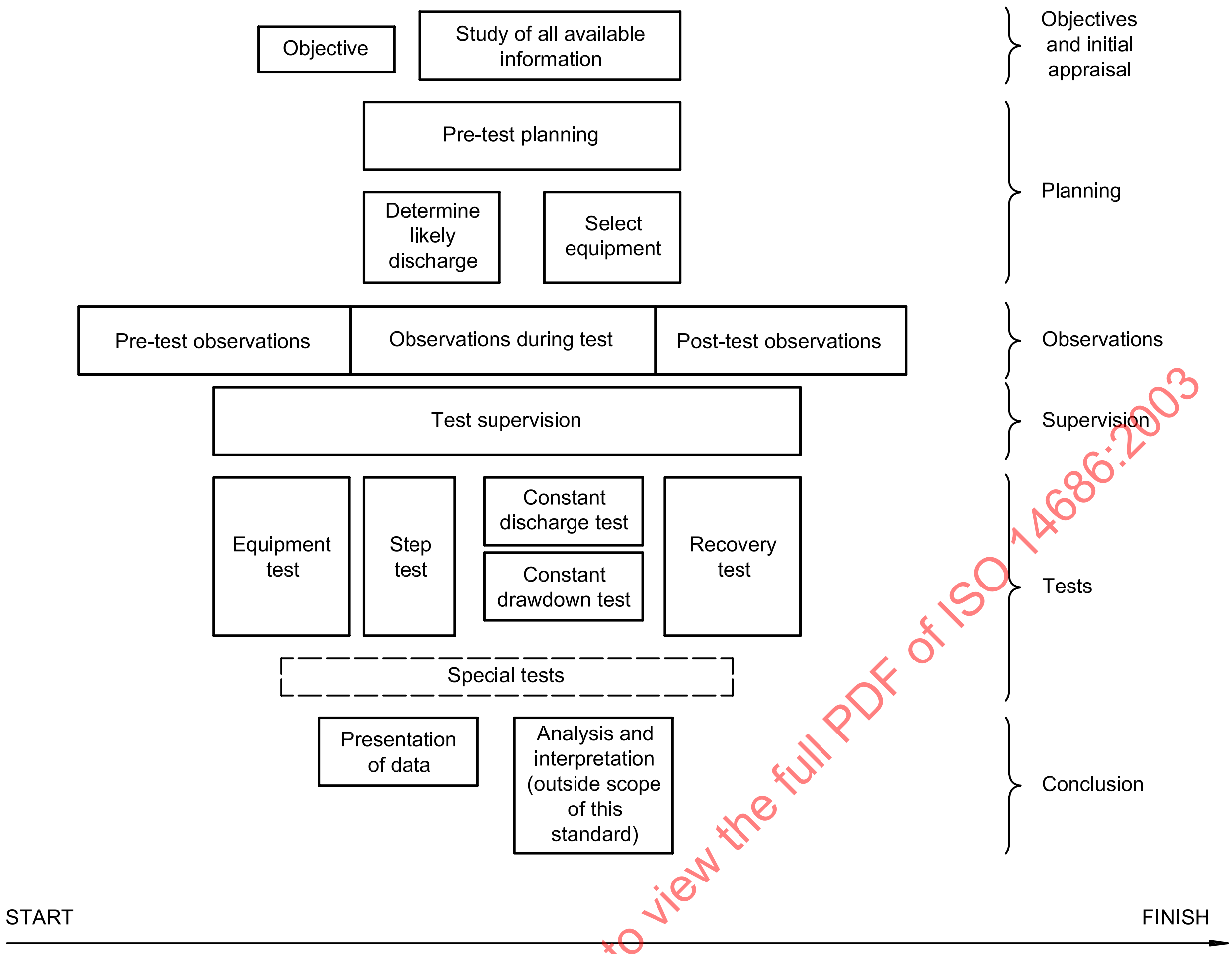


Figure 1 — Typical pumping-test procedure

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

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.

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

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

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.

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.

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.

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.

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).

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.

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

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.

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.

Table 2 — Location of observation wells for selected lithologies

Aquifer state	Transmissivity m²/day	Measurable response	Typical lithology	Spacing from test well m
Unconfined	50 to 500	Slow	Unfissured sandstone, sand, silt	25 to 35
Unconfined	Over 500	Fast	Fissured limestone, sandstone, gravel	25 to 60
Confined	50 to 500	Slow	Unfissured sandstone, sand, silt	60 to 100
Confined	Over 500	Fast	Fissured limestone, sandstone, gravel	10 to 200

Attention should be paid to boundary conditions that may affect the location (see 3.5). The distance from the test well may need to be reduced if the boundary is in close proximity.

4.4.3 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 different 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 performed, 4.4.3 c) should give reasonable results.

4.4.4 Observation well design

An observation well should adequately reflect variations in aquifer water level (Black and Kipp, 1977). 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 minimum internal diameter of the well to be three times the diameter of the probe on the dipper. Where the water level is at a considerable depth (> 100 m), a much larger diameter dipper tube or casing (100 mm) may be required to reduce adhesion between cable and tube. Perforation of the dipper tube may be needed to equalize density differences in the tube due to heat from the pump motor.

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 the 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. 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.

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.

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 Annex C should be taken into account.

4.4.5 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 Annex D). 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.

4.5 Test well

4.5.1 General

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

4.5.2 Groundwater entry into the well

The design of the well should allow free entry of water from the aquifer but preclude entry of aquifer particles, while ensuring that the well does not collapse and that the yield does not decrease over the long term.

The depth of the well must 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 might relate only to that thickness of the aquifer that is screened or open in the test and observation wells.

The well construction should be sufficient to contain the pump and column pipe and any additional equipment required in the well. The length of casing should afford proper placement of pumps with requisite suction head for the designed discharge of the well. The diameter should 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, granular 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.

4.5.3 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 volumes, 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 6.3.2) that may give rise to thrust-bearing failure if the condition is prolonged. Using a variable-speed drive would minimize this. It is recommended that the pump capacity be sufficient to allow a discharge of up to 25 % more than the required yield of the well for normal duty. The pump should be installed low enough in the well to remain below the pumping-water level when the well is discharged at the desired rate(s). Sufficient space should be left underneath the pump to allow any sediment to settle 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 cased section of the well. In all cases, the pump should be placed so 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 be 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. 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.

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 back-flushing 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 back-flushing 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 4.3.6).

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 air valve 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 4.5.5).

When a generator is required to power the pump and/or 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.

4.5.4 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 Annex C). If a vertical-flow meter is to be used, an additional tube of larger diameter sufficient to accommodate this is required.

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

4.5.5 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. Descriptions of V-notch and rectangular weirs can be found in Annex C and in pertinent texts.

Weir tanks and similar devices are only accurate if they are properly installed, correctly levelled and used with great care, and if the notches or orifices are accurately machined and kept perfectly clean. In many cases, a flow meter can be at least as accurate as a weir device if correctly installed and recently calibrated. In cases where the water meter is placed between the control valve and weir tank, care should be taken that the discharge line rises between the meter and the tank, as shown in Figure 2. To do otherwise may result in a partially filled discharge pipe and would give erroneous metered results.

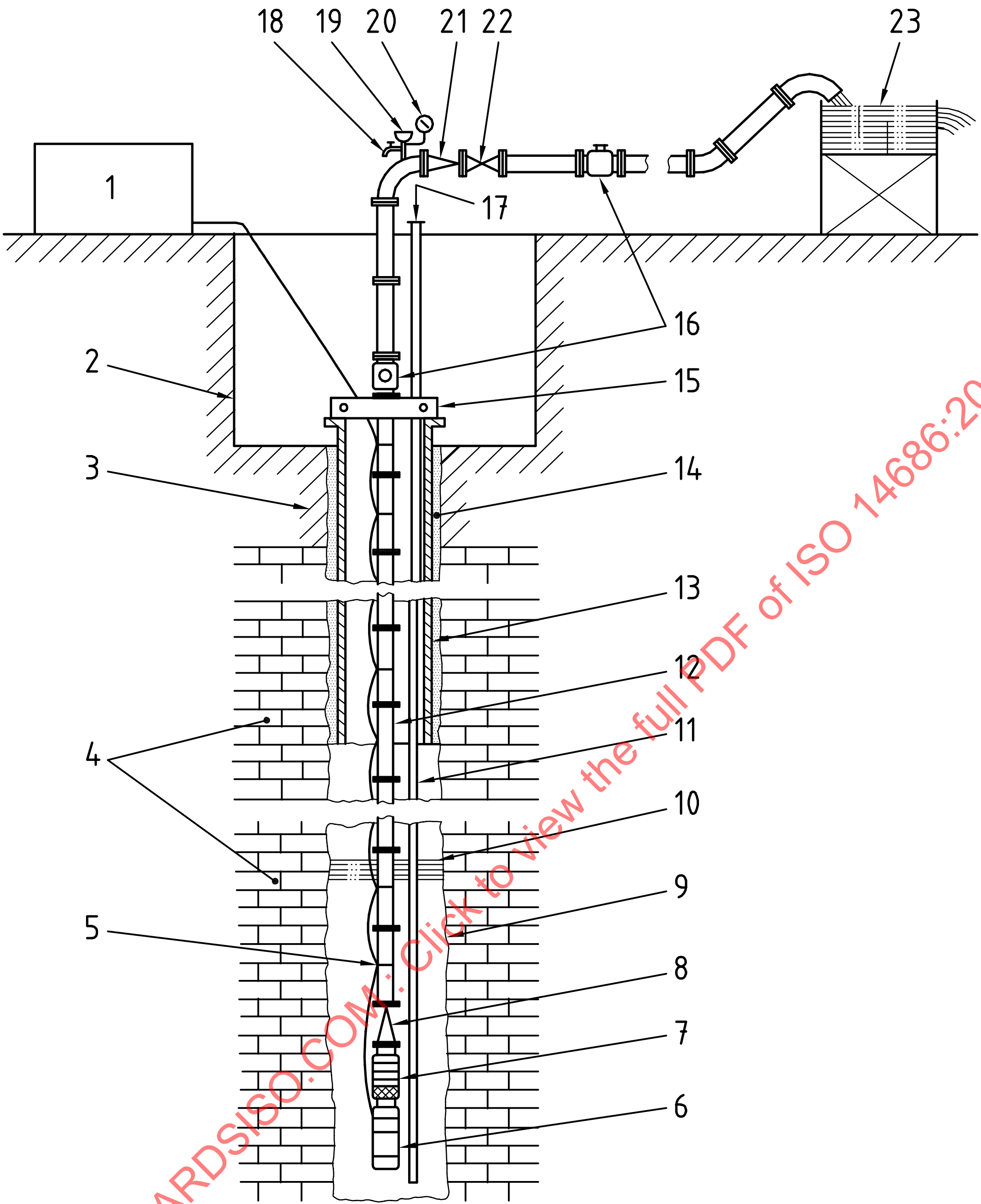
An alternative to the weir tank is a sharp-edged orifice plate attached to the end of a horizontal pipe at least 2 m in length. This method is fairly accurate, convenient and responds more rapidly to changes in flow than a weir tank.

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 cumulative 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.

4.5.6 Frequency of discharge measurements

The discharge rate should be measured and recorded at the same frequency as water-level measurements (see 4.6.2). If continuous recorders are being used, it may still be necessary to make manual measurements where instrument resolution is inadequate. Further information on methods of measurement and equipment for measuring pumped discharge are given in Annex C.



Key

1 power supply and pump starter
2 surface pit if required
3 surface deposits
4 aquifer
5 cable clipped to rising main
6 motor
7 pump
8 foot valve
9 unscreened zone of well
10 water surface
11 access tube
12 rising main (column pipe), flanged or threaded
13 lining tube
14 grout
15 pipe hanger
16 alternative water meter positions
17 well datum
18 sample tap
19 air valve
20 pressure gauge
21 non-return valve (if no foot valve)
22 control valve
23 weir tank

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

4.6 Groundwater-level measurement

4.6.1 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 in the required time. 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, and calibration by manual dipping will still be necessary.

4.6.2 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 i) relate only to the collection of data and are not recommendations for the actual length of the test (see 4.3).

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 It is desirable, when possible, to make measurements of water level in observation wells 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 2 min thereafter until the completion of 20 min of pumping.

d) Every 5 min thereafter until the completion of 60 min of pumping.

e) Every 10 min thereafter until the completion of 100 min of pumping.

f) Every 20 min thereafter until the completion of 300 min of pumping.

g) Every 50 min thereafter until the completion of 1 000 min of pumping.

h) Every 100 min thereafter until the completion of 3 000 min of pumping.

i) Every 200 min thereafter until completion of the test, unless other influences (such as tides) warrant more frequent measurements.

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.

4.7 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.

5 Pre-test observations

5.1 General considerations

Hydrological, hydrogeological and climatological factors 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 Clause 3).

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.

5.2 Surface water

5.2.1 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 spring tides. 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 seawater should be made to establish the characteristics of the water. 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.

5.2.2 Non-tidal water

5.2.2.1 Still water

Stage measurements should be made of surface water, such as lakes or ponds, which 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 that may occur during the test.

5.2.2.2 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 that 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.

5.2.2.3 Chemical analysis

Samples of water from the sites given in 5.2.2.1 and 5.2.2.2 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.

5.2.2.4 Radioisotopes

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

5.3 Groundwater

5.3.1 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.

5.3.2 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 5.2.2.3 and 5.2.2.4.

5.4 Meteorological parameters

5.4.1 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. The effects of barometric pressure on water levels in wells and calculation of a barometric efficiency have been described in a number of text books, such as Kruseman and de Ridder (1990), Walton (1970; 1987) and Todd (1980).

5.4.2 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 rain gauge networks.

5.5 Abstractions and discharges

All pumped wells, spring discharges and 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 at 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.

6 Pumping test

6.1 General considerations

6.1.1 Test programme

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

a) equipment test (see 6.2);

b) step test (see 6.3);

c) constant-discharge test (see 6.4) or constant-drawdown test (see 6.5); and

d) recovery test (see 6.6).

6.1.2 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.

6.1.3 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 4.6.2) and the accuracy of measurement required. Staff need to be advised of any safety regulations in force.

6.1.4 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.

6.1.5 Timing

The supervisor should be responsible for determining the actual times 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.

6.1.6 Records of measurements

The supervisor should be responsible for issuing suitable forms for recording measurements and collecting and collating the completed forms (examples are shown in Annex F). 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 6.8).

6.1.7 Record of well dimensions and distances

Depth, diameter, level above 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.

6.2 Equipment test

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

Groundwater level should be measured in the test well and in any observations 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.

6.3 Step test

6.3.1 Discharge rate, duration and number of steps

The discharge rate, duration of each step and number of steps will have been determined in advance (see 4.3.3). 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.

6.3.2 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. 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. Best results are obtained with an automatic flow-rate control on a variable-speed pump.

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

6.3.3 Test procedure

6.3.3.1 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, however.

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.

6.3.3.2 Intermittent-step test

The amount of change in the pumping rate between steps may be progressive or intermittent (see 4.3.3). Each step should be considered as a discrete test and should start under the procedure described in 6.3.2. At the end of each step, the pump should be stopped and groundwater levels allowed to recover before commencing the next step.

6.3.4 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 4.6.2. 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.

6.3.5 Analysis of step test

Full analysis of the step test is beyond the scope of this International 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.

6.4 Constant-discharge test

6.4.1 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 6.3.5).

6.4.2 Start of test

The procedure as recommended for step tests should be used (see 6.3.2).

6.4.3 Measurement of pumped discharge

The pumped discharge should be measured as described in 4.5.5.

6.4.4 Measurement of groundwater levels

Groundwater levels should be measured in the test well and in all observation wells at the intervals recommended in 4.6.2.

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.

6.4.5 Duration of test

The duration of the test should be as recommended in 4.3.4.

6.5 Constant-drawdown test

6.5.1 General

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

6.5.2 Start of test

If the well is to be pumped, the start procedure is similar to that in 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.

6.5.3 Measurement of discharge

The discharge should be measured continuously as described in 4.5.5.

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

6.5.4 Measurement of groundwater level and static head

The groundwater level or static head should be measured in the test well prior to commencing the test at the intervals recommended in 4.6.2. 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 4.6.2. 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.

6.5.5 Duration of test

The duration of the test should be sufficient for the discharge to reduce to about 1 % of the initial rate. A test may be terminated if discharge reduces to lower than 1 % of the initial rate.

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

6.5.6 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. A methodology is described by Kruseman and de Ridder (1990). 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.

6.6 Recovery test

6.6.1 General

A recovery test should only be performed in the test well 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.

6.6.2 Start of test

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

6.6.3 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.

6.6.4 Measurement of groundwater levels

Groundwater levels should be measured in the test well and in the observation wells at the intervals recommended in 4.6.2, commencing at the time discharge ceases.

6.6.5 Duration of test

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

6.7 Interruptions of tests

6.7.1 Breakdowns

Normally, the 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 constant-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 results from previous test steps may still be valid. Once a constant-discharge or constant-drawdown test has been in progress for 24 h, there may be breaks in pumping of up to 1 h, although provisions 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.

6.7.2 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.

6.7.3 Developing wells

Test wells that have been inadequately developed may show some development during the test. In these circumstances, a constant-discharge or constant-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 Annex D).

Failure of an observation well to show drawdown 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 further developed before testing.

6.7.4 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.

6.8 Measurement of aquifer response during constant-discharge and constant-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. These plots can be the basis for the determination of aquifer properties in the vicinity of the pumping and observation wells. It is beyond the scope of this International Standard to describe the interpretation of water-level data for this purpose. Kruseman and de Ridder (1990) and a number of other references describe aquifer-test interpretation options.

6.9 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 5.2.2.3. Geophysical logging may be of assistance in determining the position of suitable sampling points when these are in the well itself.

6.10 Stream flow depletion

Surface water (streams, canals, etc.) may be captured by a pumped well and be reflected by the water level and response in the pumped and observation wells. Flow measurements from bodies of surface water should be made before, during and after constant-discharge or constant-drawdown tests by structures or by current meter gauging (see 5.2.2.2). As a minimum, a record of stage should be kept from any nearby bodies of water. If possible, this stage record should be of a continuous type (15 min measurement frequency). 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.

7 Special tests

7.1 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 their 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, the main features of which are summarized in 7.2 and 7.3.

7.2 Slug test

7.2.1 General

The slug test involves relatively small displacements of water levels in a borehole by the rapid injection of a “slug” of water 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 in 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.

7.2.2 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.

7.2.3 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 between 1 m and 2 m beneath the displacer or bailer when this is at its lowest point. The cable connecting the transducer to the wellhead may require protection within an access tube. When water injection is being used, the transducer should be located between 1 m and 2 m beneath the rest water level.

7.2.4 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.

7.2.5 Procedure

When the displacer is used, first lower it into the borehole until its base is resting within the water surface. When the recording instruments are running, lower the displacer rapidly until 95 % submerged. When the water levels have stabilized, raise the displacer rapidly until it is clear of the water and allow the water levels to stabilize again. 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 analogous 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, lower it until approximately 80 % submerged and allow the water levels to stabilize. Then lift the bailer rapidly until clear of the water surface, thus simulating the withdrawal of the displacer.

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

7.2.6 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.

7.2.7 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 on 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.

7.3 Packer test

7.3.1 General

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 one or more packers isolate the chosen section of the well, 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 tub leading from the wellhead 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 that 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 being tested 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.

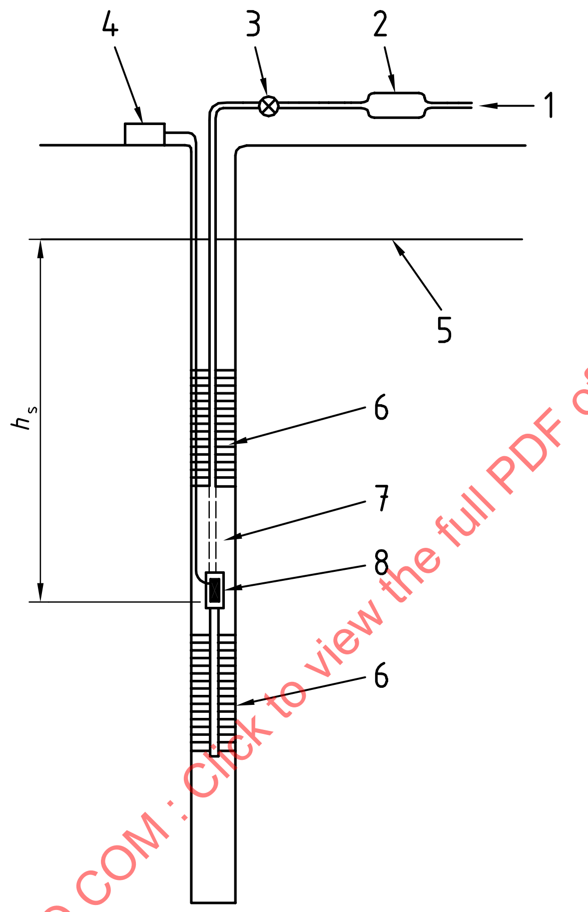
Pump-out packer tests are used where the aquifer has a moderate or high permeability, and they require a well of sufficient diameter to allow the passage of pumps and water level measuring apparatus. A water supply is not needed. Samples of water should be taken for chemical analysis (see 6.9).

Injection tests can be used in aquifers with either a low permeability or a high permeability. The technique is used frequently for site investigation. Large amounts of water are likely to be required (see 4.2.4). Figure 3 shows the typical arrangement of equipment for a double-packer injection test. It is essential that the water used for injection testing be free of particulate matter, which may otherwise clog the test section.

7.3.2 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 Annex D). However, should a wall-cake be present, suitable interpretation techniques should be used to separate its effect.

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. Downhole geophysical measurements can be used to determine those sections of borehole that would be most worthwhile to test. A caliper log is especially useful in locating suitable smooth borehole sections to seat the packers.



Key

1 from pump
2 flowmeter
3 valve
4 pressure recorder
5 water table or potentiometric surface of test interval
6 packer
7 test interval
8 pressure-measuring device

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

7.3.3 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 can be fixed or can be configured to straddle a particular lithologic or stratigraphic horizon, depending upon the test requirements.

7.3.4 Test schedule

A test cycle normally consists 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.

In the special case of using packers to isolate zones of low permeability for slug tests, the valve should be located less than 10 m above the anticipated equilibrium head in the interval being tested to avoid conditions in the tubing changing during the test from a full water column to a falling water-level column because of formation of a free surface at or near zero absolute pressure (Neuzil, 1982).

7.3.5 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 test 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, accuracy within an order of magnitude is attainable.

7.3.6 Overflowing wells

Although packer tests can be used in overflowing wells, it is possible also to use the same techniques as described in 4.3.5. Allowances should be made for partial-penetration effects during the analysis of the results.

8 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 3.2 could continue for a period after recovery to establish trends prevalent during the test-pumping period.

9 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 that relate to both the pre-test observations discussed in 3.2 and to the test methods.

The first chart is a vertical section through the test well, extending to a maximum of about 5 km or to the extent of significant drawdown, 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, 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 show continuous plots of precipitation, barometric pressure, surface water flow or levels (if appropriate), tidal fluctuations (if appropriate), 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)]. Examples of using pre-test data, described in 3.2, to adjust water-level data collected during the test are provided by Kruseman and de Ridder (1990), Walton (1987), and Todd (1980), among others.

A table should also be included which summarizes key dimensions and statistics of the test, including the following information:

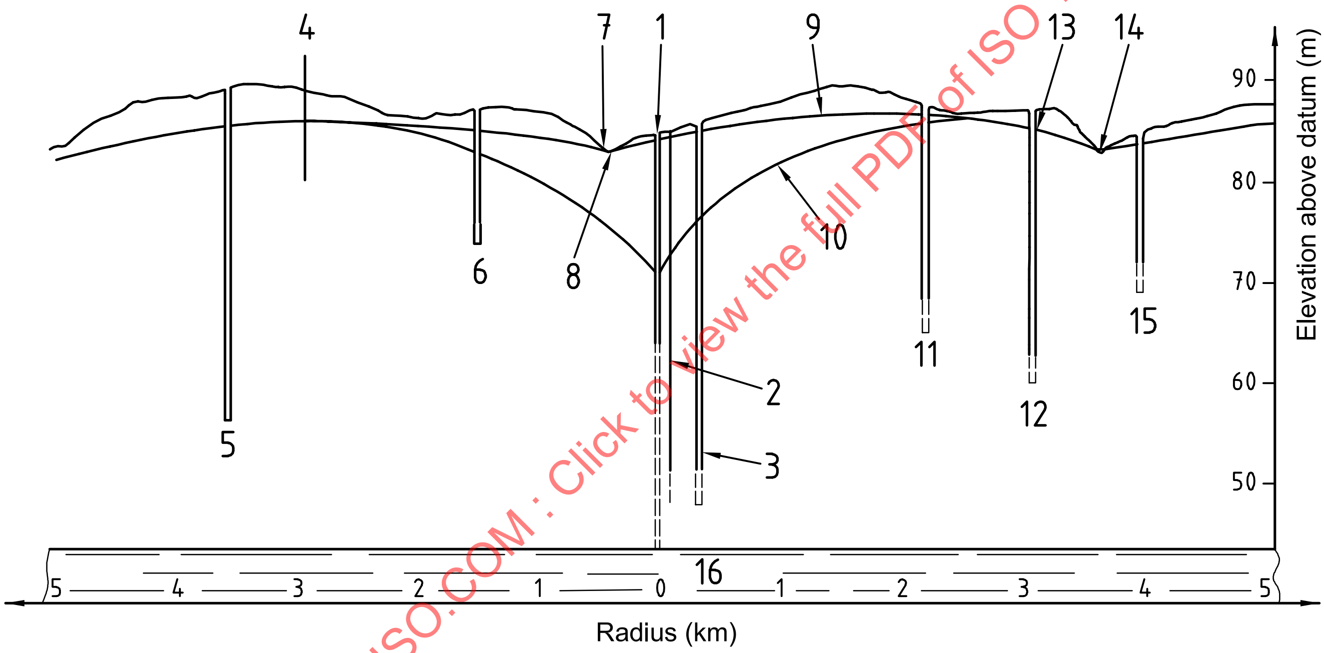
a) pumping well radius;

b) radius and direction to all observation wells;

c) elevation of top and bottom of open interval in all wells;

d) time and dates of all pumping/resting operations during test with durations calculated; and

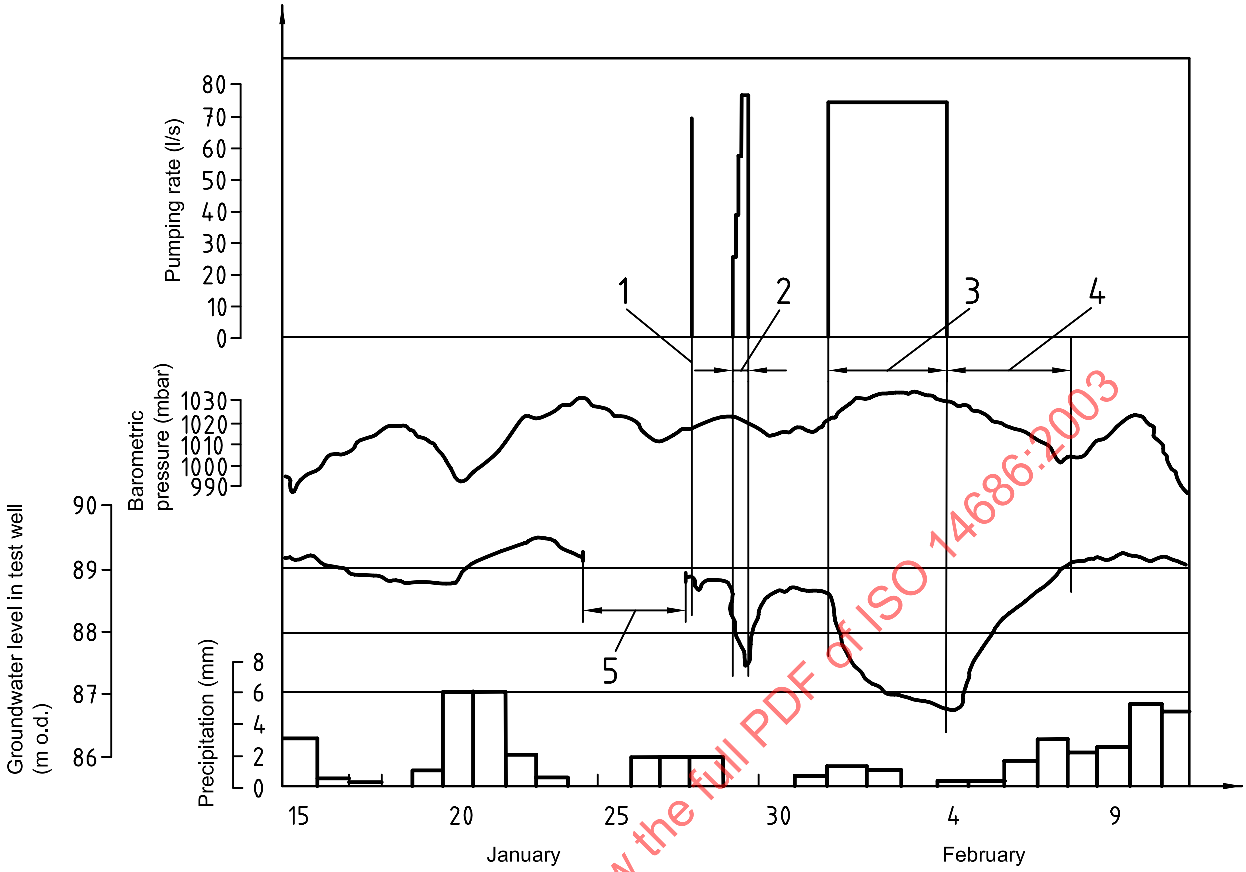
e) pumping rates used with times of change and durations indicated.



Key

1 test well
2 observation well 1
3 observation well 2
4 aquifer
5 dairy
6 Hope School
7 river
8 no measurable change in flow after 7 days pumping
9 water table
10 pumping-water level after 7 days
11 Hill Farm
12 Home Farm
13 no discernible effects from pumping
14 stream
15 Beck Farm
16 confining bed

Figure 4 — Typical vertical section through test well and environs



Key

1 equipment test
2 step test
3 constant-discharge test
4 recovery test
5 no data (development by surging)

Figure 5 — Continuous plot of pumping-test data

Annex A
(informative)

Well construction

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), barites 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 limestone).

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 Annex 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, a 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.

Annex B
(informative)

Groundwater conditions and aquifer states

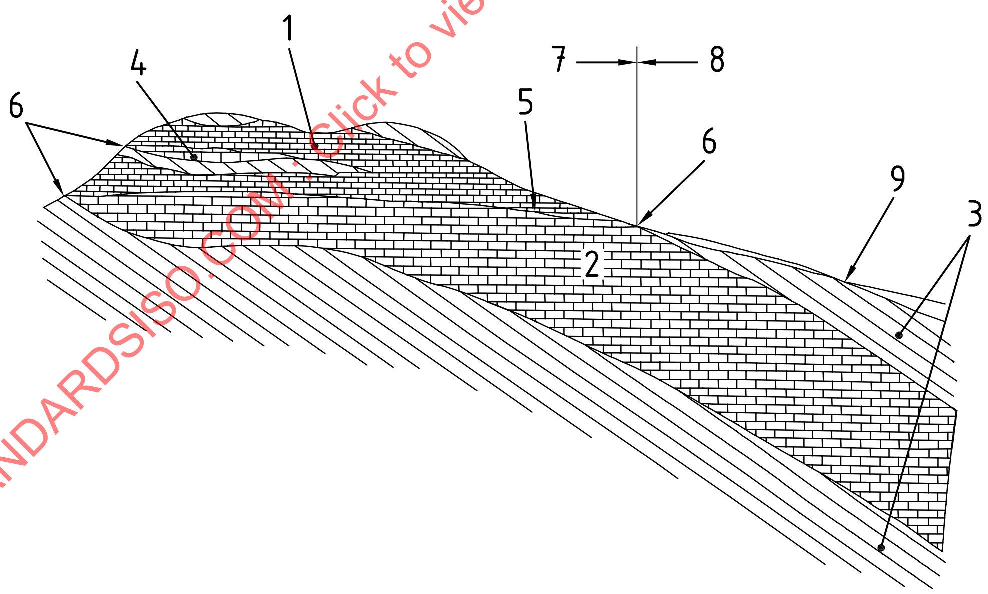
This annex is intended to clarify certain terms in general use beyond the definitions contained in Clause 2. Figure B.1 illustrates many of the terms considered.

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 in this zone is at or less than atmospheric pressure.

Eventually, the infiltrating water reaches a level where 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.

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 that 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.



Key

1 unsaturated zone of aquifer
2 saturated zone of aquifer
3 confining bed (impermeable strata)
4 perched groundwater
5 potentiometric surface
6 springs
7 unconfined or water table conditions
8 confined conditions (potentiometric surface)
9 wells penetrating aquifer will overflow

Figure B.1 — Groundwater conditions and aquifer state

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 potentiometric surface.

An aquifer can be confined in one area and unconfined in another. In this case, the potentiometric surface continues into the water table. When the potentiometric surface in relation to a confined aquifer is above the ground surface, water will be discharged without pumping form 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 fissured 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.

Annex C
(informative)

Water-level and discharge-measuring devices

C.1 Measurement of water level

C.1.1 Continuous water-level recorders

This annex 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.

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) a spares list;

f) dismantling and transport.

Levels in a borehole are required to the nearest 0,01 m. Those in the 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 4.4.4). 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 plastic chart. The chart itself is graduated or pre-printed to facilitate the reading of times and levels.

Punched-tape recorders produce a set of point readings at regular intervals by punching a series of holes in a paper or plastic 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 time interval 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 4.6.2 with a resolution of 1 min. The advantage of a punched-tape recorder is the ease of subsequent analysis that could be undertaken by computer.

C.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.

C.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.

C.1.4 Transducers

Instead of float-operated recorders, strain gauge transducers can be used. The disadvantage of most transducers that 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. Transducers 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 the pressure of 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 that must be recorded separately.

C.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 hand-held 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.

C.1.6 Measurements in overflowing wells

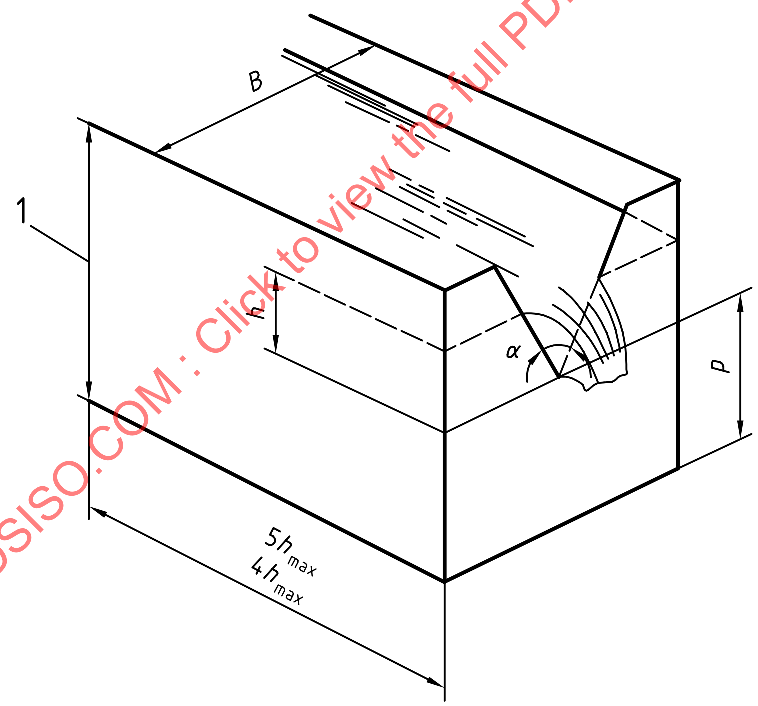
Heads in overflowing wells can be measured by a manometer fitted to the wellhead or, if the pressure head reaches only to a short distance above ground level, a standpipe can be attached. It is important to allow sufficient time for levels in standpipes to stabilize, and to recognize their sensitivity 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.

C.2 Measurement of discharge

C.2.1 Weir tanks

The accuracy of discharge measurements is of prime importance in the subsequent calculation 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 C.1 and C.2). ISO 1438-1 describes methods for the measurement of water flow using such thin-plate weirs.



Key

1 head measurement section

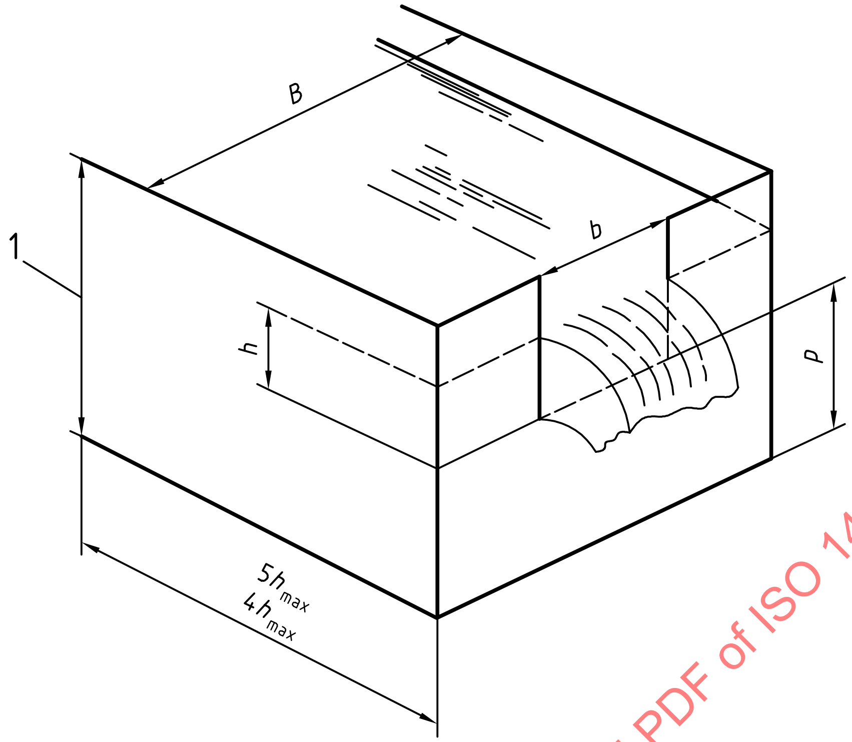
α notch angle, i.e. angle included between sides of notch

B width of approach channel

h head

p height of vertex of notch with respect to floor of approach channel

Figure C.1 — V-notch thin-plate weir



Key

1 head measurement section
b measured width of notch
B width of approach channel
h head
p height of crest relative to floor

Figure C.2 — Rectangular-notch thin-plate weir

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 that takes into account the head on the weir, the geometrical properties of the weir and of the approach channel (or weir tank) and the dynamic properties of water.

ISO 1438-1 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 ISO 1438-1, uncertainties attributable to the coefficient of discharge will not be greater than 1 %.

The experimental results in ISO 1438-1 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.

The notch should be truly horizontal as required in ISO 1438-1. Regular measurements of the horizontal position of the notch should be taken before and after the test.

The details of notch design and construction can be found in ISO 1438-1. 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. Several pipes 200 mm to 300 mm in diameter positioned halfway between the notch level and the base of the tank should preferably connect the tanks.

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 4.6.2, although readings just after a change in 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 the 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 any 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 a distance 4 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 C.5 and C.6).

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 ISO 1438-1, 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 the 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 ISO 1438-1 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 head-measuring 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.

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 C.1 gives values of C_D in the equation for a 90° V-notch and of C_e in the Kindsvater-Carter equation for a contracted rectangular notch, specified in ISO 1438-1.

Table C.1 — Discharge coefficients for a 90° V-notch, C_D, and for a rectangular notch, C_e, fitted in small tanks

Tank size (length × width × height)	90° V-notch [a] Head h			Rectangular notch [b] Head h		
	115 mm	150 mm	180 mm	65 mm	100 mm	135 mm
2,62 m × 0,92 m × 0,45 m	0,593	0,590	0,587	0,609	0,592	0,588
1,5 m × 0,92 m × 0,45 m	0,603	0,592	0,587	0,604	0,592	0,585
1,0 m × 0,92 m × 0,45 m	0,603	0,592	0,587	0,604	0,590	0,585
2,62 m × 0,75 m × 0,45 m	0,597	0,592	0,590	0,606	0,593	0,588
2,62 m × 0,5 m × 0,45 m	0,605	0,596	0,595	0,611	0,598	0,598
2,62 m × 0,92 m × 0,3 m	0,600	0,590	0,586	0,606	0,592	0,588
2,62 m × 0,92 m × 0,3 m	0,602	0,597	0,593	0,613	0,598	0,595

[a] Where $Q = C_D \times \frac{8}{15}\sqrt{(2g)}h^{5/2}$ (see also ISO 1438-1)

[b] Where $Q = C_e \times \frac{2}{3}\sqrt{(2g)}b_e h_e^{3/2}$ (see the Kindsvater-Carter equation in ISO 1438-1)

Some indication of the influence of sediment deposits is given in Table C.2, which shows values of C_e for a tank with dimensions conforming to ISO 1438-1 but with differing amounts of sediment deposited against the weir plate. The uncertainty of these coefficients is approximately 1 %.

Table C.2 — Discharge coefficients C_e for rectangular notches with sediment deposits

Tank size (length × width × height)	Maximum level of deposits at weir crest mm	C_e values for rectangular notches [a] Head h mm		
		65	100	135
2,62 m × 0,92 m × 0,45 m	– 150	0,605	0,591	0,588
	– 40	0,606	0,597	0,590
	– 40 (+ 100 at sides)	0,613	0,601	0,595

[a] Where $Q = C \times \frac{2}{3}\sqrt{(2g)}b_e h_e^{3/2}$ (see the Kindsvater-Carter equation in ISO 1438-1)

Within the range of tank sizes and heads covered in Table C.1, the location of the head-measuring device is relatively unimportant. Positions between 100 mm and 720 mm upstream of the weir produce discharge coefficients that 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.

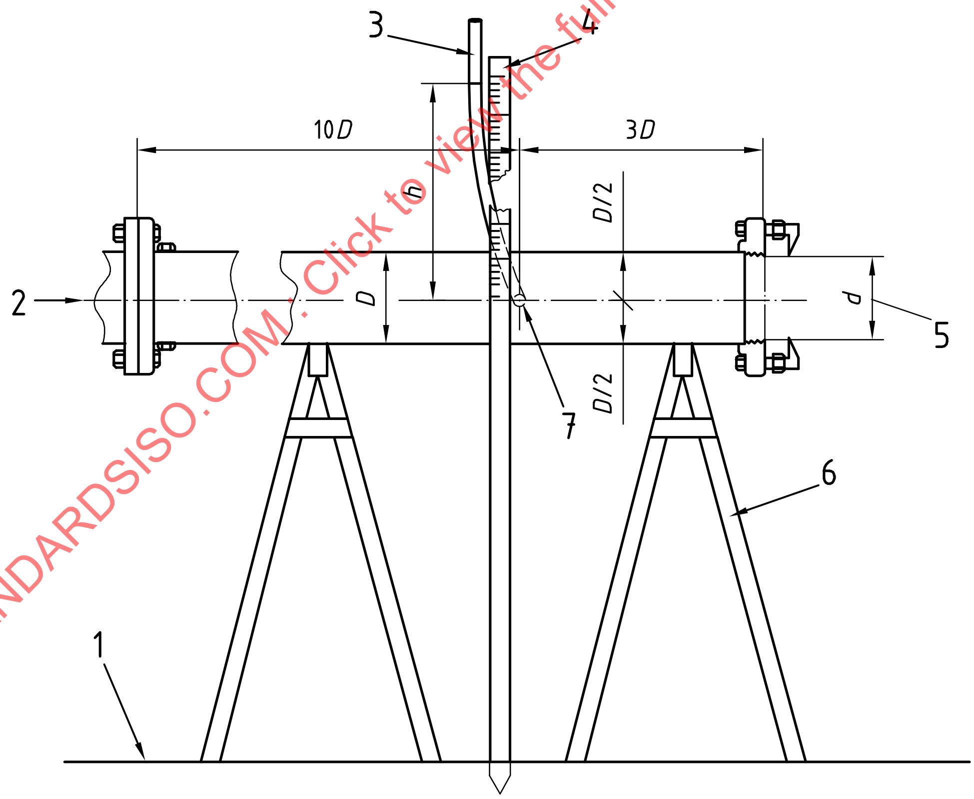
Tests have shown that non-uniform flow at entry and surface disturbances in the tank are the largest potential sources of error in flow measurement. If delivery is through a flexible pipe placed behind a slotted baffle as described above, random errors of between 5 % and 10 % in the discharge coefficient 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. With a slotted baffle alone, some improvement can be achieved by arranging the delivery pipe to discharge underwater and upstream against the closed end of the tank along its long axis. The coefficients in Table C.1 can then be applied, but the uncertainty attached to them has to be increased to 2,5 % at higher flow rates.

C.2.2 Sharp-edged orifice plate

The sharp-edged orifice plate (also referred to as a circular-orifice weir or free-discharge pipe orifice) is a popular device to measure the rate of discharge from a turbine or centrifugal pump. It will not measure the pulsating flow from a piston pump.

The orifice plate is commonly placed at a free discharge on the end of the pump discharge pipe. The pump discharge is calculated from a head measurement taken from a manometer in the pipe and the specific characteristics of the geometry of the pipe and orifice. Numerous combinations of pipe and orifice sizes can be used. Many references pertaining to using this method to measure well-pump discharge are available, notably Driscoll (1986, p. 537) and U.S. Department of Interior (1977, p. 233). Most references on free-discharge measurements draw upon the method and tables developed at the Engineering School of Purdue University (Purdue University, 1949).

Figure C.3 shows the essential details of construction and assembly of this apparatus. If constructed, set up and operated as described below, the method gives an accuracy of about ± 2 % (U.S. Department of Interior, 1977, p. 234).



Key

1 ground surface
2 pump-discharge or valve flange
3 manometer tube
4 scale
5 orifice opening
6 pipe supports
7 manometer tap

Figure C.3 — Details of sharp-edged orifice plate used for measuring pumping rate at a free-discharge pipe (modified from U.S. Department of Interior, 1977, Figure 9-1)

An orifice may be machined from a threaded pipe cap or from 4 mm to 7 mm steel plate stock and attached to the pipe by a threaded coupling. The orifice should be carefully machined into the plate or cap as a true circle that is sharp, clean and free from any rust, pits or imperfections. The recommended ratio of the orifice diameter to the inside diameter of the discharge pipe is 0,4 to 0,85 (U.S. Department of Interior, 1977, p. 242). The orifice should be centred on the pipe opening. The downstream edge of the orifice should be bevelled at an angle of about 45° but leaving a root of uniform width of 1,59 mm (1/16 in) on the upstream side (see Figure C.3).

To assure accurate measurements, the pipe orifice assembly should be installed as follows (after U.S. Department of Interior, 1977, p. 241):

a) The discharge pipe on which the manometer and orifice assembly are mounted should be horizontal.

b) The position of the manometer tube tap should be at least three pipe diameters from the orifice plate. For pipe diameters of 200 mm or less, 600 mm is customary. The tap should be located on the horizontal centreline of the pipe.

c) The manometer tube tap should be at least 10 pipe diameters ahead of any elbow, valve, reducer or similar fitting.

d) The manometer tap fitting should have an inside diameter of 3 mm to 7 mm and should be smooth and flush with the inside surface of the pipe.

e) The pipe should be full of water at all times and the water should fall freely from the orifice into the air without any obstruction.

f) Before any measurement, the bottom of the pipe immediately behind the orifice plate should be cleaned of sand and other debris.

g) The interior of the pipe should be smooth and free of grease.

h) The manometer hose should be free of air bubbles whenever a reading is made.

i) Manometer readings should not be less than 25 mm greater than the inside radius of the pipe or greater than 1 500 mm. If readings are not within that range of values, the orifice and/or pipe size should be changed.

j) There should be no leaks between the pump and the orifice plate.

Usual practice is to secure a 2-m-long scale in a vertical position with the zero point accurately located at the centreline of the pipe (coincident with the manometer tap). A 1,5 m to 2 m length of plastic hose or tubing of 6 mm to 14 mm inside diameter is then attached to the manometer tap. Clear hose should be used and held against the scale when it is to be read. A recommended method is to use a 300 mm to 600 mm length of 25-mm-diameter clear glass or plastic tubing with a hollow rubber plug with a glass or brass tube at the bottom to which the smaller-diameter hose is attached. This arrangement dampens any surging associated with the pump, permitting easier and more accurate readings. If regular surging is evident in the tube, the range of such surging should be noted and the mean taken of the readings.

It is good practice to lower the manometer hose and tube to a level below the manometer tap and allow water to flow through it for a short time to clear all air bubbles and sand from the system before making a reading. When lighting conditions are poor, adding a few drops of vegetable colouring or cooking dye to the clear tube just before making the reading may facilitate reading the manometer.

The determination of discharge is accomplished by measuring the head in the manometer and then applying the formula

$$Q = KA\sqrt{2gh}$$

where

Q is the orifice discharge, in m^3/s;

K is the discharge factor, a constant relating discharge to pressure head (see Figure C.4);

A is the area of the orifice opening, in m^2;

g is the acceleration due to gravity (9,8 m/s^2);

h is manometer head measurement, in m.

The discharge factor K is read from Figure C.4, based upon the ratio of the orifice diameter to the inside diameter of the discharge pipe.

For very large pump discharges, multiple discharge pipes and orifices can be used. The design of a multiple discharge assembly should insure that any junctions, tees, etc., are placed at least 10 pipe diameters from the manometer tap [see item c) above]. The sum of the individual discharges will yield the total discharge.

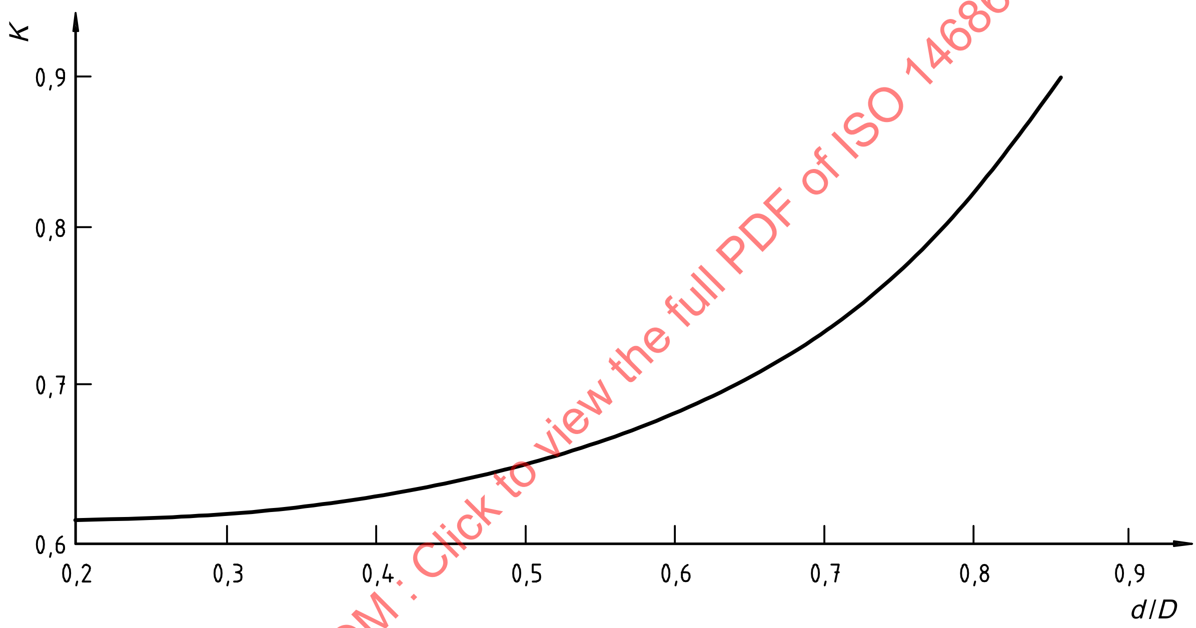


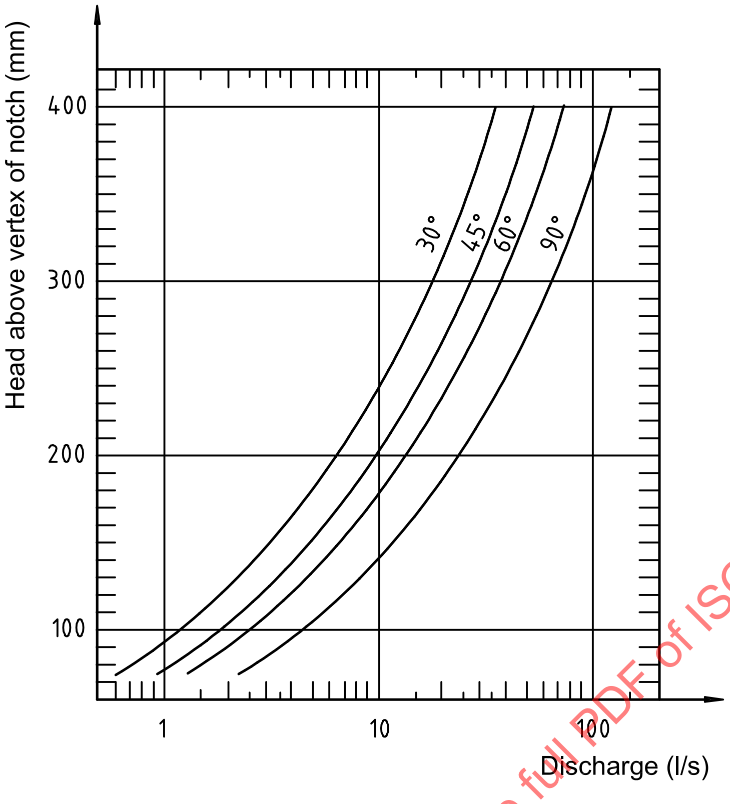
Figure C.4 — The orifice discharge factor, K, and the pipe orifice discharge equation
(modified from U.S. Department of Interior, 1977, Figure 9-3)

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

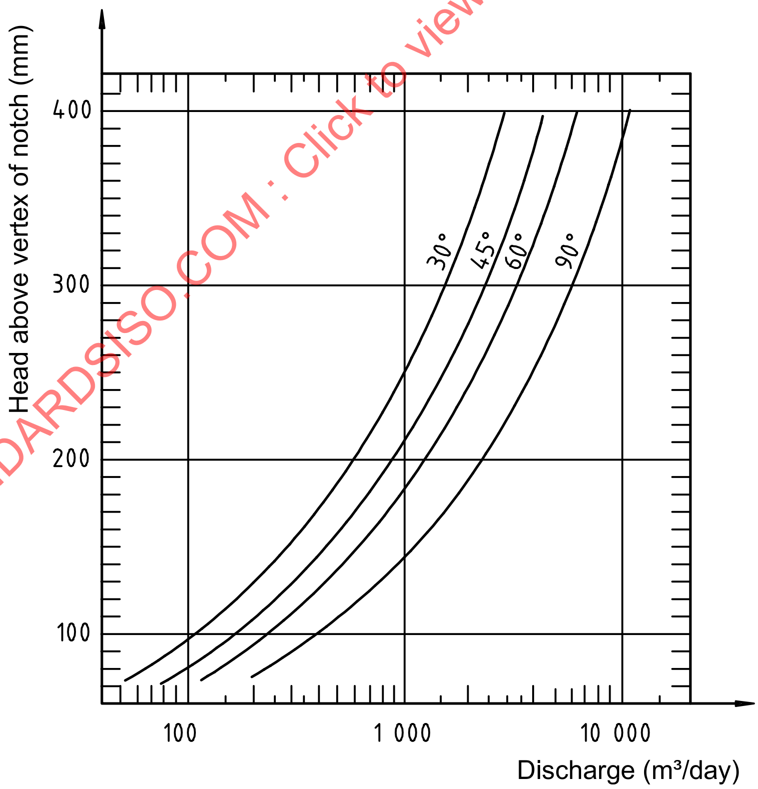
As noted in C.2.1, it is very important that data collected for the purpose of analysing the performance of a water well and the aquifer is accurate, within known practical tolerances. ISO 1438-1 gives details of all those factors affecting the performance of thin-plate weirs, and reference should be made to that International Standard for guidance on converting the head h measured at the notch to an accurate rate of discharge Q.

However, the accuracy of measurements provided by the tables in ISO 1438-1 is not vital when setting the control valve on the rising main to its initial setting prior to commencing a test.

Figures C.5 and C.6 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.



a) **Relationship of discharge in litres per second to head in millimetres**



b) **Relationship of discharge in cubic metres per day to head in millimetres**

Figure C.5 — Approximate flow over V-notch thin-plate weirs of notch angles 30°, 45°, 60° and 90°