MINISTRY OF WATER AND SANITATION

Code of Practice for Test Pumping of Boreholes

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This Code of Practice (CoP) was prepared by the. The Code was prepared by a technical team comprising staff from the Ministry of Water and Sanitation, Water Resources Authority, GIZ, Kenya Water Institute and Geological Society of Kenya

This Code of Practice should be read in conjunction with the following documents: –

- The Water Act, 2016
- The Water Resources Management Rules, 2007 and amendments in 2012
- The Code of Practice for the Siting of Boreholes
- The Code of Practice for the Construction of Boreholes
- The Code of Practice for the Supervision of Construction of Boreholes

FOREWORD

Falkenmark water stress index measures *per capita* water availability and considers the following divisions (cited in Sullivan 2002): –
No stress: > 1,600 m^3/head/yr.
Water stress: 1,000 – 1,600 m^3/head/yr.
Water scarcity: 500 – 1,000 m^3/head/yr.
Water barrier (chronic water scarcity): < 500 m^3/head/yr.

The draft National Water Resources Management Strategy (NWRMS) (MoWI 2006) stated that Kenya lies in the water scarcity category, with gross per capita renewable water availability then estimated at 647 and currently at 500 m^3/yr (WRMA Performance Report No. 2 of 2011) and which is reinforced by the NWMP 2013 to be 586, 393 and 294 m^3/yr. for the years 2010, 2030 and 2050 respectively. The available resources per capita in the foregoing indicate that Kenya is in the water scarce category of the Falkenmark water stress index as above and tending to chronic water scarcity by the year 2050. Water-scarce countries can face severe consequences, with food production and economic development easily disrupted. Groundwater resources are used to bridge the gap especially in adverse climate circumstances.

In estimating groundwater recharge FAO Penman-Monteith for estimation of evapotranspiration adopted by the NWMP 2030 put it at 21,462, 19,419 and 19,291MCM/yr. (National Water Master Plan, July 2013) for the years 2010, 2030 and 2050 respectively of which 10% of it has meanwhile been adopted to be the sustainable yield. This is still credible a water source for the country especially in the face of climate change and augmenting water supply where surface water is not available.

The NWRMS includes among its goals an increase in groundwater use from its 2005 level of 0.18 billion cubic meters (BCM) per year to 2.1 BCM/yr. by the year 2007; at present there are estimated to be some 19,000 boreholes in the Republic, a significant proportion of which are out of commission at any one time. To meet the longer term objective of increased abstraction the 2005 Strategy estimates that the capacity to drill 1,500 boreholes per year will be needed by the year 2020.

CODE OF PRACTICE FOR THE TEST PUMPING OF BOREHOLES

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1 DEFINITIONS

For the purposes of this Code of Practice the following definitions apply.

"Abstraction" means the removal of water from any groundwater source, either permanently or temporarily.

"Aquifer" means a lithological unit or group of lithological units or part of a lithological unit containing sufficient saturated permeable material to yield significant quantities of water to borehole or springs.

"Aquifer loss" (C) means the head loss in a borehole associated with groundwater flow through the aquifer to the wellbore.

"Aquifer properties" means the properties of an aquifer determining its hydraulic behaviour and response to abstraction. These include transmissivity, storage coefficient (or specific yield), leakage etc …

"Borehole" means a hole, usually vertical, drilled to determine ground conditions for the extraction of water or measurement of groundwater level. The word is synonymous with well.

"Borehole development" means the physical and chemical treatment of a borehole to achieve minimum resistance to movement of water between well and aquifer.

"Borehole efficiency" means a measure of the performance of a production well.

"Casing" means a tube, usually of steel or uPVC, used as temporary or permanent lining for a borehole.

"Cone of depression" means that part of the potentiometric surface that is lowered as a result of pumping from a borehole.

"Confining bed" means a bed of impermeable material above, below or adjacent to an aquifer that restricts or reduces the natural flow of groundwater to or from the aquifer.

"Dipper tube" means a pipe inserted into a borehole to permit the installation of a dipper or dipmeter that safeguards them from touching or becoming entangled with the pump, cable or other equipment in the borehole. The bottom of the pipe must be blinded, and the pipe perforated below static water level in the borehole.

"Discharge" (Q) means the volumetric flow rate, expressed as cubic metres per hour (m3/hr).

"Drawdown" (s) means the reduction in static head within the aquifer brought about by pumping. This is the static water level or potentiometric surface minus the dynamic water level at any time in test pumping.

"Foot valve" means a non-return valve fitted at the bottom of the suction pipe of a pump.

"Gravel pack" means a granular material introduced into a borehole between the aquifer and screen or perforated lining to prevent or control the movement of particles from the aquifer into the borehole. The word is synonymous with "filter pack".

"Groundwater" means water within the saturated zone.

"Hydraulic conductivity" (*K*) means the volume of water that moves through a porous medium per unit time under a unit hydraulic gradient at right angles to the direction of flow. It is expressed in units of Length / Time, typically as metres per day (m/d).

"Hydraulic gradient" (*i*) means the change in static water level per unit distance in a given direction (dimensionless).

"Hydrogeology" means the study of groundwater.

"Impermeable material" means a natural geological or introduced material that prevents the perceptible movement of water through it at the hydraulic gradient normally present.

"Incompetent" means a geological unit unable to stand without support.

"Isotropic" means having the same properties in all directions.

"Lithology" means the physical character and mineralogical composition defining the properties of a rock.

"Observation borehole" means a borehole used for observing groundwater levels or water quality.

"Overflowing well" means a borehole from which groundwater discharges at ground surface under natural head, incorrectly called artesian.

"Permeability" means the characteristic of a material that determines the rate at which fluids pass through it under the hydraulic gradient normally present.

"Permeable material" means a material that permits water to move through it at perceptible rates under the hydraulic gradient normally present.

"Phreatic surface" means the upper surface of an unconfined aquifer at which water pressure is equal to atmospheric pressure.

"Potentiometric surface" means the surface that represents the static head of groundwater, the static water level.

"Pump blank" means a length of plain casing within a screened portion of a borehole that allows cooling water to pass the motor of an electric submersible pump from the lower screen.

"Radius of influence" means the radius of the cone of depression of a pumped borehole.

"Rising main" means the pipe carrying water from within a borehole to the point of discharge.

"Rock" means one or more minerals that may be consolidated or loose, but which excludes topsoil.

"Running plot" means a graph of a variable against elapsed time continually updated as measurements are collected, that should be made during a test pumping exercise to monitor test progress. The plot may illustrate important changes in borehole or aquifer response to pumping.

"Saturated zone" means that part of an aquifer in which all voids are filled with water under pressure greater than atmospheric.

"Screen" means a type of casing with apertures designed to permit the flow of water into a well while preventing the entry of aquifer or filter pack material.
"Slurry" means the mixture of fluid and rock fragments formed when drilling or developing a borehole.

"Specific capacity" means the rate of discharge of water from a borehole divided by the drawdown in the borehole (m^3/m/d or m^2/d).

"Specific yield" (S_y) means the volume of water released by an unconfined aquifer per unit surface area per unit decline of head (dimensionless).

"Static head" means the height relative to an arbitrary reference level of a column of water that can be supported by the static pressure at a given point.

"Steady flow" means flow in which parameters such as velocity, pressure, density, temperature and water quality do not vary sufficiently with time to affect the accuracy of measurement.

"Storage coefficient" (S) means the volume of water released from storage per unit surface area of an aquifer per unit decline of head in a confined aquifer (dimensionless).
"Supervisor" means a licensed hydrogeologist

"Pumping test"means is a field experiment in which a well is pumped at a controlled rate and water-level response (drawdown) is measured in one or more surrounding observation wells and optionally in the pumped well (control well) itself; response data from pumping tests are used to estimate the hydraulic properties of aquifers, evaluate well performance and identify aquifer boundaries. Aquifer test and aquifer performance test (APT) are alternate designations for a pumping test.

"Test Borehole" mean the borehole which is being pumped during a pumping test exercise.

"Transmissivity" (T) means the rate at which water is transmitted per unit width of saturated aquifer per unit hydraulic gradient (m^2/d).

"Unconsolidated rock" means a rock that lacks natural supportive strength.

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

"Unsaturated zone" means that part of an aquifer between the land surface and the water table.

"Water table" means the surface of a groundwater body at which the water pressure is atmospheric.

"Well" means a hole sunk into the ground for abstraction of water or for observation purposes. Synonymous with borehole. In Kenya a "well" is often a hand-excavated, unlined shallow well that encounters an unconfined aquifer.

"Well loss" (B) means the head loss resulting from the flow of groundwater across the screen face, including any part of the aquifer affected by drilling, and any gravel pack or casing, into the borehole and up or down the borehole to the pump.

1 INTRODUCTION

1.1 The need for a minimum standard

This Code of Practice describes the factors which must be considered and the measurements which must be made when designing and conducting a test pumping exercise. There are varied test pumping practices because of the great diversity of objectives, aquifers, groundwater conditions, technology and legal contexts. This Code therefore provides guidelines for field practice, indicating how it may vary to take into account particular local conditions. It discusses the types of test pumping commonly carried out for water supply purposes in which water is pumped from the entire screened, perforated, or unlined interval(s) of a borehole.

The interpretation of data collected during a test pumping is referred to in this Code only in the general sense. For full details of the analysis and interpretation of test data reference should be made to specialized texts, a number of which are included in the bibliography
The prominence of groundwater as the water supply for the future in Kenya is evidenced by the great demand for boreholes in the major cities as well as in the arid and semi-arid regions. As a result of climate change, groundwater is bound to be exploited more.

Boreholes are the most significant means by which deep groundwater resources are exploited. They also provide information on what crucial decisions relating to the development and management of the groundwater resources are based. It is imperative that the test pumping exerciseis conducted professionally to enhance optimal and useful data for determination of hydraulic parameters and well performance.

The CoPs for test pumping are outlined in this document to guide practitioners in keeping with best practice.

1.2 Objective of test pumping

There are two overarching pumping test objectives:
To develop an understanding of the characteristics of the well (operational data)
To develop an understanding of the hydraulic characteristics of the aquifer (technical data).

Test pumping is carried out to obtain data from which it is possible to:

i) Assess hydraulic behaviour of a borehole and determine its ability to yield water, predict its performance under different pumping regimes,
ii) select the most suitable pumping plant for long term use and give some estimate of probable pumping costs;
iii) Determine the hydraulic properties of theaquifer or aquifers which yield water to the borehole; these properties include the transmissivity andhydraulic conductivity, and the presence, type and distance of any hydraulic boundaries.
iv) Determine the effects of pumping uponneighbouring boreholes, streams or springs;
v) Provides an opportunity to obtain water quality data,
vi) Determine Permit abstraction levels which will become conditions to the Water Permit (WRMA 010).

A test should be conducted to meet any or all of the objectives (i) to (v)above.If all are satisfied it could be said that the hydraulic characteristics of borehole and aquifer can be understood other data, particularlyaquifer recharge and the effects of neighbouring abstraction boreholes, are required to predict the long term effects of abstraction on an aquifer. A test and the analysis of test data alone maynot be useful in determining key information, such as sustained safe borehole yield or the effects of pumping on the aquifer.

1.3 Justification of pumping Test

In practice PumpingTest has been restricted to a simple format 24 hour constant discharge test on the pumping borehole, followed by a recovery test. In many cases the discharge from the tested borehole is far below the capacity of the boreholeas it is deduced from the capacity of the pump during the purported test. To address this short coming the contractor carrying out the test pumping must be able to ascertain the suitable capacity of the pump to be used for the test. This is possible with proper pre-test preparation.Step- drawdown test is useful in determining the optimum discharge of the borehole because the yield of the borehole can be increased systematically until optimum yield is achieved (Step drawdown test is described in section 9.1.3). It would be prudent to collect data from observation boreholes, because this would be in interests of groundwater resources management, giving more information on the aquifer. More dedicated observation boreholes should be constructed for the purpose of collecting aquifer data in pumping testing exercises.

Drilling programmes shouldincludethe collection and analysis of step drawdown test data. This will provideknowledgefor better understanding of our aquifers.The quality of test pumping data has been poor. The quality of the data needs to be enhanced by the drillers and supervisors through capacity building of the players.

It must be understood that not all boreholes or aquifers necessarily need a rigorous (more than 24hrs and recovery) test programme. It is the intention of the Authority to specify test requirements for proposed or existing boreholes for which hydrogeological or demand conditions require a greater degree of intensity in data collection, or a greater range of tests. This may, in cases, include an explicit requirement for observation wells, either those that already exist or new boreholes to be constructed as a component part of a groundwater evaluation and development programme.

The aim of this Code of Practice to describe test pumping in sufficient detail that groundwater practitioners (Government personnel, LicensedDrilling Contractors and Licensed Hydrogeologists) to enableshould supervise and / or conduct tests to a standard that ensuresas much dataas possibleof acceptable quality is collected. The datawill be used to improve the understanding of the country’s aquifers, to the ultimate benefit of all Kenyans.

1.4 Challenges faced in conducting test pumping

There are a number of challenges faced in carrying out test pumping;

- Making many precise measurements to a rigorous time schedule.
- The need for numerous data collection points.
- Using a small capacity pump in a borehole capable of higher discharge

    - The cone of depression radiating outwards from a pumped borehole is very rarely circular and symmetrical; the absence, or limited number, of observation boreholes provide a small number of sampling points with which to determine the shape of the cone.

- A dense data collection network will inevitably be expensive in capital cost terms, and test pumping itself will also cost more than a standard test of the type conducted at present.

It is important to consider the cost of a groundwater development programme and a careful balance between data collection and programme cost is reached. It is also important that limitations and difficulties are borne in mind when designing and analysing test pumpingexercises and particularly when using the results in real-world applications.

Annex 1 givesa generalised sequence of events in thetest pumping process.

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2 HYDROGEOLOGICAL CONSIDERATIONS

When water is pumped from a well, the water level in the well reduces, creating drawdown and that creates a localised hydraulic gradient. This causes water to flow to the well from the surrounding aquifer. The head in the aquifer also reduces, the effect spreading outwards from the well. This is the cone of depression in the potentiometric surface formed around the well. The shape and expansion of the cone of depression is a function of discharge rate, time and aquifer properties. Recording changes in the potentiometric surface in observation wells located around the pumping well allow the growth of the cone of depression to be monitored, from which hydraulic characteristics may be determined. The shape of the cone of depression immediately around the borehole is influenced by additional head losses incurred as water passes from the aquifer face through well screen into the borehole.

The drawdown consists of two components:

i) Head loss through the aquifer (C)
ii) Head loss in the well (B).

Before a test pumpingexercise is carried out, a full assessment of the hydrogeological conditions at and around the test site should be carried out.Relevant information can be obtained from the borehole siting report, or from published geological reports or studies carried out by Government bodies or the private sector. This will have included a survey of existing boreholes and shallow wellsduring the field survey phase of the borehole siting exercise.

Due to the wide range of situations in which test pumpingmay be carried out, and the possibility that the aquifermay be partly or nearly fully exploited already, an analysis of existing borehole data and associated water levels and flows are essential prerequisites to such tests.

2.1 Aquifer response characteristics

Two parameters define the quantitative hydrogeological properties of an aquifer, namely permeability and storage.

Permeability is defined as the ability of an aquifer to permit groundwater flow under a hydraulic gradient. Storage is the volume of water available within the aquifer and subsequently released when water levels are depressed around a pumping borehole.

Together these parameters define the response time for pumping effects in an aquifer. In an aquifer with low permeability and high storage coefficient, the cone of depression will expand slowly. Conversely, an aquifer with high permeability and a low storage coefficient would show rapid growth of the cone of depression. Therefore careful consideration of the anticipated aquifer response to pumping is important when locating sites for observation boreholes.

2.2 Groundwater conditions

The storage coefficient in a confined aquifer can be two orders of magnitude smaller than in the same aquifer in unconfined conditions. This reduction is reflected in a more rapid aquifer response time. If the confining bed is not wholly impermeable the storage coefficient varies between totally unconfined and totally confined values and the aquifer response 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 allow an aquifer to demonstrate an unconfined response.

It is possible for confined and unconfinedconditions to occur in different parts of the sameaquifer, or in the same part of the aquifer, as aresult of seasonal or other movements of thepotentiometric surface.

2.3 Multi-layered aquifers

Many of our aquifers comprise volcanic and sedimentary strata deposited in superimposed layers. Successive layers may have different lithological characteristics and consequently the hydraulic conductivity in the horizontal plane tends to be greater than that in the vertical plane.

In some cases intervening layers may be impermeable resulting in a multi-layered aquifer. Boreholes penetrating such aquifer systems may intersect an unconfined layer near the surface and one or more confined layers at depth. Failure to recognise this may lead to inadequate monitoring of groundwater levels and to misleading data being obtained in a test pumping exercise.

2.4 Boundary conditions

Barrier boundaries are normally presented by geological discontinuities caused by faulting, or pinching out of an aquifer.Some aquifers may possess rapid lateral lithological changes with consequent significant changes in 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 borehole in the same aquifer will have the same effect as a boundary if the cones of influence of the two wells intersect. Such a boundary is known as a discharge boundary.

Recharge boundaries occur when water other than from groundwater storage effectively contributes to an aquifer drawn on by a pumping well. Recharge boundaries may be surface watercourses, lakes, or the sea if these lie within the radius of influence of the pumped borehole.All these may be regarded as discrete recharge boundaries and can often be defined as point or line recharge sources during analysis. Recharge boundaries have the effect of slowing the rate of drawdown, or stopping drawdown altogether. Leakage from overlying strata or the interception of natural flow through the aquifer may simulate a recharge boundary by slowing drawdown, but the effects cannot always be linked to a localised source

2.5 Other hydrogeological factors

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

The thickness of the aquifer should be ascertained or estimated. Corrections for partial penetration by a pumping borehole may be necessary in analysis. The degree of penetration of observation boreholesis also important to ensure the measurement of realistic water levels.

Unconfined aquifers may show delayed yield from storage. The rate of drawdown during the early stages of a test may be nearly horizontal for a period from an hour to several weeks before responding more normally.It may be necessary in these circumstances to prolong the test to obtain sufficient drawdown data after the effects of the delayed yield have ceased.

During a test in a confined aquifer, water levels in the pumping borehole and possibly in observation boreholes may fall below the confining bed. If this possibility exists the depth of the base of the confining bed must be determined in all test boreholes (pumping and observation) to ensure proper analysis of the test data.

3 PRE-TEST PUMPING PLANNING

Before a test is conducted, there are a number of aspects that must be considered.

3.1 Statutory requirements

Attention is drawn to Acts, By-laws, Regulations relating to matters dealt with in thisCode of Practice. Both work and equipment used must comply with the appropriate regulations. Amongst others particular attention is drawn to the following Acts current in the Republic of Kenya at the date of publication of this code of practice:

1. the Environmental Management and Coordination Act 1999, Amendment Act, 2015
2. the Water Act 2016,
3. Water Resources Management Rules 2007,
4. CountyGovernment By-laws,
5. Occupational Safety and Health Act,2007 and any other statutory requirements.
6. Urban Areasand Cities Act, 2011

3.2 Site facilities and organization

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

3.2.1 Space

It is necessary to ensure that sufficient space is available for all test equipment and pumping plant required on the site. Parking space for vehicles should be designated; and overhead obstructions such as power cables and trees should be noted and clearly marked if necessary.

3.2.2 Safety of personnel on site

Every care should be taken to reduce 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.

Paths between site offices, the test and observation boreholes should be marked if this is necessary, as should any hazards (fences, cables, mud pitsetc.).

Drillsites typically degenerate into a slippery morass around wellhead and discharge areas. Provision must be made for duckboards and walkways for the working and supervisory teams, should site conditions show these to be necessary.

If the test extends into the hours of darkness, adequate and reliable site lighting must be provided. At the very least this must provide light sufficient to read water level and discharge measurement equipment.

3.2.3 Power supply

If mains power is unavailable or unreliable, an alternative source of motive power must be provided, typically a generating setof suitable capacity. In such a case electrical earthingrequirements can be met by cross bonding the pump pipework and generator and providing an earth probe. Any generating set provided for test purposes must be adequately proofed against any weather that may be anticipated during the test period. The same provisions apply to temporary switchgear.

3.2.4 Site accommodation

A suitable adequately lit shelter must be erected at the site. This mayinclude tables and seats for eating meals and facilities for boiling water and heating food. The shelter would 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 must be arranged for off-duty personnel.

A wellhead shelter must also be provided, to protect test team staff from the elements. This need not be large or expensive, but must provide shelter from both sun and rain.

Sanitary facilities should be available at the test site; if the test is a long-duration test, simple ablution facilities should be provided.

3.2.5 Site communications

Communications between observation and pumping boreholes during testsmay be carried out by visual or audible means appropriate to the circumstances(radio, mobile telephony etc). Under some conditions visual signals may be inadequate. In any event, it is important that test personnel all possess timepieces that are synchronised to a common time, and that all staff know when a test is to commence.

3.2.6 Pollution control and disposal of wastes

The disposal of liquid or solid wastes must be done in a manner that will not pollute boreholes, aquifers or the surrounding area. Human wastes may be disposed of by means of a mobile toilet or dug pit latrine, provided this does not constitute a risk to water resources in the area and provided it is backfilled at the completion of works. Alternatively, waste water may be discharged directly into a sewerage system or be collected and removed for offsite treatment and disposal. Disposal of waste waters to a soak-away, even if it is remote from the wellhead, ditches or watercourses, must not be undertaken without the consent of the appropriate authority (which may be the landowner or a local authority).

If an internal combustion engine is to be employed precautions must be taken to ensure that oil or fuel spillages can be contained. The engine must be mounted on a firm platform with meansto ensure that fuel or oil spillage is contained. Fuel storage areas must be sited and managed so as to prevent leakage and fire. Appropriate fire extinguishers should be made available and their positions on site clearly marked and known to all site personnel.

In addition to preventing pollution by oil or fuel, precautions must be taken to protect the borehole from infection by pathogenic and non-pathogenic organisms. The most likely source of pathogenic organisms is from latrines, which must be sited as far from the borehole as practicable. It is recommended that equipment be cleaned before installation in the borehole, in order to avoid introducing any infection resulting from the previous use of the pump and rising main pipe in an infected borehole, or during transport. It is recommended that the wellbore be sterilised after the completion of testpumpingon a borehole, to reduce the chances of biofilm; a 1 % sodium hypochlorite solution is acceptable for this purpose.

3.2.7 Disposal of pumped discharge

Arrangements should be made for the disposal of the pumped discharge, including pipelines or lined furrows if required.The discharge point should be sited to eliminate any possibility of aquifer recharge during the course of tests, which is particularly important when unconfined aquifers are to be tested. If necessary, the location of the discharge point should be cleared with local authorities, landowners, and the Authority.

The discharge of turbid water into watercourses may not be permitted, so early advice should be sought from the nearest WRMA office. Discharge into watercourses should be carried out in such a fashion as to avoid scouring of bed and banks.

3.2.8 Noise

Continuous noise can be exhausting and have anadverseeffect on the reactions of personnel. It is therefore important to consider the siting of internal combustion engines deployed as far away from the wellhead as practicable.

This is particularly important if the site is located near permanent habitation where noise during the night may be unacceptable. Special arrangements may be required for damping engine noise by the use of sound deadening enclosures around internal combustion engines.

3.2.9 Maintenance and storage of equipment

Plant test and measuring equipment should be inspected at regular intervalsin accordance with manufacturer recommendations. In the case of plant which is subject to corrosion, steps should be taken to make repairs before corrosion reaches dangerous limits. It is particularly important to ensure that the probes of dippers / dip meters are confirmed clean and rust- or oil-free before any tests.

Trailing cables on the test site should be elevated, buried or clearly indicated to avoid any possibility of site personnel tripping over them and thus risking personal injury or test termination.

3.3 Data Collection process

3.3.1 Pumping Test supervision

Pumping test should be supervised by a licenced hydrogeologist. The supervisor must be appointed to supervise the entire process. All decisions regarding data collection and recording before, during and after the test must be subject to the supervisor's approval.

3.3.2 Staffing

The supervisor must ensure that all staff are familiar with the tasks they are to perform during tests and with any instruments that they are required to use. All staff should be aware of the frequency of measurements to be taken and the accuracy of measurement required. Staff must be advised of any safety regulations in force.

3.3.3 Equipment

The supervisor must ensure that all necessary equipment is on site and in working order, and that spare equipment or spare parts, including batteries and bulbs for dippers, are readily available.

3.3.4 Timing

The supervisor in consultation with the contractor is responsible for determining the time at which tests start and stop. The contractor must also ensure that the times when measurements are to be taken are clearly signalled to all staff involved.

3.3.5 Recording measurements

The contractor shall take and record the pumping test readings in the prescribed form as guided by the supervisor who is responsible for collecting and collating the completed sheet. Test pumping record sheets is in the Appendix.

The contractor must keep a record of test progress, with details of all operations carried out, the supervisor is responsible for running plots of drawdown levels and discharge against time in the case of a constant discharge test, so that an indication can be gained of the type of aquifer response.

3.3.6 Record of well dimensions and distances

The depth, diameter, level above datum and other details of the test and observation boreholes must be recorded. These records should be attached to the test record data set. Records must include the distances of observation boreholes from the test borehole. A plan showing the relative positions of observation and test boreholes must be included. This is essential for meaningful analysis.

4 OBSERVATION BOREHOLES

4.1 Purpose and characteristics of observation boreholes

In over-exploited aquifers, special aquifers or if otherwisedetermined by the Authority, it may be necessary that test pumpingincludes the collection of water level information from observation boreholes. This would be necessary if, for example, a proposed borehole is to pump at a rate of abstraction that may adversely affect neighbouring groundwater users. A comprehensive test will allow the analyst to predict the effects of the new borehole on pre-existing ones, and so guide the Authority in approving a higher or lower Permit discharge for the production borehole.

The Authority may include in its Conditions in the Authorisation to Construct Works for the Use of water the requirement that specified nearby boreholes be monitored during the course of a test on a borehole. In such a case the Authorityshall ensure access to the neighbouring borehole or boreholes under S. 90 (a) of the Water Act 2002 and S.11 of the WRM Rules, if the Conditions to the Authorisation require that such borehole or boreholes be monitored during the test pumping of a new borehole.

For the accurate determination of the transmissivity and particularly the storage coefficient of an aquifer, observation boreholes are indispensable. Transmissivity is calculated from studying the shape of the cone of depression shown in water level changes in observation borehole surrounding the pumping borehole.

Existing wells should be used if their dimensions and particularly their locations are suitable. In other cases observation wells may have to be constructed before the test takes place. Furthermore, existing production boreholes within a specified radius of the test borehole may have to be monitored.The time for drawdown to affect observation boreholes is proportional to their distance from the pumped borehole. Once drawdown commences at any point it may be rapid, irrespective of radial distance from the test borehole. The magnitude of the drawdown is attenuated in proportion to the square of the distance from the pumped borehole.

4.2 Distribution of observation boreholes

Preliminary calculations using estimated transmissivityor values from pre-existing boreholesshould be made to indicate the likely response in observation boreholes to pumping and hence to determine the ideal spacing from the test borehole and the timing of observations.

The ideal number of observation boreholes is four, arranged in two rows at right angles to each other. In most cases, however, one to two observation boreholes will be adequate. When a number of observation boreholes are required, their distance from the test borehole should approximate to a geometric series.

Attention should also be paid to boundary conditions which may affect the location of observation boreholes; if a boundary is known to be in close proximity to a test borehole, the radial distance to observation boreholes may need to be reduced commensurately.

4.3 Depth of observation boreholes

Observation boreholes should be constructed in the same part of the aquifer as the test borehole.They may need to be drilled to a shallower depth in some specific cases, such as an investigation of the significance of leakage from a shallower aquifer.

In multi-layered aquifers inaccuracies arise if observation boreholes penetrate only the uppermost layer or layers. The options available in such a case are to drill: –

i) a single observation borehole to the full depth of the test borehole and install nested piezometers astride each aquifer screened by the test borehole;
ii) a number of observation boreholes to different depths, casing off all levels except one in each borehole;
iii) a single observation borehole open to the sameaquifer levels as the test borehole.

Option iii) above will give reasonable results in most situations.

If screens are installed, a minimum of 5 % open area is needed to minimise the lag time between water level change in the aquifer and in the observation borehole. If instruments are to be installed in an existing borehole, the recommendations above should be taken into account.

4.4 Appropriate drilling methods, observation boreholes

Observation borehole drilling and construction should avoid the use of non-biodegradable drilling fluids (such as bentonite), or if used they must be fully developed, as a production borehole is developed. This is particularly important in boreholes constructed in fissured aquifers where drilling slurry may seal off productive aquifer zones. If pre-existing boreholes are proposed for use as observation boreholes, the method used for their construction must be borne in mind and additional development carried out if this is called for.

5 TEST BOREHOLES

There are four key objectives in correctly designing a test borehole: –

- To facilitate the entry of groundwater into the borehole;
- To allow operation of pumping plant;
- To collect data from the borehole; and
- To measure pumped discharge.

5.1 Optimizing groundwater flow into a borehole

Borehole design must allow free entry of groundwater from the aquifer andprevent the entry of aquifer material into the wellbore. It must also prevent aquifer material collapse and should be so designed as to maximise borehole yield for as long as possible. Borehole depth should be sufficient to safeguard the anticipated production discharge while minimising drawdown.

It must be understood that calculated transmissivityfrom tests typically relate only to the thickness of aquifer that is screened (or left open) in test and observation boreholes. Borehole design should also ensure that casing diameters are wide enough to allow safe installation and operation of the pump and rising main, as well as dipper tube and any other instruments that may be inserted into the borehole.

In all boreholes it is essential that surface casing is installed to prevent the ingress of surface water and soil water,and to contain any collapse of weathered near-surface material. Surface casing must be extended to greater depths if geological material is incompetent. In unconsolidated aquifers (such as sediments, poorly-cemented sandstone or fractured lavas), screens are necessary to prevent collapse and allow groundwater entry. Introduced gravel pack is usually installed in such cases; in some aquifers it is possible to develop a natural gravel pack from *in situ* material.

5.2 Test pumping equipment specifications

One objective of test pumping is to determine the size of pump suitable for production purposes in the borehole.The test pump may therefore require a range of yields, although some indication of the likely range may be available if pre-existing boreholes are located nearby. The fact that a test pump may be operated at sub-optimum efficiency during a test is not significant.

It is not advisable to use the production pump for test pumping, as it may sustain damage during the process.

If the test programme requires a wide range of yields, electrical submersible pumps may overload at very low discharge rates, something that is often required in a step-drawdown tests.

It is broadly recommended that test pump capacity allows a discharge of 25 % more than the anticipated test yield of a borehole.The pump should be installed as deep as possible to ensure that maximum water level drawdown can be achieved and so determine well capacity.
However, sufficient space should be left beneath the pump to allow settlement of any sediment in the base of the borehole and prevent damage to the pump; and the pump should not be located in thescreened sections of a borehole.This to avoid damaging the well screen or leading to the collapse of open hole during pump installation and operation.

To protect the pump from running dry, pumping water level must always be kept a few metres above the pump intake level. With electrical submersible pumps, care should be taken to ensure that the cooling requirements of pump motors are met: this may require that a “pump blank” is installed within a screened section, to facilitate motor cooling.

The rising main must be of sufficient diameter to allow maximum yield without excessive head loss.It is strongly recommended that the rising main is fitted with a non-return valve, which may be positioned either at the bottom of the pipe above the pump or at surface. The first is the preferred layout, with the valve located in the discharge outlet of a submersible pump or on the suction of a vertical spindle pump. If recovery tests are to be conducted on the borehole after commissioning, a non-return valve at the foot of the rising main is essential.

There are two situations where a surface-mounted non-return valve is justified: the rising main pipe is lighter when it is empty, allowing lighter plant to be deployed for pump removal. If pumped water is dirty due to inadequate development or because of sloughing from an incompetent stratum, back-flushing down the rising main cleans the pump and prevents sand-locking. Surface-mounted non-return valves are not recommended where the total length of rising main in the borehole exceeds 100 m, as the velocity of backwashing water may damage the pump.

Acontrol valve must be fitted to the head of the rising main pipe at wellhead to control discharge rate. This should be either a gate or a globe valve, and is normally operated manually; a globe valve is much more convenient for changing discharge rates during a step-drawdown test, especially if installed with an upstream manometer calibrated to 20 bar. An air-valve upstream of the control valve may be useful in some circumstances for releasing trapped air at the beginning of a test. A sampling tap is useful for taking water samples for analysis during the test, and for routine sampling once the borehole has been commissioned.A discharge pipe connects the control valve to the flow measuring device.

If a generating set is required to power the pump, the power output should be approximately two and a half times the power requirement of the pump so that high starting currents can be accommodated without excessive slowing of the generator. This can be avoided if “soft start” control panels are used.

5.3 Measurements in the test borehole

Instruments used in the test borehole during testingare lowered through a designated “dipper tube” which extends at least 2 m below the pump intake level. It is recommended that 25 mm diameterpipe of suitable material be used for this purpose.
It is recommended that the dipper tubes are installed in the annular space between the borehole wall and the casing as this will ensure non-interference during subsequent borehole servicing.

Vertical flow meters, temperature and electrical conductivity probes can be used to detect inflow horizons. Geophysical logging and down hole television cameras can be used to supplement this information; however, most geophysical logs are run before borehole construction.

5.4 Measurement of discharge

There are a number of methods available to measure discharge from a test borehole:

5.4.1 Weirs

The most reliable method of measuring pump discharge is to use a weir tank, with the pumped water dischargingover a V-notch or rectangular notch weir. This is an infrequently used flow measurement method, despite its simplicity and accuracy. Weirs are only accurate if they are properly installed, correctly levelled, used with care, and if the notches or orifices are accurately machined and kept perfectly clean. Weirs are relatively insensitive to high levels of suspended solids in the pumped water.

5.4.2 Orifice plates

A less accurate alternative to the weir tank is an orifice plate attached to the end of a horizontal pipe at least 2 m in length. This method has some disadvantages because it is not as flexible in range or accuracy as the weir tank, but offers simplicity of installation and ease of use. Like weirs, orifice plates are relatively insensitive to high levels of suspended solids.

5.4.3 Mechanical flow meters

A flow meter is accurate only within a strictly specified range of flows, but 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, so counter values should be used. However, the flow rate indicator can be useful for setting the discharge rate. Flow meters are sensitive to high levels of suspended solids in water.

5.4.4 Ultrasonic flow-meters

Ultrasonic flowmeters may be applicable in certain circumstances (where very large discharge rates are envisaged, for example). These have specific installation requirements that are beyond the scope of this Code of Practice.

5.4.5 Volumetric methods

The most frequently used discharge measurement method used at present is the volumetric method, in which the time to fill a container of known volume is measured. As presently applied in the drilling sector, this is rarely undertaken properly. For this method to be accurate it is essential that the following conditions are observed: –

- The container – which may range from a 20 litre bucket to a 220 litre drum – must retain its shape without leakage throughout the test period; this is rarely the case in test conducted at present.Cut-down plastic 25 litre oil or foam containers to an approximate volume are not acceptable, and care must be taken to ensure that 220 litre fuel drums are properly round throughout the test process.
- The container must be set level for all measurements; if set at an angle off the vertical, the time-to-fill will be incorrect and indicate an erroneously high discharge rate. If the container is left standing on the ground surface, erosion from discharge water inevitably leads to inaccurate measurements. The use of levelled rising main pipes or drillpipe and a steel sheet (which may or may not be perforated to facilitate water drainage) on which to set the container is recommended. The steel sheet is checked horizontal by means of a spirit level.
- Times-to-fill should ideally be measured by the same individual using a stopwatch to one-tenth of a second or better. Modern digital watches frequently have a stopwatch function, and test personnel familiar with these can return accurate and duplicable times. The use of the second hand on an analogue watch to measure times-to-fill is unacceptable except with containers of large volume at low discharge rates. Similarly, the use of mobile telephone stopwatches is not yet considered sufficiently practical for test pumping purposes. If the running plot shows that discharge values are varying in a way that cannot be explained in terms of borehole response to abstraction, repeated time-to-fill measurements should be made until either the yield change is unequivocal or the value is within acceptable limits for the pump in use at the observed drawdown. A working compromise is to take three or five readings and calculate the average time-to-fill.

If test personnel are uncertain about the true volume of a volumetric flow measurement container, they should physically measure the volume; assuming that a topless fuel drum has a capacity of 220 litres is perhaps reasonable if the drum is new, but not when it is crumpled and battered. If there is any doubt, steps must be taken to measure it.

Volumetric flow measurement methods are not recommended unless no alternative methods exist. Since alternative methods are adequately described in the literature or details may be obtained from the Authority, failure to use these reflects either incompetence on the part of test personnel or an inability to plan on the part of management. The Authority encourages the application of more modern, more reliable flow measurement methods.

A general comment on the collection and presentation of discharge data is appropriate. When an electric submersible pump is used as a test pump in a borehole in which significant drawdown occurs, flow measurements will not stay the same throughout the test (in any case, if volumetric measurement methods are used there is expected to be some variation, due simply to observer error).Yields will decline as the total head on the pump increases. Tests in which discharge measurements are identical from start to finish will therefore be unacceptable unless there are sufficient grounds to prove otherwise.

The Authority may, in certain circumstances, instruct that such tests be repeated if they have reason to believe that data collection has been negligent. The Authority will not be responsible for the costs of such repeated tests, as they infringe not only the principles of good practice but also this Code of Practice.

5.5 Frequency of discharge measurement

Discharge ratesideally should be measured and recorded at the same frequency as water level measurements (see S.8.2). If continuous recorders are used it may still be necessary to make manual measurements where instrument resolution is inadequate. It is not always easy to measure discharge at 30 second intervals in the early stages of a test (see S. 8.2 below), but the attempt should be made.

6 GROUNDWATER LEVEL MEASUREMENT

Water levels in the test borehole and any observation boreholes must be measured throughout the test.

6.1 Methods of water level measurement

Water level measurements in the test borehole must be ±10 mm or better. Groundwater levels in the test borehole must be measured using either a dipper or a pressure transducer. If the latter is used, care must be taken to ensure that the transducer is able to measure throughout the anticipated range of drawdown at the required resolution. The measurement datum should be clearly marked for each borehole.

Water level measurement resolution in observation boreholes must be ±5 mm or better. Unless data loggers are used here, manual measurements are necessary during the initial phase of a test.

Data logger systems provide a means of monitoring test and observation boreholes and generate data in a format suited to immediate computer analysis and presentation. However, it is essential that careful attention be paid to the resolution and accuracy of the equipment. Calibration by manual dipping may still be necessary.

6.2 Frequency of water level measurement

Data analysis is considerably simplified if measurements taken in observation boreholes 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 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 intervals shown in Table 2below can be used as a guide.

Table 2 Frequency of data collection (water levels and discharge)

Test period	Measurement interval	Test period	Measurement interval
Before start	At least 1 measurement	4 to 8 hours	Every 30 minutes
First 10 minutes	Every 30 seconds	8 to 24 hours	Every hour
10 to 20 minutes	Every 2 minutes	1 to 2 days	Every 2 hours
20 minutes to 1 hour	Every 5 minutes	2 to 4 days	Every 4 hours

1 to 2 hours	Every 10 minutes
2 to 3 hours	Every 15 minutes
3 to 4 hours	Every 20 minutes
4 to 7 days	Every 8 hours
More than 7 days	Every 12 hours

It is strongly recommended that a “running plot” is made during all tests; monitoring the running plot will indicate erroneous measurements as well as illustrating trends that the test supervisor should know about; whether, for example, the test has encountered a barrier boundary, or whether a delayed-yield response has ended.

The application of a blanket 24 hour constant discharge test is acceptable in many, if not most situations likely to be encountered. However, there are exceptions and sector practitioners need to know that circumstances will in the future alter cases. The Authority will provide guidance to Water Permit applicants and drilling contractors, though supervising hydrogeologists and drilling supervisors should be responsible for the design and implementation of test pumping at the field level.

6.3 Measurement of time

The means used to measure time mustbe capable of measuring to the nearest second. During thefirst 10 minutes of a test, an error in timekeeping greater than 5 secondsshould be avoided. For the sake of general accuracy, time should be recorded to within 30 seconds thereafter until 1 hour of pumping is completed, and to within 1 minute from then until the completion of the test. Timing devices should be synchronized prior to the start of the test, especially where observation boreholes are spread over a large area. The start and completion of events should be recorded in clock time. It is most convenient to start a test on the stroke of the hour.

7 PRE-TEST OBSERVATIONS

Hydrological, hydrogeological and climaticfactors influence the hydraulic behaviour of anaquifer before, during and after tests. It is vital toassess the significance of key variables before testing,so that their effects can be allowed for in subsequent analyses. Some variables will be independent of the test pumpingprocess (such as rainfall or barometric pressure). Others will be directly affected by the test (such as groundwater levels or spring discharges). Many of these variables may require measurement throughout tests;some may also be continued as post-test observations. Some observations may be required outside the area immediately affected by the test.

Before carrying out pumping test in the borehole, it is necessary to carry out water quality analysis for both surface and groundwater in the vicinity.

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

7.1 Tidal waters

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

Chemical analyses of groundwater from different depths in coastal boreholes and shallow wells, and of sea water may be made to establish the characteristics of the waters. Repeated sampling of waters or measurements of electrical conductivity during one or more full tidal cycles will indicatewhether a saline interface intersects a borehole or well.

7.2 Still waters

Stage measurements must be made of surface watersthat may be affected by tests (lakes, ponds and streams). If levels are not measured continuously, manual measurements should be made at specified intervals. The period over which observations are made must be sufficient to quantify any natural trend which may occur duringtests.

7.3 Streamflow

Discharge rates from boreholes are typically 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 borehole will be measurable. Nevertheless, measurements of stream flow should be made, if this is possible, on watercourses that might be affected by the test. Such measurements can be made either at existing flow gauging stations or at specially constructed sites. Temporary weirs or current meter sites may need to be established for the test period. Observations should be made where possible on a continuous recorder and should start at least 2 weeks in advance of tests.

7.4 Water Quality

Before carrying out pumping test, water samples of still waters and streamflow should be taken and analysed to establish the quality.

On-site measurements may be made for pH, electrical conductivity, temperature, redox potential, , dissolved oxygen and other ions of specific interest (such as fluoride). Laboratory determinations should be made for all major and minor ions, as well as bacteriological analyses.

The following is the recommended minimum parameter set for a basic full chemical analysis:

General	Metals	Non-metals	Organo-leptic
Electrical conductivity	Sodium	Carbonate	Colour (Hazen)
pH	Potassium	Bicarbonate	Turbidity (JTU)
Total dissolved solids	Calcium	Chloride	
Free CO_2	Magnesium	Sulphate	
O_2 absorbed	Iron	Fluoride	
Silica	Manganese	Nitrate	
Hardness		Nitrite	
		Total alkalinity	

Bacteriological analysis should comprise not less than total *coliforms* and *E. coli*.

Environmental (^{2}H, ^{3}H and ^{18}O) and radioisotope ($^{12}C/^{13}C/^{14}C$) determinations may be required if it is necessary to determine the origin or relative age of waters, in order to assess whether recharge is occurring and what path or paths recharge follows.

7.5 Groundwater levels

Groundwater levels must be measured in specified observation and pumped boreholes within the area likely to be affected by tests. 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 a test or a minimum of 2 days, prior to the start of pumping.

7.6 Groundwater quality

Groundwater samples must be taken from pumped boreholes and may be taken from specified observation boreholes or shallow wells in the vicinity of the test site. The analyses to be carried out should be similar to those inS. 7.4.

7.7 Meteorological parameters

In unconfined aquifers in which barometric efficiency is known or believed to be high, barometric pressure should be recorded in conjunction with groundwater levels for a period sufficient to determine the barometric efficiency of the aquifer prior to the start of tests.

In the vicinity of the test site rainfall must be recorded in conjunction with groundwater levels for a period sufficient to determine the response of groundwater levels to such events.

7.8 Abstraction and discharge

All pumped boreholes and shallow wells, and spring discharge in the vicinity of the test borehole must be monitored so that their effects on groundwater levels and quality may be taken into account during the analysis of test data.

Pumped boreholes in the vicinity of the test site should not necessarily cease pumping during tests; they should be held as nearly as possible to a constant rate, both during pre-test observations and during tests. If pumping is stopped then groundwater levels should be permitted to recover fully before the start of the test. It is acknowledged that this will present particular problems in many Kenyan contexts, and it is important that Authority and supervisory staff retain a measure of flexibility in applying this aspect of the Code of Practice.

8 PUMPINGTEST

The sequence of events for a comprehensive test of both borehole and aquifer would typically be as follows: –

i) pre-test/trial test;
ii) step drawdown test;

iii) constant discharge test;
iv) recovery test.

8.1 Test design

The test should be designed to meet the objectives set out in this Code. The approach to test design must take into account site specific hydrogeological conditions, and the interpretation methods proposed for data analysis. The Supervisor will design the test in consultation with the Contractor.

A systematic approach ensures that the maximum information is collected regarding both borehole and aquifer. This calls for close control of design and conduct of the test, but can be achieved with little or no additional expense. It must be appreciated that the test is a scientific exercise providing information on both the aquifer and the groundwater in it.

Other types of test – such as constant drawdown, slug and packer tests – are not discussed further in this Code of Practice. Should such tests need to be conducted, reference to specialised literature is advised.

The equipment or pre-test/trial test is carried out to check that the equipment is fully functional and to guide the test team in selecting suitable valve settings for the tests. Step-drawdown tests provide information on borehole hydraulics. Constant discharge and recovery tests provide information on aquifer properties.

8.1.1 Pre-test/Trial test

The pre-test checks that pumping equipment, and discharge and water level measuring instruments are functioning satisfactorily. All equipment must be in safe condition and with all safety devices fully functional. The pre-test also provides information for planning later tests, in particular the step-drawdown test valve settings.
The borehole must be pumped for a short period at discharge rates which need to be measured only approximately, along with water levels for each discharge rate. A check on the effectiveness of a borehole's development also should be made at this stage. Groundwater levels should be measured in the test borehole and any observation boreholes prior to the start of pumping and in observation boreholes just before the end of the pre-test. These measurements indicate the range of water level decline anticipated during formal tests.

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

Stream flow gauging equipment should be checked (if used).

Control valve settings should be noted during the pre-test so that in subsequent tests it is possible to set the valve approximately to the pumping rate required without calling for minute and time-consuming adjustments. A pressure gauge is also useful for determining settings for discharge rates in step drawdown tests. A rough yield-drawdown curve should be drawn up; a second rough curve relating valve positions (or pressure gauge values) to discharge rates should also be drawn up.

8.1.2 Step-drawdown test

Step-drawdown tests establish the intermittent yield-drawdown relationship and define the elements of head loss attributable to laminar and turbulent flow.

In a step-drawdown test the borehole is pumped in a number of steps, each at stepwise increase different discharge rate. Each step is Specific of constant discharge. Not less than four steps are required, with the final discharge rate approaching the maximum estimated yield of the borehole (or the highest discharge the pump is capable of). Care must be taken to avoid excessive drawdown and so risking the pump running dry.

The steps may be taken consecutively, in which the pumping rate is increased at the end of each step; or intermittently, with pumping stopped after each step to allow water level recovery before commencing the next step. In consecutive steps the pumping rate must be increased in equal increments from the first to the last step. In intermittent steps the pumping rate may be changed at random and the data analysed as a series of discrete tests.

Each step must be of equal duration. It is rarely necessary for steps to exceed 2 hours; it is often convenient if each step lasts 100 minutes, and this is what the Authority recommends.

If observation boreholes are available, groundwater level measurements should be made in addition to the pumping well. Observation boreholes are unnecessary in the analysis of step-drawdown tests, but will give some indication of the range of groundwater level fluctuation that will take place in longer-duration tests.

Discharge rates, duration and number of steps

The discharge rate, step duration and number of steps will have been determined in advance by the supervisor. The pressure-discharge curve obtained during the pre-test should be used as a guide.

Start of test

Pumping starts instantaneously at the predetermined rate and is maintained until the next step starts. In practice this is difficult to achieve; however, the following procedures are quite adequate: –

i) If a foot valve is not fitted the pump is started against an empty rising main and with the control valve open to the first step setting.
ii) If a foot valve is fitted the pump is started against a full rising main with the control valve opened to the first step setting.

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

Rest water levels are measured in the test and any observation boreholes prior to the start of pumping.

Test procedure

Consecutive step-drawdown tests

It is most convenient to start the step-drawdown test at low rates of pumping and to increase step by step to the highest rate.

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

Intermittent step-drawdown tests
The amount of change in the pumping rate between steps may be progressive or intermittent. Each step is considered as a single test and starts under the procedure described in paragraph10.3.2 above. At the end of each step the pump is stopped and groundwater levels allowed to recover before commencing the next step.

Measurement of groundwater levels

For each step groundwater levels are measured in the pumped well and observation wells at the intervals given in Section 8. If a constant discharge test is to be performed later, groundwater levels during the step-drawdown test should be measured in one or two observation boreholes close to the test borehole, since more distant boreholes may not show significant drawdown during the relatively short duration of the step-drawdown test. If a constant discharge test is not to be performed, the water levels in all available observation boreholes must be measured during the step test.

Analysis of step-drawdown data

Analysis of the step-drawdown test is often used to estimate the maximum safe yield for the borehole. This is also required for the design of the constant discharge test to ensure dynamic water levels remain above the pump suction. The usual method is to plot specific drawdown (drawdown divided by discharge rate) against discharge rate for each step. The point at which the gradient of the line changes is the optimal safe yield of the borehole. Thedrawdown is determined by extrapolation of the water level trend of each step to the end of the next step (Kruseman*et* al 1992: Clark 1977).

8.1.3 Constant discharge test

Constant discharge tests pump the borehole at a constant rate for a period of time dictated by discharge rate and local hydrogeological conditions. Constant discharge tests obtain data on the hydraulic characteristics of an aquifer within the radius of influence of the pumped well. In certain circumstances observation wells are necessary in order to determine fully the aquifer properties; such circumstances will be determined by the Authority.

A delayed yield response delays the development of the time-drawdown relationship on the running plot. It is impossible to estimate in advance the duration of this delay (unless data from nearby wells in the same aquifer are available). If delayed yield is expected, the supervisor must be prepared to extend the duration of the test.

Barrier boundaries increase the rate of drawdown and are a potentially significant constraint on the yield of the borehole.
Test durations may need to be increased in order to adequately observe the effects of barrier boundaries, especially if they appear towards the end of the initially anticipated test period.

This Code requires that all constant discharge tests last for not less than 24 hours. However the

Authority may vary the required discharge period at its discretion, and shall explain why this is required in the Conditions to Authorisations to Construct Works (Form WRMA 004).

The design discharge rate should be determined prior to the start of the test from the results of the step-drawdown test or pre-test/trial test if no step-drawdown test was conducted. The selected discharge rate should be approximately the anticipated production rate.

However, it is considered important that the instantaneous discharge rate during the constant discharge test does not exceed either the maximum step-drawdown test rate or the safe yield defined by the step-drawdown test.

Test duration will be determined by the supervisor.

8.1 Recovery test

Recovery tests must be carried out on any borehole after a constant discharge test, and after a variable discharge test if this is the only test to be conducted on a borehole. The recovery test is a useful check on transmissivity values derived from a discharge test.

The specific yield or storage coefficient can also be determined from a recovery test, but in unconfined aquifers with less accuracy than during the discharge phase because of incomplete re-saturation of aquifer pore spaces that were dewatered during the discharge phase.

A recovery test dependent upon water levels measured in the test well can only be performed if a foot valve has been fitted to the rising main. In the absence of a valve there is a rapid rise in water level as water surges in from the rising main when the pump is turned off. Recovery tests can be performed using water level data collected in observation boreholes if the rising main in the test borehole has no foot valve.

The Authority will require that all recovery tests last for not less than 12 hours or at least 95 per cent recovery, whichever comes earlier. However the Authority may vary the required recovery period at its discretion, and shall explain why this is required in the Conditions to Authorisations to Construct Works (Form WRMA 004).
Recovery tests in the test borehole should only be performed if a non-return valve is fitted to the bottom of the rising main. Recovery tests carried out after step-drawdown tests are difficult to analyse but they provide a further check.

The recovery test follows immediately after the termination of the constant discharge test. The discharge should be stopped at the designated moment by stopping the pump.

The recovery test should be continued for not less than 12 hours or 95% recovery, whichever comes earlier.

8.2 Test interruptions

Pumping plant and associated equipment should have been serviced prior to commencing pumping. If breakdown occurs such that it stops the pump discharging at the designated rate at any time during a step-drawdown test, or during the first 24 hours of a constant discharge test, groundwater levels must be allowed to fully recover and the test restarted.

Measuring devices do malfunction; it is recommended that standby spares, especially in the case of dippers, in order to avoid breaks in the collection of data. This is particularly important in long-duration tests involving many observation boreholes, as repeating such a test because of unacceptable data collection is an expensive exercise.

8.2.1 Reducing groundwater levels

If groundwater level in the test borehole approaches pump suction and it appears likely that suction will soon be reached before 24 hours has elapsed, pumping should stop. A further test shall then be carried out at a lower discharge rate. .

8.2.2 Under-developed boreholes

Boreholes that have been incompletely developed will show signs of development during test pumping. If incomplete development occurs during the step-drawdown test, the test should be stopped immediately and the borehole properly developed before testing recommences.

Failure of an observation well to show drawdown may be due to incomplete development. Incomplete or partial hydraulic isolation of water in the wellbore from the aquifer is unacceptable and such an observation borehole must be properly developed before testing recommences. Note however that if the transmissivity of the aquifer has been over-estimated, the edge of the cone of depression may not reach the observation borehole within the test period.

8.2.3 Other interruptions

Once a test has started it must be completed. That a particular borehole proves to have inadequate yield for its proposed operational requirement is not sufficient reason for abandoning a test.

8.3 Aquifer response during constant discharge tests

During a discharge test time-drawdown should be kept for test and observation boreholes. These graphs should be constructed both on semi-log and log-log paper, in both cases with time plotted on a log scale. Theis type curves for *W(u)* against *u* and *1/u* should be prepared in advance on log-log paper of the same scale.

Comparison of observed curves with the Theis type curve will show departures from the ideal case. Similarly, departure from the normal straight line response on the linear-log plot will also indicate boundaries.

If departures from the type curve are observed, the supervisor should immediately check that the measurements have been correctly taken, that pumping plant is functioning properly, and that the discharge rate is being maintained. If these are not at fault it can be assumed that the departure is due to an aquifer condition; some departures due to well losses may be found in the pumped well. Kruseman*et al* (1991) show log-log and semi-log plots for common aquifer types (Chapter 2, pp 48 – 53), and the Code strongly recommends that this standard text, or a text showing similar data, is available at the test site for comparison purposes.

8.4 Quality of groundwater from the test borehole

Samples of water must be taken from the test borehole to determine the groundwater quality, and whether there is any variation. Analyses may include those in S. 7.4.

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

8.5 Stream flow depletion

Surface water monitoring

In some circumstances, the abstraction of groundwater will affect watercourses at surface, so spring and stream flow depletion needs to be considered during the test on the borehole. This is especially important if the proposed production borehole discharge is high.

The study of this effect (if any) depends on 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 depends on several factors; the scale of abstraction relative to surface flow; the distance between test borehole and the surface feature; the point of discharge of pumped water; and the accuracy and frequency of surface flow measurement.

In especially favourable conditions the effects may be observed within a few days, though this is not typical. Tests might need to be conducted for at least 2 weeks, and in exceptional cases 12 weeks or more, in order to generate data from which to calculate the effects of groundwater abstraction on surface water flows. Care must be taken when designing a test on a borehole that may influence surface water flows to ensure that any chance of induced recharge of pumped water is avoided. It may be necessary to consider test timing in relation to normal seasonal variations in surface water flow.

Stream flow measurements may be made during constant discharge tests by permanent or temporary structures or by current meter gauging. Weirs should be fitted with continuous recorders. Where current meters are used it may not be possible to make frequent measurements of flow. Abstraction 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 or base flow.

9 SPECIAL TESTS

9.1 General

Tests may be carried out using a single borehole in order to study the characteristics of an aquifer along the open section of the borehole. This is the norm at present in Kenya. Such tests comprise pumping with concurrent observations of water level within the borehole. The value of such tests is limited in the absence of observation boreholes. In conducting such tests exactly the same procedure is adopted as is described previously, except that no observation boreholes are monitored during tests.

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. Slug and packer tests are also useful where pumps cannot be installed or where insufficient depth of water is available for normal pumping. Slug and packer tests are specialized procedures and should be undertaken only with specialist advice. The main features are summarized below.

9.2 Slug tests

9.2.1 Introduction

Slug tests involve relatively small displacements of water level in boreholes by the rapid injection of a 'slug' of water with a bailer, or by the introduction of a mechanical displacer.

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

Analysis of slug test data can provide information on the transmissivity of the formation which is open or screened in the borehole being tested. Given some knowledge of the transmissivity a slug test in an observation borehole 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.

9.2.2 Displacer

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

9.2.3 Water level measurement

A float-operated recorder is usually unsatisfactory for slug tests; furthermore, the electrical contact-type-dipper cannot measure changes in the water level sufficiently quickly

The ideal instrument is a pressure transducer sensitive over a range of a few metres. The transducer should be located 1 to 2 m beneath the displacer when this is at its lowest point. The cable connecting the transducer to the well head may require protection within an access tube. If a slug of water is to be injected the transducer should be located 1 m to 2 m beneath rest water level.

9.2.4 Recording apparatus

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

9.2.5 Procedure

The displacer should first be lowered into the borehole until its base is resting within the water surface. When recording instruments are running, the displacer should be lowered rapidly until 95

% submerged. When water levels have stabilized the displacer should be raised rapidly until it is clear of the water and water levels again allowed to stabilize.
The test should be repeated several times. Adjustments in recording speed may be required to obtain usefully spaced data, depending upon the speed with which water levels recover.

Water injection is analogous to the insertion of the displacer, but cannot simulate its withdrawal. The injection should comprise a volume of water equivalent to 2 to 3 m depth of the borehole. When a bailer is used it should be lowered until approximately 80 % submerged, and water level allowed to stabilize. The bailer then should be lifted rapidly until clear of the water surface, thus simulating the withdrawal of the displacer. Tests should be repeated until at least five comparable cycles have been completed.

9.2.6 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 gravel pack.

9.2.7 Screened boreholes

If a borehole has been fitted with a screen with a limited open area per unit length, a slug test will provide little useful information on 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.

9.3 Packer tests

9.3.1 Introduction

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

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

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

Borehole testing using packers can be undertaken by: –

i) pumping water out of a borehole;
ii) injecting water into a borehole, often at positive pressures.

In the first case, the permeability of the strata within the section of the borehole under test is evaluated from the relation developed between 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.

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.

9.3.2 Types of packer test

A test with 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.

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. 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.

9.3.3 Equipment

The equipment comprises the packer units, inflators, a pump for abstracting or injecting water, and equipment for measuring pressures and flow rates. The equipment is specialised 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 to 200 mm diameter, although diameters up to 300 mm are available. Above this size packers may have to be manufactured to order.

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

9.3.4 Test schedule

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

9.3.5 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 are used to measure the pressure in the tested section directly, the length, diameter and material of the pipework also need to be recorded since the applied pressure needs to be corrected for pipe friction loss. The interpretation of the results involves the calculation of permeability from simple formulae and with care;accuracy within an order of magnitude is attainable.

10 POST-TEST OBSERVATIONS

The measurement of significant variables during recovery from pumping until the return of pre-test conditions forms an integral part of the test; monitoring of the variables described in Section 4should continue for a period after recovery to establish trends prevalent during the test pumping period.
Analysis of pumping test data

11 PRESENTATION OF INFORMATION

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

At the very least, the report describing a test pumping exercise must include all raw and processed data, and graphs showing drawdown and recovery curves, step-drawdown test curves and calculations of transmissivity and storage coefficient (or specific yield), as applicable. These data must be appended to the Form WRMA 009a or 009b (as applicable), together with water quality data.

12 REFERENCES

The following reference list details further sources of information on various aspects of test pumping and associated activities described in this Code of Practice. It includes details of general references on groundwater hydraulics and of texts offering guidance on analysis of data obtained from a successfully conducted test pumping exercise.
It is not exhaustive but it is hoped that users of this Code will nevertheless find it useful.

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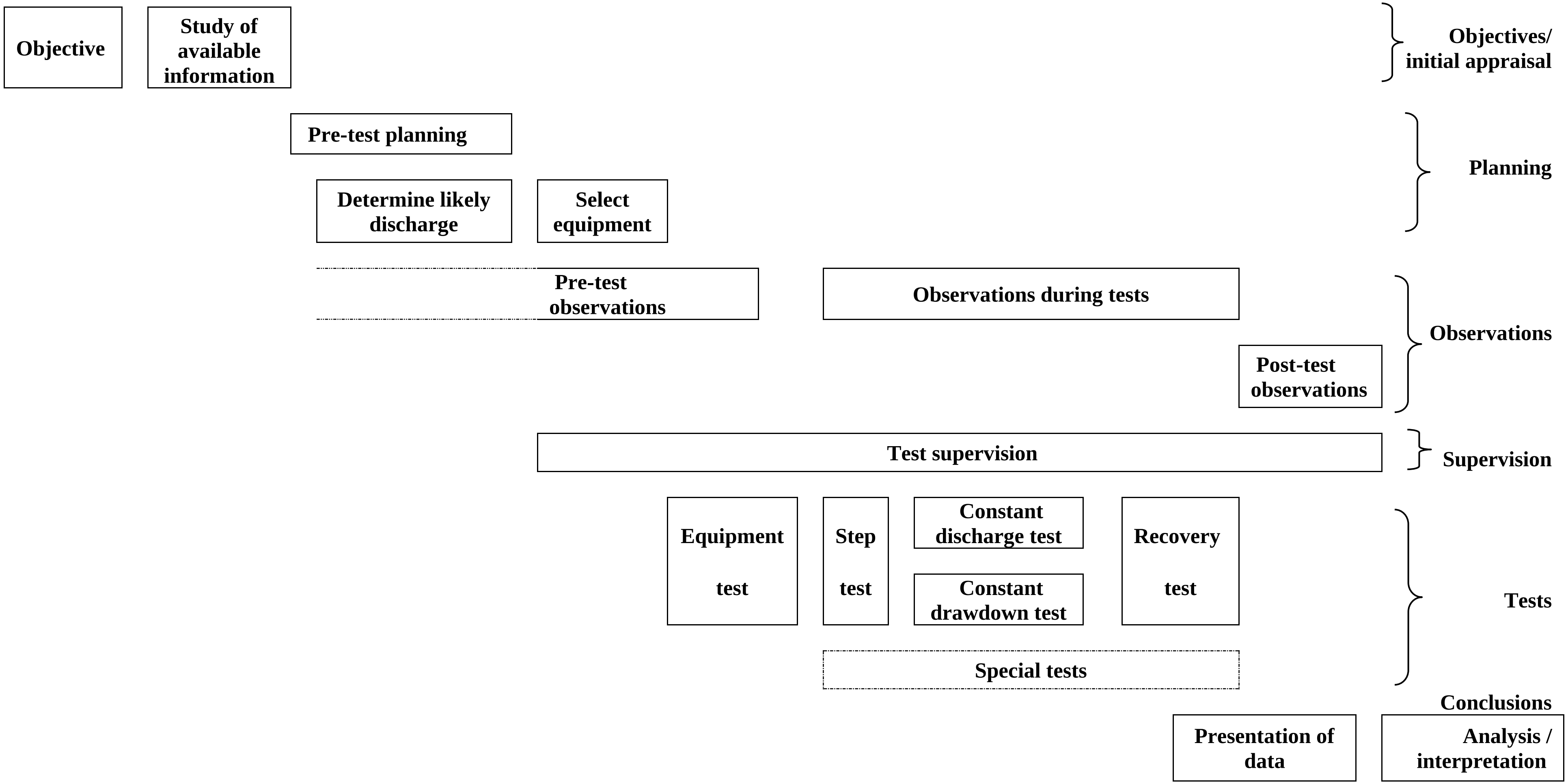
ANNEX 1: The Pumping Test Process



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