

Government of India & Government of The Netherlands



Groundwater Quality Monitoring

Objectives, Networks and Data Acquisition

March 1998

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1. Introduction

The Hydrology Project (HP) aims to establish a Hydrological Information System (HIS) at Agency, State and National level for hydro-meteorological, surface water and groundwater quantity and quality data. The system comprises the infrastructure, human resources and activities involved in data acquisition, processing, validation, storage and dissemination. The physical infrastructure components of the system include observation networks, laboratories and data centres equipped with databases and tools for data entry, processing, and retrieval, whereas the human resources comprise well-trained staff with a variety of skills who can operate and execute the activities involved in the system

A major objective of the Hydrology Project is to improve and modernise the groundwater observation-well networks in all the participating states, through construction of purpose-built piezometers, installation of digital Automatic Water Level Recorders (DWLR) in key wells, and setting up a modern water quality monitoring programme. The expansion of the infrastructure and the functional integration, via the HIS, of both the monitoring networks maintained by the states and those maintained by Central Ground Water Board (CGWB) is significantly modifying the present situation in four respects, namely:

- increased density of observation points
- increased frequency of readings
- exploitation of deeper aquifers
- additional quality-related parameters to be analysed

As such, the layout, design and operations exercised with regard to monitoring should be reviewed and optimised in the light of monitoring objectives, prevailing hydrogeological regimes, human activities and historical data.

The following document reviews and discusses water quality monitoring issues and focuses on guidelines for groundwater quality data acquisition procedures in the context of monitoring objectives. It addresses network design, parameters, sampling, field measurements and sample handling. To sustain the compatibility of the databases in the HIS, and promote comparisons and integrated data processing, the overall approach taken in this document maintains, as far as possible, analogy with the surface water quality monitoring programme developed simultaneously under HP.

2. Monitoring Objectives

The objectives for quality monitoring of groundwater may be stated as follows:

- a) to provide background data against which future changes can be assessed
- b) to allow early tracing of both slow and rapid quality changes and deterioration processes
- c) to check for compliance with standards for designated use (e.g. abstraction for use in potable water supply)
- d) to allow analysis of water and solute evolution, including evaluation of primary and secondary sources and processes
- e) to allow identification of anomalous concentrations of natural and anthropogenic pollutants
- f) to characterise water bodies, including tracing of flow direction and mixing processes

These objectives may be considered under three categories, as follows:

1. Baseline/Trend - long-term standardised measurements in order to define status or trends ('a' and 'b' above)
2. Surveillance - continuous specific measurements for the purpose of water quality management and operational activities ('c' above)
3. Survey - a finite duration, intensive programme to measure for a specific purpose ('d', 'e' and 'f' above)

These three sampling categories can be further split into a number of sample types, each of which has a specific objective. These sample types and their associated objectives are described in the first three columns of Table 1.

3. Network Layout and Design

3.1 Density and Sampling Frequency

For each sampling type referred to in Table 1, it is necessary to determine where each site will be located and how many sites there will be. This is known as the *network density* of the overall monitoring programme which approximates the number of sampling points per unit area. This measure may vary markedly according to objective, known or suspected spatial variability of the quality parameters and specific local conditions. As such, a given value for groundwater network density is only a general measure to assess a network layout; it should never be applied directly for setting up such a network even if density figures are derived through sophisticated statistical analyses of historical data.

Sampling frequency is the number of samples taken per unit time at each sampling point. The sampling frequency is also closely linked with the monitoring objectives, the expected variability of the measured parameters, the capacity of the laboratories and the cost of the sampling and analytical effort.

With reference to Table 1, the network density and sampling frequency appropriate to each sample category is discussed below. It should be noted that at least for the first three years, sampling sites for both Surveillance and Survey sampling categories may partly overlap that of the Baseline/Trend category, though for different parameters and/or varying densities and frequencies.

3.2 Baseline and Trend (Baseline/Trend Category)

In terms of groundwater sampling, the Baseline/Trend category is designed to establish the groundwater quality conditions which prevail at any given site at the beginning of the monitoring programme. Preferably, such baseline conditions should reflect the original undisturbed situation, before significant abstraction started and at early stages of anthropogenic pollution. However, since widespread development has taken place for some considerable time, it may only be possible to use historical data to reconstruct undisturbed conditions for a limited number of parameters.

As quality parameters are directly related to the groundwater flow regime, quality baseline monitoring network layouts should closely correspond to the water level network. Maintaining this relationship allows for integrated water level and water quality data processing which is required for the identification of pollutant sources, flux and change in storage of any given aquifer. However, because the quality of groundwater systems is usually quite homogeneous, and changes and fluctuations are slow or limited, both density and frequency of quality sampling may be lower than required for water level monitoring. In the event that the available laboratory capacity is not sufficient to allow analysis of all the potential monitoring sampling sites, it will be necessary to further reduce the network density to a feasible level. Discontinuing sampling for one or several of the sites should be done after consideration of similarities in historical water level and quality records in closely spaced observation wells (if available) and on the basis of the local hydrogeological conditions, soil characteristics and land use. Methods commonly employed to identify such similarities in data derived from neighbouring observation wells include scrutinising of tabulated data, analysis of water level and quality hydrographs and spatial contour maps, and execution of regression and correlation matrix tests.

Sampling for baseline characterisation will continue for an initial period of three years (minimum) after which all of the data collected should be reviewed with the objective of redesigning the baseline sampling network. At that time, depending upon the analytical results obtained from each sampling borehole, it may be possible to discontinue some sampling sites, particularly where adjacent boreholes are seen to have been giving similar analytical information. Further, this review of the sampling network will identify areas where insufficient baseline data have been collected thereby allowing recommendations to be made regarding the installation of additional sampling boreholes.

Trend monitoring sites are designed to show how groundwater varies over time at a particular borehole, often as a result of anthropogenic influences. Through regular sampling of such stations it is possible to detect slow and rapid changes and potential deterioration processes. Under the present project, trend analysis needs to be performed over the entire quality-monitoring network for an initial period of three years, after which it should be similarly reviewed for effectiveness and adequacy. In order to record possible seasonal variations and relationships with water level fluctuations, selected key wells (purpose-built piezometers equipped with DWLRs) should be monitored for a limited number of parameters at a higher frequency (4 - 6 times a year).

Samples for the determination of both baseline and trend should, unless special circumstances apply, be obtained once per year. It should be mentioned that in order to get a 'representative sample' (see Section 5.1) the monitoring network should include both observation wells and operational production wells; a mixture with a ratio of about 7:3, respectively, is recommended.

3.3 Water Use (Surveillance Category)

This type of sample is obtained to check that water is fit for the use for which it is being abstracted. Potential uses of groundwater are: drinking water, irrigation water, livestock watering and various industrial processes not discussed here.

Sampling stations should be sited at all points of use, providing that this is practical and does not entail unnecessary duplication. That is, if irrigation water is obtained through several boreholes in the same area from the same aquifer it is probably sufficient to sample only one borehole from this group rather than all of them.

Sampling frequency will depend on the use of the water as follows:

- i. drinking water - twelve samples per year
- ii. irrigation water - one sample per year
- iii. livestock watering - one sample per year

With regard to drinking water supply boreholes, it may be possible to reduce the number of samples obtained if a reliable field test kit can be used to screen the abstracted water. Such a test kit must be capable of detecting pesticide, nutrient and microbiological contaminants and, in certain areas, unacceptable levels of fluoride.

3.4 Management and Research (Survey Category)

These are samples which are taken for special purposes including the following:

- to allow characterisation of water bodies, flow directions, and mixing processes
- to allow identification of pollutants, possible inter-relationships, and sources
- to allow reconstruction of water and solute evolution

Samples of this type will normally be taken as part of a survey designed to gather information in order to address a particular problem. As such, each survey must be planned individually and the number of sampling sites, the parameters to be analysed and the frequency of sampling will depend on the problem, the objectives of the survey and the information required.

4. Parameter Selection

Suggested parameters for each sample type are given in Table 2 (Baseline/Trend Category) and Table 3 (Surveillance Category). For convenience, the parameters have been split into the following groups:

- *general* - basic parameters, many of which can be measured instrumentally either in the field or in the laboratory
- *nutrients* - nitrogen and phosphorus parameters which measure plant nutrients and major fertilisers and collectively reflect the impact of agricultural practices on groundwater composition
- *organic matter* - parameters capable of estimating the likely effect on water bodies of the discharge of organic matter
- *major ions* - the inorganic anions and cations which describe the chemical composition of the water, determine its classification and help to assess pollution
- *other inorganics* - miscellaneous inorganic species which are important for certain water uses or for classification purposes
- *trace elements* - ion species which are highly toxic even at trace concentrations and are useful indicators of the presence of other ion species; the specific elements included are known to be present in groundwater in some parts of India
- *trace organics* - particular species which are important due to their toxicity, effect on potability of water, or effect on the environment
- *microbiology* - one indicator species for the presence of faecal pollution of water

The choice of parameters for each sampling type is carried out in a similar fashion to network density and sampling frequency selection, that is on the basis of the stated sampling objectives, as discussed below.

4.1 Baseline and Trend (Baseline/Trend Category)

The purpose of baseline samples is to characterise the natural state of groundwater and to form a datum in time and space to which anomalous concentrations may be referred. Thus, in addition to a number of general parameters, nutrients, major ions, and other inorganic species need to be determined.

Analysis for the parameter group 'trace elements' should usually be carried out on an area specific basis. That is, if contamination by one of the trace elements is known to be present in a particular area, then the determination of this element should be undertaken. However, if no reliable historical data are available trace elements need to be included in the initial phase of the monitoring programme. Determination of particular parameters in the 'organic' parameter group need only be undertaken if pollution from these species is thought to be present in the area of the borehole being sampled, or if no relevant data are available.

As trend monitoring is carried out to detect changes in groundwater chemistry a full range of analysis should be undertaken. However, it is possible to reduce the number of analytical parameters to be determined by selecting them according to the contaminants known or suspected to be present in the groundwater in the area of the borehole to be sampled. Thus, from inspection of Table 2 it can be seen that many parameters are designated as area specific (that is, should be determined if such contamination is known to be present in groundwater in the area of the borehole or no reliable data are as yet available), whilst a number are pollution specific (that is, should be determined if this type of pollution is thought to be present in the groundwater body which the borehole is sampling).

4.2 Water Use (Surveillance Category)

Table 3 gives suggested parameters for three different groundwater uses - drinking water, irrigation and livestock watering. Parameter selection has been carried out so that pollutants particularly important to each use are screened. For example, certain crops are sensitive to high boron concentrations so this chemical is included in samples of irrigation water.

It should be noted that no attempt has been made to sample groundwater which is to be abstracted for industrial process and cooling water use. This is because the water quality required for this type of use varies according to the industrial process. Moreover, since those abstracting such water will almost always analyse the water themselves, official sampling of such abstractions is not considered necessary.

4.3 Management and Research (Survey Category)

As each particular survey undertaken within this sampling type will have its own objectives, no general guidance can be given on the parameters which should be determined.

It is important to remember that the parameters suggested in Table 2 and Table 3 for baseline/trend and surveillance represent a minimum suite of parameters for each sample type. This is to maintain a sensible balance between the desire for more information and analytical costs. It should be noted, however, that some potentially important parameters have not been included in the lists (e.g., certain heavy metals). It may be, therefore, that for selected aquifers some research effort should be directed towards ascertaining whether or not certain pollutants, which are not routinely covered by the programme, are present in unacceptable concentrations. Pollutants which could usefully be subjected to this type of investigation are:

- heavy metals such as lead, copper, nickel, and chromium
- organic pollutants such as polychlorinated biphenyls (PCBs) and certain types of pesticide (e.g. DDT)
- certain organic solvents

If any of the above, or other, parameters are discovered in unacceptable concentrations in an aquifer this pollutant should be added to the parameter list for that sampling point for either or both of baseline/trend and surveillance. The frequency of the parameter's analytical determination will then depend on the polluting nature of the substance and its concentration in the aquifer.

5. Sample Collection

5.1 Representative samples

The objective of water quality sample collection is to obtain a small portion of material that accurately represents the characteristics of the water body being sampled. This is referred to as taking a 'representative sample' and is vitally important if the analysis that follows sampling and the conclusions that are ultimately drawn from the data are to have any validity.

Groundwater samples are normally obtained from observation wells and from operating production wells. If the source of groundwater is a well equipped with a pump or a flowing spring, the sample can simply be obtained at the discharge point. When sampling groundwater in this way, it is important to allow the water to flow for some time to ensure that water from the aquifer, rather than that which has been standing in the well, is sampled. This process, known as purging, ensures that standing water, which may differ markedly from aquifer water, does not contaminate the sample. Note that a sample taken after purging is not the same as taking an agitated sample as is often believed. An effective way to ensure that the water is 'fresh' groundwater is to monitor the temperature, electric conductivity (EC), pH and oxidation-reduction potential (ORP) of the emerging water as it is run to waste. Once the readings are constant for some minutes and the amount of water purged approaches the estimated volume of the well, the sample can be taken. In case of sampling in purpose-built piezometers not equipped with an installed pump, samples need to be obtained by means of a portable lifting device such as a submersible pump (see Sections 8.1).

When sampling with a submersible pump, the device is lowered into the well and switched on. The purging and sampling can then be carried out as if the well were equipped with a fixed pump, although the rate of discharge may be lower and more time will be required to ensure proper purging.

Special care is required when shallow wells not equipped with a pump are sampled manually. In this situation the sample can be collected by lowering a specifically designed bailer sampler or a sampling can into the well. It is important that the can is not allowed to touch the sides or bottom of the well as it is likely that this will contaminate the sample with solid matter.

Special precautions are required if it is desired to obtain a groundwater sample for dissolved oxygen analysis. Such samples are best taken by inserting a plastic tube into the discharge pipe and placing the other end at the bottom of a so-called BOD bottle (a 300 ml glass bottle with a ground glass stopper). Water should then flow into the bottle until the volume of the bottle has been displaced at least three times. Care should be taken to ensure that no air bubbles are introduced into the sample bottle. After sampling, the dissolved oxygen must be chemically 'fixed' (see Section 7.1) as soon as possible and certainly before transportation of the sample.

5.2 Purging Requirements

Purging of the well before sampling is required in order to ensure that aquifer water is drawn in preference to standing water. Complete removal of stagnant well water is however not possible because during purging there will be an accelerated inflow to the well resulting in mixing of aquifer and well waters. Therefore the *purging efficiency* is defined as the volume of aquifer water per unit sample volume. Pump specifications and operation procedures should be related to the desired purging efficiency.

Some workers have recommended 'rule of thumb' purging guidelines based on removal of three, five or ten initial well volumes (initial well volume defined as the total volume of water standing in the well, which is not under pumping). The number ranges from 1 to 20 (Humenick et al, 1980, Unwin and Huis, 1983) and is subject to some debate. Generally, 3 to 5 well volumes are considered sufficient (Lloyd and Heathcote, 1985). Others (Gibb et al., 1981) have recommended calculation of the purging requirement from the geometry and hydraulic performance of the wells to be sampled. This approach is followed in Appendix A. The purging efficiency is expressed as a function of the pump discharge, the time of purging, the diameter of the well, the draw-down and the initial thickness of the water column in the well. A sample calculation under certain conditions, characteristic for many hard-rock terrain in India, shows that in order to obtain a purging efficiency of 85% at least 6 initial well-volumes need to be replaced. The assumed conditions for this specific calculation are listed in Table 5.

In case field conditions unfavourably change, e.g. as detailed in the right-hand column of Table 5, the number of initial well volumes to be replaced increases. It may be noted that well depth, static water level, pump discharge and pumping time, though essential in assessing the required pump capacity and horsepower, do not influence the number of well volumes to be replaced for a selected purging efficiency.

5.3 Checking Purging Performance During Field Operation

As mentioned in Section 5.1, it is recommended to verify the purging efficiency during pumping by on-line field measurement of parameters like temperature, pH, EC and ORP. Purging should continue until reasonable stability indicates that the required high proportion of aquifer water is being drawn. A field kit for these parameters, preferably mounted in a so-called flow-cell (to prevent air contact), should be available with the submersible pump.

5.4 Application of Submersible Pumps

The number of well-volumes required to be replaced in order to obtain a selected purging efficiency (say 85%) is given by the well and aquifer hydraulics. The time allowed for purging however is controllable, and should be considered carefully by the agency carrying out the monitoring programme. For example, in order to decrease the purging time by 33% (from 30 to 20 min) a 65% more powerful pump is required (see Appendix A and Figure A-3). The logistics of a monitoring programme should be given serious thought before finalising the pump requirements. In addition, it is advised that pumps with differing specifications be obtained to cope with the each different field condition that may be encountered. In that case, the pump performance curve, which shows the decrease in discharge with increasing head, should be used to match the pump specifications with the variation in field conditions.

6. Field Measurements

It is often necessary to measure a number of water quality parameters in the field. Normally, this is because these parameters are likely to change their value before they can be analysed in a laboratory.

In the context of the present programme, there are three physical-chemical parameters that normally need to be measured in the field. These parameters are temperature, pH and conductivity. A description of the field techniques, which can be adopted for these determinands, is presented in the following paragraphs.

6.1 Measurement of Temperature

Water temperature is usually measured in degrees Celsius, using a thermometer or a thermistor. Normally, if temperature is measured electronically using a thermistor this device is built into an instrument which is capable of taking other water quality measurements (e.g., pH) as well.

6.2 Measurement of pH

Measurement of pH is carried out to determine the acid balance of the water on a scale of 1 (strongly acidic) to 14 (strongly alkaline). Ideally, pH will be measured in the field at the time of sampling using either indicator paper (which changes colour depending upon the pH of the water) or a purpose-built meter. As portable pH meters are more accurate than indicator papers and relatively inexpensive, this is the recommended method of measuring pH. The operation of such a portable device needs to follow its specific manual which usually also includes instructions for field calibration.

6.3 Measurement of Conductivity

Conductivity is a measure of the ability of water to conduct electricity. This, in turn, is directly related to the concentration of dissolved ions. Therefore, the conductivity of water gives a reasonable indication of the concentration of dissolved solids in the water. Like pH, conductivity is ideally measured on site at the time of sampling. Measurement is effected with a purpose-built conductivity meter with automatic temperature compensation.

NOTE: Rather than use separate meters for temperature, pH, and conductivity it is preferable to purchase an instrument that will measure all three parameters.

6.4 Measurement of Oxidation Reduction Potential (ORP)

Measurement of ORP (also called Eh) is carried out to characterise the oxidation-reduction state of the water on a scale from approximately -300mV (strongly reducing) up to +500mV (strongly oxidising). Ideally, ORP will be measured in the field at the time of sampling. Measurement is conducted potentiometrically by a non-reactive electrode (platinum) in combination with a suitable reference electrode.

Although the measurement of ORP is straightforward, interference with other factors limit its interpretation, and the Eh values measured in the field usually correlate poorly with Eh values calculated from the redox couples present (such as O_2/OH^- , Fe^{++}/Fe^{+++} , SO_4/S^{--}). Therefore, the main application of this parameter is in recording significant changes in the redox potential like those expected when purging a stagnant water column in a piezometer and replacing it with "fresh" groundwater. Measurement of ORP should be conducted within the flowing discharge pipe of the submersible pump in order to avoid contact with air.

7. Sample Handling

The preservation, transportation and storage of samples is another vital link in the sampling chain, as failure to carry out these operations with sufficient care can change the characteristics of the sample and give false analytical results. Some guidelines on how these procedures should be undertaken are given below.

7.1 Preservation

As a general rule, water quality samples should be stored at a temperature below 4°C and in the dark, as soon after sampling as possible. In the field this usually means placing them in an insulated cool box together with ice or cold packs. Once in the laboratory, samples should be transferred as soon as possible to refrigerators or a cold room. Not all water quality samples necessarily need to be stored in this way, but it does no harm and it is simpler to treat all samples in the same fashion. To preserve storage space, the size of the sample should be optimal for analytical requirements and care should be given to avoid unnecessarily large samples.

When sampling for dissolved oxygen analysis, it is important that the sample is chemically fixed as soon as possible because the dissolved oxygen concentration in the sample bottle can change rapidly from its original value. Chemical fixing of dissolved oxygen is carried out by adding 1 ml of manganese sulphate solution, 1 ml of alkaline iodide-azide solution, and 1 ml of concentrated sulphuric acid to a 300 ml water sample. The analytical determination may then be carried out up to 8 hours later with no loss of accuracy.

If samples collected for chemical oxygen demand (COD) analysis cannot be determined on the day of collection, they should be preserved below pH = 2 by addition of concentrated sulphuric acid. This procedure should also be followed for samples for ammoniacal nitrogen, total oxidised nitrogen, and phenol analysis.

Samples which are to be analysed for the presence of trace metals should be acidified to below pH = 2 with concentrated nitric acid (see Table 6). If the water is high in suspended matter, filtration of the water is required before acidification, to avoid dissolution of solids. Such acidified samples can then be kept up to six months before they need to be analysed except for mercury determinations which should be carried out within five weeks.

7.2 Transportation

Normally, a motor vehicle with a reasonable weight carrying capacity, such as a light van or car, should be used for the transportation of water quality samples. This is because a one day sampling run encompassing a number of sampling points implies that many bottles of water are collected. This is particularly the case where a range of parameters are to be determined, each of which requires a different type of sample bottle.

To minimise staff and transport costs, and to ensure samples are analysed as soon as possible (preferably within a day), it is best to plan a sampling run such that it can be completed in one day. Ideally, this will entail visiting a number of sampling points in a logical order and ending the day's journey at the laboratory where the samples can be analysed or at least refrigerated until the following day. If samples cannot be analysed until the following day, such sampling runs should not be carried out the day before a laboratory staff holiday.

7.3 Storage

As discussed above, many samples need to be stored in the dark and below 4°C so that the determinand values do not change. For this reason it is good practice to store all water samples in the refrigerator until they can be analysed.

When a sample has to be analysed for a number of different parameters, it is important that the determinands, which are likely to degrade within a short time, are analysed first. Thus, when a batch of samples is received by the laboratory the analytical capabilities and priorities need to be carefully planned to reflect the existing capabilities.

One important factor, which can help to minimise the storage time for samples, is sensible long-term planning of the sampling programme. For example, the programme should be planned such that the laboratory does not receive at one time any more samples than it can readily analyse or store under proper conditions. It is better, therefore, to plan for the laboratory to receive samples in small batches rather than all at one time in order to ensure that the analytical results are as accurate as possible.

Another factor which needs to be considered in planning the sampling programme is the necessity of avoiding taking too many samples just before weekends and laboratory staff holiday periods as this will unnecessarily increase storage times.

Table 4 gives 'recommended' and 'required' maximum storage times for each proposed water quality parameter.

8. Equipment

8.1 Water Quality Samplers

The objective of water quality sample collection is to obtain a small portion of water from the well that accurately represents the water in the aquifer being sampled. This is referred to as taking a 'representative sample' and is vitally important if the analysis that follows sampling and the conclusions, which are ultimately drawn from the data, are to have any validity.

A suitable sampling device meets the following requirements:

- allows removal of stagnant water from the well (called purging) so that the sampled water represents the water in the aquifer
- avoids degassing of the sample and volatilisation of components in it
- prevents oxidation caused by contact with the atmosphere
- avoids contamination of the sample and the well

Three conventional and one sophisticated technique (recommended under HP) are reviewed briefly with respect to their capability of providing representative samples. The aspect of costs is not discussed here.

Conventional Techniques (not recommended under HP):

- i. *Bailers or depth samplers* are so called grab samplers that operate by lowering the device to a known depth in the water column, closing it and raising it to the ground surface. Major limitation is the high atmospheric contact during sampling. Furthermore bailers are difficult to clean (dead-volumes) and the risk of contamination from one well to another (cross-contamination) is high. In addition, contamination of the well water during sampling can be foreseen when a large bailer scrapes the casing of small diameter wells. Purging of the well before sampling by the use of bailers is very time consuming.
- ii. *Suction devices* lift the water sample by applying suction directly to the water or via a collection bottle. Suction can either be generated manually or by a pump (e.g. peristaltic or centrifugal type) but the sampling depth is limited to 8 or 10m. The major limitation is degassing and aeration that cannot be controlled. As with bailers, effective purging is very time consuming using suction devices.
- iii. *Gas driven devices* apply positive gas (air) pressure directly on the water which drives it from the borehole - back flow being prevented by check valves. Usually compressed air is pumped down the borehole through a delivery tube. The air then forces water up a second tube (acting as an airlift pump) and the air water mixture emerges at the head of the well. The intense contact between high-pressure air and the sample causes oxidation and disturbance in the dissolved gas balance of the sample water, namely, degassing and volatilisation, which in turn can cause precipitation of contaminants. This will mean that the sampled water is no longer representative of the groundwater from which it was taken.

Sophisticated Technique (recommended under HP):

iv. *Submersible pumps* are lowered into the borehole and water is driven out continuously at the surface. The following three principles are used drive out the water: gears or rotor assembly (electric centrifugal pump), gas operated plunger (piston pump) or by a gas operated diaphragm (bladder pump). Submersible pumps of these three types are rated acceptable for sampling groundwater for all parameters, including volatile organic carbon, trace metals and dissolved gasses and is therefore recommended as the lifting device for the current water quality programme under HP.

If a submersible pump is used to obtain water samples from boreholes it should ideally have the following characteristics:

- Variable pumping rate: the capacity assessment has been calculated in Appendix A. And a variable pumping rate is also necessary, which allows high speed for rapid purging and slower speeds for sampling.
- Size: the outer diameter of the pump should be considerably less than the smallest inner diameter of the boreholes or piezometers in the monitoring programme. A gap of at least 3 cm is needed to guarantee that the pump does not touch the sides of the wells during lowering and lifting. The smaller the pump compared to the inner diameter of the well, the easier the lowering and lifting will be. If the well is equipped with an automatic water level recorder (AWLR), it is recommended that the AWLR is removed before insertion of the submersible pump to avoid physical damage to the equipment, tubes or cables.
- Material: the material of the pump, tubing and fittings (all parts that make contact with the well water) should be inert and resistant to corrosion. The most common material used is stainless steel.
- Power supply: a portable generator set together with an adjustable frequency converter (to regulate the pumping speed) is required.
- Portability: the weight and size of the complete set should be such that it is easily transported through off-road terrain (is the site accessible by car; if not how many people are available and how far must the equipment be carried?). A battery start will decrease the portability of the set. Technically speaking, there are no objections against manual starting; even if the site is accessible by car a lighter set is easier to handle and will increase the ease and speed of transportation and positioning.
- Noise: the noise level of the sets should be acceptable and for this purpose an exhaust silencer with muffler is advised (provided the weight is not excessive because in that case it is better to install the generator somewhat further away from the well).
- Cleaning: the pump and tubes must be easy to clean (no 'dead-volumes') in order to avoid cross-contamination of wells.
- Maintenance and repair: the pump must be easy to repair in the field and all tools and spare parts must be included with the portable set.
- Accessories: a water level indicator and a flow cell in which field parameters like temperature, pH, conductivity and dissolved oxygen electrodes can be mounted are worth considering.

For manual sampling of hand-dug-wells all that is required is a weighted sampling can with a rope attached to its handle. The can is then carefully lowered down the well until it fills with water and then recovered. Although virtually any style of sampling can is acceptable for this application there are a number of features that are preferable as follows:

- small volume and diameter - it is preferable that the sampling can has a relatively small volume and diameter. This makes it easier to haul the can up the well when it is full of water and helps to ensure that the can does not touch the sides of the well
- plastic - this makes the sampling can lighter, easier to clean and less likely to chemically react with the parameters to be determined in the water sample. For the same reasons the rope attached to the bucket should also be made of a synthetic fibre
- lipped - the provision of a lip to the sampling can makes pouring the water into a sample bottle much easier

8.2 Field Kits (for Temperature, pH, ORP, Conductivity and Dissolved Oxygen)

In addition to sampling, field operatives also need to be able to take measurements and chemically 'fix' certain samples so that their parameter values do not change prior to laboratory analysis.

The measurements that need to be taken in the field are those of temperature, pH and conductivity. These can most usefully be determined in the field by means of a small portable instrument capable of measuring all these parameters. As meters of this type require at least daily calibration and regular maintenance, a supply of distilled water, pH buffers, standard solutions, batteries, and basic spare parts should also be carried with the meter.

As discussed above, any samples obtained for dissolved oxygen analysis must be chemically 'fixed' as soon as they are obtained, by adding three different reagents (see Section 7.1). Therefore, it is necessary to equip every field operative with three 'pipetted' glass or plastic stoppered 500 millilitre bottles containing these solutions. As these solutions can be corrosive, the three bottles should be carried in an appropriately sized bottle carrier to ensure they do not tip over and spill their contents.

Samples for metals analysis should be acidified with concentrated nitric acid as soon as they are obtained, and in case of high concentrations of suspended matter, filtration of the sample is required prior to acidification. Therefore, the sampler also needs to carry a bottle of concentrated nitric acid in a bottle carrier and a field filtration device.

8.3 Sample Containers

In order to cover the range of parameters which need to be sampled and analysed, a variety of sample containers are required as discussed below:

- BOD bottles (300 ml) with ground glass stoppers for dissolved oxygen samples
- millilitre glass (or Teflon) bottles with Teflon lined caps for pesticides and phenols
- millilitre polyethylene bottles for metals (except mercury)
- millilitre glass bottles for mercury and phosphorus
- millilitre polyethylene bottles for all other chemical parameters
- strong thick-walled glass bottles of at least 300 millilitre capacity for microbiological analysis. These should be fitted with screw caps capable of maintaining a good seal even after multiple sterilisations in an autoclave

8.4 Preparation and Sterilisation Equipment

Bottles that are to be used for collecting microbiological samples must be thoroughly washed before use. This can be done by hand but, if there are many bottles to wash, it

is often best undertaken by machine. At the sampling site bottles should be rinsed with the water to be sampled.

Bottles to be used for the collection of microbiological samples must be sterilised prior to use. This can be carried out by placing them in an autoclave at 121°C for fifteen minutes or, if the caps of the bottles do not contain plastic or rubber materials, in an oven at 170°C for at least two hours. Therefore, any laboratory that needs to prepare bottles for microbiological samples requires either an autoclave capable of sterilising at least twenty bottles at one time or an equivalent size sterilising oven.

8.5 Transportation Boxes

After sampling, many water quality parameters undergo chemical or biochemical reactions in the sample bottle, causing the concentration to change from their original values. To prevent this alteration of parameter values, samples should be kept at a temperature below 4°C until they are analysed. In the field, the best way to ensure that samples are kept cold is to pack them into insulated cool boxes containing either an ice/water mixture or a large number of ice packs. Therefore, a number of cool boxes sufficient to contain a full day's sampling run should be available to each field operative who is required to take water quality samples.

8.6 Other Items

In addition to that specified above, a field operator will need certain other items of equipment for taking water quality samples as specified below:

- list of, and relevant information on, sampling sites including historical data on EC, temperature and pH
- keys to the premises of the well sites and protection covers, tools, and PVC tubing
- maps marked with relevant sampling points and travelling routes
- a sampling programme split into daily tasks
- bottles with distilled water
- standard glass and plastic-ware required for sampling and related measuring and treatment procedures
- a supply of labels, pencils, and marker pens
- report forms and a field notebook
- first aid kit

9. Observation Practice

9.1 Taking Samples

If a sampling can or a bailer is used to take manual samples from hand-dug wells, the sampling device should be rinsed out several times with the water to be sampled before any bottles are filled; each sample bottle should be similarly rinsed out before filling.

In order to prevent samples degrading and giving false analytical results, it is necessary to chemically pre-treat some samples as soon as they are obtained. Also, many parameters require particular sample containers for the same reason. Table 6 gives the type of container that should be used and the pre-treatment method required for each proposed water quality parameter.

For all samples, except those for dissolved oxygen analysis, it is good practice to leave a small air space at the top of the sample bottle to allow for mixing prior to analysis. For samples intended for dissolved oxygen analysis, care should be taken to exclude excess air from the sample. Therefore, sample bottles should be filled to the brim; the sample should be poured carefully to avoid agitation, and the bottle should be gently tapped once full to dislodge any air bubbles clinging to its inside surface.

When taking samples for microbiological analysis it is important to prevent contamination of the inside of the bottle or cap by touching with fingers or any non-sterile tools. Samples for this type of analysis should be obtained before other sample types.

9.2 Purging Prior to Sampling

To be worked out in detail. Check italics also

The minimum purging requirement for each well to be sampled need to be worked before starting the field sampling programme, in accordance with the approach detailed in appendix A.

In the field the observer should have the following information before he goes to the well:

- Minimum number of initial well volumes to be replaced (*default value 6* but well-specific adjustments based on calculations (as in Appendix A) using static field data for the specific well is recommended)
- Depth and diameter of the well (static well data)
- Available pump rate (limited by the maximum permissible purging rate of *100 lpm*)

At the site the field observer should obtain:

- The actual static water level (SWL)

From this information he must calculate the minimum required purging time according to:

$$MPT = \frac{2.5\pi \times \phi^2 \times (H - SWL) \times MPV}{Q}$$

- MPT = minimum required time of purging, minutes
 MPV = minimum number of purging volumes, -
 H = initial thickness of water column, m
 SWL = depth to static water level, m
 ϕ = internal diameter of well, cm
 Q = pump discharge (limited to 100), lpm

The monitoring of the various field parameters (T, pH, ORP and EC) should start at the same time as purging. Do not stop purging before all these parameters have stable readings for a minimum of 5 minutes and the purging time exceeds the minimum required purging time. The initial and final values for T, pH, ORP and EC should be recorded along with all other data related to the sampling operation.

If the well is equipped with an AWLR it should carefully be removed conform instructions provided with the instrument.

Before starting purging, the technical condition of the well needs to be checked and its suitability for the insertion of a submersible pump needs to be verified. This is usually performed by inserting a metal body similar in shape to the submersible pump, into the well. Once smooth insertion of the metal body to the required depth and its subsequent removal is performed, the submersible pump can be safely inserted and the purging operation may start.

9.3 Labelling and Coding of Samples

Immediately after sampling, the sample bottles should be labelled and given a unique code number. Information on the label should include:

- sample code number
- date and time of sampling
- sample point description and code number (if applicable)
- depth of the sample and well diameter
- analysis to be carried out
- pre-treatment carried out on the sample
- any special notes for the analyst
- sampler's name

After labelling the samples should be placed in a purpose-built bottle carrier for transportation.

9.4 Recording of Field Observations

All water quality sampling personnel should carry with them a field notebook in which observations and records can be kept. At the time of sampling this notebook should be filled in with the following information:

- all the information on the sample label (see above)

- details of which samples were collected
- the on-site measurements made and the results obtained
- the weather conditions, including the shade air temperature, at the time of sampling
- any details about the condition of the sample which may be relevant (e.g., if it has an odour)

The above information will be of considerable value when interpreting the subsequent analytical results

9.5 On-site Measurements

Water quality sampling personnel are also required to measure some water quality parameters in the field. First, because it is more convenient to do so and second because a number of these parameters can change their value before they can be returned to the laboratory for analysis. These parameters, which provide immediate information on the specific site, should be compared with historical data as a validation measure. Significant departure from previous data requires repeated measurements and, if confirmed, the samples from this point should be given for detailed laboratory analyses.

9.5.1 On-site Measurement of Temperature

Temperature can be measured in the field with a glass thermometer or a thermistor attached to a suitable meter. If a pH or conductivity meter (or a combined meter) is being used for water quality, a temperature measurement can normally be obtained directly from this device.

Water temperature must be determined in the sample immediately after it is collected from the borehole. Temperature should be measured in Celsius to the nearest 0.1°C after the reading has become stable.

9.5.2 On-site Measurement of pH

The most accurate method of measuring water pH in the field is by means of a portable, purpose-designed meter. Such meters are normally capable of measuring pH to the nearest 0.05 of a pH unit by using a 'glass' and a 'reference' electrode (although these are often combined in a single probe).

Before measuring pH, it is necessary to calibrate the meter. This should be done at least once per day, before the first pH measurement is attempted. The procedure for a pH meter with automatic temperature correction (as most now have) is as follows:

- i. After removing their protective caps, the electrodes are rinsed in distilled water and carefully blotted dry with soft absorbent paper. *NOTE: Care needs to be exercised here as the electrodes can be very fragile.*
- ii. The electrodes are then placed in a fresh buffer solution and, after allowing time for meter stabilisation, the pH reading of the meter is adjusted to the pH of the buffer solution (normally pH = 7)
- iii. The electrodes are then rinsed again with distilled water and blotted dry
- iv. If a pH measurement is not to be taken immediately, the electrodes should be replaced in their protective caps. Normally, the glass electrode cap is filled with distilled water before replacement to prevent the electrode drying out.

Once calibrated, the pH meter can be used to directly measure water pH by placing the electrodes in the water sample immediately after it is obtained. Care should be taken to ensure that the electrodes are rinsed with distilled water before and after each

determination, and that distilled water is placed into the glass electrode cap for transportation.

9.5.3 On-site Measurement of Conductivity

Conductivity can be measured in the field with a purpose-designed meter in milliSiemens per centimetre ($1 \text{ mS/cm} = 1000 \text{ } \mu\text{mhos/cm}$). Before measuring conductivity it is necessary to calibrate the meter. This should be carried out at least once per day, before the first measurement is taken. Calibration is achieved by determining the conductivity of a known, fresh solution of potassium chloride and adjusting the meter accordingly. In order to ensure the conductivity reading is accurate, it is necessary to adjust the conductivity reading to compensate for temperature changes. In most modern meters this is done automatically, however.

Once calibrated, the conductivity of the water can be measured by immersing the electrode in a sample of water as soon as it is taken. It is important to remember that conductivity meters often take some minutes to stabilise. The reading must, therefore, be taken after this stabilisation has occurred.

9.5.4 On-site Measurement of ORP

ORP can be measured in the field with a purpose-designed platinum (Pt) electrode and meter in mV. Before measuring the ORP it is necessary to calibrate the meter. This should be carried out at least once per day, before the first measurement is taken. Calibration is achieved by determining the ORP of a solution with known ORP (Zobell's solution). For correct interpretation, simultaneous recording of the temperature of the water sample is necessary.

Once calibrated, the ORP of the water can be measured by immersing the electrode in a sample of water as soon as it is taken. Contact with air should be prevented as much as possible. It is important to remember that an ORP electrode often takes some minutes to stabilise, the reading must therefore be taken after this stabilisation has occurred.

10. Concluding Remarks

Commonly, groundwater quality networks and programmes evolve over time from baseline data collection to trend and surveillance data collection. Such evolution reflects a change in monitoring objectives, and implies on the one hand, a reduction in the density of the observation sites, and on the other hand, increasing the variety of parameters monitored. The frequency of sampling and the list of parameters covered routinely is gradually modified into an area-specific monitoring programme, reflecting the background configuration established through baseline monitoring and the outcomes of survey monitoring programmes.

Special attention needs to be given to regions prone to rapid quality deterioration which include:

- shallow groundwater associated with irrigation (command) areas
- highly developed and over-exploited aquifers where the groundwater table has been lowering over the years
- coastal multi-aquifer systems where the fresh/seawater interface balance has been disturbed
- industrialised and intensively urbanised regions
- polluted surface water sources which recharge shallow groundwater aquifers

The change in the quality monitoring setting is actually an on-going process that often reflects the impact of human activities on the environment. To keep pace with this dynamic process, the agencies who are in charge of groundwater monitoring need feedback from land-use planning and development agencies in order that monitoring objectives can be continually assessed and monitoring plans and activities can be modified accordingly.

Table 1 Groundwater Quality Monitoring Objectives, Network Densities and Sampling Frequencies

Category	Type	Objective	Network Density	Sampling Frequency (per year)	Parameters
Baseline/ Trend ¹	Baseline	Baseline concentrations	Initially to correspond 1:1 to water table monitoring networks, provided the analytical capacity is available	1 (unless special circumstances apply) 4-6 temporarily for shallow wells	see Table 2 limited parameters
	Trend	Early tracing of slow & rapid quality changes & deterioration processes	As above	As above 4-6 temporarily for shallow wells	limited parameters
Surveillance ²	Water Use	Check that water is fit for use	At all points of use	Drinking water: 12 ³ Irrigation water: 1 Livestock watering: 1	see Table 3
Survey ⁴	Management & Research	Reconstruction of water and solute evolution. Identification and source of pollutants. Characterise water bodies	Dependent upon scale of survey required	Sufficient to characterise problem & likely solution	Depends upon needs of each survey

¹ Baseline/Trend: Long-term, standardised measurement in order to define status and trends

² Surveillance: Continual, specific measurement for the purpose of water quality management and operational activities

³ If reliable fast screening of drinking water supply boreholes can be accomplished with field test kits it may be possible to reduce this sampling frequency

⁴ Survey: A finite duration, intensive programme to measure for a specific purpose

Table 2 Groundwater Quality Parameters (Baseline/Trend)

Parameter Group	Parameter	Baseline	Trend
General	Temperature	X	X
	Suspended Solids	X	X
	Conductivity	X	X
	pH	X	X
	Total Dissolved Solids		
Nutrients	Ammonia Nitrogen		
	Total Oxidised Nitrogen	X	X
	Total Phosphorus	X	X
Organic Matter	Chemical Oxygen Demand		A
	Biochemical Oxygen Demand		X
Major Ions	Sodium	X	A
	Potassium	X	A
	Calcium	X	A
	Magnesium	X	A
	Carbonates and Bicarbonates	X	A
	Chloride	X	X
	Sulphate	X	A
Other Inorganics	Silica	X	A
	Fluoride	X	A
	Iron	X	A
	Boron	X	A
Trace Elements	Cadmium	A	A
	Arsenic	A	A
	Mercury	A	A
	Zinc	A	A
Organics	Pesticide Indicator	P	P
	Synthetic Detergents	P	P
	Organic Solvents	P	P
	Phenols	P	P
Microbiology	Total coliforms	A	A

X = Analysis of parameter required.
A =Area specific - analysis of parameter is required unless previous analyses indicate that concentrations are stable and far below any limiting thresholds.
P = Pollution suspected - analysis of parameter only required if this type of pollution is known or suspected.

Table 3 Groundwater Quality Parameters (Surveillance)

Parameter Group	Parameter	Water Use ¹		
		D	I	L
General	Temperature	X	X	
	Suspended Solids	X		
	Conductivity	X	X	X
	pH	X	X	X
	Total Dissolved Solids		X	
Nutrients	Ammonia Nitrogen	X		
	Total Oxidised Nitrogen			X
	Total Phosphorus			
Organic Matter	Chemical Oxygen Demand			
	Biochemical Oxygen Demand	X		
Major Ions	Sodium		X	
	Potassium			
	Calcium		X	
	Magnesium		X	
	Carbonates and Bicarbonates			
	Chloride	X	X	
	Sulphate			
Other Inorganics	Silica			
	Fluoride	X		
	Iron			
	Boron		X	
Trace Elements	Cadmium			
	Arsenic			
	Mercury			
	Zinc			
Trace Organics	Pesticide Indicator	X		
	Synthetic Detergents			
	Organic Solvents	X		
	Phenols	X		
Microbiology	Total coliforms	X	X ²	X ²

¹ D = Water Abstracted for Treatment as Drinking Water, I = Water for Irrigation, L = Water for Livestock Watering

² It is recognised that practically, even though high concentrations of coliforms may exist in irrigation and livestock watering waters, it may not be possible to discontinue the use of a particular water source

Table 4 Water Quality Parameters Maximum Storage Times

Parameter Group	Parameter	Recommended ¹	Required ²
General	Temperature	Immediate	Immediate
	Suspended Solids	7 days	7 days
	Conductivity	28 days	28 days
	pH	Immediate	Immediate
	Total Dissolved Solids	7 days	7 days
Nutrients	Ammonia Nitrogen ³	7 days	28 days
	Total Oxidised Nitrogen ³	---	28 days
	Total Phosphorus	---	---
Organic Matter	Chemical Oxygen Demand ³	7 days	28 days
	Biochemical Oxygen	6 hours	48 hours
Major Ions	Sodium ³	6 months	6 months
	Potassium ³	6 months	6 months
	Calcium ³	6 months	6 months
	Magnesium ³	6 months	6 months
	Carbonates and	24 hours	14 days
	Chloride	28 days	28 days
	Sulphate	28 days	28 days
Other Inorganics	Silica	28 days	28 days
	Fluoride	28 days	28 days
	Iron ³	6 months	6 months
	Boron	28 days	6 months
Trace Elements	Cadmium ³	6 months	6 months
	Arsenic ³	6 months	6 months
	Mercury ³	28 days	28 days
	Zinc ³	6 months	6 months
Trace Organics	Pesticide Indicator)	7 days	7 days
	Synthetic Detergents	---	---
	Organic Solvents	---	---
	Phenols ³	---	28 days
Microbiological	Total coliforms	8 hours ⁵	24 hours ⁵

¹Time limits taken from those recommended in: 'Standard Methods for the Examination of Water and Wastewater', 19th Edition 1995, Eds: Eaton A D, Clesceri L S and Greenberg A E; Published by: APHA, AWWA and WEF

² "Required" means that unless the parameter is determined within this time period the results will have little validity. Times correspond to limits imposed by the US Environmental Protection Agency (EPA) for 'regulatory' samples.

³ After recommended pre-treatment

⁴ Time limit stated is equivalent to that given for 'alkalinity' analysis

⁵ Storage times taken from recommended and maximum times stated in: 'Standard Methods for the Examination of Water and Wastewater', 19th Edition 1995, Eds: Eaton A D, Clesceri L S and Greenberg A E; Published by: APHA, AWWA and WE

Table 5 Parameter values giving 85% purging efficiency when 6 well volumes are replaced

Parameter	Value	More well-volumes required if
Well Diameter	10 cm	diameter larger then 10 cm
Transmissivity	20 m ² /d	transmissivity lower then 2 m ² /d
Specific Yield	2 %	specific yield lower then 2 %

Table 6 Water Quality Parameters - Sampling Containers and Pre-treatments Required

Parameter Group	Parameter	Sample Container	Sample Pre-treatment
General	Temperature	None - on-site analysis	None - on-site analysis
	Suspended Solids	1	None
	Conductivity	None - on-site analysis	None - on-site analysis
	pH	None - on-site analysis	None - on-site analysis
	Total Dissolved Solids	1	None
Nutrients	Ammoniacal Nitrogen	2	6
	Total Oxidised Nitrogen	2	6
	Total Phosphorus	3	None
Organic Matter	Chemical Oxygen Demand	2	6
	Biochemical Oxygen Demand	1	None
Major Ions	Sodium	2	7
	Potassium	2	7
	Calcium	2	7
	Magnesium	2	7
	Carbonates and Bicarbonates	1	None
	Chloride	1	None
	Sulphate	1	None
Other Inorganics	Silica	1	None
	Fluoride	1	None
	Iron	2	7
	Boron	1	None
Metals	Cadmium	2	7
	Arsenic	2	7
	Mercury	3	7
	Zinc	2	7
Organics	Pesticide (Indicator)	4	None
	Synthetic Detergents	1	None
	Organic Solvents	1	None
	Phenols	4	6
Microbiology	Total coliforms	5	None

Notes:

1. 1000 millilitre polyethylene bottle
2. 500 millilitre polyethylene bottle
3. 100 millilitre glass bottle
4. 1000 millilitre glass (or Teflon) bottle with Teflon lined caps
5. Strong thick-walled, screw-capped glass bottle (300 millilitre capacity)
6. Samples should be acidified with 2 ml of concentrated sulphuric acid
7. Samples should be acidified with 2 ml of concentrated nitric acid.

(Information adapted from 'Water Quality Monitoring', Edited by Bartram J & Ballance R, E & F N Spon, London, 1996)

A Specifications for Submersible Pumps

The specifications for capacity and discharge of submersible pumps depend largely on the situation in the field (depth of the water table, hydraulic characteristics of the aquifer, diameter of the well, initial thickness of the water column, time available for the sampling procedure etc.). The effect of varying field conditions on the required pump capacity are calculated and presented in Table A-1. In these calculations the following assumptions are made:

- pump heat loss is 20% (η , efficiency = 80%)
- specific yield is 2%
- Darcy-Weisbach coefficient is 0.04 (for both casing and delivery tube)
- transition losses add up to 1 m
- height of delivery point above ground is 2m
- diameter of the delivery tube is 3.81cm (1.5 inch)
- depth of pump below the dynamic water level is 2m

The set-up of the well under purging is presented in Figure A-1. In the calculations it is assumed that mixing of well water and aquifer water is complete and instantaneous. The fraction aquifer water in the water pumped from the well is expressed in Equation A-1. The formula is composed of the quotient of the volume of water purged from the aquifer ($Q \times t$ minus draw down volume) and the total volume of water involved ($Q \times t$ plus the initial well volume). Rewritten in Equation A-2 it shows that the ratio of the volumes of pumped and initial water almost equals the ratio of the fractions of aquifer and non-aquifer water. The additional term ($s/H/(1-C)$) represents the effect of the relative drawdown (s/H). The formula to calculate draw down is expressed in Equation A-3.

$$C = \frac{Qt - \pi r^2 s}{H\pi r^2 + Qt}$$

Equation A-1

$$\frac{Qt}{H\pi r^2} = \frac{C}{1-C} + \frac{s/H}{1-C}$$

Equation A-2

$$s = \frac{2.3Q}{4} {}^{10}\log \frac{2.25Tt}{r^2 S}$$

Equation A-3

where:

- C = purging efficiency expressed as fraction of aquifer water, (-)
- Q = pump discharge
- t = time of purging
- s = drawdown
- H = initial thickness of water column
- r = internal radius of well
- T = aquifer transmissivity
- S = specific yield

These equations are dimensionally homogenous and as such any consistent system of units may be used.

The required capacity of the pump is calculated as given Equation A-4, it computes the product of discharge, Q and total height to overcome (consisting of actual height ($h_d + d + s$), virtual height caused by friction in tubes, h_{vt} and casing, h_{fc} and the energy contents of the out-flowing water, $v^2/2g$).

$$\square \quad \text{Pump Capacity} = \frac{1000 Q (h_d + s + d + h_{ft} + h_{fc} + h_t + \frac{v_t^2}{2g})}{75}$$

with:

$$h_{fc} = \frac{f_c (H - s - d_p) v^2}{4gr} ; v = \frac{0.33Q}{r^2}$$

$$h_{ft} = \frac{f_t (d_p + s + d + h_d) v_t^2}{4gr_t} ; v_t = \frac{Q}{r_t^2}$$

Equation A-4

where:

- HP = horsepower of the pump
- h_d = height of delivery tube above ground level
- d = depth to static water level
- s = draw-down
- h_{ft} = friction loss in tubing
- h_{fc} = friction loss in casing
- h_t = height loss in transitions (bends etc.)
- v_t = stream velocity in delivery tube
- g = gravity (9.81 m/s^2)
- η = pump efficiency
- f_c = Darcy-Weisbach coefficient of well casing, (-)
- d_p = depth of pump below dynamic water level
- r = internal radius of well
- f_t = Darcy-Weisbach coefficient of delivery tube, (-)
- r_t = radius of delivery tube
- v = stream velocity in well

These equations are applicable in metric system only, Pump Capacity in horsepower

A.1 Pump discharge

Figure A-2 shows the effect of pumping time on purging efficiency for different pump discharges. As expected, purging efficiency increases with pumping time and pump discharge applied. This figure can be used to select the appropriate pump discharge for a required purging time.

A.2 Pump capacity (HP)

The required pump capacity (in terms of power consumption) is a function of the dynamic lift head of the water in the well, the discharge rate needed to obtain the

desired purging efficiency within the time available and the heat loss of the pump. Table A-1 presents the conditions used in the calculations. The dynamic head is a function of the depth to the static water, the draw-down caused by pumping and a few other factors, like friction in tubing, as listed in Equation A-4. Figure A-6 shows the build up of the dynamic head for various depth' to static water level. As shown, all factors except friction loss in casing and the energy content of the out-flowing water have practical importance at small depths to SWL. For greater depth to SWL only the depth to SWL itself is contributing significantly to the dynamic head (all other factors become relatively unimportant also caused by the decline in Q).

Figure A-3 shows the pump capacity as a function of static water level depth. The curve shows a maximum pump capacity at moderate depths to SWL. At lower depths to SWL the pump capacity requirement is relatively low because of limited lift head. At higher depths to SWL the pump capacity requirement is also relatively low because of a low discharge needed to purge the small initial well volume. This figure also shows the effect of purging time. In order to decrease the purging time by 33% (say from 30 to 20 minutes) a 65% more powerful pump is needed (1.8 instead of 1.1 HP). This disproportionate increase is caused by the additional draw-down resulting in increased lift head and this effect will be larger in aquifers with lower transmissivity.

Figure A-4 shows that the transmissivity of the aquifer determines to a large extent the required discharge and capacity; lower transmissivities require higher capacity (HP) pumps!

Figure A-5 shows that a larger well diameter requires a larger capacity pump. The required capacity increases by almost a factor of three when the well diameter increases from 2.5 to 4 or from 4 to 6 inches. The most commonly applied diameter of purpose build piezometers under Hydrology Project is 4 inch (*is this correct?*). In many countries in Europe and the US a diameter of 2 to 2.5 inch is common for this type of monitoring piezometers. From a monitoring point of view one can state that the smaller the diameter the better, for practical reasons (drilling, availability of material and experienced contractors etc.) a larger diameter may be preferred.

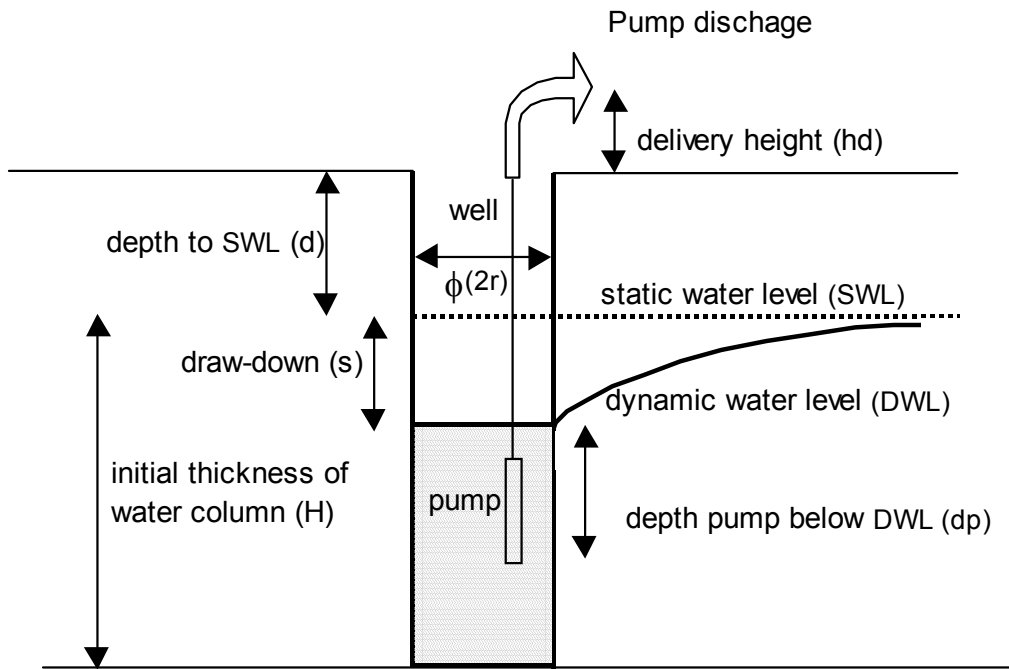


Figure A-1 Schematic Presentation of Well Under Purging (pumping) Operation

Conditions	Field	Initial water column (H)	(m)	85	80	70	60	50	40	30	20	10	5	3
		Depth to static water level (d)	(m)	5	10	20	30	40	50	60	70	80	85	87
		Transmissivity (T)	(m ² /d)	20	20	20	20	20	20	20	20	20	20	20
		Specific yield (S)	(-)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
		Well Diameter (ϕ)	(inch)	4	4	4	4	4	4	4	4	4	4	4
	Equipment	Depth of pump below dynamic water level (dp)	(m)	2	2	2	2	2	2	2	2	2	2	2
		Height of delivery above ground level (hd)	(m)	2	2	2	2	2	2	2	2	2	2	2
		Head loss in transitions and bends (ht)	(m)	1	1	1	1	1	1	1	1	1	1	1
		Tube Diameter	(inch)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
		Darcy-Weisbach coef. for casing (fc)	(-)	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Darcy-Weisbach coef. for delivery tube (ft)		(-)	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	
Chols	Pumping Time (t)	(min)	30	30	30	30	30	30	30	30	30	30	30	
	Pump Discharge (Q)	(lpm)	143.7	136.1	119.0	102.0	85.0	67.9	50.9	34.0	17.0	8.5	5.1	
Calculations	Initial Well Volume	(l)	689	648	567	486	405	324	243	162	81	41	24	
	No. of Initial Volumes Purged	(-)	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	
	Draw-down (s)	(m)	8.1	7.6	6.7	5.7	4.8	3.8	2.9	1.9	1.0	0.5	0.3	
	Dynamic Head	(m)	20.1	24.2	32.2	40.5	48.9	57.5	66.2	75.1	84.0	88.5	90.3	
	Purging efficiency (C)	(-)	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	
	Velocity in casing (v)	(m/s)	0.098	0.093	0.082	0.070	0.058	0.047	0.035	0.023	0.012	0.006	0.003	
	Velocity in delivery tube (vt)	(m/s)	2.101	1.991	1.741	1.491	1.243	0.993	0.745	0.497	0.248	0.124	0.074	
	Friction head in casing (hfc)	(m)	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	Friction head in delivery tube (hft)	(m)	3.80	3.32	2.38	1.63	1.06	0.62	0.32	0.13	0.03	0.01	0.00	
	Height of delivery above ground level (hd)	(m)	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
	Head loss in transitions and bends (ht)	(m)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
	Pump Capacity (efficiency 80% assumed)	(HP)	0.80	0.91	1.07	1.15	1.15	1.08	0.94	0.71	0.40	0.21	0.13	
	Pump Capacity (efficiency 80% assumed)	(W)	599	682	795	855	861	809	699	528	295	155	95	
After 30 minutes of pumping, 85% of the water pumped originates from the aquifer and 15% from stagnant well water.														

Table A-1 Pump Capacity in a 90 m-deep, 4-inch diameter Well with Varying Depths to Static Water Level

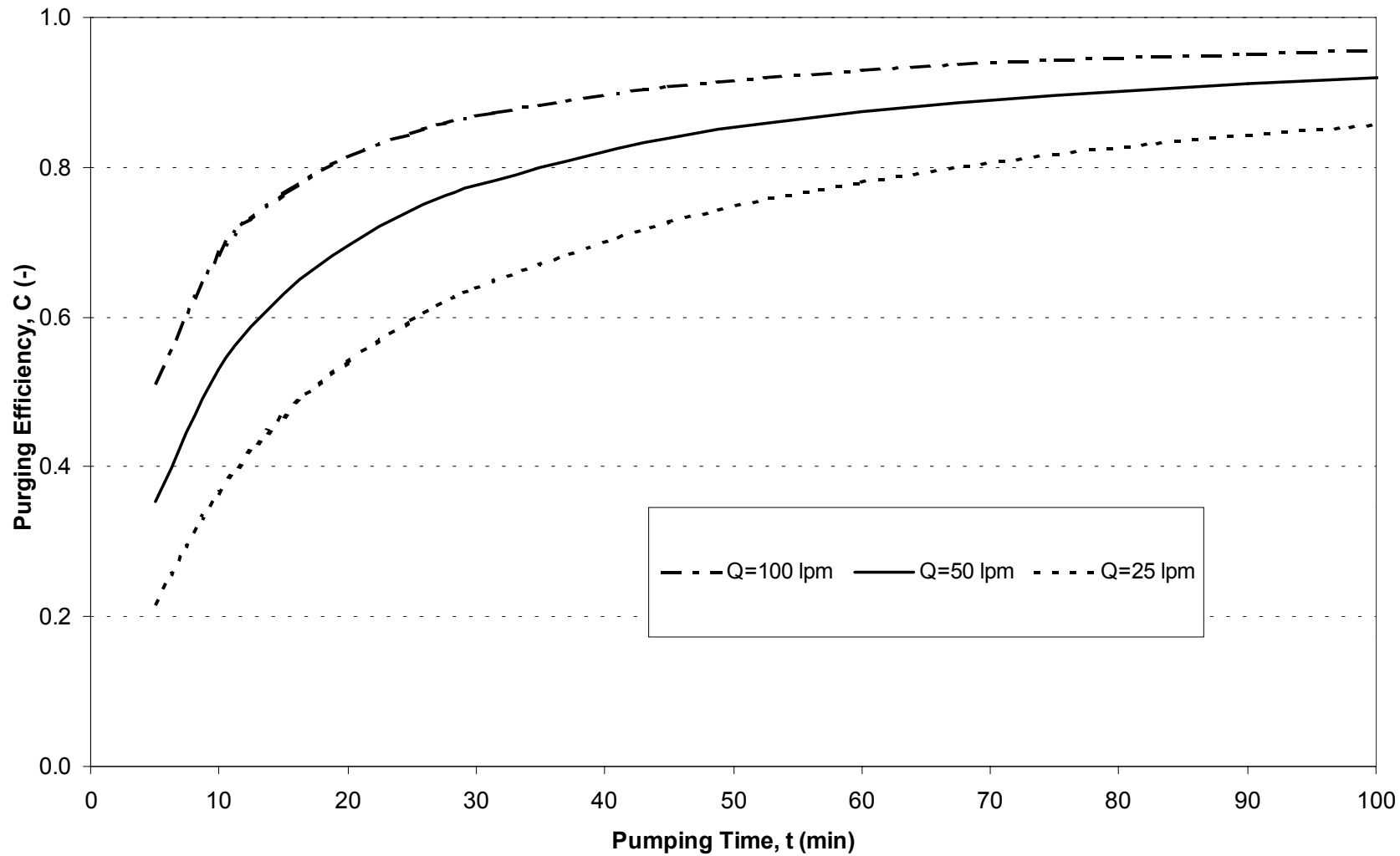


Figure A-2 Purging efficiency as a function of pumping time for different pump discharges.

Conditions: depth to SWL=40m, Well Depth=90m, $T=20\text{m}^2/\text{d}$, $S=2\%$, Pump Efficiency =0.8, $\phi=4"$, $f_c=f_t=0.04$)

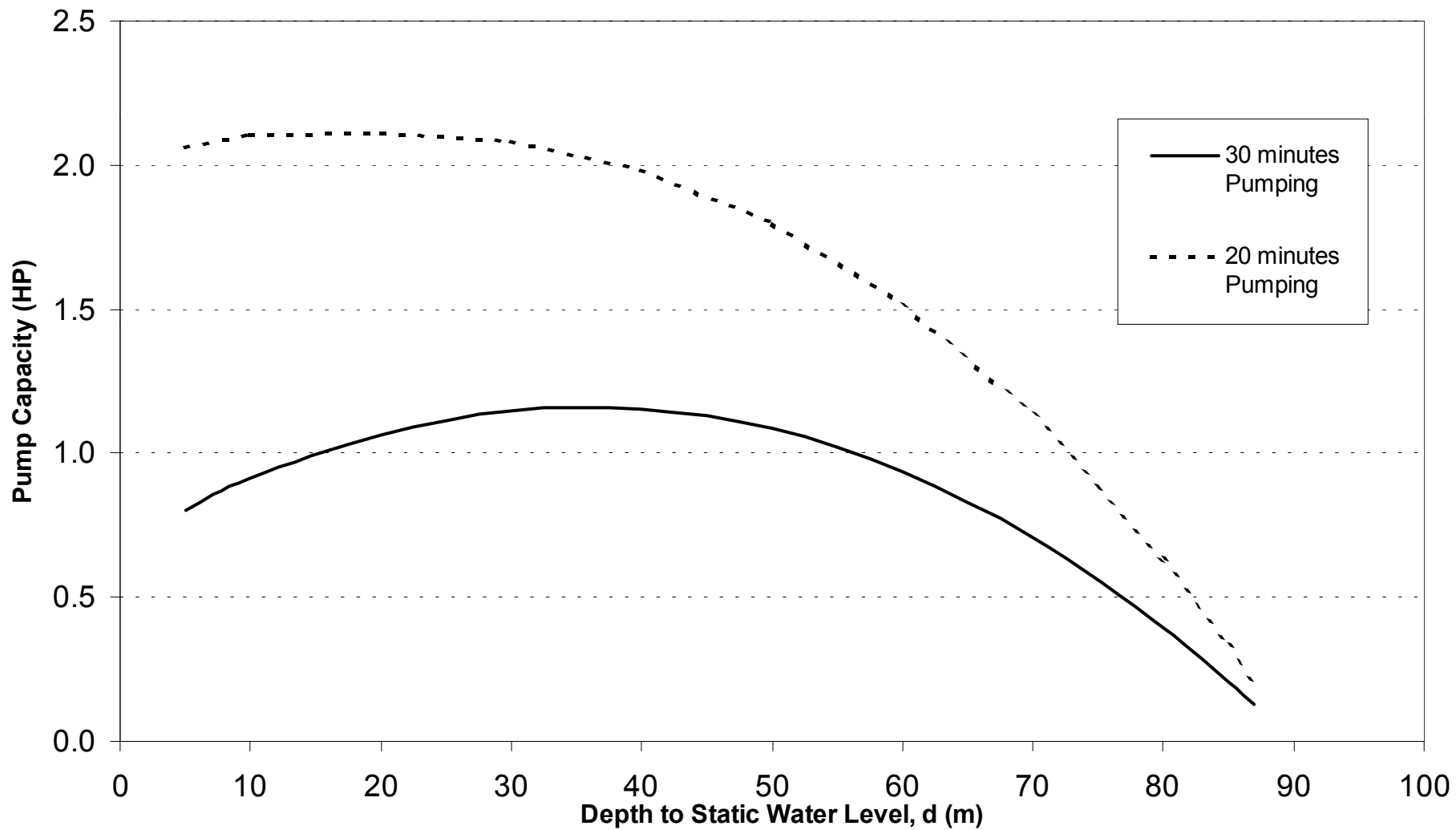


Figure A-3 Pump capacity required to obtain a 85% % purging efficiency as a function of depth to the static water level and purging time.

Conditions: Well Depth=90m, $T=20\text{m}^2/\text{day}$, $S=2\%$, Pump Efficiency=0.80, $\phi=4"$, $f_c=f_t=0.04$

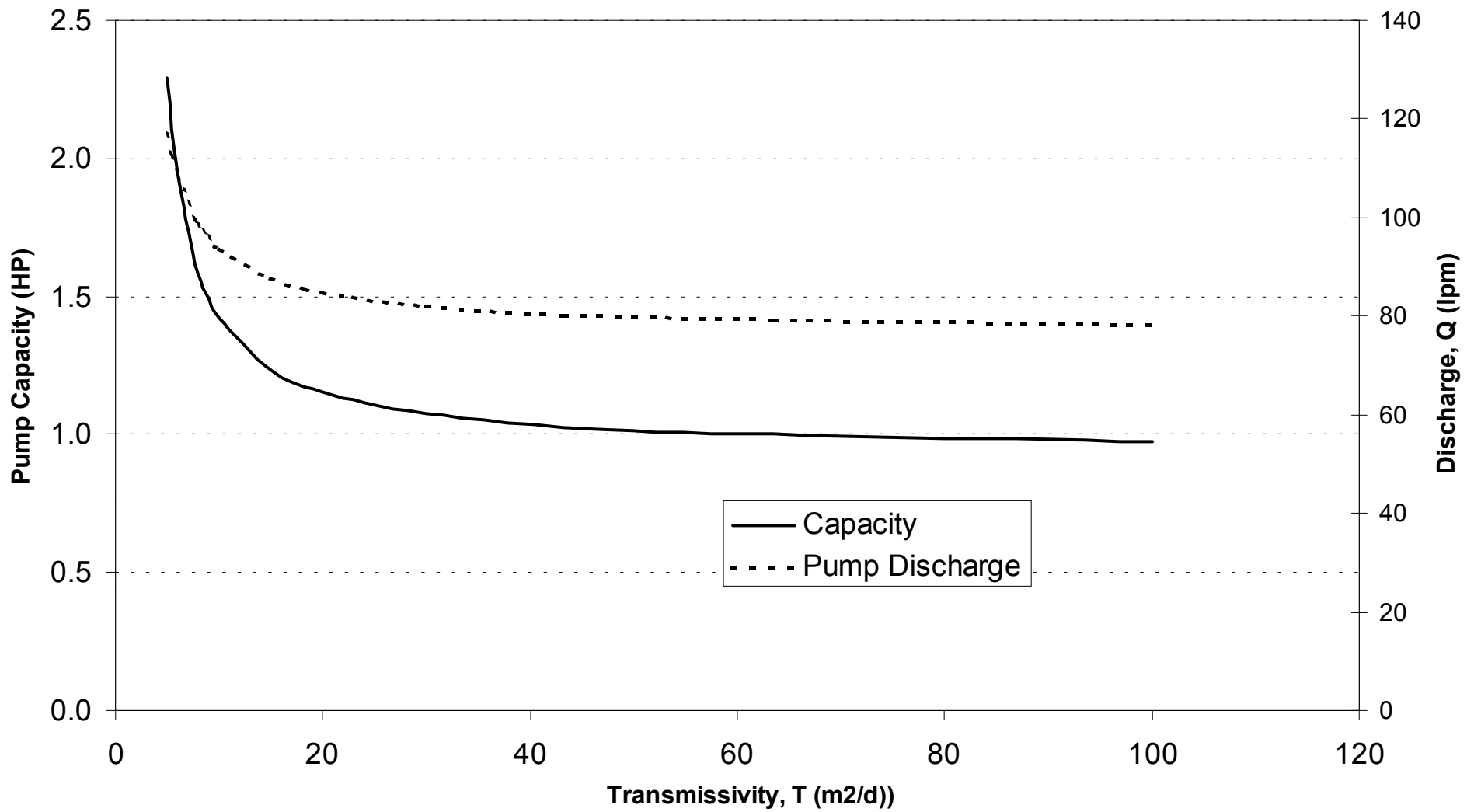


Figure A-4 Pump capacity and discharge required obtaining 85% purging efficiency after 30 minutes as a function of aquifer transmissivity.

Conditions: depth to SWL=40m, Well Depth=90m, $\phi=4"$, Pump Efficiency=0.80, S=2%, $f_c=f_t=0.04$

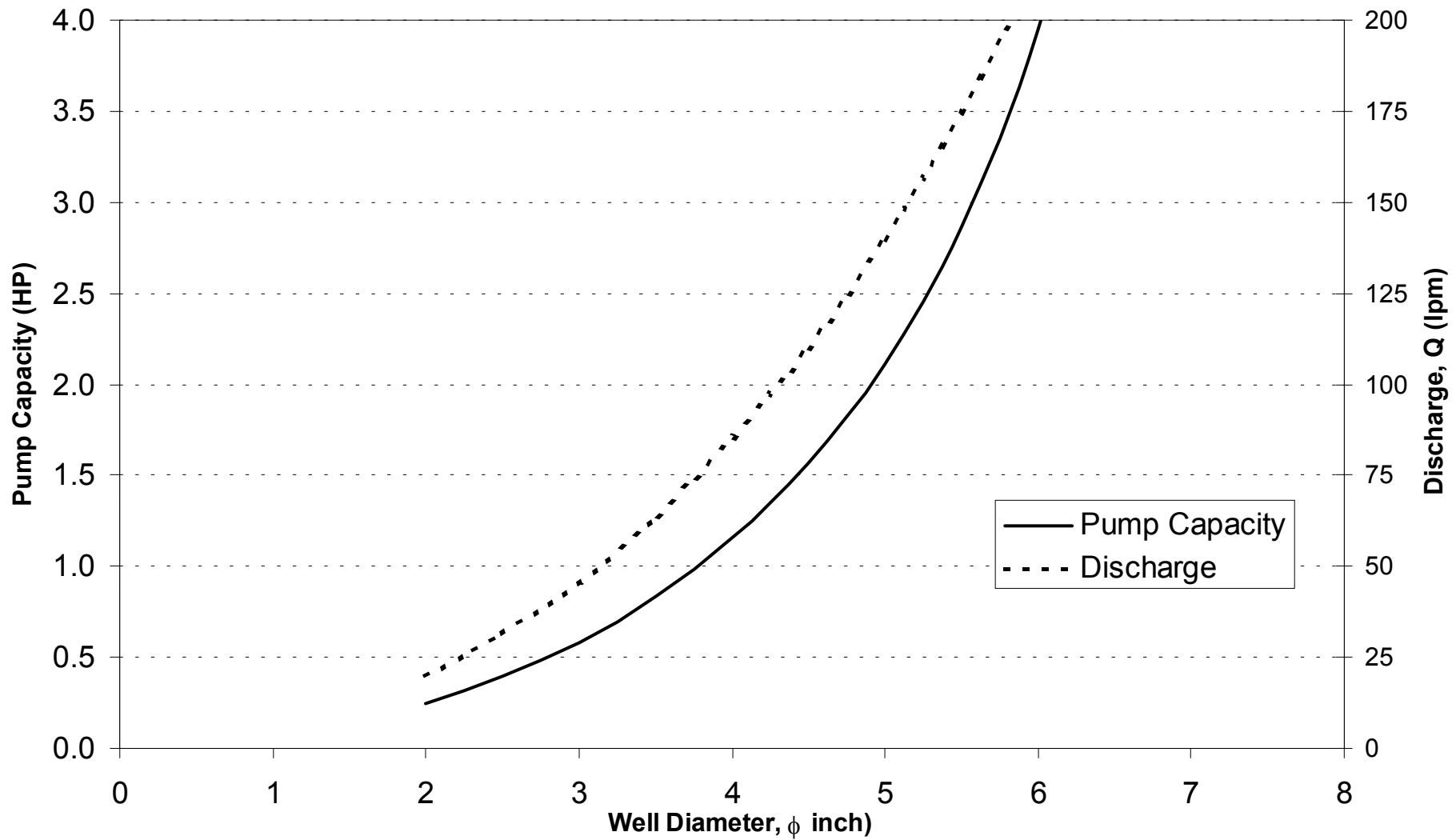


Figure A-5 Pump capacity and discharge required obtaining 85% purging efficiency after 30 minutes as a function of well diameter.

Conditions: depth to SWL=40m, Well Depth=90m, $T=20\text{m}^2/\text{d}$, $S=2\%$, Pump Efficiency = 0.80, $f_c=f_t=0.04$

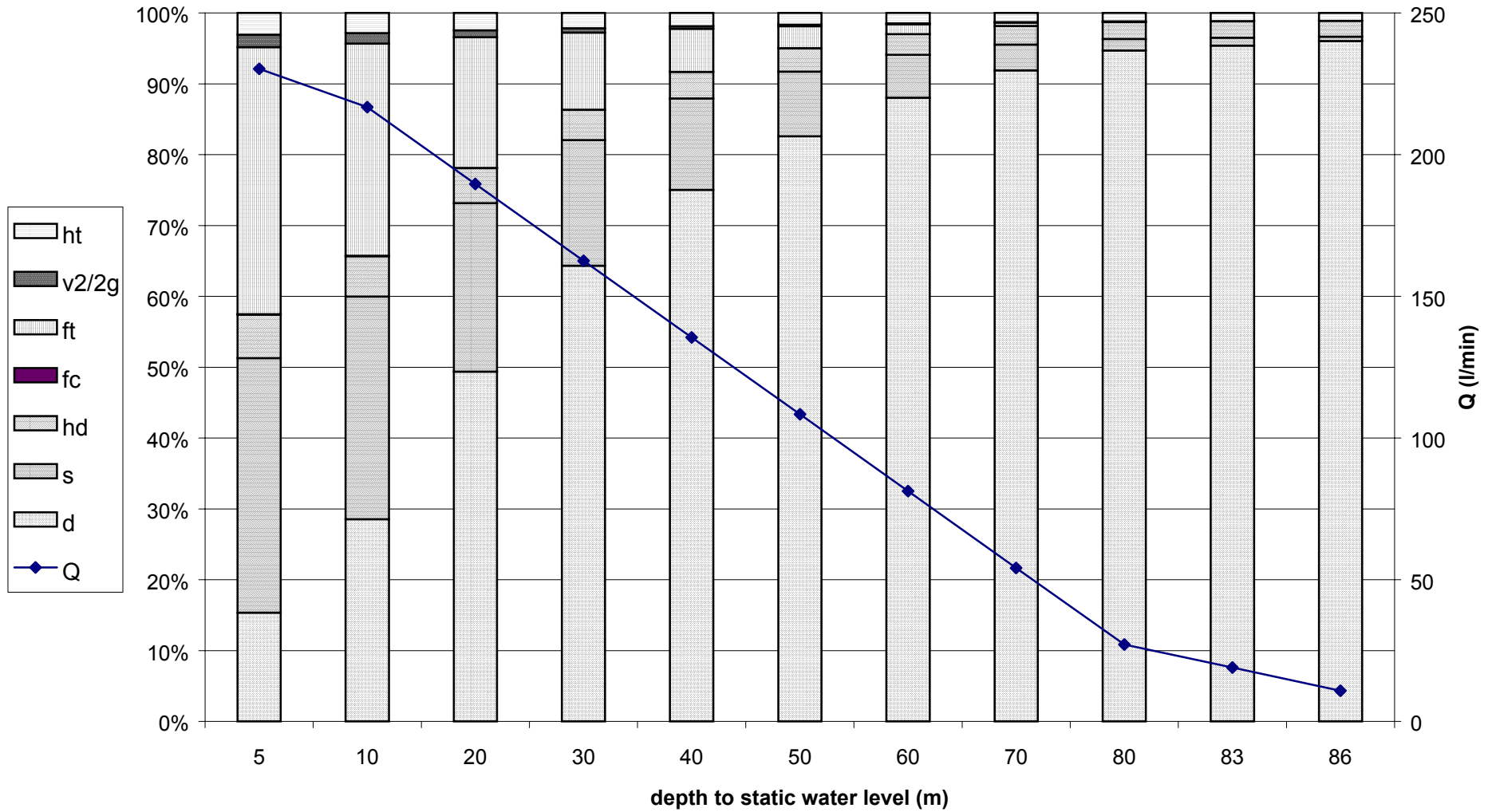


Figure A-6 Relative importance of various components contributing to the Dynamic Head of a 90m deep well for various SWL