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Characterization of groundwater flow for near surface disposal facilities

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FOREWORD

The objective of adioactive waste disposal is to provide long term isolation of waste to protect humans and the environment while not imposing any undue burden on future generations. To meet this objective, establishment of a disposal system takes into account the characteristics of the waste and site concerned. In practice, low and intermediate level radioactive waste (LILW) with limited amounts of long lived radionuclides is disposed of at near surface disposal facilities for which disposal units are constructed above or below the ground surface up to several tens of meters in depth. Extensive experience in near surface disposal has been gained in Member States where a large number of such facilities have been constructed. The experience needs to be shared effectively by Member States which have limited resources for developing and/or operating near surface repositories.

A set of technical reports is being prepared by the IAEA to provide Member States, especially developing countries, with technical guidance and current information on how to achieve the objective of near surface disposal through siting, design, operation, closure and post-closure controls. These publications are intended to address specific technical issues, which are important for the aforementioned disposal activities, such as waste package inspection and verification, monitoring, and long-term maintenance of records.

Equally important is the issue of groundwater flow characterization in the sense that groundwater is the main medium which can transport radionuclides by natural processes from the disposed waste to the biosphere and, moreover, its flow characteristics can be highly complex. Although groundwater flow characterization is of prime concern during the pre-operational phase, it also remains important throughout the operational and post-closure phases. Continued development of the understanding of the groundwater system is required to incorporate any changes from the predicted conditions detected in the monitoring programme.

The issue of groundwater flow has been addressed by a number of IAEA publications as part of site investigation studies. Nevertheless, none of them has been intended to deal with overall matters with sufficient detail on characterization of groundwater flow for near surface disposal facilities. It is, therefore, meaningful to prepare a report focusing on groundwater flow characterization in an integrated way.

This report encompasses technical issues of groundwater flow characterization for near surface disposal facilities, mainly from the viewpoint of approach and programme establishment, methodologies including investigation techniques and modelling, and use of the results for design and performance assessment of the repository. Readers are reminded of the fact that the actual technologies that need to be applied and the programme of work required will be specific to each site.

The report was developed with the help of consultants and through an Advisory Group meeting held in 1996. K.W. Han of the Division of Nuclear Fuel Cycle and Waste Technology was the IAEA officer responsible for this publication.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Through the years the IAEA has developed a logically consistent framework for the safe disposal of radioactive waste. Details are contained in Refs [1, 2]. One of the key features of the scheme is the requirement that the longevity of the isolation barriers be commensurate with the longevity of the waste. This means that only short lived low and intermediate level waste [3] can be placed in near surface disposal facilities [4].

Near surface disposal can be implemented in different ways ranging from repositories where the disposal units are located on the original ground surface, or just a few metres below ground, to rock caverns at a depth of several tens of metres. In respect to the isolation barriers, disposal units can consist of trenches or wells, relying almost entirely on the geological materials for containment, and of engineered units where the man-made barriers provide adequate containment without the backup of the geosphere [5, 6].

As in practically all underground disposal systems, subsurface water is the potentially critical mobilization and transport vehicle of the hazardous substances contained in the waste. Consequently a thorough characterization of the relationship between subsurface water and disposal units and of the groundwater flow regime is essential for the assessment of the safety of near surface disposal facilities.

Since the migration of hazardous substances contained in solid waste needs to be preceded by mobilization, usually consisting of leaching by infiltration of water or groundwater, it goes without saying that a critical objective of the siting and design of near surface repositories should be to prevent (or at least to minimize) the contact between waste and water. The most effective way of avoiding the generation of leachate is to ensure that the bottom of the disposal units is always above the water table and that the defences against water infiltration from the vadose zone are effective.

On the other hand there are many areas where, for climatic or geological reasons, it is impractical to place all disposal units above the water table, therefore alternative repository designs, capable of dealing with this potentially less favourable situation, are also required. It should be pointed out that repositories in rock caverns, due to their greater depth, are likely to be located below the water table unless the host rock is characterized by high permeability and the climate of the area is relatively arid.

1.2. OBJECTIVES

The main objective of this report is to provide a description of the site investigation techniques and modelling approaches that can be used to characterize the flow of subsurface water at near surface disposal facilities, in relation to the various development stages of the repositories. As one of the main goals of defining groundwater flow is to establish the possible contaminant migration, certain aspects related to groundwater transport are also described.

Secondary objectives are to discuss the implications of various groundwater conditions with regard to the performance of the isolation systems.

On the other hand, this report is not intended to be used for comparing different near surface disposal options, nor as a guide on how to develop a disposal facility.

1.3. SCOPE AND STRUCTURE

In addition to the descriptions of site characterization techniques and modelling approaches (Sections 6 and 7), this report includes discussions of the following items:

— implications of groundwater flow regimes for near surface disposal facilities (Section 3);
— factors controlling near surface groundwater flow (Section 4);
— structuring groundwater characterization programmes (Section 5);
— QA requirements for characterization of groundwater flow (Section 8);
— groundwater flow and performance assessment (Section 9).

The emphasis of the discussion is on subsurface water flow at facilities with the disposal units below ground but near the surface (maximum depth some meters). This is due to the fact that disposal units above the original ground surface are usually disconnected from groundwater circulation, while groundwater flow in and around a repository in a rock cavern requires characterization methods analogous to those employed in the investigations of deep geological repositories for long-lived waste. The importance of the use of groundwater flow in the understanding of any contaminant migration is addressed throughout the report, in particular, Sections 3, 4 and 5.

2. DEFINITIONS

The more significant technical terms used in this report are defined and referenced below [4, 7, 8, 9]. Others may be found in the IAEA Radioactive Waste Management Glossary [4]. Wherever appropriate the IAEA Glossary definitions have been used, but sometimes these have been adapted or replaced in order to include details more specific to the current report and are detailed below.

Advection. The process by which solutes are transported by the bulk motion of the flowing groundwater [9].

Aquiclude. A hydrogeological unit which, although porous and capable of absorbing water, does not transmit significant quantities under ordinary hydraulic gradients [8, 9].

Aquifer. A hydrogeological unit of permeable rock (due to either porous or fracture permeability), or capable of yielding significant quantities of water under ordinary hydraulic gradients [8, 9].

Aquitard. A hydrgeological unit of a rather impervious and semi-confining nature which transmits water at a very slow rate compared to an aquifer [8].

Diffusion. The process in solutions whereby ionic or molecular constituents move under the influence of kinetic activity in the direction of their concentration gradient. Diffusion occurs also in the absence of any bulk hydraulic movement of the solution [9].

Dispersion (hydrodynamic). The tendency of a solute to spread out from the path that it would be expected to follow according to the advective hydraulics of the flow system. It occurs due to mechanical mixing during fluid advection and molecular diffusion due to the thermal kinetic energy of solute particles [9].

Dispersion (mechanical/hydraulic). Dispersion caused entirely by motion of the fluid [9].

Hydraulic conductivity. Combined property of a porous medium and the fluid moving through it in saturated flow, which determines the relationship, called Darcy's Law, between the specific discharge and the head gradient causing it [8].

Hydrogeological unit. An aquiclude, aquifer, aquitard or possible combination of these [8].

Infiltration. The process of entry of water into the soil that is made available at the ground surface, together with the associated flow away from the ground surface within the unsaturared zone [9].

Porosity. The ratio of aggregate volume of interstices in rock, soil or other porous media to its total volume [4]. The effective porosity is the total porosity actively involved in transport [7].

Porous medium. Material that contains dispersed voids through which water and gas can flow [4].

Recharge. Process, natural or artificial, by which water is added from outside to the zone of saturation of a hydrogeologic unit, either directly into a formation, or indirectly by way of another formation [8].

Retardation. A reduction in the rate of the movement of waterborne substances through the geological materials due to the interaction (e.g. sorption) with an immobile matrix. The degree of this retardation can be quantified [4].

Retardation coefficient (R_d). A measure of capability of porous media to impede the movement of a particular radionuclide being carried by fluid. The term $1 + (?_b/n)\ .\ K_d$ is referred to as the retardation coefficient, where $?_b$ is the bulk mass density of the porous medium, n is the porosity and K_d is the distribution coefficient [4].

Skin factor. This factor reflects the change in hydraulic conductivity in the immediate vicinity of a borehole. The hydraulic conductivity can be increased or decreased by pore or fissure clogging or washout due to drilling or to testing in the borehole [8].

Solutes. Dissolved substances within the groundwater system [9].

Storage coefficient (storativity). Volume of water removed from (or added to) an aquifer per unit horizontal area and per unit decline (or rise) of head [8].

Transitivity. Rate at which water is transmitted through a unit width of the hydrogeological unit under a unit hydraulic gradient. It is expressed as the product of the hydraulic conductivity and thickness of the saturated portion of the hydrogeological unit [4].

Vadose zone. The zone between the ground surface and the water table. This zone contains some water usually held to soil particles by capillary forces. Soon after the infiltration of meteoric water or under bodies of surface water, free moving water percolates through the vadose zone. The vadose zone is called also unsaturated zone, but the first term is to be preferred because portions of the vadose zone may actually be saturated, even though the water may not move according to the gravitational field [8].

3. FUNCTION AND NEEDS OF GROUNDWATER FLOW CHARACTERIZATION

Groundwater is the critical dissolving, mobilizing and transport medium of radionuclides contained in the waste. It is therefore important that mechanisms leading to the inflow of water into the disposal units are well understood. The same is true for the outflow of contaminated water from the facility. A good knowledge of the behaviour of water in and out of the disposal units is a prerequisite for facility design and an essential input for performance and safety assessment [10].

3.1. INTERACTIONS OF GROUNDWATER FLOW WITH NEAR SURFACE DISPOSAL FACILITIES

Depending on the design of the facility, the nature of the geological medium and the location of the disposal units in respect to the water table, a number of different conditions can be anticipated. Examples from various near surface disposal facilities could be used to illustrate some of the anticipated conditions in a hydrogeologically suitable environment.

The degree of interaction between disposal units and groundwater depends on the location of the disposal facility in relation to the water table. In a conceptual way, this can be described by a number of basic situations, namely:

- disposal units above the water table surface, either:
    - constructed above the ground surface or,
    - below the ground surface such as in trenches;
- disposal units, entirely or partially below the water table, at least part of the time;
- disposal in rock caverns below the water table;
- disposal in rock caverns, above the water table.

When disposal units are located above the water table either above the original ground surface (Fig. 1), such as earth mounds, or below ground, such as trenches (Figs 2 and 3), the water table below the disposal units should not be displaced in a significant way since infiltration is prevented both during waste emplacement and after cover construction.

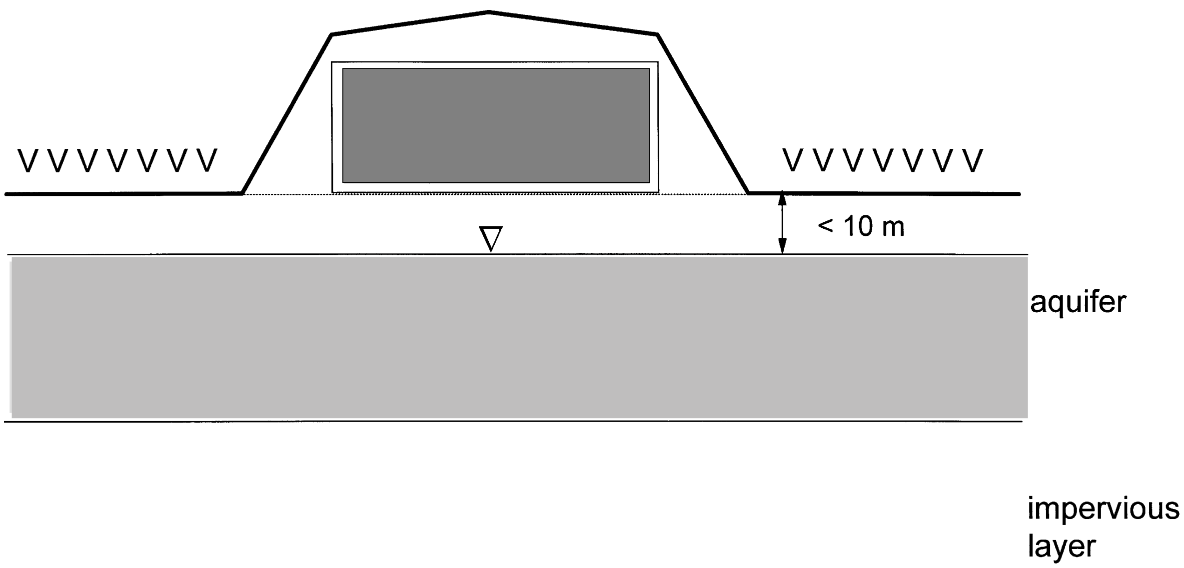

FIG. 1. Disposal units above the ground surface.

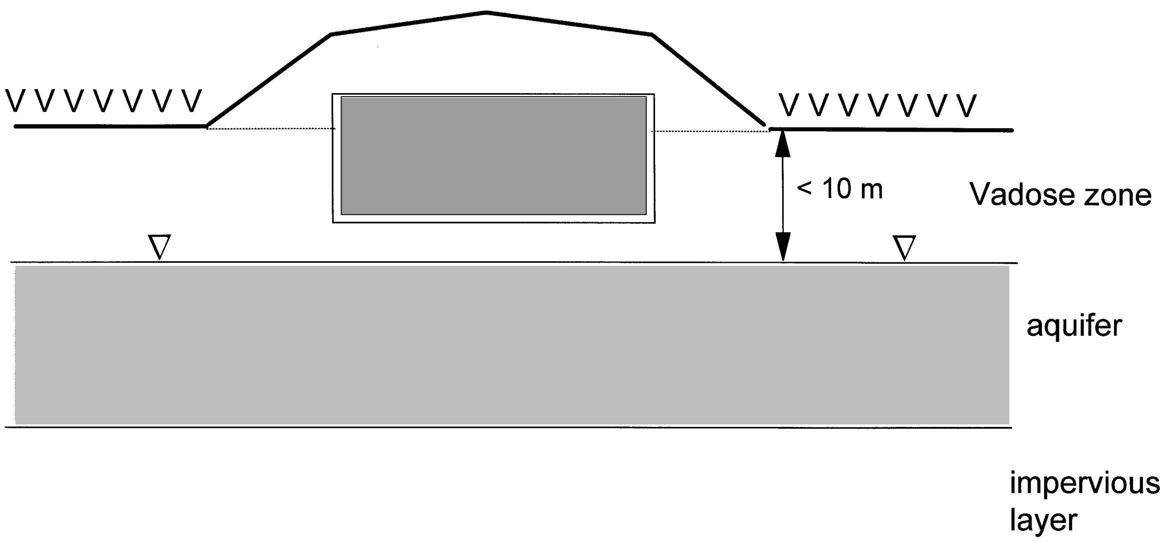

FIG. 2. Disposal units in trenches above the water table.

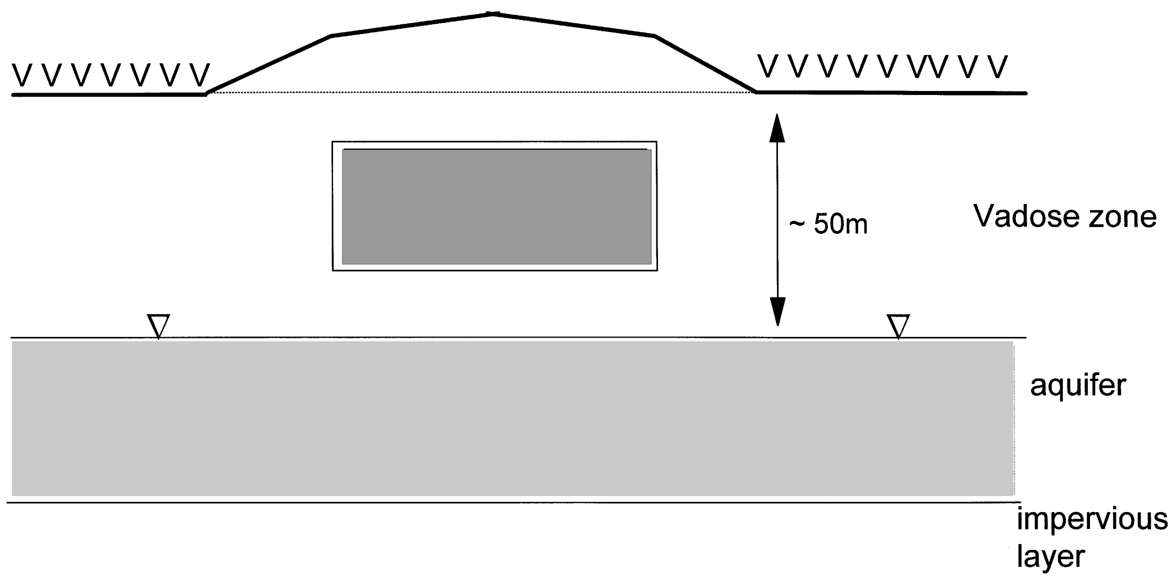

FIG. 3. Disposal units in trenches above the water table.

Since mounds are founded on concrete platforms and any drainage from the platforms is collected, no interaction between disposal units and groundwater is anticipated. In this case, where contact between groundwater and foundations is not designed, it is necessary to demonstrate that this situation remains even under extreme precipitation conditions.

In the case where repositories are located above the water table, the main concern is with infiltration of water from above or from the sides. The facilities may be subjected to infiltration of meteoric water which percolates through the waste and accumulates on the bottom of the disposal units. The percolating water may either be removed by artificial means (man-made drainage or pumping) or left in place where it will percolate through the underlying materials and, eventually, reach the water table. In trenches, water can also inflow from the sides of the disposal units, even in the presence of impermeable covers.

Normally the design of repositories which are above the water table includes a multilayer cover that consisting of impermeable drainage and erosion protection elements. If properly built and maintained, this should prevent or reduce infiltration from above for long periods of time.

If disposal units are, at least partially, below the water table (Fig. 4), some water inflow can be anticipated. Even if the disposal units are totally closed boxes of impermeable material, it is difficult to ensure that the performance of the hydraulic barriers will not decay with time. On the other hand the data needs for design and performance assessment are straightforward; the main objective, for both purposes, is to define reliably groundwater flow and the potential for radionuclide migration. These objectives are the same for all the situations.

A specific situation of interest is that of disposal units located in the vadose zone (Fig. 5), such that water percolation results in the temporary formation of saturated strata usually supported by less permeable layers (aquitards). Within these perched aquifers, in the presence of hydraulic gradients, water movement can take place horizontally. Consequently, if disposal trenches are excavated in materials of variable permeability, as most stratified sediments are, the inflow of water from the sides, particularly after heavy rainfalls or significant snow melts, is likely to occur. Therefore, for disposal units with impermeable covers, it would appear logical to assess the potential inflow from the sides and to consider the addition of hydraulic barriers capable of preventing the horizontal movement of infiltration water. Water flow in the vadose zone is basically different from flow under saturated conditions. While saturated flow occurs in the interstices of the rock and uses all connected pore space, flow in the vadose zone takes place mainly in the film of water that surrounds soil particles. It follows that a hydraulic barrier in the vadose zone, besides consisting of a layer of impermeable material, can consist also of a layer of very coarse material, that, due to its low specific surface, cannot transmit much water. In other words in an unsaturated porous material the air filled pores are an obstacle to water movement. It follows that trenches in the vadose zone can be protected from horizontal infiltration also by surrounding them with vertical walls of coarse, loose material.

For disposal facilities in rock caverns below the water table (Fig. 6) some groundwater will eventually enter the disposal units. Also in this case groundwater flow and migration potential of radionuclides need to be defined for the purpose of assessing the performance of the geological barrier. Long travel times and long flow paths result from low hydraulic gradients and low permeability of the rock surrounding the facility.

Finally, the case of disposal in a rock cavern, above the water table (Fig. 7) should be considered. An example of such condition could be a natural cave in a limestone or a man-made excavation in a hard-rock formation with groundwater circulation occurring below the cavern. No back-up barrier of a geological-geochemical nature would exist to restrict the migration of radionuclides in case of an unforeseen release.

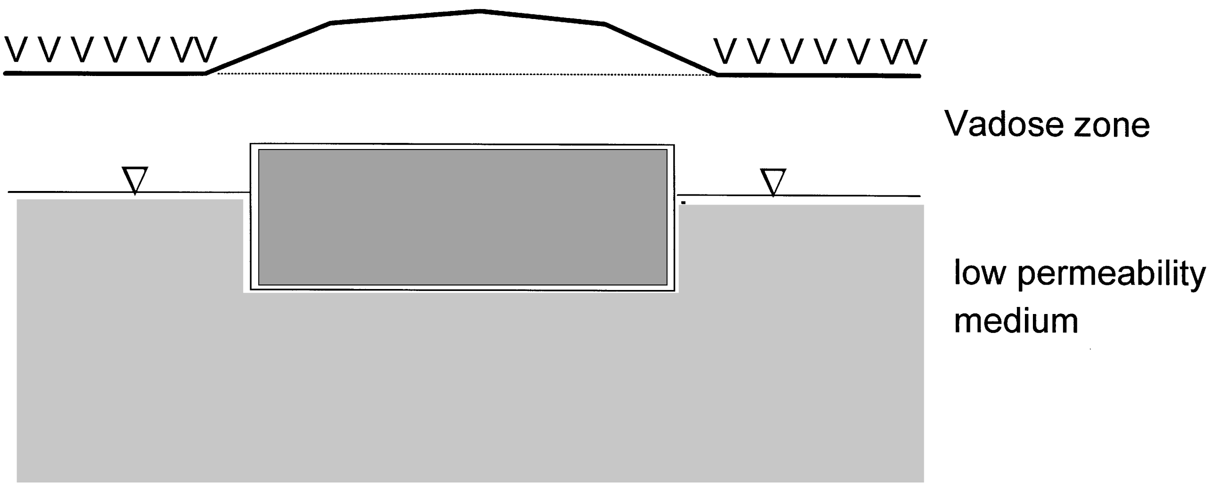

FIG. 4. Disposal unit, entirely or partially below the water table.

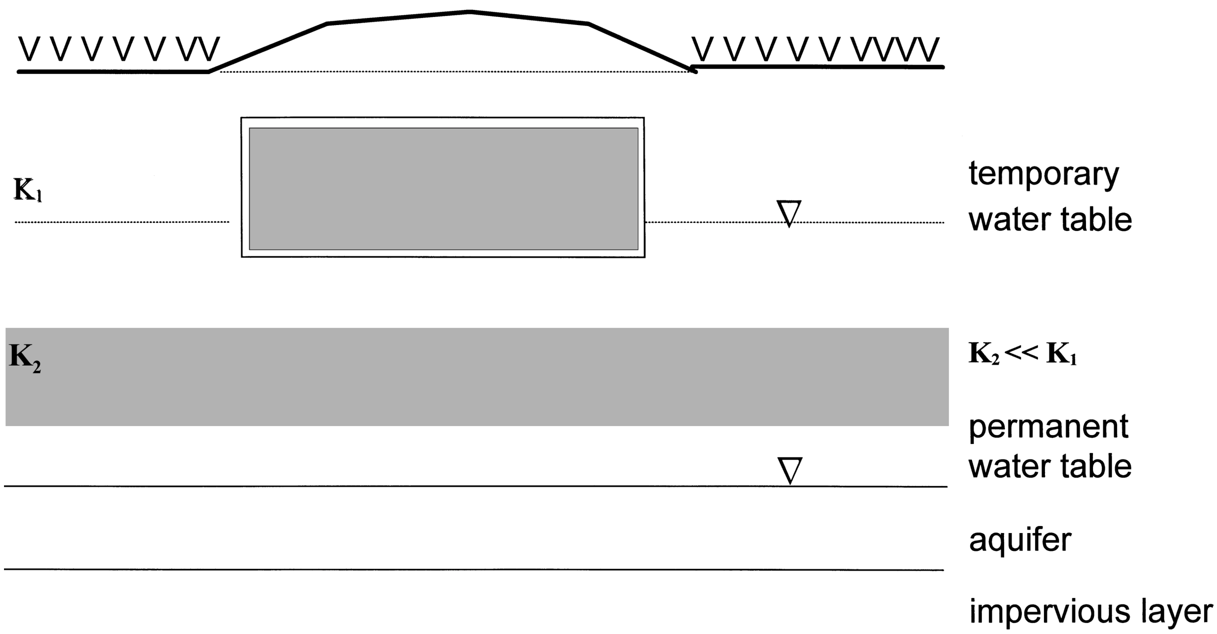

FIG. 5. Disposal units temporarily above the water table.

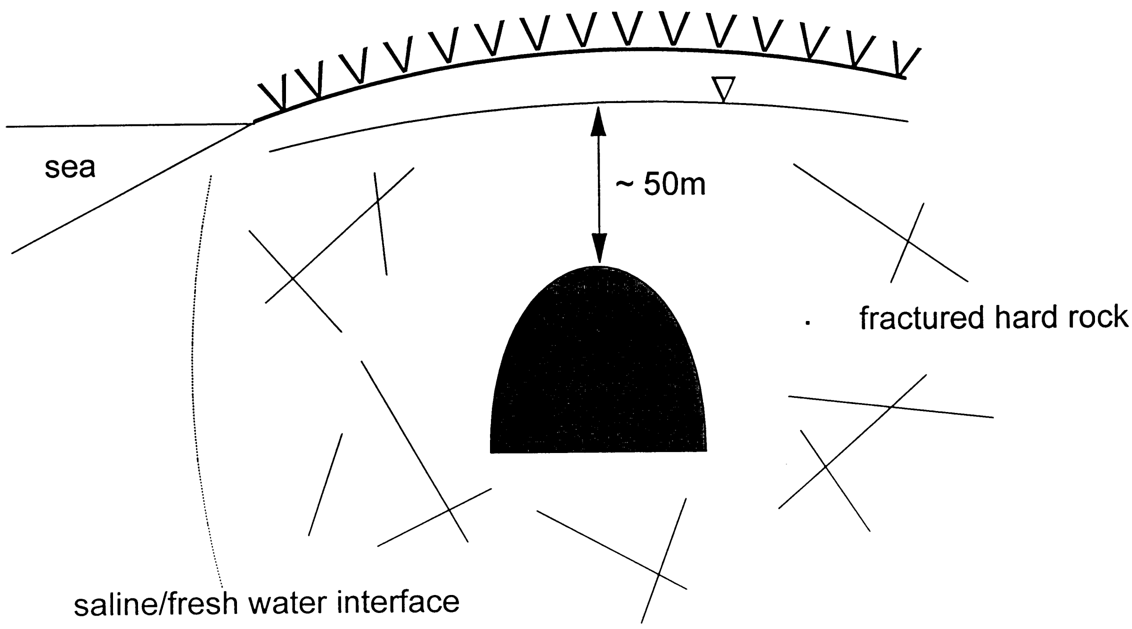

FIG. 6. Disposal in rock caverns below the water table.

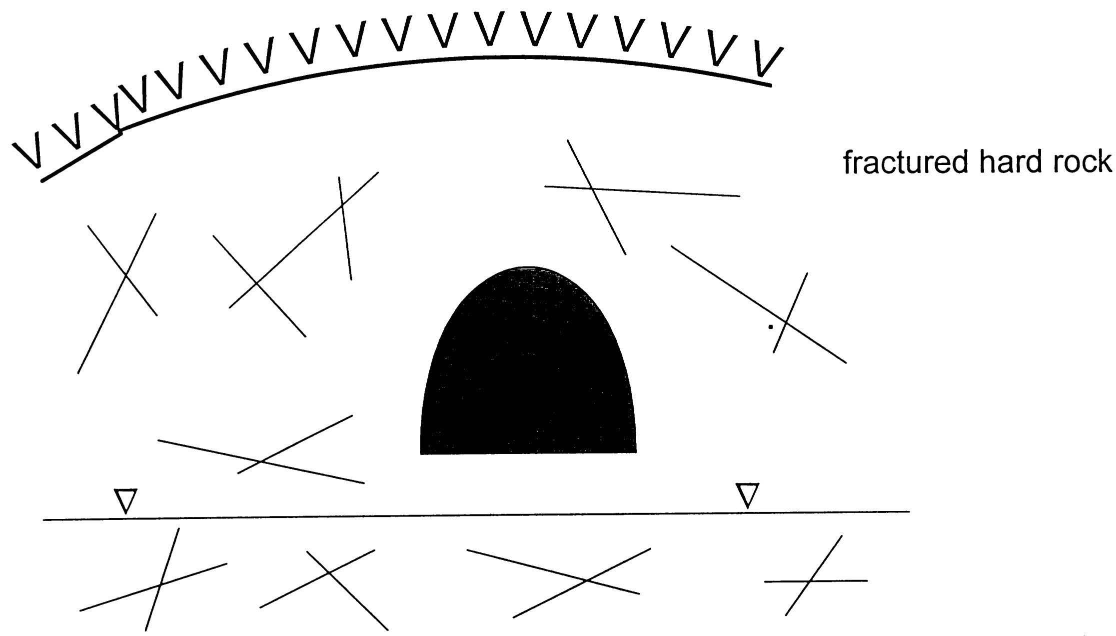

FIG. 7. Disposal in rock cavern above the water table.

This brief description of the possible relationships between groundwater and disposal units in near surface repositories indicates that groundwater flow needs to be characterized in detail in all cases for performance assessment. If radionuclide release is expected to occur below the water table the data needs are similar to what is required in other waste disposal operations, namely:

— dimensions and hydraulic properties of hydrogeological units;
— flow times to discharge or potential utilizations;
— retention properties of the aquifer.

If the disposal units are above the water table — usually the most favourable situation — there is the additional requirement of characterizing in detail the water flow in the vadose zone. This is essential not only for performance assessment purposes, but also to optimize the design of the disposal units.

In many cases, performance assessment is undertaken without the inclusion of the vadose zone. This is undertaken to provide details for a conservative or worst case situation. The aim being to ensure a more robust design. It is however, necessary, for each specific case to confirm the validity of the assumption that this is the conservative case.

3.2. OBJECTIVES FOR UNDERTAKING GROUNDWATER FLOW CHARACTERIZATION

The principal objectives of the hydrogeological assessment for the disposal of radioactive waste site are:

(a) To support the construction of the installation and longer term integrity of the repository by understanding:

- The relationship of the groundwater level and its fluctuation in time with respect to the proposed construction. The response of the ground and the foundations to the groundwater;
- The chemical content of the water. For example, the effects such as corrosion, dissolution and other chemical alteration of the construction materials.

(b) To understand the possible effects of the installation upon the groundwater in normal circumstances or in the event of an accident (i.e. such as the loss of integrity of the engineered barriers). That is to guarantee that the disposal facility emplacement does not produce undesirable effects on:

- Water quality (chemical and radiological). Detection of anomalous concentrations that constitute an inadmissible risk or that indicate the unsatisfactory function of the facility;
- The natural groundwater flow such that conditions are created producing desiccation or flooding in the vicinity of the disposal facility.

(c) To provide additional input to other programmes of work, for example:

- Consequence Analysis. Indentification of hydrogeological units and their connection to any affected areas of discharge and recharge. Prediction of the contaminant evolution and application of mitigation techniques;
- Environmental radiological monitoring programs or environmental impact assesment. groundwater characterization studies provide information on the wells, springs and surface water bodies connected to ground water, with higher probability of being affected by a release.

4. FACTORS DEFINING GROUNDWATER FLOW

4.1. INTRODUCTION

The importance of groundwater flow characterization in near surface disposal site selection has been established in Section 3. In order to enable the study of groundwater flow, the controlling factors, their relative importance and the collection of site specific values are required. The goal of this Section is to identify these key factors which then become the targets for a characterization program (see Section 6).

The factors will be controlled by the framework of geological conditions within which the groundwater flow system occurs and is determined by such features as sediment texture, pore space, geologic structure, fractures, etc. This provides a most important input to the hydrogeological interpretation. Although, not detail here, the most recent and appropriate geological data recording and interpretation methods should be employed. Any interpretation of a site should be consistent with the most recent understanding and chronology of the region in which it is located.

Groundwater flow at any specific location is part of the hydrologic cycle and is mainly determined by hydraulic gradients between higher ‘head’ recharge areas and lower head discharge areas.

As water infiltrates into the ground, the pore space can be filled either partially or totally. This defines two separate zones — the vadose and saturated zone. The basic law of groundwater flow is Darcy's Law — a relationship involving hydraulic gradient and hydraulic conductivity, and when it is put together with an equation of continuity that describes the conservation of fluid mass during flow through porous media, a partial differential equation of flow is the result that defines the flow in the saturated and vadose zones [11, 15]. Flow in the vadose zone is also a function of moisture content.

The analysis of flow in fractured rocks may be performed using either a continuum or non-continuum approach. The continuum approach involves replacement of the fractured media by an equivalent continuum which can be defined with respect to hydraulic conductivity, porosity and soil water retention. This approach is usually valid on intermediate and regional scales. The non-continuum approach is required on more localized scales, and involves the analysis of the flow hydraulics in individual fractures.

In the majority of cases near surface repositories will need to consider unconfined aquifers.

4.2. SATURATED ZONE FLOW

When simple regional groundwater models are required, a range of assumptions (such as average values) can be made to reduce the complexity of the system. However, when detailed site characterization is required, the site complexity becomes paramount in determining suitability of the location for a repository.

This complexity requires the determination of a range of factors that affect the flow of groundwater.

At an elemental scale, groundwater flow is affected by the:

— distribution of hydraulic parameters, including hydraulic conductivity, porosity, storativity;
— spatial and temporal variation of hydraulic head;
— geometry of the flow domain.

Flow in the saturated zone can be mathematically represented. For a confined aquifer in two dimensions, assuming the aquifer to be homogeneous and isotropic, this is represented by the following equation:

$$\nabla^2 H = \frac{S}{T}\frac{\partial H}{\partial t} \tag{1}$$

where

T is the transmissivity
H is the total head
S is the storage coefficient
t is the time
∇ is the del operator.

As already indicated in the majority of cases near surface repositories will need to consider unconfined aquifers. The flow equations for such aquifers incorporating Dupuit's assumption that velocity is uniform and essentially horizontal with:

$$\frac{dZ}{dt} = 0; \frac{d\theta}{dt} =; H = z; \theta = S_y$$

have the form:

$$\frac{d\theta}{dt} = -\nabla \cdot \vec{V} \tag{2}$$

$$\nabla^2 H^2 = \frac{2S_y}{K} \cdot \frac{dH}{dt} \tag{3}$$

where:

S_y is the specific yield (effective porosity) in the y direction
K is the hydraulic conductivity
z is the elevation head
$\vec{v}$ is the Darcy's velocity (flow velocity)
? is the moisture content.

To further define groundwater flow within the context of characterizing the whole system, the following factors will require investigation:

- geometry and extent of geologic features, including thickness, areal extent, degree of connection between hydrogeological units;
- identification of recharge and discharge areas;
- recharge and discharge rates, including infiltration, evapotranspiration, water balance, extraction volumes;
- groundwater flow system boundaries, including rivers, etc.;
- the relationship between the different hydrogeological units;
- groundwater flow velocity and residence time of groundwater in the system;
- fracture geometry/size and distribution, for fractured systems;
- groundwater chemical characteristics, including environmental isotopes.

The purpose of the investigation methods described in the following sections is to clarify the effects of these factors on groundwater flow, to assist in the siting process and to allow a reliable assessment of the performance of the near surface repository.

4.3. VADOSE ZONE FLOW

As mentioned in Section 3, water flow in the vadose zone is the movement of the water that partially fills the voids. Larger air filled voids represent an obstacle to water movement. Moisture content within the vadose zone varies through time in accordance with temporal variation of recharge or climatic conditions. During periods of higher recharge pores may fully saturate for short periods of time in some parts of the profile.

Groundwater flow in the vadose zone can be mathematically represented given the assumption that no air pockets exist in the hydrogeological media and d z/d t = 0 by the following equation:

$$\left[\left(\frac{\theta}{n'}\right)\alpha' + \beta'\theta + \frac{d\partial}{dh}\right]\frac{\partial h}{\partial t} = -\nabla \cdot \vec{V} \qquad (4)$$

where:

n' is the total porosity
a' is the modified coefficient of compressibility of the medium
ß' is the modified coefficient of compressibility of the water
h is the pressure head.

Fluid potentials are less than atmospheric in the vadose zone. This negative potential results from capillarity forces that bind water to solid. The lower the moisture content, the higher the suction and the lower the potential and hydraulic conductivity.

Therefore at an elemental scale in this zone groundwater flow is affected by the factors detailed for saturated conditions, and fluid pressure and hydraulic conductivity relationships. Due to the dependence of the flow on the moisture content in the vadose zone, factors in addition to those mentioned above need to be determined. These additional factors are:

- moisture content variation;
- fluid pressure (tension, suction) variation;
- hydraulic conductivity as a function of moisture content and fluid pressure.

4.4. DISPOSAL FACILITY INFLUENCE

It needs to be noted that construction of the disposal facility will change some of the conditions influencing groundwater flow at the site. Consideration of these effects must be included during the characterization/design phase.

5. STRUCTURING GROUNDWATER FLOW CHARACTERIZATION PROGRAMMES

5.1. THE FRAMEWORK FOR GROUNDWATER FLOW CHARACTERIZATION

Although groundwater flow characterization is of prime importance during the pre-operational phase, it also remains important throughout the operational and post-closure phases. This is to demonstrate that the site will provide adequate isolation of radionuclides from the biosphere for the desired period of time (which may be a few centuries in duration), taking into account the facility design and waste packaging [10].

Consideration of the hydrologic requirements for the different stages (pre-operational, operational and post-closure) of the repository are given below.

5.2. PRE-OPERATIONAL PHASE

This phase includes the necessary siting and design studies and the period during which the facility is constructed.

It must be emphasized that iteration in groundwater flow characterization is not only desirable but essential, and comprises the following steps:

- a review of existing data;
- data acquisition programme;
- construction of conceptual model(s);
- investigations for collection of additional data;
- development of a groundwater models;
- testing of models.

Groundwater flow characterization programmes consist largely of the steps investigation and modelling. To obtain maximum benefit from the site characterization programme it is vital that these two steps of activities are well integrated and that they meet the needs of the wider siting and safety assessment programme of which they are part.

The site investigation and modelling activities which are appropriate at each stage of the siting and assessment process will now be discussed briefly (a discussion of activities relevant to each stage is given elsewhere [10]).

In the case of a new facility, the objective of groundwater characterization is to aid in the systematic selection of a suitable site for disposal. This siting process, used in most countries, consists of four stages:

- conceptual and planning stage;
- area survey stage;
- site characterization stage;
- site confirmation stage.

Groundwater flow considerations need to be taken into account during each of the four stages. The purpose of the different stages are discussed below.

5.2.1. Conceptual and planning stage

This stage is to develop an overall plan for the site selection process, to establish the siting principles and to identify desirable site features which can be used as a basis for the area survey stage.

This stage identifies what desirable hydrogeological features, adapted to local conditions, should be present at potential sites.

5.2.2. Area survey stage

The area survey stageis to identify one or more candidate sites for further evaluation, often by systematic screening of regions of interest.

Sometimes this stage is omitted if, for example, sites have been volunteered by communities or land owners, or a specific site is designated for consideration by a local or national authority. However, the conceptual planning, site characterization and site confirmation stages are still needed.

Guidelines for the hydrogeological setting of sites for new disposal facilities emphasize the requirement for low groundwater flow velocities and long flow paths to allow the decay of radionuclides during transport. In many instances this will be best achieved by siting the disposal facility well above perched and regional water tables. However, as outlined in Section 1.1, it may be impractical to place a new facility completely above the water table for climatic and/or geological reasons. In existing facilities that are located partly, or mostly, beneath the water table, the siting of these facilities still requires low groundwater flow velocities and long flow paths giving long transit times necessary for the decay of the radionuclides. However, many times low groundwater flow velocities imply very complex hydrogeological systems (e.g. fractured rocks). This is reason why, sometimes, it is preferred to select a location with material that is easy to define (the flow paths and physical and chemical properties are predictable) and to monitor.

During this stage, the hydrogeological characteristics of an area or site may not yet be available in sufficient detail. However, the following information should be analyzed as a minimum:

- identification of the approximate geological structure and stratigraphy;
- location of major recharge areas;

— data on existing and projected major water uses;
— identification of major discharge and extraction points;
— estimates groundwater properties and flow direction and velocity.

Here, the extent to which modelling can be used in the decision making process largely depends on the level of existing hydrogeological information. In particular, sufficient and similar levels of data must exist for each of the candidate sites under consideration so that all candidate sites can be included to the same extent in the modelling exercise and modelling results for the various candidate sites are of comparable reliability.

In this stage, identification of which sites are suitable for further evaluation may result from some very simple groundwater flow modelling, carried out to evaluate average groundwater velocity and flow path length. These two parameters are indicators of the travel time of radionuclides, and other solutes, in the groundwater.

5.2.3. Site characterization stage

This stage is to investigate one or more candidate sites to determine if they fulfill safety and environmental requirements. This stage is required for both existing and new facilities. In the case of existing facilities, site characterization may be used to supplement available data for further refinement of the models and better understanding of the behaviour of groundwater flow if remedial measures become necessary.

For this stage, the following information relevant to groundwater flow and transport should be obtained as indicated below:

— more detailed information on the geological structure and stratigraphy;
— location, extent and interrelationship of the important hydrogeological units in the region;
— average flow rates and prevailing directions of groundwater flow;
— recharge and discharge of the major hydrogeological units (natural and anthropogenic);
— regional and local water tables and their seasonal fluctuations;
— site topography;
— location of existing and planned surface water bodies;
— definition of areas containing poorly drained materials;
— data on the flood history of the region;
— meteorological information, including precipitation, evapotranspiration, extreme weather phenomena and hydrological balance;
— parameters for flow and transport;
— soil moisture profile;
— hydrogeochemical characteristics of the site;
— interaction with the facility;
— existing and foreseeable water and land uses.

Detailed of the techniques that can be used to provide this information are contained in Table 6.1. However, in this Table the techniques are listed by the different aspects to be investigated. They do not directly correspond to the items in the list above but cover the same scope of data collection.

5.2.4. Site confirmation stage

In the case of new sites, the site confirmation stage is to conduct detailed site investigations at the preferred site(s) to:

— support or confirm the selection;
— provide additional site specific information required for detailed design, safety and environmental impact assessment and licensing.

For existing near surface facilities, this is intended to:

— determine or confirm, by continued monitoring and analysis, whether the site is suitable for further disposal and, in the case of post-closure, to assess deviations (if any) from the predictions of a groundwater flow model;
— provide additional information for safety and environmental impact assessment to support continued licensing.

This stage may require detailed information on the hydrogeological characteristics of the site selected. The type of data should, in general, express quantitatively the characteristics indicated above.

5.2.5. Comments

During the site characterization and site confirmation stages, groundwater flow modelling generally progresses, through an iterative process, from a relatively simple representation to a much more detailed one through a 'fit-for-purpose' understanding at each iteration. The simple representation is based on initially available data; subsequent representations will include additional data made available from the results of further field and laboratory investigations. Sensitivity and uncertainty analyses, from previous iterations, should be performed to indicate which new data would give the greatest reduction in remaining uncertainties (see Section 7.4). The iterative process may conclude when the representation of physical phenomena are sufficiently refined to satisfy safety and performance assessment requirements.

The data acquisition programmes that are established to support the hydrogeological characterization include the collection of 'monitoring' data that allow for details such as the establishment of pre-operational conditions (baseline hydrogeological data). This allows confirmation of the hydrogeological conceptual model and development of the mathematical models.

5.3. OPERATIONAL PHASE

This phase includes the period of operations at the facility and the closure of the facility. The closure process includes decontaminating and removing or sealing redundant structures systems or equipment, disposal of decontamination waste, updating of disposal archives and implementation/continuation of monitoring as required. For disposal at or near the ground surface, closure may include the placement of a final cover on the disposal system or structure, whereas for a rock cavity disposal , it may include sealing of access routes [2]. It should be noted that closure of a part of the site may take place during the operational phase prior to the complete and final closure being undertaken.

Monitoring programs that have been initiated during the site characterization stage are continued during the operational and post-closure phases as a surveillance mechanism. During the characterization stage, they give basic hydrogeological and geochemical information about the system. In subsequent stages, the program is used to determine whether there have been any changes in the hydrogeological behaviour and to detect possible releases. This is commonly a regulatory requirement. They also can be used to verify preventative and mitigating design systems have been effective.

A basic program is to monitor groundwater through boreholes and wells; it may be, however, sometimes possible to monitor the groundwater that reaches the surface through springs or natural depressions. These boreholes and wells must be designed to last for the lifetime of the facility and for a considerable period after closure of the facility. Areal and vertical spacing of monitoring wells should be such that all hydrogeological units that are related to the groundwater flow are monitored. Monitoring should be focused towards relevant release scenarios that were established during characterization and confirmation stages. The frequency and distribution of sampling and measurements should also be based on these scenarios.

Operational phase monitoring may require additional supporting studies and data collection. This information and analyses may be useful in directing or redirecting monitoring efforts with respect to changes in site specific conditions that may occur as a result of site construction, or other artificial or natural changes that may occur over the active phase while institutional controls are in force.

The monitoring results may indicate changes in conditions from the earlier predictions. In this case the understanding of the hydrogeological system in operation at the site will need to be readdressed. This probably will require additional modelling work normally supported by collection of additional data. Such additional data collection will be directed by the results from the monitoring programme.

5.4. POST-CLOSURE PHASE

This phase includes any activities following closure of the disposal facility (eg. periods of active or passive controls).

Once the understanding of the hydrogeological system and its interaction with the facility has been established during the previous stages, the monitoring program provides information as part of the demonstration of the safety of the repository during institutional control. This monitoring will consist of the measurement of groundwater level and collection of chemical and radiological data.

The objectives within this phase remain effectively the same as in the previous phase. Importantly, additional works may be required during this stage if results indicate any significant deviation from the predicted conditions.

As detailed in [2] there is a need to develop a quality assurance programme that can be applied to the structures, systems, components and activities related to the closure and post closure of the facility. In particular, this needs to provide for the collection and preservation of all the information collected during the previous phases that may be important for safety in the future. It has already been indicated how the hydrogeological understanding is of prime importance to repository safety.

6. CHARACTERIZATION METHODS AND TECHNIQUES

6.1. METHODOLOGY AND APPROACH

The groups of factors that are important in controlling groundwater flow were given in Section 4. This section reviews the various methods and techniques that can be used to obtain values of these factors undertaken in quantitative terms.

The need to collect good quality specific data especially from techniques such as drilling, pump tests and monitoring must be emphasized. Construction of wells and boreholes allows measurement of fundamental hydrogeological parameters that describe flow in the groundwater system. Fundamental parameters also include surface measurements that define inflow and outflow to the groundwater system. Qualitative and infilling techniques including many geophysical techniques are useful for initial scoping or prospecting and connection between 'firm' borehole data but are not a replacement for them. The list of techniques included is an attempt to give a wide spread of all those available. However, the large number of geophysical techniques included is not and indication of their importance.

Due to the extreme range of these factors and the large number of possible techniques it is not expected that those included here are exhaustive. A more complete description of techniques are included in a number of references, in particular [16, 17]. Nor should all of these methods and techniques be employed at all sites. Discretion should be used in selecting methods and techniques that are most applicable to the hydrogeological conditions at the site.

A break down of the fundamental factors/parameters as previously established as being required, along with the main techniques or type of techniques available for their collection are given in Table 6.1. Some advisory comments are provided as appropriate. These techniques have been listed on an 'aspects to be investigated' basis and generally follow the order of data collection. Further details of some of the most useful techniques are given in subsequent sections.

There are a number of important considerations to take into account:

- often there is a change in scale (reducing) of the area to be studied during selection/site characterization and different techniques maybe more applicable at different stages;
- the iterative nature of site investigation works linked with feedback from and improvement of the understanding and modelling of the characteristics of the site;

- field works are often required for the collection of data for a number of purposes such as geological/hydrogeological characterization, geotechnical information for repository construction and groundwater/safety monitoring etc. The integration of the programme is important in order to be cost effective and maximize use of data;
- certain techniques are more applicable in certain climatic conditions and in different hydrogeological regimes;
- consideration should be given to determination of critical values by more than one independent method to increase the certainty in the measured value;
- collection of the best quality data is very important not only for the obvious reasons of accuracy but also that inaccurate results can be misleading to other associated works and be exceedingly costly both in terms of time and money;
- previous data should always be used prior to undertaking any determinations. Characterization should be an iterative process involving the use of models, or previously collected data, as appropriate. Prior to the use of the data, an assessment to check if they are representative should be undertaken;
- investigations should utilize properly qualified personnel to ensure measurements are correctly conducted. A number of national standards exist for undertaking numerous tasks and collection of data;
- much of the data required is collected over a period of time and appropriate monitoring systems will need to be utilized at the different stages of the characterization.

6.2. SURFACE BASED METHODS AND PARAMETERS

The aim of the surface studies is to understand in detail the hydrogeological environment of a potential repository area and to evaluate potential pathways for radionuclide migration.

6.2.1. Identification of hydrological features

In order to estimate the water balance of a study area, the characteristics of local streams and lakes, such as flow rates, water levels and infiltration rates in different seasons have to be defined; also the properties of discharge zones and the location and the rates of pumping for water supplies have to be determined. Data on the following parameters have also to be collected: precipitation, evapotranspiration, soil retention capacity, stream flow, temperature, and the proportion of snow in the annual mean precipitation (where relevant). Data collection programs should reflect the variability of the local conditions and the site of interest at which the user is working. Projected long-term trends in precipitation patterns must be considered, as well as future land use and development that could influence the groundwater flow regime.

The groundwater conditions of an area are determined by its topographical, geological and climatological conditions.

An important aim of the hydrological studies is to evaluate the relations between run off and infiltration rate and the surface water flow. From the analysis of the water balance in the area it should be possible to estimate the recharge and the potential amount of water which could affect the waste repository.

TABLE 6.1. SITE INVESTIGATION ASPECTS AND TECHNIQUES APPLIED

Aspects to be investigated	*Techniques*
Geology	
Geological structure, stratigraphy and tectonics Geological materials, geochemistry Geomorphology and topography	mapping and cartography borehole drilling and coring geophysical methods remote sensing laboratory methods
Hydrology	
- precipitation, temperature	rain gauge measurement temperature measurement
- evaporation, evapotranspiration	measurement pan evaporation direct ET methods isotopic and hydrochemical methods
- surface hydrology	mapping remote sensing
- stream discharge	stream gauging runoff
Geological Medium (Rock Properties)	
- texture	laboratory methods on cores
- infiltration capacity	field based methods
- retention capacity	field based methods laboratory methods on cores
Hydrogeology	
- hydraulic conductivity, transmissivity	pump tests, slug test, etc laboratory methods
- specific storage	pump tests, slug tests
- porosity	laboratory methods borehole geophysical methods tracer methods

- moisture content	laboratory methods borehole geophysical methods (neuron probe)
- dispersion (dispersivity) - diffusion (diffusivity) - retention/retardation (distribution coef.)	tracer test laboratory methods (batch column)
- hydraulic head (water table, piezometric configuration)	wells/piezometers geophysical methods
- water potential, pressure (vadose zone)	tensiometers
- recharge and discharge areas	mapping water balance isotopic methods hydrochemistry
- recharge and discharge rates	water balance isotopic methods tracer determinations seepage measurements hydrograph methods chemical balance
- flow velocity and direction	tracer tests isotope determination direct field measurements
- residence time	isotopes hydrogeochemistry
Hydrogeochemistry	
- major ion geochemistry - physicochemical parameters	laboratory determinations field methods (sampling & measurements) wireline logs
- environmental isotopes	laboratory determinations

The main parameters to be measured are briefly discussed below.

6.2.1.1. Precipitation

These data can be obtained:

— using rain recorders which automatically measure the cumulative amount of rain;
— in certain areas by the use of radar techniques which can determine rainfall patterns over a large area;
— using snow and ice recorders.

6.2.1.2. Runoff and infiltration

It is important to determine the fraction of precipitation that percolates underground. Some determination of infiltration and runoff can be performed on a sample of standard surfaces from which the outflow of water under different meteorological conditions can be measured.

6.2.1.3. Evapotranspiration

This can be measured directly with evaporation pans or tanks, percolation gauges and lysimeters. The amount of evapotranspiration can also be established by using water balance analysis and via isotopic methods.

6.2.1.4. Stream discharge

The stream discharge can best be determined in specially constructed gauging stations which measure the flow velocity distribution on a cross-section of the channel. Integration of the flow velocities over the area of the channel gives the total flow rate. Direct flow measurements are also possible using ultrasonic gauging or electromagnetic gauging. Indirect measurements are possible by use of tracer dilution, floats etc.

6.2.1.5. Recharge

Although recharge is mentioned under hydrogeological behaviour in Table 6.1, it has a close relationship with the hydrological features of the site.

Besides the water balance technique, recharge can also be estimated by isotopic methods, by analyzing groundwater level fluctuations (hydrograph method), tracer determinations, lysimeters and soil zone chemical mass balance methods. Recharge is one of the most important parameters to be determined for characterizing groundwater flow. It has to be considered at the local scale, that recharge can be severely modified by construction activities.

6.2.2. Preliminary characterization of hydrogeological units

6.2.2.1. Remote sensing methods

The use of remote sensing methods can provide information relatively quickly and economically. Remote sensing is a complement for conventional hydrological and geological surveys. Some techniques that could be used in a hydrogeological programme are given below.

(a) Aerial photography and satellite images

Acquired from aircraft or satellites, aerial photography and multi-spectral scanned images, combined with computer processing techniques, provide a large amount of information on the main geological features, recharge areas, surface flow paths and discharge zones. Infrared imagery, based on the analysis of visible and near infrared spectral reflectivity, provides information on surface temperatures and near surface water conditions. Infrared images allow the detection of groundwater discharges when there is sufficient temperature contrast between the discharging water and the normal background. Infrared images are suitable for any geological environment but the performance is strongly controlled by topography, climate and weather conditions.

(b) Radar imaging system

A recent system for geological applications is the side looking airborne radar (SLAR). In this system a transmitter generates short bursts of radiofrequency energy which are confined on a narrow path. Radiofrequency energy which is backscattered towards the antenna on the aircraft is converted to a video signal. This signal is a complex function of the moisture content of the ground, the rock type, the orientation of the surface, the transmitted and received polarizations and the radar frequency. As well, the radar imaging system can be used for the determination of the water table in areas with thin surface cover.

Other airborne geophysical methods, such as magnetics, are used to provide geological data. Remote sensing methods are also widely used, particularly for regional site selection, for defining surface hydrologic features.

6.2.2.2. Ground surveys

(a) Mapping and cartography

Geological and hydrogeological ground surveys are used to determine the characteristics of the main rock units in terms of their broad hydrogeological properties. In addition, the position of springs and groundwater seepages as well as soil and vegetation changes are required in order to understand the factors controlling near surface flow.

These investigations will result in hydrogeological maps showing the structure and the organization of surface drainage and their linkage to shallow aquifers.

(b) Surface geophysical methods

Among the geophysical methods commonly used in geological prospecting, five are of interest for hydrogeological studies most useful in the pre-operational phase.

(i) Electrical methods

The most commonly used electrical or geoelectrical method in groundwater investigations is the resistivity survey or direct-current method. Electrical resistivity surveying is based on evaluating the apparent resistivity of subsurface material (minerals, waste, etc.) by passing a known electric current through the ground and measuring the potential difference between two points. Thickness and depth of aquifers, aquitards, and aquicludes can be identified by changes in resistance of alternating layers of impermeable and permeable rocks and sediment. At most sites resistivity will limit the effective depth of most commercially available system to about 50 m.

Lateral resistivity surveys or geoelectric mapping can be carried out laterally with a constant electrode spacing; whereas, vertical resistivity surveys, which are also called geoelectic soundings or vertical electric soundings (VES) can be carried out with a variable electrode spacing. The lateral survey provides an isoresistivity map which shows the discontinuities of the aquifer. Vertical resistivity surveys have been used to determine the depth of the water table and to locate the fresh-saline water interface. The depth of unconfined aquifers usually cannot be determined with great accuracy, because the water content in the vadose zone, particularly in proximity to the water table, is often too high to yield a measurable contrast between the resistivity above and below the water table. The primary limitations of VES are the inability to identify very thin beds, and confusion because of multiple equivalent solutions. The geophysicist must select the result that agrees best with his knowledge of the geology and hydrology.

Electrical conductivity or induced polarization methods can also provide useful information regarding geologic layers. There are two types of induced polarization: metallic which occurs at the surface of highly conductive minerals, and boundary layer polarization which though weaker than metallatic polarization still develops an accumulation of cations at the boundary of the electrolyte. Induced polarization is prevented where saline water exist, because the high conductivity prevents ion accumulation over the pore walls of siliceous rocks.

Self-potential (SP) measurements are obtain from natural geoelectic fields. Measurement of their distribution may provide information about inhomogeneties related to electrochemical reactions between rock, groundwater, and rock fluids. The main advantage of SP surveys are there simplicity and speed. The primary disadvantage is the typically qualitative results.

Micro resistivity techniques have been developed and may be more applicable and give improved results at some sites. The derivation of three dimentional images of bulk resistivity variation through the utilization of electrical resistance tomography (ERT) is being developed and can be undertaken between boreholes.

(ii) Seismic surveys

Seismic surveys are based on measuring the velocity of shock or sound waves in the various strata. Since the velocity of sound in underground materials increases with increasing density and water content, the result can be interpreted in term of porosity and water content of the materials.

In a seismic refraction survey, the geophones are uniformly spaced on a straight line from the shot point to record the arrival of the first shock waves. Seismic waves are refracted upon passing into a bed with higher velocity. The waves travel along the interface of the two beds and continuously emit seismic energy to the surface. Because the refracted wave travels faster in the lower layer, it will overtake the direct wave at a critical distance from the seismice source point. This distance is a measure of the depth of the boundary between the two beds, and the seismic velocities are inferred by complex mathematical evaluation. Seismic refraction is particularly advantageous at depths of 50 m or less. The analysis of the seismic profile, in simple cases, allows to indicate the position of the water table.

Unlike seismic refraction, seismic reflection is not well suited for depths less than 50m. A third seismic method is the air-acoustic method. It is most effective at shallow depths because its signal can be varied over a wide range and thus be adapted to the seismic properties of shallow sedimentary strata.

(iii) Electromagnetic surveys

Electromagnetic mapping or EM survey is usually undertaken with movable, horizontal and coplanar coils. Vertical polarized sinus oscillations are transmitted and received. The alternating primary field that is transmitted induces in rocks and sediments with dissimilar specific electric resistities eddy currents. The resulting field produced is received at the surface. Considerable care in the spacing and orientation of the coils is necessary. Buried metallic features such as cable or pipes can create anomalies that disturb and EM survey. Effective depth is based in large measure on the frequency used which ranges from 800 to 7000 Hz.

One of the most commonly used electromagnetic methods in groundwater characterization is the very low frequency or VLF method. The VLF method measures the magnetic field strength of distant radio transmitters in the frequency range 12–25 kHz. There are seven active stations with different frequencies and outputs that are located in Bordeaux, France, Rugby Great Britain, Moscow, Russian Federation, Cutler, Maine and Seattle Washington in the USA, Tavolara, Italy and NW Cape, Australia. The electromagnetic field of a VLF transmitter has a magnetic vector which is oriented almost horizontally to the direction of the transmitter and an electrical vector which is almost vertical. The survey lines must be laid out at right angles to a straight line from the VLF transmitter and the site to achieve high anomalies and avoid distortions. Depth limitations for most site conditions is approximately 50 m.

A variation called VLF resistivity (VLF-R) or radio ohm method, gauges the resistivities of the ground. This method measures both the horizontal and perpendicular component of the magnetic field in the air. Using this method it is possible to determine: the vertical and horizontal components of conductive bodies (e.g. clay layers), total magnetic intensity, apparent specific resistivity. Flat topography is preferred for this technique. Despite the techniques dependence on distant VLF stations, it is fast and inexpensive.

The rock characteristics and the water content affect the distribution of the electromagnetic waves and cause anomalies that can give information on the rock structure. This technique is used to detect fracture zones with increased water content.

These geophysical methods may not be accurate for defining detailed hydrogeological information, but provide good complementary data to other more direct methods. In particular their use in interpolation between borehole based data locations can be both efficient and economical.

(iv) Ground-penetrating radar (GPR) surveys

The GPR method is commonly used to define subsurface features and sedimentary layers. With modern software it is possible to obtain real-time data and present results in the field in colour. The GPR method measures the radar reflections. Its special advantage is the capability to identify and define in some detail linear and none linear features of non-conductive materials, which can not be found nor delineated by geomagnetics nor by VLF techniques. It is probably the best technique for detection of near-surface cavities and fractures in hard rocks except where overlain by clay.

Perhaps the most important limitation is the shallow depth of penetration (less than 10 meters), and even less where the presence of ground water moisture or strongly contrasting layers are present.

(v) Geomagnetic ground surveys

Magnetic measurements enable identification of anomalies in the geomagnetic field; however, the accurate interpretation of these anomalies and thus the identification of the subsurface feature creating the anomalies requires additional information. Because of the specific geologic conditions needed to make this technique useful, its application has been limited in site characterization studies. The instruments used measure the inductive and remnant magnetization of iron-bearing rocks, sediment, or waste. Small objects can be located at depths of up to 5m, but definition rapidly decreases between this depth. The configuration of magnetic anomalies is related to the inclination of the magnetic field of the earth, or the geographical latitude at the site. The instruments are easy to use, simple, and allows for a rapid survey.

Numerous new developments are in progress and may become useful in the future. However, it should be remembered that the acceptance of details obtained from geophysical techniques especially those newly developed, by the regulators and public is not achieved.

6.3. SUBSURFACE BASED METHODS

The programme of subsurface investigations should be designed on the basis of results from both previous and surface investigations, taking into account the needs of the wider siting and characterization process.

The characteristics of the hydrogeological units which are relevant to the performance of near surface disposal systems can be determined directly by investigation methods which allow direct underground access of a variety of measuring devices and samplers.

The standard method for gaining access to the underground is drilling boreholes. Additionally, at many near surface sites having unconsolidated sediments other methods, such as the cone penetrometer, may also provide useful information at a much reduced cost.

Although of greater value for geological characterization the undertaking of trial pits/trenches can provide data especially three dimensional information close to surface which is particularly useful in the provision of structural information. Such works can be easily undertaken to depths of some 5 m with readily available commercial equipment and can be provide rapid information collection and be cost effective. Boreholes and wells provide the essential access to obtain quantitative data of the groundwater system, therefore, great care must be taken in the drilling, sample collection, testing, construction and testing depths chosen of these boreholes and wells.

The aim of the hydrogeological measurements is to define a hydrogeological framework, the important pathways and their flow velocities.

The methods discussed briefly below provide some of the most important information for characterizing groundwater flow.

6.3.1. Borehole drilling and completion

Many of the values to be collected are required over a period of time to be of most use, in particular for the development of numerical models. When subsurface programs are being planned, future monitoring requirements should be addressed. These requirements are discussed in section 6.4 below.

6.3.1.1.Drilling

Consideration should be given to the drilling techniques and core sampling methods which will be used in the site investigation programme. Methods include auger, percussive and rotary drilling. Although not strictly hydrogeological information, knowledge of the characteristics and location of the different lithological units at the site are prerequisite to constructing a hydrogeological conceptual model. This in turn means that there is a need to ensure good core recovery during borehole drilling. An additional advantage of good core recovery is that it provides undisturbed samples for laboratory testing. Special care is required to obtain representative cores in unconsolidated materials. Also, the borehole provides access for use of geophysical well logging.

Several factors are important when choosing the drilling technique(s):

— *Geological characteristics*: Different drilling techniques give different core recovery depending on the geological characteristics of the material which is being drilled. Rotary and shell and auger techniques tend to give good recovery in loosely consolidated materials. It is very difficult to get good core recovery in unconsolidated materials such as gravel.

— *Aquifer contamination*: Many drilling techniques require the use of drilling fluids. Techniques which use biodegradable polymers are generally to be preferred to non-biodegradable substances such as bentonite slurries which may cause long-term alteration of the aquifer (water contamination and alteration of hydrogeological properties) in the vicinity of the borehole. Some drilling techniques do not require the use of drilling fluids; this is obviously the preferred choice in terms of preventing aquifer contamination but there are disadvantages in terms of drilling time (see below).

— *Resources*: As already discussed some techniques are to be preferred because they give better core recovery and are less likely to contaminate the aquifer. However, the same techniques are often slower, meaning that they are also more expensive. Choices will have to be made as to whether it is preferable to have fewer boreholes yielding high quality in geological, hydrogeological and geochemical information as opposed to a larger number of poorer quality boreholes.

In the case of near surface repositories, the depth of interest is usually in the order of some tens of meters, even if in some areas the depth to be investigated can be greater. Examples of near surface repositories requiring underground investigations at greater depth are some facilities in rock caverns and repositories in arid zones with a deep water table.

Boreholes can be drilled in any kind of material to practically any depth; they allow to sample the materials of interest, to run logs which can determine many in situ properties of the geological materials surrounding the borehole walls and to place underground a variety of instruments for ad hoc determinations and long-term monitoring. However, borehole drilling is expensive and too many boreholes, at least in some sites, could disturb the natural hydrogeological conditions and interfere with the performance of some isolation barriers.

As a consequence, the use of alternative technologies capable of performing direct measurements underground should be considered.

For sites in relatively fine sedimentary materials — clay to coarse sand — and for depths up to a maximum of 70 to 80 metres, the cone penetrometer is a possibility.

Cone penetrometer testing (CPT) is a technique that has been widely used in the geotechnical field for about fifty years. The standard application is for in situ determination of geotechnical properties of soils but recent developments allow CPT to determine a variety of environmentally relevant parameters, to obtain samples of gas, water and soil, and to install instruments (including piezometers). The method does not provide the detail that conventional boreholes provide but can be more rapidly installed at much reduced cost and have potentially an important role to play for recharge and infill purposes.

6.3.1.2. Coring/sampling

Core and sample logging is the essential first phase of borehole investigation during which the drilling progress is closely monitored to detect water transmitting zones.

During core and sample logging, the rock type, lithology and general properties are noted, together with the depth, orientation and physical properties of fracture surfaces and other discontinuities.

Routine core sampling is used for analyzing geotechnical parameters (elastic modulus, compressive, tensile and shear strengths, acoustic velocity, etc.) as well as hydrogeological and hydrogeochemical parameters.

The hydrogeological parameters which can be measured in cores are porosity, hydraulic conductivity, dispersion and diffusion. The results of these investigations have to be used with care as the measurements can only be performed on good quality cores. On the other hand it should be kept in mind that the scale of the measurements is not the scale of the phenomena under consideration. Many geotechnical parameters can be obtained from laboratory techniques of samples. These can provide useful additional and supporting information on the characterization of the geology and hydrogeology.

6.3.1.3.Borehole geophysics

Following the drilling of boreholes and collection of core samples it is common practice to undertake borehole wireline logging. Borehole logging can provide very useful continuous information about the characteristics of rocks and their fluid content, lithology, geometry, electrical resistivity, bulk density, porosity, moisture content, etc. For hydrogeological investigations of potential sites, certain borehole geophysical logs are particularly useful. Further details on the usual suite of borehole logs are described in detail in [16, 17]. The addition of core logs and borehole geophysics to characterization can improve the usefulness of surface geophysical data collected between boreholes many times.

Information on general lithology can be obtained by using: caliper, natural gamma, and gamma density. Information on porosity can be obtained from the use of neutron-neutron and sonic logs. In the vadose zone calibrated neutron logs provide details of moisture content. Spontaneous potential, electrical resistance, and temperature are also useful in providing information on hydrogeological regimes. Composites of varios geophysical logs using ratios or data fusion methods can provide information regarding hydrogeologic properties. Qualitative and semi-quantitative relative values can be determined for each lithologic layer encountered usually with far better accuracy than core logging. Of particular note is combinable magnetic resonance (CMR) logging, which has the ability to provide a continuous, reconnaissance-level, vertical distribution of permeability for short formation distances from the borehole (0.3 cm horizontal). The combination of CMR wireline logging and selected hydrologic testing presents an optimized approach for hydrologic characterization: with the CMR providing a continuous (reconnaissance-level) measure of hydrologic properties used to focus selection of detailed hydrologic tests, which in turn can be used to calibrate the CMR logs to provide a more accurate, continuous log of hydrologic properties.

More recently, geochemical type logs have been developed that may provide data on the chemical properties of the aqueous phase.

Certain specialized wireline logs can be used during pumping tests to provide details on water flow. Mechanical flowmeter logs are limited to higher flow rates from the more productive hydrogeologic unit. More recently developed borehole flow meters utilizing a packer and magnetic flowmeter can detect lower flow rates.

Geophysical wireline logs can provide complementary and additional data to that obtained from core and other measurements, thereby increasing confidence in interpretations. Data can be used useful in the provision of geotechnical parameters for construction purposes.

(a) Use of standard logs

Standard logs include nuclear logs and electrical methods. Nuclear logs most commonly used include: natural gamma, gamma spectrometry, gamma-gamma, neutron-neutron, and neutron-gamma. These tools are designed primarily for sedimentary rocks with high porosities, but have also been used very successfully in certain types of igneous and metamorphic rocks in identifying groundwater flow pathways. Standard logs are the basis of all hydrogeological studies but some of them are of particular interest. For example, gamma rays which arise from the natural radioactivity in the formation can be used to identify clay zones as opposed to high permeability flow zones. Neutron porosity tools provide an estimate of the bulk rock porosity. This tool has to be calibrated in the laboratory or at field calibration sites with samples of the geological materials. Nuclear logs are particularly useful in unconsolidated sediments where steel casing has to be used to keep the borehole open. The presence of steel casing prevents the use of electrical logs in the borehole.

Electrical logs include: spontaneous potential (SP), single-point resistance, normal resistivity log, and lateral resistivity. One of the most useful is the lateral resistivity log that provides a good discrimination between aquifers and impervious zones. This log is particularly useful when there are zones of different salinity or where the borehole wall has been invaded by drilling fluids, which commonly occurs with rotary and high speed percussion drilling techniques.

(b) Thermal and electrical conductivity logs and flowmeter logs

The vertical distribution of hydraulic conductivity within an open borehole test section can be determined directly by measuring the distribution of inflow rate into the borehole test section during a constant-rate pumping test. A variety of flow-meters are available for measurement of inflow rate including: mechanical, heat-pulse, electromagnetic and acoustic. Generally, mechanical flow meters are reserved for pumping tests conducted in higher permeability formations, while other flow-meter types are designed for lower inflow (or outflow) measurement.

Analysis of flow-meter inflow data, using the Cooper and Jacob [18] method, provides a means of calculating the hydraulic conductivity for a particular interval, once the inflow rate and composite borehole drawdown is known. The Cooper and Jacob method assumes that flow to the borehole is horizontal and that horizontal head gradients are uniform away from the borehole. As indicated in reference [19] these conditions are established relatively early in composite borehole tests even for conditions where permeability contrasts between layers is large. Kabala [20] provides a means for analyzing flow-meter tests for situations where this is not the case.

Direct flow-metering tests are usually conducted within borehole sections having intermediate to higher permeabilities. The flow-meters previously identified do not possess the resolution capabilities to measure fluid inflow within low permeability borehole sections. Measurement of small inflow or discrete inflow features (e.g. fractures), however, can be accomplished indirectly using hydrochemical monitoring surveys identified below.

During a constant-rate pumping test, downhole hydrochemical monitoring (e.g. Eh, pH, fluid conductivity, temperature) with a sensor provides the opportunity to not only determine the hydrochemical character of inflowing water to the borehole with time (at depth), but also the means to indirectly calculate the inflow rate for low permeability borehole sections. One technique reported by Tsang [21] that uses fluid conductivity profile changes within a borehole section during constant-rate pumping tests indirectly calculates inflow rates for discrete depth intervals. For an example reported by Tsang [21], 9 discrete fracture zones within an open borehole granite section in Switzerland were identified using this method. Estimated inflow rates as low as 0.01 L/min were measured for fracture intervals during this test. Calculated hydraulic properties based on these inflow rates provided comparable results to standard hydrologic tests (e.g. pulse tests) for the fractured test intervals.

Other hydrochemical parameters (e.g. temperature) may also be analyzed using this technique to estimate the vertical distribution of hydraulic properties within a low permeability borehole section. As noted by Tsang [21], the hydrochemical monitoring method offers a useful technique that complements existing flow-meter methods for open borehole characterization.

(c) Flowmeters

Horizontal flow velocities in static conditions can be measured with special probes originally developed for oceanic surveys or for deep boreholes surveys, but successfully modified for monitoring well screened intervals.

Two types of probes are used in research programmes:

- thermal probes,
- acoustic probes.

In theory these tools can measure flow velocities of less than 1 cm/day. This velocity seems to be the lowest reliable resolution limit, but the practical range is more within 5 to 5000 cm/day.

(d) Thermal or electrical conductivity measurements

This test consists of creating a contrast of temperature or electrical conductivity between a fluid injected in the borehole and the fluid in the formation. The evolution of temperature or conductivity is followed by logging as described previously. The analysis of the temperature or the electrical conductivity versus time provides an estimate of water velocity. This method can be used in aquifers with velocities down to 5 cm per day, but as the test is performed in a single borehole, the flow direction cannot be measured.

(e) Other borehole logging methods

Other logs include: calliper, sonic, tube wave technique, dipmeter, borehole televiewer, television camera, borehole radar, temperature, magnetic, crosshole techniques. Although all of these can provide useful information some are usually more valuable than others. For example, calliper logs in sediments can identify where clays have swelled or sands have washed out, which would effect the accuracy and usefulness of nuclear logs. Caliper logs also are valuable for identifying the distribution and depth of fractures in competent rock. Sonic logs are particularly useful if logging for porosity and discounting cement or other permanent casing sealants outside the casing. Tube-wave is primarily applicable to identify fracture permeabilities in crystalline rock. A dipmeter can detect features including fractures, foliation, and changes in lithology in crystalline or sedimentary rocks. Other techniques have useful applications, but their usefulness will depend on site characteristics. Like all borehole logging techniques the knowledge of the geophysicist will determine the appropriate suite of geophysical logs specific to each sites hydrogeology. Often it is not possible to know in advance for certain, which set of nuclear, electrical, or other logs will be most useful for characterization. Therefore, after some initial logging techniques, the most appropriate suite can be selected for obtaining the data needed for effective characterization.

6.3.1.4.Completion

Boreholes should, as far as possible, be planned, installed and completed in accordance with both the short-term and long-term needs of the site investigation. There are several excellent references for borehole completion as monitoring wells or structures [22, 23, 24]. Whereas the short term needs are likely to focus on obtaining information on the geological strata, perched and regional groundwater levels, hydrogeochemistry and hydrogeological characteristics (e.g. permeability), the long term requirements are likely to focus on monitoring changes in water levels and natural and contaminant concentrations in groundwater. Several options are available for completing boreholes, including:

— single completions in clusters of boreholes with each borehole targeting a specific depth;
— multiple completions separated by packers;
— newer multilevel samplers.

Care must be taken that the completion design:

— provides isolation from other water sources, particularly water from the surface;
— targets each important flow zone, screens location;
— does not provide a preferential pathway allowing cross-contamination between aquifers;
— is appropriate for the formation which is being monitored; this generally means that the screen, sampling ports, or packers can only be chosen once the particle size distribution of the core has been analyzed;
— suitable development and maintanence of the facilities to ensure functionality.

Other useful information can be collected from borehole log analysis. There are many useful logs with respect to hydrogeological investigations such as nuclear and electrical methods. However, more sophisticated logs, such as geochemical logs, can also be obtained using commercially available probes; these are commonly used to identify flow paths.

The development and compliance with quality assurance procedures for the entire of the data and sample collection and analysis undertaken is required. Purging of borehole completions in order to obtain representative samples from the groundwater aquifers selected for monitoring is especially important. Details of requirements can be found in the available literature. The current availability of micro-purging technique/equipment that allows for reduced volume purges, downhole borehole pumps and discrete samples from depth profiles is of note.

6.3.2. Measurement of hydrogeological parameters

6.3.2.1. Vadose zone

While most techniques described below are generally applicable to hydrogeological investigations there are a few tests that are specific to the vadose zone.

(a) Soil moisture measurement

As discussed previously, water migration in the vadose zone is highly dependent on the degree of saturation. An effective way to measure the degree of saturation of soil is by means of the neutron probe. Properly calibrated for the specific material, this tool can provide reliable measurements of the water content of the soil. Information on wetting and drying characteristics can also be useful.

Laboratory methods consist of the weighing, drying and re-weighing of the sample. An unaltered sample is required in order to obtain good results.

Other laboratory details such as grain size distribution can be useful back up information and provides input into the geotechnical data requirements for construction.

(b) Pressure measurements

In order to measure the pressure in the vadose zone, tensiometers are commonly used.

A tensiometer is composed of a ceramic porous cell to be inserted in the soil; the water contained in the cell will eventually come in equilibrium which the water contained in the surrounding material. The suction, that is the difference between atmospheric pressure and water pressure, is measured with a manometer.

(c) Hydrograph method to estimate recharge

Coupled with the detailed measurement of a precipitation event the response of one or more piezometers, in the saturated zone below the site of interest, can provide information on the recharge rate. Since the water percolation will partially depend on the soil water content at the beginning of the observation period, it would be useful to combine this observation with a preliminary neutron probe survey. It is also important to understand the flow mechanisms, particularly the occurrence of lateral flow.

6.3.2.2.Saturated zone

Hydrogeological parameters relating to permeability, storage capacity and dispersion are obtained by field techniques using single or multiple boreholes.

(a) Hydraulic head

Hydraulic head measurements, together with hydraulic property determinations, provide the basis for determining the velocity of groundwater in the subsurface, and for delineating the impact of natural and man-related factors (e.g. disposal facility construction) on aquifer dynamics and groundwater flow patterns. Collectively, head measurements obtained during borehole characterization provide the vertical distribution of hydraulic head, which provides information pertaining to the vertical groundwater flow potential at that location. When combined with vertical head profile information obtained at other borehole sites, the lateral and vertical groundwater flow potential can be determined. Systematic head measurements obtained from boreholes having long-term monitoring systems, also provide valuable information pertaining to groundwater flow dynamics and response to external stresses (e.g. earthtides). When compared with other monitoring zone responses, hydraulic head data may also indicate possible hydraulic connectivity with other zones.

Hydraulic head values are commonly determined from field water-level or downhole pressure measured within wells that penetrate or isolate an individual test interval. Hydraulic head measurements are normally expressed as an elevation above a prescribed datum, which for most hydrological investigations is mean sea level.

In formations having isotropic hydraulic properties, observed hydraulic heads can be used to develop potentiometric maps and infer lateral groundwater flow directions. In situations where fluid-column densities vary significantly within the study area, observed hydraulic heads must be corrected to a reference density fluid prior to use in potentiometric maps. The reference density fluid normally used in hydrologic investigations is water at standard temperature and pressure conditions, with a density equal to 1.00 g/cm3 (actually 0.999014 g/cm3) [25]. The observed hydraulic head value corrected to this reference density fluid is referred to as a fresh-water head [26, 27]. Contouring area wide fresh-water heads produces a relief map of the potentiometric surface within a hydrogeologic unit. Analysis of a fresh-water potentiometric surface provides qualitative information concerning the lateral direction and rate of ground-water flow.

Spane and Mercer [25] present a computer program, HEADCO, that can be used to calculate fresh-water head values from field measurements. Calculation of the fresh-water head based on water-level measurements requires that the average fluid-column density within the borehole be known. The principal factors influencing fluid-column density include temperature, pressure, salinity, and suspended solids. In addition, the effects of external stresses (see Section 4.5) should be known and removed from the field measurements. The removal of external stresses requires the systematic correlation of baseline head monitoring measurements with observed external stress fluctuations. Once the relationship between the external stress and well hydraulic head measurements is established, the rise or decline caused by the external stress can be effectively removed from the hydraulic head measurement.

(b) Hydraulic property characterization

In hydrologic characterization investigations, in-situ hydraulic properties of subsurface units are commonly determined by analytical techniques that relate the effects of a known imposed stress to hydraulic properties (i.e. transmissivity, storativity). Standard hydrologic test methods routinely used include constant-rate discharge tests (in which ground water is removed from the test interval at a constant rate for an extended period of time) and slug tests (which are characterized by the instantaneous removal or injection of fluid). Analysis of the drawdown and recovery phases of these hydrologic tests is normally accomplished by type-curve fitting of log-log plots or straight-line analysis of semilogarithmic data plots of pressure change versus time. Recent developments in hydrologic test analysis based on the derivative of pressure with respect to the natural logarithm of time has been shown to significantly improve the diagnostic and quantitative analysis of various hydrologic test methods.

Hydrologic test analysis based on the derivative of pressure (i.e. rate of pressure change) with respect to the natural logarithm of time has been shown [28, 29, 30] to significantly improve the diagnostic and quantitative analysis of hydrologic tests. The improvement in test analysis is attributed to the sensitivity of the derivative to small variations in the pressure change that occurs during testing, which would otherwise be less obvious with standard pressure change versus time analysis. The sensitivity of the pressure derivative to pressure change facilitates its use in identifying the effects of wellbore storage, boundaries, and establishment of radial flow conditions on the test. The use of pressure derivatives has also been extended to the analysis of slug test response within confined aquifers [31, 32]. Pressure derivative analysis, used in conjunction with standard test analysis methods, is discussed in references [33, 34].

(i) Pumping test

The hydraulic properties of aquifers are determined by pumping a well normaly at a constant rate and observing the drawdown of the piezometric surface in observation wells at some distance from the pumped well. Two types of test are used: steady-state and transient-state tests.

With steady-state tests, pumping is continued sufficiently long for the water level in the observation wells to approach equilibrium drawdown, which then enables the transmissivity (T) to be calculated.

With transient pumping tests, changes in water level in the observation wells are measured in relation to time, which then yields not only transmissivity but also specific storage (S) values, as well as location and type of boundaries within the flow domain.

The specific storage coefficient is related to the quantity of water which can be released from a unit volume of a confined aquifer when the hydraulic head is changed by one unit. The released volume depends on the compressibility of the aquifer (pore volume compressibility), the water compressibility, the porosity and the water density. The determination of this coefficient is very difficult when the formation is inhomogeneous and when the permeability is low. For unconfined aquifers the specific storage is equivalent to the effective porosity of the material.

Most other methods of analyzing pumping test data require certain simplifying assumptions to be made about the transmissivity and storage properties of the aquifer so that mathematical formulae can be applied. Today computer programmes exist that can take into account non-ideal situations (e.g. boreholes of large diameter, partially penetrated aquifers) and many different sorts of boundary conditions.

These tasks are of particular importance and allow the collection of good quality parameter values of most significance. The very detailed nature of these tests are the subject of much literature and established standard procedures and can not be included here.

During pumping tests (also referred to as constant-rate discharge tests), groundwater is withdrawn from a well with discharge regulated and maintained at a constant rate. Water-level response within the well is monitored during the active pumping phase and during the subsequent recovery phase after termination of pumping. The analysis of drawdown and recovery water-level response within the stress well (and any nearby monitored wells) provides a means for estimating the hydraulic properties of the tested aquifer, as well as for discerning formational and non-formational flow conditions (e.g. wellbore storage, skin effects, presence of boundaries). Standard analytical methods that are used for constant-rate pumping tests include type-curve matching and straight-line methods.

In ground-water hydrology, type-curve matching methods [35, 36] are reserved for analyzing individual or collective observation well response. Type-curve analysis is not normally used for quantitative analysis of the pumped well, since part of the drawdown or recovery water-level response within the stress well is associated with well/formation inefficiencies or damage induced by the drilling process. In the petroleum industry, the effects of well/formation inefficiencies or damage are lumped together and referred to as the "skin effect". In petroleum reservoir analysis, storativity (S) is independently estimated for the test formation; transmissivity (T) and skin effect (Sk) are calculated simultaneously by matching the log-log drawdown or recovery response with appropriate type-curves for various skin-effect conditions [37].

For straight-line analysis methods, the rate of change of water levels within the well during drawdown and/or recovery is analyzed to estimate hydraulic properties. Since skin effects are constant with time during constant-rate tests, straight-line methods can be utilized to quantitatively analyze the water-level response at both pumped and observation wells. In ground-water hydrology, the semi-log, straight-line analysis techniques commonly used are based on either the Cooper and Jacob [18] method (for drawdown analysis) or the Theis [35] recovery method (for recovery analysis). These methods are theoretically restricted to the analysis of test responses from wells that fully penetrate non-leaky, homogeneous, isotropic, confined aquifers.

The straight-line solutions represent an approximation of the general equation describing radial flow to a well and are valid only after a specified period of time and after infinite-acting, radial flow conditions have been established. Infinite-acting, radial flow conditions are indicated during testing when the change in pressure, at the point of observation, increases in proportion to the logarithm of time. Lohman [38] indicates that the time required for the straight-line approximation to be valid (mathematically) can be calculated from the following:

$$t \geq (r^2 S)/(4T\,u) \tag{5}$$

where r is observation distance from the pumped well and u equals 0.01.

The recent development of pressure derivative methods [28, 29, 39] has significantly improved the analysis of pumping tests, using type-curve or straight-line methods. The improvement in hydrologic test analysis through use of pressure derivatives is attributed to the sensitivity of the derivative response to small variations in the rate of pressure change that occurs during testing. The sensitivity of pressure derivatives to pressure change responses facilitates their use in identifying the presence of wellbore storage, boundaries, and establishment of radial flow conditions within the test data.

Wellbore storage produces a characteristic "hump" in the pressure derivative plot, which increases in amplitude and duration as the associated dimensionless wellbore storage value increases. Infinite acting, radial flow conditions are indicated during testing when the change in pressure at the point of observation, increases in proportion to the logarithm of time. This is indicated when the pressure derivative curve becomes horizontal (i.e. when the pressure derivative becomes constant). Test data displaying this derivative pattern can be analyzed using confined aquifer, semi-log straight-line methods [18].

The previous discussion pertains only to the analysis of drawdown data obtained during pumping tests. Recovery data following termination of pumping tests can also be analyzed using the same procedures, provided that the recovery buildup pressure is plotted versus the equivalent time function described by Agarwal [40]. The Agarwal equivalent time function accounts for the duration of the discharge time period, thereby permitting the use of drawdown- type curves for the analysis of recovery data. The equivalent time function (te) is defined [40] as:

$$t_e = (t \times t')/(t + t') \qquad (6)$$

where t is duration of the discharge test, and t' is the time since discharge terminated. If radial flow conditions have been established during the recovery period, the straight-line analysis methods described in references [35, 40] can be utilized.

Recovery analysis also requires that the discharge rate is constant during the pumping period. For cases where variable discharge rate conditions are exhibited, a multi-rate superposition time function can be utilized for recovery data analysis. The multi-rate superposition time function is developed by representing the discharge period as a series of constant-rate pumping tests, whose effects are ‘superimposed’. A description of its calculation and use is provided by Earlougher [37] and Horne [30].

(ii) Slug test

This test consists in quickly withdrawing (or injecting) a small discrete volume of water into a borehole. The hydrostatic pressure of the tested interval is evaluated by measuring the water level change as a function of time. T and S can then be estimated using programmes based on transient flow theory. More accurate determination of T can be obtained by use of packers to isolate different sections of the borehole and without such isolation determinations of S are usually unreliable.

Depending on the existing test formation properties and influence of inertial/friction effects, slug tests can respond either as an overdamped (i.e. an exponential decay pattern) or underdamped (i.e. oscillatory) test response. A number of analytical methods are available for the analysis of overdamped and underdamped slug tests. In the following sections, the preferred analytical methods for the respective slug tests are discussed.

Over-damped conditions: In an over-damped well response situation, water levels recover to the static, pre-test level in an exponential manner. Slug tests that exhibit an over-damped response indicate that frictional forces within the well-aquifer system are dominant over inertial forces (i.e. represented primarily by the mass of water within the well column). Because of this force relationship, over-damped well response is associated with test formations possessing low to moderate transmissivity, for wells of shallow to intermediate test depths.

Analytical methods used in the analysis of the slug tests exhibiting overdamped responses (i.e. exponential decay pattern) include the type-curve matching method for unconfined and confined aquifers, as presented in references [34, 41]. Because these analytical methods can use all or any part of the slug test response in the analysis procedure, they are particularly useful in the analysis of unconfined aquifer tests (e.g. for HSU-1 test sites). They also do not have any of the inherent analytical weaknesses of the commonly used Bouwer and Rice method (e.g. assumption of steady-state flow, isotropic conditions, etc.), as originally suggested for unconfined aquifer slug tests.

Under-damped conditions: For under-damped slug test response cases, recovery water levels oscillate about the static water level with amplitudes that decrease with time. The oscillatory behavior exhibited indicates that inertial forces within the well-aquifer system are significant and must be accounted for in the test analysis. This type of well response is commonly exhibited by transmissive test formations, and/or well test systems possessing large volumes (i.e. mass) of water.

There are several analytical methods available for the analysis of underdamped slug tests exhibiting oscillatory test responses [20, 42, 43, 44]. Because of the ease of application and frictional head loss considerations, the analytical methods described by Van der Kamp [42, 43] are recommended for the analysis of slug tests exhibiting underdamped responses.

(iii) Pulse test

The pulse test (or pressure pulse test) is normally conducted in a test zone which has been isolated from overlying and underlying units by packers. Either an increase or decrease in pressure is applied during a short period of time and the evolution of the pressure is analyzed as a function of time.

Pulse tests are particularly suitable for measuring low permeabilities where the well storage is small. The duration of a pulse test is short compared to the duration of a slug test. However, it is important to note that the measured conductivity value is only representative of the immediate surroundings of the tested interval of the borehole. Compliance effects in the testing equipment (e.g. packer deformation) can seriously affect the results obtained from the pulse test.

Pulse or pressurized slug tests have been widely used for hydraulic characterization of low-permeability (i.e. <10–8 m/s) test formations. They differ from standard slug tests in that the dissipation of the instantaneous stress occurs under closed test system conditions. As shown by Bredehoeft and Papadopulos [45], the closed system conditions cause the stress application to dissipate more rapidly than a standard slug test response, since the pressure change during a pulse test is controlled by fluid volume changes associated with the compressibility/elasticity of water and the surrounding test system.

The same equations described for analysis of overdamped slug tests can also be used to analyze pulse tests. Equations having the well casing radius, rc, however, must be modified to account for the closed system test conditions by replacing the term for well casing radius, rc, with:

$$r_{c^{\cdot}} = (V_w C_w \gamma_w / \pi)^{1/2} \qquad (7)$$

where

V_w is the closed test system volume;
C_w is the compressibility of water;
γ_w is the specific weight of water.

Neuzil [46] also identified the importance of evaluating the compressibility of the test system, C_{obs}, and replacing the C_w with this parameter, when C_{obs}, > C_w in Equation 7.

Because the volumes of fluid are smaller (per unit pressure change) during pulse tests in comparison to slug tests, the radius of investigation is accordingly smaller. This fact makes pulse tests more susceptible to near well formation heterogeneities and skin effects. These characteristics and susceptibilities of pulse tests were described in detail in Reference [47]. Reports that summarize the application and interpretation of pulse tests for low permeability characterization are provided in references [48, 49].

(iv) Drill stem test

Like the pulse test, the drill stem test is commonly used in the oil industry. This method requires the use of a sophisticated packer tool.

The drill stem test is a combination of production period, slug test and pressure build up period under fully confined conditions for the test zone.

Interpretation methods and software have been extensively developed for this test in recent years and provide an evaluation of T, S and skin factor. As for the pulse test, the compliance effects of the testing equipment have to be minimized.

The drill-stem test (DST) is a standard test conducted in the petroleum industry to provide initial characteristics (e.g. flow production) of formations encountered during drilling and prior to final well completion. The test requires use of a downhole packer test system and shut-in tool. The standard DST consists of two inflow periods (open shut-in tool position) and following recovery periods. The first flow period and associated recovery usually are of short duration and intended to clear the test system of drilling fluid and equilibrate the test interval. Test analysis is usually performed on test data obtained from the second flow period and recovery. For flow period test data, the slug test analysis method is normally used, which is based on the type-curve approach [50, 51]. For recovery data, multi-rate analysis methods are normally used. One common method is to represent the variable-rate flow period as a series of constant-rate periods, whose effects are superimposed for the recovery analysis. This type of multi-rate analysis is described by Earlougher [37].

Because of its short test duration, a DST can provide preliminary information concerning hydraulic properties and static formation pressure conditions for test intervals having intermediate to higher permeabilities. This information can be useful for the design of more detailed hydraulic tests, e.g. constant-rate pumping or injection tests. Because the DST requires a flow period, its use for initial characterization of low permeability test intervals is not recommended. For low permeability situations, the pulse withdrawal test is recommend for initial test interval characterization.

(v) Slug Interference or sinusoidal test

This test method produces a stress in one borehole or well, which is compared to stress in an adjacent borehole or well. Depending on whether there is confinement the response will vary. This technique is useful over a wide range of hydraulic conductivities. Application and usefulness of this technique is found in references [49, 52].

Slug interference testing provides an alternative to constant-rate pumping tests for obtaining intermediate-scale formation hydrologic properties without extracting large volumes of groundwater and generally take less time to complete. The tests are conducted by instantaneously changing the water level at one borehole and monitoring the response at one or more observation boreholes. Analysis of the pressure response at the observation well provides estimates of aquifer transmissivity and storativity, and, under favorable conditions, estimates of vertical anisotropy and specific yield. Slug interference test response is a function of the applied stress, test formation hydraulic properties (i.e. T, S, S_y, K_D), and test well/aquifer relationships (i.e. well diameter, radial distance, aquifer thickness, well depth/aquifer penetration characteristics). A detailed description of the performance and analysis of slug interference tests is contained in references [41, 52, 53, 54, 55].

(vi) Other tests

Numerous other more engineering type tests can be carried out including Lefranc and Lugeon tests. Mostly these involve the injection of fluids into the formation, an undesirable feature when trying to determine the real hydrogeological properties of the system. In should be noted that the injection of fluids with different chemical composition to that of the groundwater can give rise too very inaccurate results.

(c) Porosity

The values of porosity and bulk density are usually obtained by laboratory measurements of samples taken from boreholes. Information on porosity of a stratum can also be obtained from field measurements by means of geophysical techniques used directly in the open hole. It is important to realize that porosity determined in the laboratory represents only the intact material and has limited applicability to hydraulics at sites where porosity along fractures is important. Also, the potential for errors in laboratory measurements of unconsolidated sediments is substantial because of the impossibility of obtaining an undisturbed sample.

Effective porosity is an important parameter and is best measured by the use of tracer methods.

(d) Measurement of dispersion

The artificial injection of tracers into a groundwater system is used to determine flow directions and groundwater flow rates and effective porosity. Tracers spread out during transport; this spreading, which occurs both in the direction of groundwater flow and perpendicular to this direction, is called dispersion.

Longitudinal dispersion can be determined from the breakthrough of a water soluble non sorbing tracer in the observation borehole in a single or multiple well tracer test. Additional boreholes are needed for the determination of the transverse dispersion component.

To design the test it is important to define the scale on which the dispersion has to be determined. The results are strongly dependent on the dimensions of the test area.

(e) Tracer tests

In a tracer test, groundwater is tagged with a water soluble, non sorbing substance and its transport velocity between boreholes in a groundwater flow system is measured. Example tracers include tritium, rhodamine, bromide, chloride, or iodine solutions.

The tracer concentration versus time after injection is measured in sealed off fracture zones, permeable units or entire boreholes, giving breakthrough curves. A breakthrough curve together with basic test data such as total mass of tracer injected and withdrawal capacity can be used to determine the following parameters of an aquifer or a fracture system:

— direction and velocity of groundwater flow;
— dispersion, diffusion and dilution;
— hydraulic fracture conductivities;
— flow porosity;
— retardation/retention.

Nevertheless many factors can influence the results and their unambiguous interpretation is difficult to attain.

Different field tracer test methods are used in dynamic conditions:

— the tracer is injected into a well and is then pumped back out of the same well ("the drift and pump-back method or alternate radial flow method");
— the tracer is injected into a central well and samples are taken in surrounding wells ("the radial divergent flow method");
— the tracer is injected into surrounding wells while pumping takes place continuously from a central well ("the radial convergent flow method").

6.3.3. Measurement of geochemical parameters

In situ measurements of the geochemical properties of water can discriminate between different flow zones and indicate if the water flowing in each identified zone has the same chemical characteristics and the same origin. Flow paths and residence times can also be determined comparing the groundwater chemical and isotopic content with the rock composition and the hydrogeological data.

Parameters commonly recorded directly in field are pH, dissolved oxygen, electrical conductivity, temperature, redox potential and alcalinity. Other important parameters determined at laboratory include major cations and anions, organic compounds and environmental isotopes (for example, 2H, 3H, 14C, 18O). Special care must be taken in the sampling and analysis of such data (for example, the presence of colloids may complicate obtained information). In low permeability rocks very long sampling times may be required before samples of water of acceptable quality can be obtained.

The hydrogeochemical information is also of primary importance to determine the mechanisms of transport and to address the capability of contaminants to migrate from the repository through the hydrogeological medium.

Detailed guidance on field sampling techniques is available in the literature (e.g. Ref. [56]). The main techniques used for extracting water from cores are:

— *Squeezing the cores*. This techniques can be used if the rock has a relatively low strength and if the moisture content of the rock is at least 7%, otherwise this technique cannot provide enough water for analysis;
— *Centrifuging*. A small piece of the core is placed in a centrifuge and is spun at high speed. The fluid removed from the core depends on the spin rate and the pore size distribution in the sample;
— *Immiscible fluid displacement*. Before centrifugation an immiscible, heavy and chemically inert fluid is added to the sample in the centrifuge. This fluid displaces the fluid in the core during centrifugation and can increase the fluid yield;
— *Leaching*. Solutes in the pore fluid are removed from the crushed sample by leaching in a known volume of distilled water. This technique is applicable to most sedimentary rocks.

6.4. MONITORING PROGRAMME

The definition of monitoring programs is one of the most important tools in the characterization of the groundwater flow.

A basic program is to monitor groundwater through boreholes and wells; it may be, however, sometimes possible to monitor the groundwater that reaches the surface through springs or natural depressions. These boreholes and wells must be designed to last for the lifetime of the facility and for a considerable period after closure of the facility. The requirements for the different phases of the repository life have been discussed within in Section 5. Aerial and vertical spacing of monitoring wells should be such that all hydrogeological units that are related to the groundwater flow are monitored.

The program should consist, at a minimum, of measuring groundwater levels, chemistry, radionuclides and groundwater direction and velocity (by the use of tracers). The frequency of measurement will depend on the specific characteristics of the system.

7. GROUNDWATER FLOW MODELLING APPROACHES

7.1. THE MODELLING PROCESS

Groundwater modelling is generally carried out for three separate but inextricably linked purposes:

— as a tool to develop an understanding of the observed hydrogeological behaviour of a site (this includes the integration of all the available information);
— to quantify this behaviour in parametric terms and verify their coherence;
— making predictions about the hydrogeological behaviour, as a basis for performance and safety assessment models.

Two sets of models are needed in order to support the performance assessment process: characterization models and assessment models. These are required to accommodate different approaches and current limitation of computer facilities to incorporate the very large amount of data and processing requirements associated with these very complex problems. Characterization models are used to build up a detailed understanding of groundwater processes and therefore need to represent these processes in some detail. On the other hand assessment models tend to include simple and globalized representations of the flow and transport processes which are more transparent to non-specialists. This also means that a large number of uncertainty and sensitivity analysis calculations can be carried out without excessive computational cost. However, the distinction between these two sets of models is diminishing as computers become more powerful.

Ideally, groundwater modelling studies include the stages shown in Fig. 8, which also illustrates how site investigation and groundwater modelling can be integrated in an iterative framework. The different stages in this cycle will now be discussed in more detail.

7.2. CONCEPTUAL MODEL DEVELOPMENT

There is no generally agreed definition of the term conceptual hydrogeological model but it is usually taken to be a subjective understanding of the processes controlling groundwater flow at the site. Conceptual models are:

— a means of coherently organizing all the information about the hydrogeological behaviour of the flow system;
— a simplified representation of the physical reality making the field problem amenable to analysis.

On the basis of available data it is possible to develop a number of conceptual models. For example, it may be possible to represent fracture flow at different levels of detail by either a uniform, equivalent permeability or by a distribution of permeabilities depending on the degree of fracturing. Similarly, it is possible to describe the aquifer by a single or multi-layered system. Saturated and unsaturated flow may be represented either separately or combined, the latter in terms of either a single saturated model or a variably saturated model.

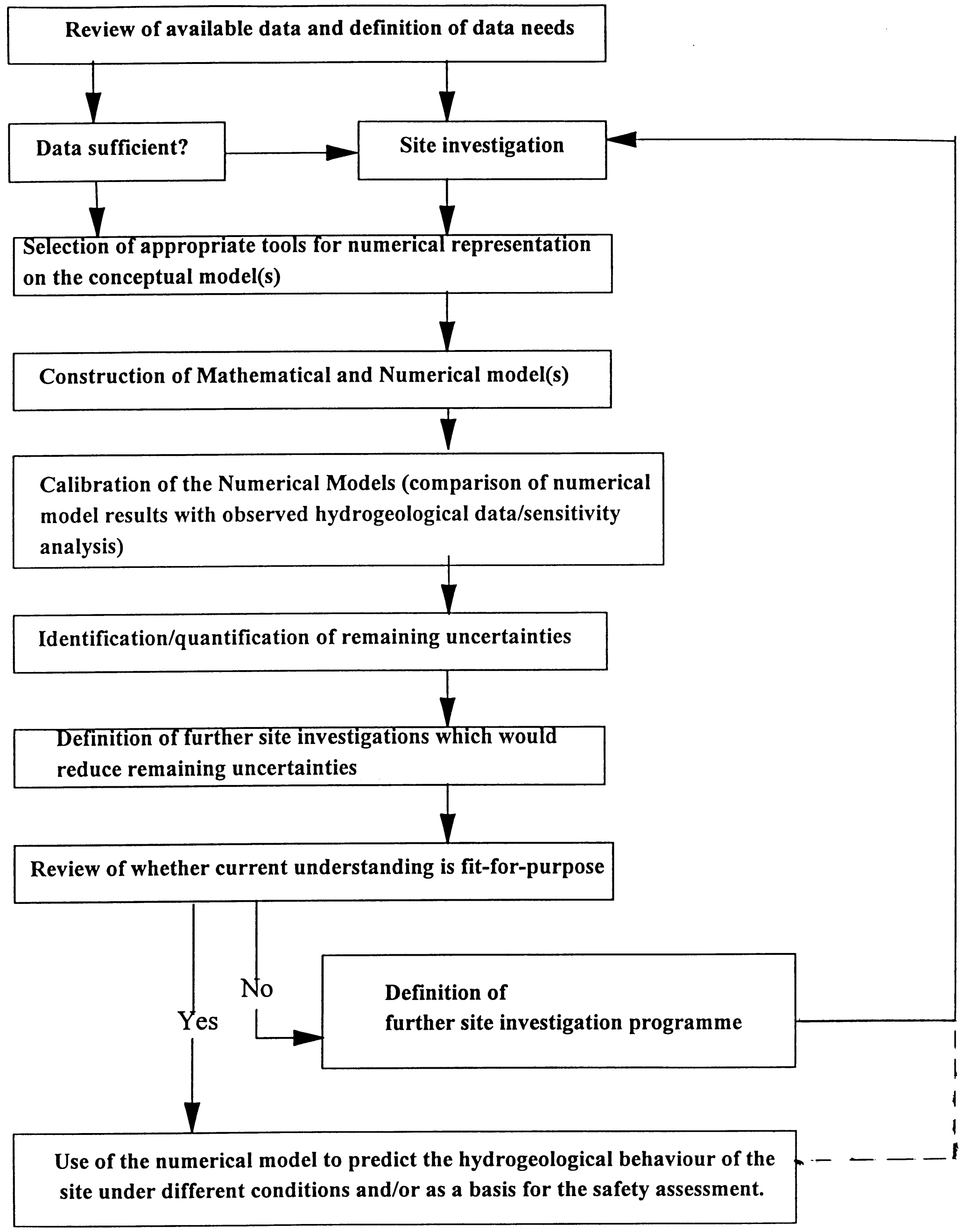

FIG. 8. Procedure of groundwater modelling studies.

The conceptual models should be updated during each iteration of the site investigation — modelling cycle. Hence, the initial conceptual model(s) may be relatively simple, based on the current understanding of the location, extent and interrelationship of the major hydrogeological units, the recharge and discharge associated with these major units, the seasonally averaged location of regional and local water tables and soil moisture profile.

Groundwater flow systems are often very complex, and therefore, efforts should be directed at establishing more than a single conceptual model. These models should take into consideration scenarios identified by safety and performance assessment. However, it is important to adopt a systematic approach to conceptual model development and document all modelling assumptions.

7.3. MATHEMATICAL MODEL DEVELOPMENT

The assumptions embodied in a conceptual hydrogeological model(s) are quantified by building a mathematical model. This model describes the behaviour of the flow system by using sets of mathematical equations and by defining the initial and boundary conditions. The equations are then solved using analytical, semi-analytical or numerical methods to predict the system behaviour, principally the piezometric head, and therefore, direction and velocity of groundwater movement.

Simplifying assumptions made in the conceptual model are realized in the mathematical model. For example, if groundwater flow is rectilinear it may be described by equations in one dimension even though, in reality, groundwater flow occurs in three dimensions. Similarly, the major hydrogeological units may be known to be heterogeneous and/or anisotropic but may be modelled by constant coefficients. The degree of simplification in the conceptual model, and imparted to the mathematical model, depends on the availability of data. Generally the complexity of the mathematical model should be commensurate with the type, quality and quantity of data which are available for the flow system. However, it may sometimes be appropriate to use models for which real data are not available for instance in order to ascertain whether describing a process in greater detail gives rise to a predicted behaviour which is significantly different from that obtained using a simpler representation.

One of the purposes of modelling is to quantify the interaction of the facility with the groundwater flow. In the mathematical model, the facility is represented either by a different hydraulic conductivity value or by means of a specified boundary condition.

Mathematical models are usually solved using computer codes. A large number of groundwater flow codes are available commercially and it is not within the scope of this document to make recommendations on these codes. However, the following are general guidelines:

- The computer code should have been developed within the framework of an internationally or nationally recognized quality assurance system;
- The applicability of the code should be well tested (see Section 7.5.1).

The groundwater flow codes used need to be integrated with other aspects of the modelling requirements, most notably transport considerations. Experience has shown that it is often necessary to adapt or customize ‘basic’ commercial codes or develop specific codes in order to satisfactorily represent the complications involved at a specific site location.

Mathematical models can be divided into four main groups:

- *Deterministic models* — in this type of model the equation that define the groundwater flow and transport are solved analytically or numerically assuming appropriate initial and boundary conditions;
- *Stochastic models* — this type of model permits a more general formulation of the groundwater flow and transport. Simulation is undertaken by adaptation of variables within a statistical structure, results being given within confidence limits. It is possible to predict the uncertainty associated with the physical properties of the medium;

– *Hydrogeochemical models* — these models can define the chemical equilibrium of the different solute species (equilibrium models), or they can describe the evolution of the constituents within the main chemical processes that take place within the hydrogeological medium (kinetic models);
– *Coupled models* — these models combine different processes such as flow, transport and chemical evolution. The solution for these kind of coupled processes are sometimes limited not only by the computing techniques but also by lack of data for the coupling phenomena and poor understanding of some coupling mechanisms.

7.4. UNCERTAINTY

7.4.1. Types of uncertainty

Uncertainty in groundwater flow modelling arises from a number of sources. The main sources are as follows.

7.4.1.1. Conceptual model uncertainty

As discussed in Section 7.2, a conceptual hydrogeological model, which may necessitate extrapolation and/or interpolation of data, is a set of assumptions about how the system works. However, it is often possible to construct more than one set of equally plausible assumptions, especially at the start of the groundwater characterization programme.

7.4.1.2. Parameter uncertainty

Groundwater flow model parameters may be uncertain because:

— values for the parameters have not been measured;
— parameter values have been measured but the measurement process is not sufficiently accurate to give an exact value;
— the parameter value cannot be measured, only inferred;
— the value of the parameter varies with external conditions but the exact nature of this variation is not known (e.g. the permeability of the strata may vary with the degree of saturation in a manner which may be difficult to accurately quantify);
— uncertainty resulting from the scale dependence of the parameters;
— uncertainty associated with spatial or temporal variability (such uncertainty could be quantified using a stochastic model);
— external effects, which give rise to parameter variation;
— the parameter may vary in a stochastic manner but this variation is itself uncertain.

7.4.1.3.Model uncertainty

Uncertainty may be introduced due to errors in transcribing the mathematical equations which describe the flow process into the computer code. However, this can be minimized through verification (see Section 7.5.1) and is not discussed further.

7.4.1.4. Performance assessment uncertainty

Finally uncertainty arises in the performance assessment due to the difficulty of predicting the evolution of the groundwater system over long periods of time. This source of uncertainty cannot be reduced through groundwater flow characterization and is generally addressed through scenario analysis in the assessment. This aspect of uncertainty is beyond the scope of this document and is, therefore, not discussed any further.

7.4.2. Dealing with uncertainty

No agreed methodology for dealing with uncertainties arising from alternative conceptual and numerical models exists. There is recognition of the need to develop systematic procedures for eliciting alternative conceptual models, ensuring they are compatible with the known facts and dealing with the results of alternative models. As a minimum all conceptual model assumptions should be properly documented. Savage [7] outlines three alternative methods for dealing with the general problem of conceptual model uncertainty:

- statistical sampling of alternative conceptual models (similar to probabilistic analysis);
- use of the conceptual model which gives the most pessimistic result in the safety assessment;
- simple documentation of the possible sources of bias.

The uncertainties which arise due to the simplification which is necessary when moving from conceptual to mathematical models have received even less attention. However, in principle, these can be handled in the same manner as conceptual model uncertainties.

Possible approaches to deal with the subject of parameters uncertainty are given below.

7.4.2.1. Conservative approach

In this case, each parameter is assigned a pessimistic value. However, it is important to note that here "pessimistic" must be defined in relation to the safety assessment. For example, the use of a high value for rock permeability would only be conservative if the major risk is from groundwater pathways. If the major risk in the safety assessment is from human intrusion, then a low permeability value would be pessimistic. The major disadvantages of this approach are that it does not improve understanding of how the groundwater flow system works, highlight uncertainties or set priorities for further site investigations.

7.4.2.2. Best estimate approach

In this approach a central set of parameters is defined. Further calculations may also be carried out using "optimistic" and "pessimistic" sets of parameters. However, this approach has similar disadvantages to the conservative approach as discussed above.

7.4.2.3. Sensitivity analysis

Here, the model input parameters are varied over sensible ranges to determine the effect of these variations on the model results. This increases understanding of which parameters need to be determined with the greatest accuracy, and helps prioritize data collection requirements. Sensitivity analysis provides a logical and auditable method of making sure that limited resources are used to determine the most important parameters. It also indicates which parameters should be included in any uncertainty analysis. Further discussion of the application of sensitivity analysis in safety assessment is contained in the RADWASS programme [57].

7.4.2.4. Uncertainty analysis

Whereas sensitivity analysis shows how the groundwater model results change with variations in input parameter values, uncertainty analysis gives a numerical estimate of how the uncertainty in the input parameters propagates through to give uncertainty in the model results. However, uncertainty analysis is usually carried out as part of the safety assessment modelling (see Section 9). Uncertainty analysis for groundwater flow models is necessary to establish upper and lower confidence levels for model outputs such as groundwater flow velocities. These confidence levels may be used for the following purposes:

— specification or detailed performance analysis for engineered barriers;
— design of groundwater monitoring systems;
— design of remediation systems such as in-situ treatment or conditioning.

Further discussion of the application of uncertainty analysis in safety assessment is contained in the RADWASS programme [57].

7.5. CONFIDENCE BUILDING

Groundwater flow models are primarily used as a basis for simpler safety assessment models, including predicting how the flow system will behave under different hydrogeological conditions. Scientists, regulators, decisions makers and, if possible, the public should all have confidence in the information, insights and results provided by safety assessments. This section discusses what can be done to ensure that the groundwater flow component of the safety assessment deserves a high degree of confidence. Activities contributing to confidence building include (1) model testing, (2) sensitivity and uncertainty analyses (discussed in Section 7.4.2), and (3) peer review. Quality assurance is also important but this is discussed separately in Section 8.

7.5.1. Model testing

Confidence in groundwater models depends on two factors. First, does the method of calculation solve accurately the mathematical equations that constitute the model? The process of verification is used to answer this question. Second, does the model simulate the groundwater flow processes sufficiently accurately? Calibration and validation are meant to answer this question, although the role of validation is somewhat contentious.

7.5.1.1. Verification

Verification of the method of calculations in the mathematical model is achieved by solving test problems designed to show that the equations in the model are solved satisfactorily. If computer software is used, this should be verified by testing at the subprogramme and integrated programme levels as recommended by an internationally or nationally recognized quality management system (e.g. ISO9001-3). Verification might also include comparison of computer model results with analytical solutions and benchmarking against other codes. The results of several international intercode comparison exercises are already available. Since verification of the methods of calculation is feasible, it should be used for confidence building in groundwater modelling. While it provides no confidence that the mathematical scheme itself is a correct representation of the physical problem, it does at least show that there have been no important errors in translating it into numerical form.

7.5.1.2. Calibration

Calibration aims to reduce conceptual and mathematical model uncertainty and parameter uncertainty, and is performed by comparing groundwater flow model predictions with field observations and experimental measurements. Calibration is, therefore, a site specific procedure, whereby a set of site specific input data is used to compare predictions and observations at that site. In practice, if a groundwater flow model can be calibrated successfully for a variety of site specific conditions, an increased level of confidence can be placed on the model's ability to represent those aspects of system behaviour. However, one difficulty which is often encountered during the calibration process is that different conceptual models and their associated sets of input data produce results which show equally good agreement with the observed data. This limits the reduction in uncertainty which can be achieved.

More recently automatic calibration methods have become included within codes which save manual input effort (trial and error) and allow more time for analysis of the conceptual scheme. However, automatic calibration requires a more detailed study of the obtained parameters.

7.5.1.3. Validation

The aim of validation is to show that the model correctly simulates groundwater flow processes which are currently occurring and the evolution of the system with time. However, it is practically impossible to achieve complete validation for the following reasons:

— To show that the model correctly simulates current flow processes it is usual to compare predictions obtained using the calibrated model with observed data which have not been used in the calibration process. In practice, such efforts may not be able to obtain high levels of agreement because the preceding calibration process has not achieved sufficient reduction in the uncertainties associated with the conceptual model, mathematical model and parameters. Under these circumstances the validation exercise effectively becomes additional calibration. However, attempts to validate models can provide useful information on the remaining uncertainties;
— If a model is meant to simulate long term processes (e.g. under different climatic conditions or after disruptive events), validation is impossible because the observation of results would require an unrealistic time period.

It is argued that the term validation is misleading because models can only be invalidated. Terms such as history matching and model testing have been suggested as alternatives because they do not have the same connotation of correctness. This is not to imply that groundwater models should not be used to predict how the site behaves (or will behave), but to stress that sufficient data should be collected so that models can be rigorously tested and any predictions can be shown to be well founded.

7.5.2. Peer review

For any scientific activities the confidence in the validity of results depends to a great extent on the outcome of the peer review process. Scientific works and results are normally published in the open literature for detailed scrutiny by other experts active in the same field as well as by anyone interested in the subject.

However, the peer review process for work that constitutes the basis for safety assessments should include forms other than the typical peer review of scientific publications and programme results. National radioactive waste management programmes should have, therefore, provisions for the technical review of groundwater flow characterization programmes. The regulatory body should develop an independent capability for reviewing these programmes and the disposal facility operator or the competent authorities may organize critical reviews by independent bodies.

7.6. FIT-FOR-PURPOSE DECISIONS

Once the results of the mathematical model calculations have been compared with observed hydrogeological data and the remaining uncertainties have been identified and, if possible, quantified, it is necessary to decide whether to try and further reduce the uncertainties. Further reductions can usually only be achieved through additional laboratory and field studies which are designed to yield information to:

- improve the conceptual model(s) of the groundwater flow system;
- provide more reliable input data for the mathematical model(s);
- provide extra data against which model predictions can be tested.

Currently, there is no consensus on the methodologies which should be used in deciding if sufficient confidence can be placed in the current version of the groundwater flow model or, alternatively, whether it is necessary to undertake further investigations and iterate through the modelling phases. However, the following factors are usually important in deciding whether the remaining uncertainty is acceptable:

- the impact of uncertainty about the groundwater flow system on the results of the performance assessment;
- whether it has been possible to validate the model (i.e. compare predictions from the calibrated model with observed data which have not been used in the calibration process);
- the level of agreement which has been obtained between the model predictions and the observed data during the calibration and validation phases;
- the quality of the data which were used in the calibration and validation phases;
- the temporal and spatial frequency of the data which were used in the calibration and validation phases;

— whether alternative conceptual models give equally good agreement between predicted and observed behaviour;
— regulatory guidelines;
— the reduction in uncertainty which can be realistically expected as a result of further work;
— the risks and impacts associated with the additional programme of work; this is particularly important for existing sites with widespread contamination.

If further laboratory and/or field work is undertaken, the results of the preceding modelling phases should be used to define which uncertainties should be targeted and to set priorities for the programme.

If it is decided that the current groundwater flow model is fit-for-purpose, the reasons for this decision should be documented. The model may then be used as a basis for the final safety assessment and/or to predict the hydrogeological behaviour of the site under different conditions.

8. QUALITY ASSURANCE REQUIREMENTS

Quality assurance covers, first, the determination of a quality policy and, second, the checking that pre-determined quality control activities are being properly undertaken. Policy determinations happen at the corporate level of an organization and are typically defined in a corporate quality manual. Implementation is generally via a quality management system.

Quality assurance and quality control (QA/QC) procedures have been or are being introduced in many aspects of radioactive waste management and will be the subject of a future IAEA publications and are also considered in [2, 58]. The need to generate confidence in the results of performance assessments requires that a quality assurance procedure be applied to all the various elements of the assessment including groundwater flow characterization.

Data acquisition, development of models and methods of calculation should all be carried out within an internationally or nationally recognized quality management system from the earliest stage and throughout the programme. The quality assurance approach should provide a framework in which groundwater characterization activities are performed and recorded in databases, attesting to compliance with a documented procedure. In this way it can be shown that reliable and traceable sources of information have been used.

It is important to ensure that all the individual quality assurance procedures for the different elements of the programme (data acquisition, parameter determination, presentation of the data) are included within the quality assurance programme for the repository.

The quality assurance programme for hydrogeological aspects is required to be undertaken in all the phases of repository life as detailed in [2, 58]. The programme should be established early in the siting process to ensure compliance with relevant standards and criteria. During the design, construction and operation of the disposal facility, a design control process should be undertaken with special attention to control of changes to barrier design and operation procedures, to ensure that they do not lead to unacceptable safety consequences. In the post closure phase of the facility there is a need to provide fully quality assured monitoring methods and procedures for the collection of monitoring data. In addition there is a need to provide for the collection and preservation of all the information obtained during the previous phases that may be important for safety in the future. It has already been indicated how the hydrogeological understanding is of prime importance to repository safety.

It is generally accepted that the international standard ISO-9001 [59] is the most important standard for quality management systems. The quality assurance approach should provide a framework in which groundwater flow characterization activities are performed and recorded in databases, attesting to compliance with a documented procedure. In this way it can be shown that reliable and traceable sources of information have been used.

As an overall result, confidence in the results of the safety assessment will be enhanced.

9. GROUNDWATER FLOW AND PERFORMANCE ASSESSMENT

A principal role of the safety assessment is in the license application and approval process. Performance assessments may be required at various stages in the licensing process, including approval to construct, operate, close and whenever there are significant changes in the state of the facility.

Performance assessments play an important role throughout the various phases of a near surface disposal facility. Their use is of greater importance in the site characterization and confirmation stages (see Section 5.2). Such assessments can then be developed to assist in system optimization and facility design by carrying out comparative assessments for various combinations of alternative waste packages, disposal modules and site management and closure measures.

The process of safety assessment for near surface disposal of radioactive waste requires a wide variety of information in order to describe and predict the behaviour of the disposal system and to provide reasonable assurance of compliance with safety and regulatory requirements. The process involves the following activities:

— description of the disposal system, including site, waste form and engineered structures;
— description of the hydrogeological and geochemical properties of the ground and groundwater;
— determination of conceptual models of the behaviour of the system and its subcomponents;
— identification of the pathways potentially leading to the transfer of radionuclides from the repository to humans and the environment;
— identification and description of relevant scenarios;
— implementation of appropriate models, evaluation of the system performance through calculations, consequence analysis, sensitivity and uncertainty analysis and interpretation of results;
— verification of compliance of the assessment results with the design goals through critical review.

The completeness and robustness of the assessment will depend on the extent and quality of the data in terms of all aspects of site characterization (including groundwater flow), waste package performance and the role and performance of other engineered barriers. Close coordination of the safety assessment and the supporting data acquisition programmes is therefore necessary, with the safety assessment being a very valuable means of identifying and prioritizing supporting research and development work. Performance assessment is an iterative process during the different steps of the repository safety analysis.

From the preceding discussion it is clear that groundwater flow characterization is a necessary component of the performance assessment process. This means that it is important to ensure that the interface between the detailed groundwater flow characterization programme and the safety assessment is well organized and defined. In particular, a decision will have to be made as to whether detailed, or research-type, modelling is needed in addition to simpler assessment groundwater flow. The reasons for this decision should be documented. If more detailed modelling is undertaken then there must be a logical and auditable method for using the results of the research modelling as a basis for the assessment modelling. Care must also be taken to ensure that the supporting data from the site investigation programme are documented in accordance with the requirements of the performance assessment.

Figure 9 summarizes the integration of groundwater flow characterization with the performance assessment process.

Finally, it is important to note that there are numerous sources of uncertainty within the assessment process. It is beyond the scope of this document to discuss how all of these uncertainties arise or how they should be handled, although much of the discussion on uncertainty in groundwater modelling (Section 7.4.) is applicable in principle to the wider assessment process. However, it is important to note that uncertainty about the hydrogeological conceptual and numerical models and their associated parameters and computer codes all contribute to uncertainty within the safety assessment. Groundwater flow characterization programmes for near surface facilities can only be completed once uncertainty about the hydrogeological processes at the site have been reduced to a level which is acceptable to all interested parties.

10. SUMMARY AND CONCLUSIONS

A good understanding of groundwater flow conditions is required not only for the site selection process for a near-surface disposal facility but also for predicting potential pathways for contaminant transport and for assessing the safety of the disposal facility during the post-closure phase. This report addresses the issue of groundwater flow, as part of the site investigation studies, with particular emphasis on the methods and modeling approaches needed to characterize groundwater flow conditions at near-surface disposal facilities.

The importance of groundwater flow characterization and the factors controlling groundwater flow are discussed and highlighted in the broader context of the requirements for repository siting and safety assessment. As well, groundwater flow characterization as part of the overall site investigation studies is discussed. The report also touches on quality assurance issues that are inherently important to any groundwater characterization programme.

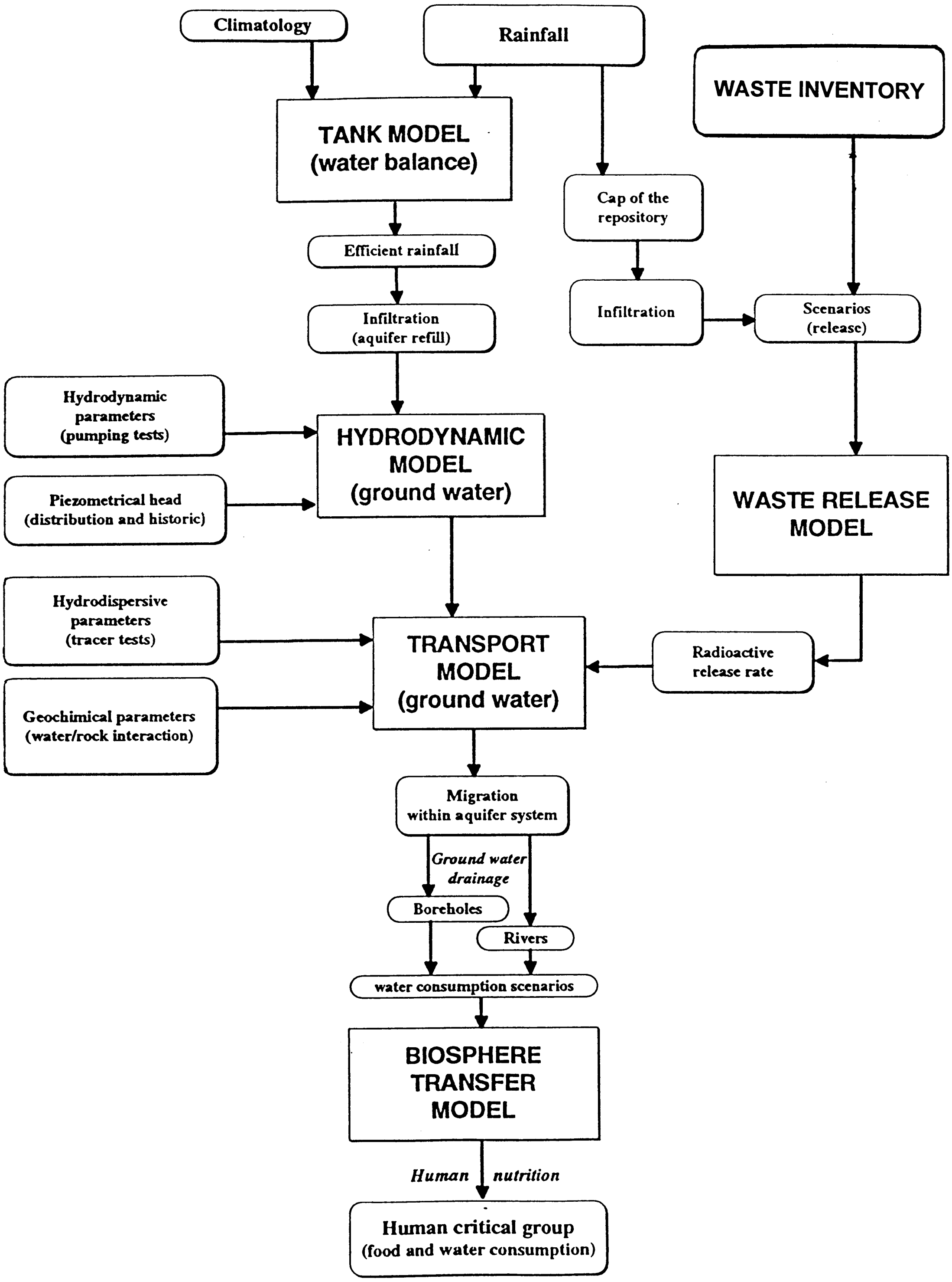

FIG. 9. Integration of groundwater flow characterization with the performance assessment process.

Given that near-surface disposal facilities may be located either above or below the water table, the report emphasizes the need and discusses the various approaches and techniques available to characterize both the vadose and the saturated zone. The range of factors and conditions that need to be investigated in order to define and model groundwater flow, both in the vadose and the saturated zone, has been discussed and considered a part of the overall site characterization studies.

A framework for the groundwater flow characterization programme is presented, discussing the specific considerations during the various phases of the repository life cycle. It is recognized though that the characterization of groundwater flow conditions is of prime importance during the pre-operational phase because it directly supports the site selection process, provides input data for safety assessment during the post-closure phase and baseline data for the monitoring and surveillance programme.

Various surface- and subsurface-based methods and techniques that can be used to characterize groundwater flow conditions have been reviewed in great detail, with particular emphasis on the measurements of specific hydrogeological parameters that are important for characterizing groundwater flow conditions both in the vadose and the saturated zone.

The report discusses the various approaches to groundwater flow modeling, in particular the need to develop a simple, conceptual hydrogeological model and then proceed to further develop a quantitative mathematical representation of the groundwater flow conditions for a given site. A large number of computer-based, groundwater flow codes are commercially available, but it is not within the scope of this report to make recommendations about the applicability of the various codes. However, experience in the Member States has shown that it is often necessary to adapt or customize the commercially available codes to represent specific site hydrogelogical conditions, processes, and factors that are being modeled. Factors contributing to uncertainty, specifically model uncertainty and parameter uncertainty, are discussed and the various approaches to dealing with uncertainty are outlined.

The report does not address specific experiences of the various Member States in groundwater flow characterization studies, but it is recognized that this information would be useful and should be compiled and included at a later date.

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, The Principles of Radioactive Waste Management, Safety Series No. 111-F, IAEA, Vienna (1995).

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Near Surface Disposal of Radioactive Waste: Safety Requirements, Safety Standards Series No. WS-R-1, IAEA, Vienna (1999).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Classification of Radioactive Waste: A Safety Guide, Safety Series No. 111-G-1.1, IAEA, Vienna (1994).

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Radioactive Waste Management Glossary, IAEA, Vienna (1993).

[5] INTERNATIONAL ATOMIC ENERGY AGENCY, Review of Available Options for Low Level Radioactive Waste Disposal, IAEA-TECDOC-661, Vienna (1992).

[6] INTERNATIONAL ATOMIC ENERGY AGENCY, Report on Radioactive Waste Disposal, Technical Reports Series No. 349, IAEA, Vienna, (1993).

[7] SAVAGE, D., The Scientific and Regulatory Basis for the Geological Disposal of Radioactive Waste, Edition 1995, West Sussex, United Kingdom (1995).

[8] DE WIEST, R.J.M., Geohydrology (1965).

[9] FREEZE, R.A., CHERRY, J.A., Groundwater, Prentice-Hall, Englewood Cliffs (1979).

[10] INTERNATIONAL ATOMIC ENERGY AGENCY, Siting of Near Surface Disposal Facilities: A Safety Guide, Safety Series No. 111-G-3.1, IAEA, Vienna, (1994).

[11] BOUWER, H., Groundwater Hydrology, McGraw Hill Series in Water Resources and Environmental Engineering, USA (1978).

[12] DE MARSILY, G., Hydrogéologie quantitative, Collection Sciences de la Terre, Paris (1981).

[13] RODDA, J.C., Facets of Hydrology, A Wiley-Interscience Publication, Edition 1976, Bristol (1976).

[14] INTERNATIONAL ATOMIC ENERGY AGENCY, Hydrological Dispersion of Radioactive Material in Relation to Nuclear Power Plant Siting: A Safety Guide, Safety Series No. 50-SG-S6, IAEA, Vienna (1985).

[15] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Power Plant Siting: Hydrogeologic Aspects, Safety Series No. 50-SG-S7, IAEA, Vienna (1984).

[16] INTERNATIONAL ATOMIC ENERGY AGENCY, Site Investigations for Repositories for Solid Radioactive Wastes in Shallow Ground, Technical Reports Series No. 216, IAEA, Vienna (1982).

[17] INTERNATIONAL ATOMIC ENERGY AGENCY, Techniques for Site Investigations for Underground Disposal of Radioactive Wastes, Technical Reports Series No. 256, IAEA, Vienna (1985).

[18] COOPER, H.H., Jr., JACOB, C.E., A Generalized Graphical Method for Evaluating Formation Constants and Summarizing Well-Field History. American Geophysical Union, Transactions **27** 4 (1946) 526–534.

[19] JAVANDEL, I., WITHERSPOON, P.A., A Method of Analyzing Transient Fluid Flow in Multilayered Aquifers Water Resources Research, Vol. 5 (1969) 856–869.

[20] KABALA, Z.J., PINDER, G.F., MILLY, P.C.D., Analysis of well-aquifer response to a slug test, Water Resources Research **21** 9 (1985) 1433–1436.

[21] TSANG, C. -F., A Borehole Fluid Conductivity Logging Method for the Determination of Fracture Inflow Parameters. LBL-23096, Lawrence Berkelely Laboratory, Berkeley, California (1987).

[22] ALLER, L., PETTY, R.J., JLEHR, .H., SEDORIS, H., NIELSEN, D.M., Handbook of Suggested Practices for the Design and Installation of Groundwater Monitoring Wells, National Water Well Association, Dublin, Ohio (1989) 397.
[23] DRISCOLL, F.G., Groundwater and Wells, Johnson Division, St. Paul (1986) 1089.
[24] SCHALLA, R., "Design and installation of groundwater monitoring wells", A Practical Handbook of Groundwater Monitoring (NIELSEN, D.M., Ed.),. Lewis Publishers, Chelsea, Michigan (1991) 717.
[25] SPANE, F.A., Jr., MERCER, R.B., HEADCO: A Program for Converting Observed Water Levels and Pressure Measurements to Formation Pressure and Standards Hydraulic Head, RHO-BW-ST-71 P, Basalt Waste Isolation Project, Rockwell Hanford Operations, Richland, Washington (1985).
[26] LUSCZYNSKI, N.J., Head and flow of ground water of variable density, J. Geophys. Res. **66** 12 4247–4256 (1961).
[27] DE WIEST, R.J.M., Flow Through Porous Media, Academic Press, New York and London (1969).
[28] BOURDET, D., WHITTLE, T.M., DOUGLAS, A.A., PIRARD, Y.M., A new set of type curves simplifies well test analysis, World Oil, **May 1983** 95–106.
[29] BOURDET, D., AYOUB, J.A., PIRARD, Y.M., Use of Pressure Derivative in Well-Test Interpretation, Society of Petroleum Engineers, SPE Formation Evaluation, June 1989 (293–302).
[30] HORNE, R.N., Modern Well Test Analysis: A Computer-Aided Approach, Petroway, Inc., Palo Alto, California; distributed by the Society of Petroleum Engineers. Richfield, Texas (1990).
[31] KARASAKI, K., LONG, J.C.S., WITHERSPOON, P.A., Analytical models of slug tests, Water Resources Research **24** 1 (1988) 115–126.
[32] OSTROWSKI, L.P., KLOSKA, M.B., Use of Pressure Derivatives in Analysis of Slug Test or DST Flow Period Data, SPE paper 18595, Society of Petroleum Engineers (1989).
[33] SPANE, F.A., Jr., Selected Hydraulic Test Analysis Techniques for Constant-Rate Discharge Tests, PNL-8539, Pacific Northwest Laboratory, Richland, Washington (1993).
[34] SPANE, F.A., Jr., WURSTNER, S.K.,. DERIV: A program for calculating pressure derivatives for use in hydraulic test analysis, Ground Water **31** 5 (1993) 814–822.
[35] THEIS, C.V., The Relationship Between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of a Well Using Ground-Water Storage, American Geophysical Union, Transactions, pt. 2, 519–524; reprinted in Society of Petroleum Engineers, 1980 "Pressure Transient Testing Methods", SPE Reprint Series, 14:27-32 (1935).
[36] PAPADOPULOS, I.S., COOPER, H.H., Jr., Drawdown in a well of large diameter, Water Resour. Res. **3** 1 (1967) 241–244.
[37] EARLOUGHER, R.C., Jr., Advances in well test analysis, Society of Petroleum Engineers, Monograph **5**, Henry L. Doherty Series (1977).
[38] JACOB, C.E., LOHMAN, S.W., Nonsteady flow to a well of constant drawdown in an extensive aquifer, Geophysical Union **33** (1952) 559–569.
[39] EHLIG-ECONOMIDES, C., Use of the Pressure Derivative for Diagnosing Pressure-Transient Behavior, J. Petroleum Technol. (1988) 1280–1282.

[40] AGARWAL, R.G., "A new method to account for producing time effects when drawdown type curves are used to analyze pressure buildup and other test data", Paper presented at the 1980 Soc. Petroleum Engineers Annual SPE Technical Conf. and Exhibition, Dallas, 1980, SPE Paper 9289 (1980).

[41] SPANE, F.A., Jr., Applicability of Slug Interference Tests for Hydraulic Characterization of Unconfined Aquifers: (1) Analytical Assessment. Ground Water, Vol. 34, No. 1 (1996) 66–74.

[42] VAN DE KAMP, G., Determining aquifer transmissivity by means of well response tests: The underdamped case, Water Resources Research **12** 1 (1976) 71-77.

[43] VAN DER KAMP, G., Underdamped Well Response Considering Friction in the Well Tubing, Saskatchewan Research Council, SRC Publication No. R-844-2-C-84, 25p (1984).

[44] KIPP, K.L., Jr., Type curve analysis of inertial effects in the response of a well to a slug test, Water Resources Research **21** 9 (1985) 1397–1408.

[45] BREDEHOEFT, J.D., PAPADOPULOS, S.S., A method for determining the hydraulic properties of tight formations, Water Resources Research **16** 1 (1980) 233–238.

[46] NEUZIL, C.E., On conducting the modified slug test in tight formations, Water Resources Research **18** 2 (1982) 439–441.

[47] MOENCH, A.F., HSIEH, P.A., "Analysis of slug test data in a well with finite thickness skin" (Proc. 17th Int. Conf. of Assoc. of Hydrogeologists, Tucson, 1985) (1985) 17–27.

[48] THORNE, P.D., SPANE, F.A., Jr., "A comparison of under-pressure and over-pressure pulse tests conducted in low-permeability basalt horizons at the Hanford site, Washington State", (Proc. 17th Int. Congress, Int. Association of Hydrogeologists, Tucson, 1985) (1985).

[49] SPANE, F.A., Jr., THORNE, P.D., Comparison of Constant-Rate Pumping Test and Slug Interference Test Results at the Hanford Site B Pond Multilevel Test Facility, Pacific Northwest Laboratory, PNL-10835, Richland, WA (1995).

[50] COOPER, H.H., Jr., BREDEHOEFT, J.D., PAPADOPULOS, I.S., Response of a finite-diameter well to an instantaneous charge of water, Water Resources Research **3** 1 (1967) 263–269.

[51] RAMEY, H.J., Jr., AGARWAL, R.G., MARTIN, I., Analysis of slug test or DST flow period data, J. Canadian Petroleum Technol. (July–September 1975) 37–47.

[52] SPANE, F.A., Jr., THORNE, P.D., SWANSON, L.C., Applicability of slug interference tests for hydraulic characterization of unconfined aquifers: (2) Field test examples, Ground Water **34** 5 (1996) 925–933.

[53] NOVAKOWSKI, K.S., Analysis of pulse interference tests, Water Resources Research **25** 11 (1989) 2377–2387.

[54] NOVAKOWSKI, K.S., Analysis of aquifer tests conducted in fractured rock: A review of the physical background and the design of a computer program for generating type curves, Ground Water **28** 1 (1990) 99–105.

[55] SPANE, F.A., Jr.,. Applicability of Slug Interference Tests Under Hanford Site Conditions: Analytical Assessment and Field Test Evaluation, PNL-8070, Pacific Northwest Laboratory, Richland, WA (1992).

[56] UNITED STATES GEOLOGICAL SURVEY, National Handbook of Recommended Methods for Water-Data Acquisition, Office of Water Data Coordination, Reston, Virginia (1980).

[57] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Assessment for Near Surface Disposal of Radioactive Waste, Safety Standards Series No. WS-G-1.1, IAEA, Vienna (1999).

[58] INTERNATIONAL ATOMIC ENERGY AGENCY, Application of Quality Assurance to Radioactive Waste Disposal Facilities, IAEA-TECDOC-895, Vienna (1996).
[59] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Quality Systems — Model for Quality Assurance in Design/Development, Production, Installation and Servicing, ISO 9001, Second edn (1994).

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Consultants Meetings
Vienna, Austria: 6–10 November 1995, 1–5 September 1997

Advisory Group Meeting
Vienna, Austria: 1–5 July 1996

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