Evaluation of Groundwater Sampling Techniques for the Investigation and Monitoring of Contaminated Sites

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1. INTRODUCTION

The collection of representative groundwater samples is an essential prerequisite in hydrogeological site evaluation and groundwater monitoring. Erroneous or insufficent sampling may lead to wrong conclusions, possibly causing considerable health and/or financial risks, especially in respect to the assessment of contaminated sites. The collection of representative water samples therefore requires the use of appropriate sampling techniques, taking into account the prevailing aquifer conditions, the borehole hydraulics and the chemical parameters to be investigated. Consequently, the definition of the most suitable sampling equipment should be based on multiple criteria. In general these are the changing temperature and pressure conditions and the contact of the water with non-inert materials, which may affect the chemical integrity of the sample during the drilling of the well, the withdrawal and pumping of the water to the ground surface as well as the storage and transport to the laboratory. The major factors have to be investigated and quantified in order to minimize all undesired effects.

In this paper the major influencing factors are discussed. Furthermore, an evaluation of various sampling techniques and sampling systems is presented. Special consideration is given to the ability of various systems to adequately sample groundwater with high organic loads. In the last section, some new sample system developments are briefly presented together with the expert system CASES (Teutsch et al., 1989), which was developed at the Stuttgart Institut für Wasserbau.

2. FACTORS INFLUENCING THE QUALITY OF GROUNDWATER SAMPLES

The aim of groundwater sampling is the determination of representative physical, chemical and biological parameters of the groundwater. The groundwater sample may be considered to be representative, if it reflects the in-situ conditions at the sampling location and at the time of sampling.

Whether a groundwater sample is representative or not is determined by the type of the monitoring well, the materials used for the well casing, the borehole hydraulics, the sampling principle selected, as well as material type and properties of the sampling and pumping equipment.

In general, hydraulic aspects have to be considered where a pronounced vertical profile of the contaminant concentration is expected. Chemical aspects have to be considered in case the parameter to be investigated might be affected by the materials in use or if a change in one of the essential thermodynamic parameters is expected during pumping of the sample to the ground surface. The development of an appropriate groundwater sampling concept therefore requires good hydrogeological information about the sampling site as well as the definition of the sampling goal, the number of parameters and the number of samples to be collected.

2.1 <u>Type of Groundwater Monitoring Well</u>

As shown in Figure 1, five types of groundwater monitoring wells may be distinguished.

(1) simple monitoring well with standard casing (usually 4" to 6")

(2) multiple piezometers in a single well (usually 2" in borehole of > 10")

(3) individual piezometers completed at different depths

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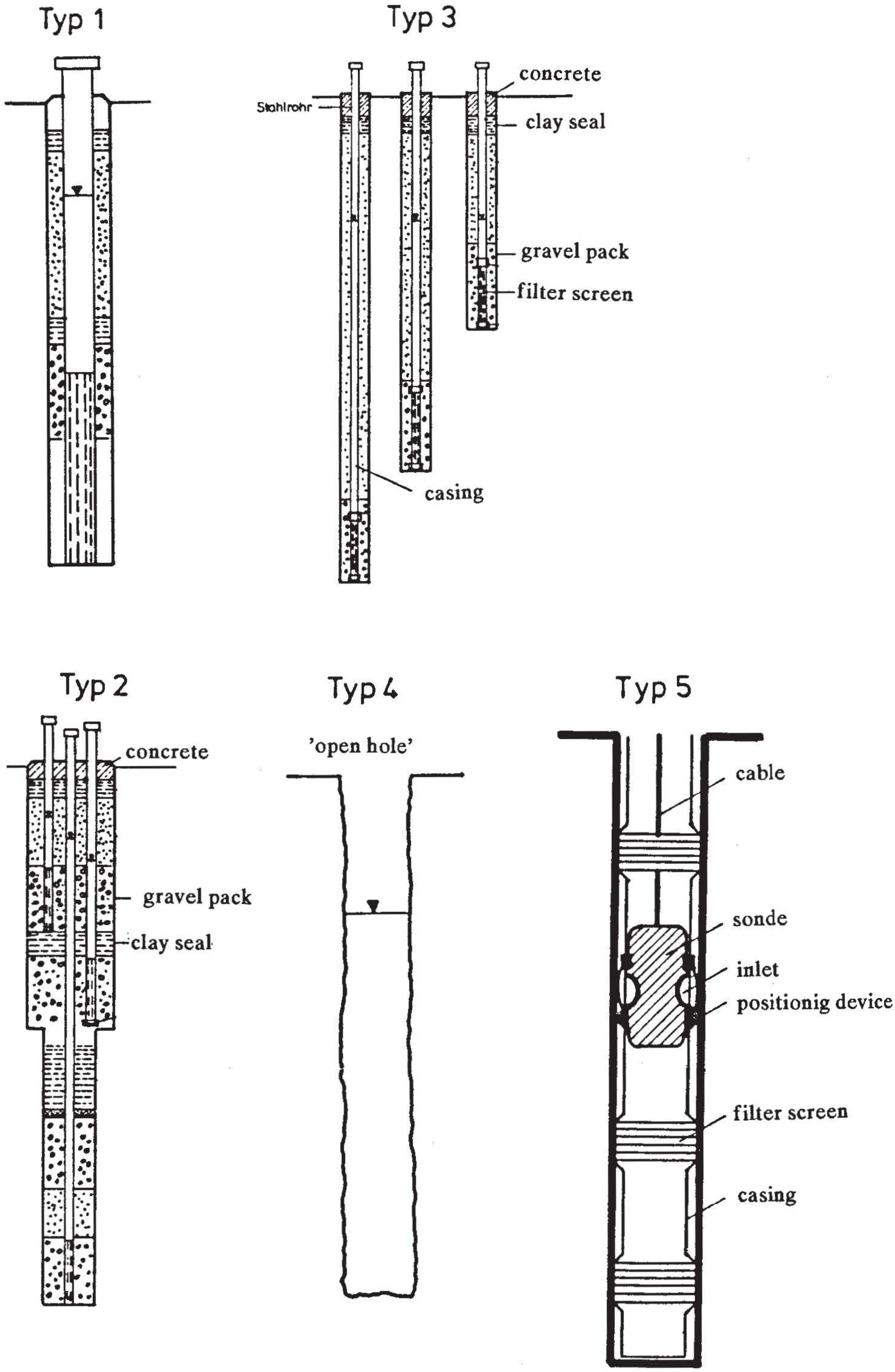

Fig. 1: Types of groundwater monitoring wells.

(4) simple 'open hole' monitoring well (only in hard rock formations, usually 4" to 6")

(5) special construction multilevel monitoring well (usually 3" to 6")

Most widely used are the type (1) simple monitoring wells. These wells have the advantage that standard hydraulic tests can be performed if a 5" or 6" diameter is used. On the other hand, depth-oriented multilevel sampling cannot be achieved without special equipment.

The type (2) multiple piezometer well is generally used where due to larger drilling depths only a single borehole can be afforded, but a depth-oriented sampling is required. The major advantage is the lower construction cost as compared to the type (3) and type (5) monitoring wells. Problems may arise mainly from leaks between the individual piezometers which are difficult to seal against each other during installation. Due to the small diameter of the piezometers, serious hydraulic tests cannot be performed after well completion.

In principle, the type (3) individual piezometer monitoring system is most suitable for the collection of depth-oriented samples. However, due to the relatively high construction costs, usually only a small number of piezometers is installed (in general 2 to 4). Due to the small diameter only very limited hydraulic tests can be performed.

The type (4) simple 'open hole' monitoring well for hard rock formations can be used for integral as well as for depth-oriented sampling. The missing gravel pack allows a depth-oriented sampling employing a simple double packer system, provided that no significant vertical fissuring occures in the vicinity of the borehole (hydraulic shortcut).

2.2 Materials for Monitoring Well Construction

The selection of appropriate well construction materials is directly related to the type of chemical parameters which are to be analysed. Profound prior planning is therefore required.

Three material categories may be distinguished:

(1) drilling fluids (additives)
(2) annular sealing materials
(3) casing and filter screen materials

In order to minimize water quality changes, the use of pure water or air circulation is recommended. However, air circulation bears the risk of accidentally flushing contaminated groundwater to the ground surface. Depending on the physical properties of the geologic formation and on the drilling equipment employed, the use of drilling additives might become necessary. The most frequently applied additives are bentonite, polymeres and surfactants. Bentonites may raise the pH-value of the groundwater considerably, whereas organic polymers may lead to an increased bacterial growth. Furthermore, all biodegradable organic compounds may affect the redox conditions in the groundwater (EPA, 1986).

The annular space is usually sealed using bentonite, bentonite-cement suspensions and concrete. For groundwater sampling the hydraulic properties of the annular sealings are of primary importance. Subsequent localisation of the seals is possible using a γ-log device, in case a γ-emmitting clay material was used.

Table 1 provides an overview on the properties and possible applications of some widely used materials for casing and filter construction. Over the past few years numerous scientific investigations have addressed the material problem. Out of those, special attention should be given to the extensive reports published by the U.S. Environmental Protection Agency (EPA). A literature survey on the topic of monitoring well construction materials and their influence on the groundwater sample integrity was recently published by the DVWK (1990).

2.3 Borehole Hydraulics

Drilling of a monitoring well implicitly changes the natural groundwater flow in the immediate vicinity of the sampling location. Depending on the hydraulic conductivity ratio between the well gravel pack and the aquifer, a focussing or defocussing of the natural flow field may occure (Palmer, 1989). On the other hand, even small vertical hydraulic gradients may cause substantial vertical flows within the monitoring well. In particular, this has been observed in wells with long filters.

TABLE 1. Solid and flexible materials used for monitoring well construction (Teutsch and Ptak, 1987)

Solid Materials:	
Teflon	chemically inert, low sorptivity in case of high quality surfaces, recommended for aggressive seepage water with high organic load, material quality varies with manufacturer
Stainless Steel	recommended for aggressive seepage water with high organic load, slow corrosion may occure at low pH especially in presence of high Cl- concentrations, corrosion products are Fe- and possibly Cr- and Ni-compounds
PVC	not resistent to aggressive seepage waters with high organic load, should be used for the monitoring of anorganic parameters only
Galvan. Steel	corrosive at low pH values, especially with high sulfide concentrations, corrosion products are mainly Fe-, Mn-, Zn-and Cd-compounds, corroded surfaces represent active adsorption sites
Flexible Materials:	
Teflon	recommended for most monitoring puposes, well suited to monitor organic content, easy to decontaminate, small cross-contamination risk
Polypropylen, PE (linear)	recommended for corrosive water but with low organic load only, small percentage of additives
PVC (flexib.)	not recommended for the monitoring of groundwater with high organic load, high percentage of additives which tend to dissolve
Viton, Silicon, Neopren	not recommended for organically polluted water, high sorption tendency, sample bias must be evaluated on a case to case basis

The importance of borehole hydraulics should be emphasized where vertical concentration gradients are present. As shown in Figure 2, a wrong observation well design may cause leakage of contaminated groundwater to higher or lower aquifer layers.

Groundwater sampling in such a well would lead to a wrong estimate of the groundwater contamination extent. Even using a packer system, one would probably not solve the problem, since the pumping time required to clean-up the contamination within the initially uncontaminated lower aquifer layer would probably be too long. Furthermore, additional contaminated groundwater would percolate to the lower aquifer layer through the well annular space after packer installation.

It is therefore recommended, that the design depth of new monitoring wells should not go beyond the maximum depth of the expected groundwater contamination. For those cases where the depth of the contamination is not known, preventive barriers (casing and annular sealing) should be installed at regular depth intervals. If required, the preventive barriers can be activated using stationary packer systems.

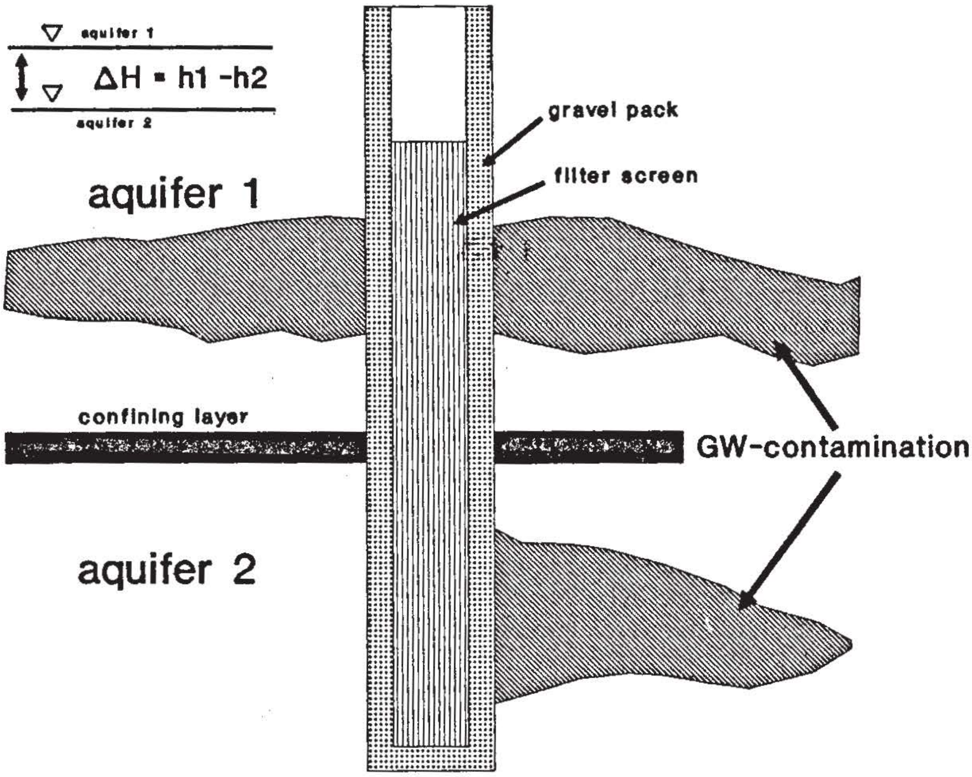

Fig. 2: Contaminant leakage to underlaying aquifer layers due to wrong monitoring well design.

2.4 Groundwater Sampling Devices

A sampling device may consist of a simple bailer, a submersible pump or a sophisticated multilever sampler. The selection of the most suitable sampling device is primarily determined by the sampling objectives. One generally distinguishes between integral and depth-oriented sampling, the latter being employed where vertical concentration profiles are to be detected.

2.4.1 Integral Sampling. Purging of the sampling well prior to the collection of an integral sample should amount to at least twice the volume of water stored within the well. Subsequently, a continuous or alternating water flow is induced through the primary or a secondary pumping system in order to collect the groundwater sample. Applying this procedure, it is generally assumed that the concentration of the groundwater sample represents the flux averaged concentration as described by equation 1.

$$c = \frac{1}{q} \int_0^m u(z)\, c(z)\, dz$$

In this equation, c represents the flux averaged concentration, q represents the specific discharge and u(z) respectively c(z) represent the vertical distribution of the flow velocity and the concentration.

The correct procedure for collecting integral samples is described in numerous recommendations (DIN 38401 - Teil 13, DVWK Merkblatt 203, Urban und Schettler, 1980), which are primarily based on practical experience. Systematic investigations concerning the representativness of integral samples were conducted by Barczewski and Marschall (1989) in a laboratory experimental setup at a 1:1 scale. It was shown, that the concentration of the flux averaged sample (integral sample) does not depend on the pumping rate, the sampling depth or the sampling system used. Based on a numerical model which considers also the friction losses within the sampling well, Kaleris (1989) could show that the integral sample concentration is affected by the sample position only within very long boreholes and only at large pumping rates.

2.4.2 Depth Oriented Sampling. Monitoring wells of type (2) and (3) or special design multilevel monitoring wells of type (5) (e.g. Westbay System) can be used for the collection of depth-oriented samples without additional installations. In the case of the type (2) and (3) wells, the location of the sample is fixed by the position of the filter screen. In the case of the type (5) well, the sampling position is fixed by the location of the sample inlets. Alternatively, one may use stationary (Rohmann, 1986), semi-stationary (Teutsch and Ptak, 1989; Barczewski and Marschall, 1990) or mobile single or multipacker systems (Andersen, 1982) within standard monitoring wells of type (1) in order to collect depth-oriented samples. The considerable advantage of depth-oriented sampling within standard monitoring wells of type (1) is the large number of already existing wells and the simple and cost effective construction of new wells. Some new multilevel sampling systems are presented in section 3 of this paper.

Systematic laboratory investigations in a 1:1 scale groundwater monitoring well showed, that the commonly used double packer systems are not suitable to determine vertical concentration profiles in fully screened observation wells (Barczewski, Marschall, 1989). Considerable improvements can be achieved employing triple packer systems (Andersen, 1979, 1982), especially for those cases, where the vertical hydraulic conductivity profile is a priori known and the pumping rates for the three packer segments can be adjusted according to the conductivity of the aquifer layers (Barczewski and Marschall, 1990).

2.4.3 Pumping Devices. A large number of different pumping devices is available for the collection of groundwater samples. Table 2 provides an overview on the properties of the most commonly used systems. In general, all systems described can be used for integral as well as for depth-oriented sampling. However, for compactness reasons only submersible impeller-, piston- and peristaltic-pump systems are used in multi packer systems for depth-oriented sampling. The most versatile pumping device, well suited to sample groundwater with high organic loads, is the stainless-steel or brass 12 volt magnetic-coil piston-pump. To our knoweledge however, this pump has not been used in commercial sampling devices so far.

TABLE 2. Pumping Systems for Groundwater Sampling (Teutsch and Ptak, 1987)

membrane pump (bladder pump)	use of fairly inert materials possible, no sample aeration, no degassing, pumping rate variable over a wide range, suitable for well purging, high pumping lift, cross-contamination can be avoided by careful cleaning
bailer	use of fairly inert materials possible, favourable ratio between air contact surface and volume and therefore low degassing of volatiles like chlorinated hydrocarbons, not suitable for purging, aeration of sample during bottling, cross-contamination can be avoided by careful cleaning, in-situ conditions can be preserved using good quality valves
mechanical displacement pump (e.g. piston pump)	use of fairly inert materials possible, high pumping lift, pumping rate variable over a wide range, degassing is minimal, cross-contamination can be avoided by careful cleaning
gas displacement pump	use of inert gases possible (e.g. N_2), oxidation may occure when O_2 is used, stripping of volatiles possible, cross-contamination can be avoided by careful cleaning
submersible pumps	use of inert materials possible, high pumping lift, pumping rate can be varied using a slide-valve, pressure changes (cavitation) may lead to degassing of the sample, cross-contamination can be avoided by careful cleaning

suction pumps	use of fairly inert materials possible for impeller-pumps, flexible tubes represent active adsorption sites when using persitaltic-pumps, maximum suction lift is 8 m, low recovery of volatile compounds, cross-contamination can be avoided by careful cleaning (impeller-pumps) or tube exchange (peristaltic-pumps)

In-Line-Packer-System (ILPS)

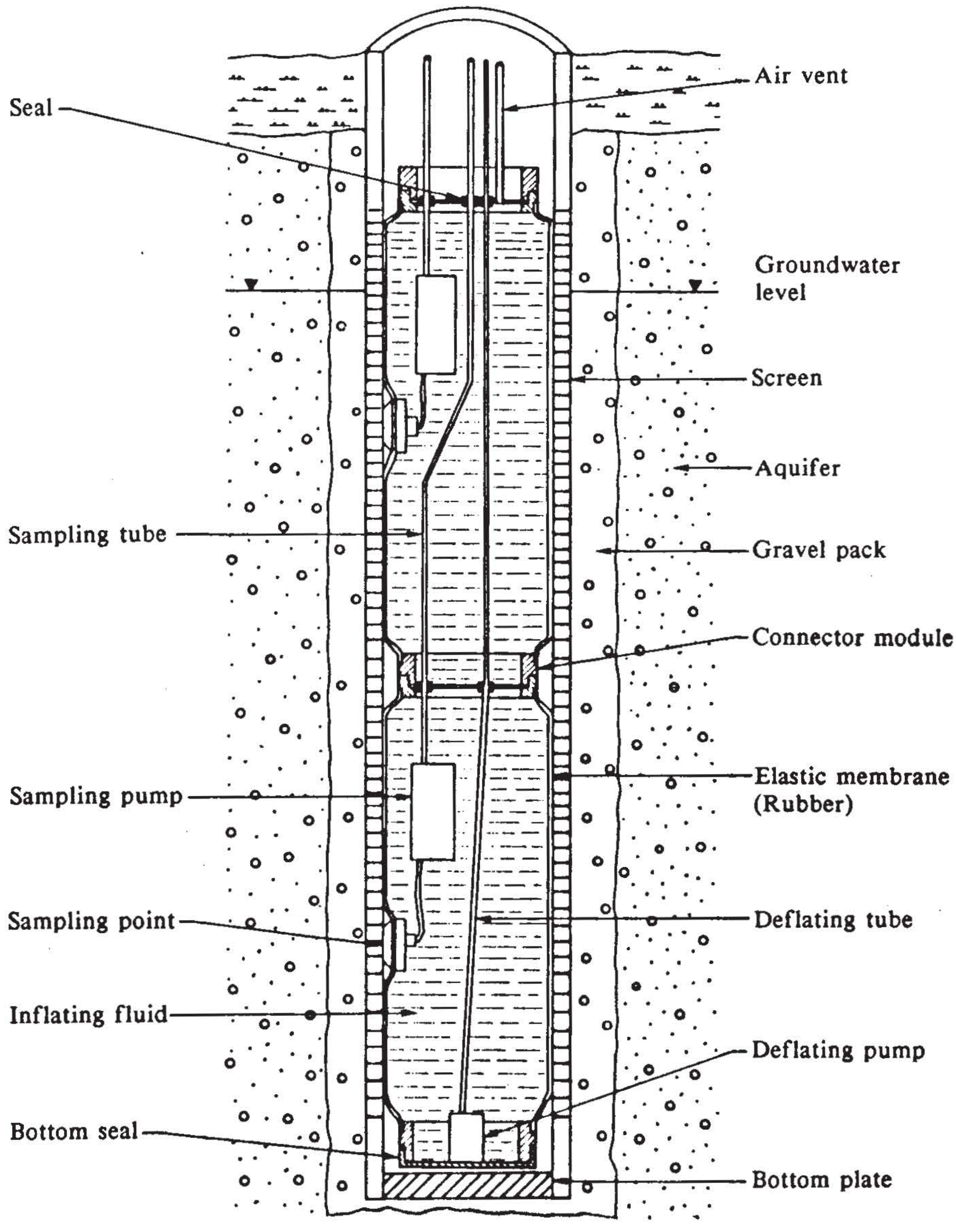

Fig. 3: The In-Line-Packer-System (Teutsch and Ptak, 1989)

3. NEW SAMPLING TECHNIQUES AND SAMPLING SYSTEMS

3.1 The In-Line-Packer-System

The In-Line-Packer-System (Teutsch and Ptak, 1989) is a semistationary, modular and removable packer system, which can be installed in standard monitoring wells of type (1). It consists of one or several packer modules, which are lowered down to the screened section of the monitoring well and then inflated through a connecting pipe using either water or air (Fig. 3). Thus, the entire water volume is removed within the well avoiding any vertical circulation. The small sample inlets which are located at different depths are pressed against the filter screen to collect the water sample directly from the aquifer. Inside the packer system the sample inlets are connected either to a pump or to a suction pipe, leading to the well head. Since the entire diameter of the borehole becomes available for the pumps and the pipes, a 5" observation well can accommodate up to 25 sampling inlets. In order to reduce the vertical flow within the gravel pack, all sample inlets are pumped simultaneously. For new monitoring wells, specially designed clay sealing-rings may be installed within the gravel pack to avoid vertical water circulation. So far, a prototype of the In-Line-Packer-System with 10 sampling points has been tested within a research project for a sand and gravel environment as well as in the laboratory. In principal, the system is equally well suited for depth oriented sampling within type (4) wells, i.e. for hard rock formations.

3.2 The Multi Packer System

The multi packer system, as developed at the Institut für Wasserbau, serves for mobile, semistationary or sationary depth-oriented sampling within type (1) wells. Fig. 4 shows a schematic drawing of the system. As compared to the In-Line-Packer-System described under 3.1, where sampling occurs almost at point locations, the multi packer system collects the sample between the packer elements. The system allows for various packer distances, packer lengths and packer diameters offering optimal flexibility. Due to the required tubing, the maximum number of packer elements is limited to 8 within a standard 5" monitoring well. Pumping from the packed segments is achieved using miniature submersible pumps, located above the top packer element. To obtain a representative sample in a mobile installation, the ratio of the pumping rates within the individual segments should roughly correspond to the ratio of the transmissivities of the pumped aquifer layers. Several depth-oriented sampling campaigns demonstrated the superiority of the multipacker system as compared to simple double packers (Barczewski and Marschall, 1990).

4. THE EXPERT SYSTEM FOR GROUNDWATER SAMPLING 'CASES'

One way to organize existing rules and facts on how to collect representative groundwater samples is the development of a so called expert system which is used to collect and objectively process all relevant information. The general ability of an expert system to deal with such a problem is primarily determined by the heuristic character of the available expert knowledge. Formal models are either entirely missing or not representable within standard programming environments.

The system was developed on the basis of groundwater sampling experience gained over the last few years at the Institut für Wasserbau, during field campaigns, laboratory experiments, development of numerous sampling devices, literature surveys and numerical simulations. In general, this experience is distributed across numerous persons, reports and publications and therefore not generally available to other parties. The design goal of the expert system CASES (Chemical Aquifer Sampling Expert System) (Teutsch et al., 1989) was to provide a unified representation and processing of the rules and facts available in the field of groundwater sampling.

System input comprises data describing the hydrogeological situation, the monitoring well (borehole) and the chemical parameters to be analysed. Given a certain situation, the program helps selecting the most suitable sampling strategy (integral sampling, depth-oriented sampling, use of simple or multi packer systems, etc.) and identifying the optimal sampling system. The selection process comprises several qualitative rules on groundwater and borehole hydraulics as well as numerous rules on chemical material compatibility with respect to the sampled parameters, the well construction material and the sampling system. Since ideal sampling conditions are hardly met in reality, the system contains many rules, which do not lead to the exclusion of a sampling system, but produce a system warning or a hint. This information is used in the so called explanation component of the system to inform the user about the reasons why for example a certain sampling technique or a

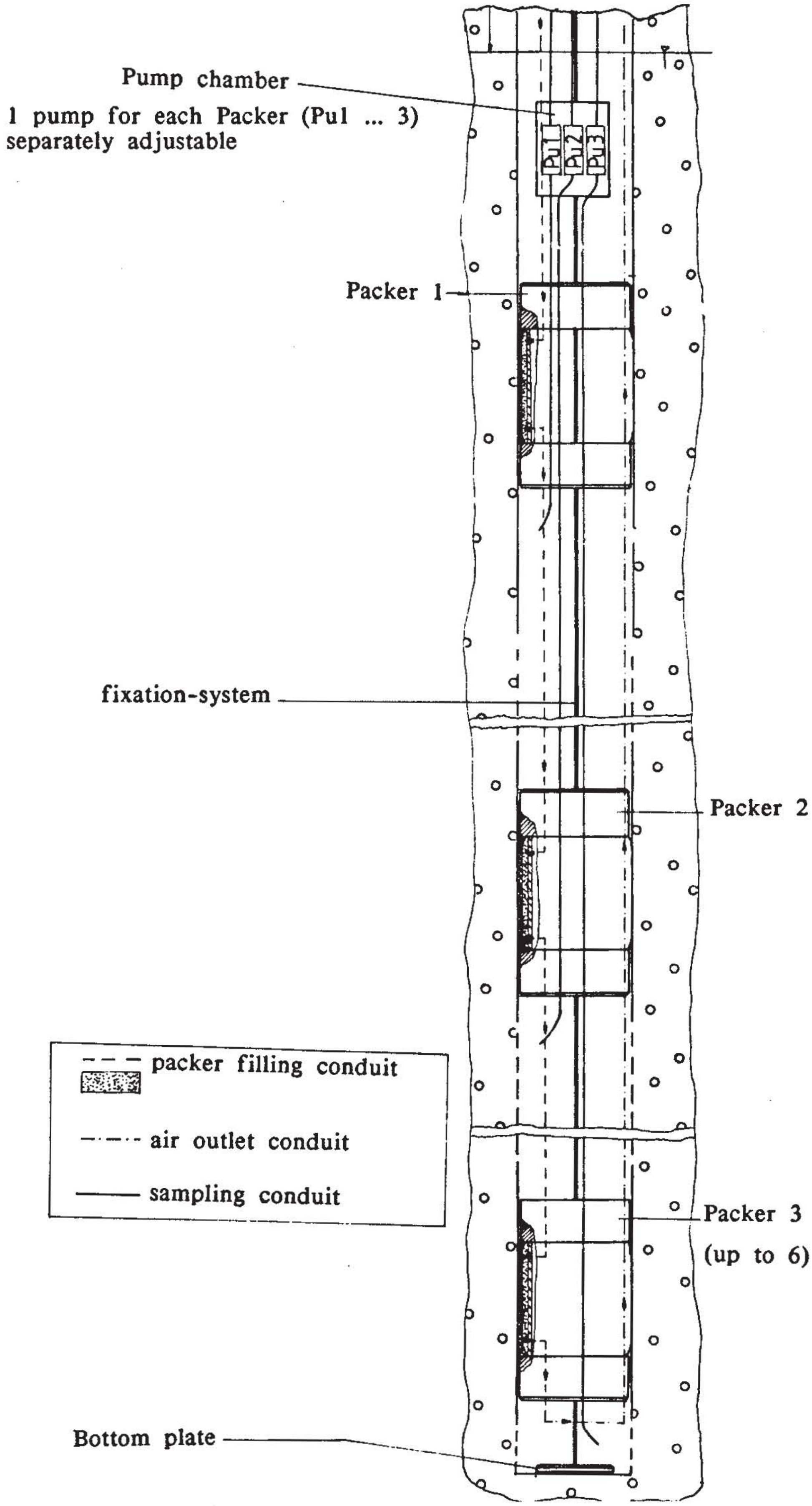

Fig. 4: The Multi Packer System (Barczewski and Marschall, 1990)

certain sampling device is less recommendable or not applicable within the given enviromental conditions.

The system is written in PRLOG and C and is presently implemented on a UNIX-workstation and on a PC in a simplified version. Present use of the system is limited to testing and users training. The intention is, to add a numerical borehole hydraulics model by end of 1991.

5. SUMMARY

In this paper the most relevant factors influencing the collection of representative groundwater samples are discussed and evaluated. These are the monitoring well construction, the borehole hydraulics, the construction materials and the type of sampling system. Special consideration is given to the techniques used for collecting depth-oriented groundwater samples. These techniques are required for risk assessment and monitoring purposes at waste disposal and contaminated sites. Two new sampler designs, especially suited for depth-oriented sampling are presented.

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