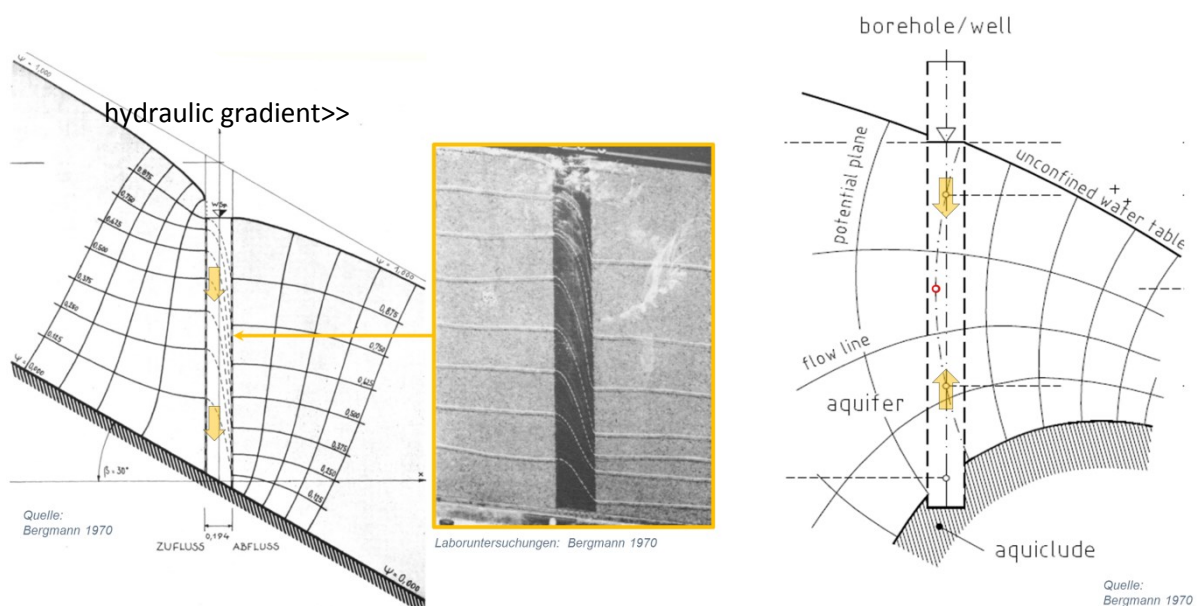


Vertical Flow in Monitoring Wells

Vertical groundwater flow within monitoring wells can have a variety of causes. In most cases, hydraulic head differences occur between individual sediment layers, resulting in a hydraulic short cut across the screened interval. Or a groundwater monitoring well connects multiple aquifer layers with different hydraulic heads.

In these cases, the free flow inside the monitoring well provides a preferential hydraulic pathway that facilitates the equilibration of hydraulic head differences. Driven by the hydraulic gradient, groundwater preferentially flows through the low-resistance well screen. This dynamic accelerates inflow at the upper sections and enhances outflow near the base. Consequently, the monitoring well acts as a hydraulic sink, which also affects the water level observed within the well.



A parallel flow field disturbed by a fully penetrating well (Bergmann, 1970). Owing to the low-resistance flow within the well in the direction of the hydraulic gradient, a steady vertical flow develops within the well screen.

What Information Can Be Obtained from Measuring Vertical Flow?

Vertical in-situ groundwater flow measurements provide information on the distribution of hydraulic heads within an aquifer, the presence of hydraulic short circuits, and the potential redistribution and groundwater mass transfer through monitoring wells.

Under induced flow conditions by pumping water from the well, the distribution of active inflow and outflow zones can be identified. In addition, hydraulically active horizons can be located and their productivity assessed. Typical applications include:

- Quantification of groundwater mass transport through monitoring wells
- Identification of leakage between underlying and overlying formations
- Assessment of contaminant migration through monitoring wells
- Information for groundwater sampling strategies and the interpretation of analytical data
- Identification of hydraulically active zones and delineation of inflow and outflow intervals

What measurement techniques are used?

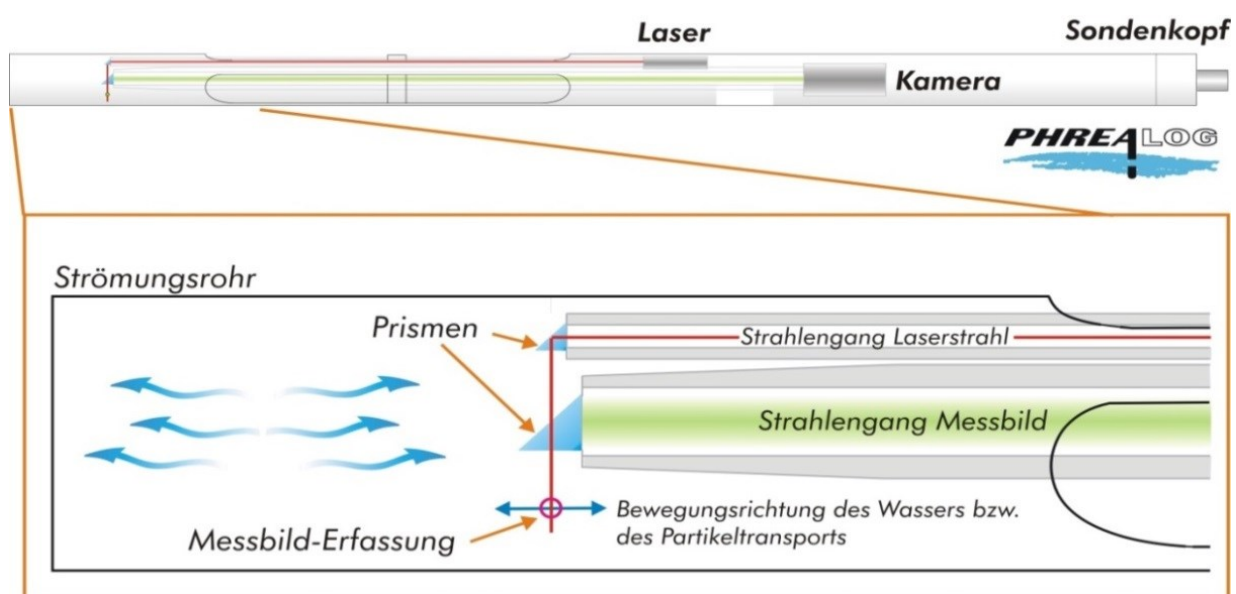
Groundwater flow measurement methods used in boreholes and groundwater monitoring wells are commonly based on impeller flowmeters, the drift of thermal pulses, cooling methods (Thermo-Flow techniques), or fluid logging techniques (saline or dye tracers).

These systems are typically operated in logging mode, meaning that measurements are performed continuously while the probe is moved through the well at a constant speed. The flow detection limit of these methods is generally known to range between approximately 10 mm/s and 1 mm/s.

Flow velocities lower than 1 mm/s are difficult to measure because they are increasingly influenced by minor hydrodynamic pressure fluctuations. These fluctuations result in a permanent hydraulic background noise that may superimpose existing groundwater flow. Hydraulic pressure fluctuations arise from a combination of natural processes, including tides, precipitation, barometric pressure variations and fluctuations in nearby surface-water levels, but may also be caused by traffic, construction activities and groundwater abstraction. Consequently, measuring vertical groundwater flow velocities below 1 mm/s requires measurements to be performed at fixed depth positions within the well screen. Continuous measurements at a fixed depth provide the advantage that the acquired data can be integrated and statistically evaluated over a certain period of time.

PHREALOG Measurement System

The PHREALOG measurement system is based on an imaging, laser-optical technique to detect and process suspended-particle patterns. The measurement probes are equipped with an integrated camera and laser system. Similar to horizontal flow measurements, suspended particles in the groundwater serve as natural flow tracers. Within a freely flowing measurement section of the probe, passing particles are illuminated by laser light. The backscattered light is continuously captured by the camera as particle patterns. The displacement of particle patterns per unit time describes the groundwater flow direction and velocity. The images are transmitted as video data to a computer, where image-processing software calculates groundwater flow vectors from successive particle patterns. Measurements are performed at sampling interval of four seconds or less, so that groundwater flow is recorded continuously and with high temporal resolution. The measured flow rate ranges from approximately 10 mm/s down to 0.1 m/day with high accuracy. The method is especially able to record very low groundwater flow velocities.



Schematic of the PHREALOG probe for vertical flow measurements

Naturally occurring fine suspended particles serve as flow tracers in groundwater. These include humic substances, sediment particles, contaminants, organic compounds and aggregates of various components, which, depending on the prevailing hydraulic conditions, are transported through or released from the pore matrix and pass through the monitoring well in correspondence with the groundwater flow. The amount of suspended matter depends on various environmental factors, such as the hydraulic conditions, the presence of particle reservoirs and depots within the aquifer, the mobilization potential of these deposits, and particle inputs from the unsaturated zone.

The measured flow rate ranges from approximately 10 mm/s down to 0.1 m/day with high accuracy. The method is especially able to record very low groundwater flow velocities.

The ability to continuously record groundwater flow at fixed depth positions makes it possible to integrate hydraulic pressure fluctuations over time and to filter out persistent flow components from the hydraulic background noise. Consequently, flow velocities below 1×10^{-5} m/s can be measured continuously and with high accuracy.

Since no artificial tracers are required, tracer-related sources of error as well as permitting requirements are eliminated. Owing to its non-contact sensing principle, the technology is maintenance-free and highly robust even under chemically aggressive conditions. The system is easy to deploy, requires only short setup times and does not require field calibration.

Flow velocities below 1×10^{-6} m/s are considered to represent the absence of groundwater flow and are therefore treated as zero, since thermal effects may dominate and obscure the flow processes at these low vertical flow movements.

Depending on the lithological and hydraulic conditions, the amount of suspended matter transported may vary considerably from one measurement depth to another. This generally has no effect on the measurement results. In rare cases, however, the number of particles may decrease significantly during a measurement, preventing reliable measurements because of insufficient particle detection. Similarly, under conditions of very high groundwater turbidity, measurements may be severely restricted or, depending on visibility conditions, not be possible at all. Such situations occur only rarely.

Under hydraulically induced flow conditions by pumping water from the well while measuring, information on preferential flow zones can be obtained and the hydraulic productivity of adjacent sediments can be determined. Owing to the high sensitivity of the measurement probe, only low pumping rates are required to induce measurable hydraulic responses. At contaminated sites, this significantly reduces the amount of groundwater that must subsequently be treated or disposed of.

Hydraulic stimulation is typically achieved using the variable-speed MP1 pump. As a standard configuration, measurements can be carried out in monitoring wells with diameters ranging from 2.5 to 7 inches and to depths of up to 100 m. The measurements can be complemented by temperature and electrical conductivity logging.

Measurement Procedure

During a measurement, the probe is lowered to predefined measurement depths according to a specified spacing interval (e.g. every 0.2–1.0 m) and positioned at each depth until steady-state flow conditions have been established.

Once a sufficient number of data points has been acquired to ensure statistical reliability, the probe is moved to the next measurement depth. The typical residence time at each measurement position is approximately seven minutes.

To measure vertical groundwater flow under hydraulically undisturbed conditions (ambient flow conditions), the probe is positioned sequentially at several fixed depths during the survey (Fig. 1). At each measurement depth, image sequences are recorded continuously and transmitted to a computer at the surface for processing and evaluation.

After a sufficient amount of flow data has been collected for reliable interpretation, the probe is moved to the next measurement depth (Fig. 2). Finally, the data from all measurement depths are evaluated and presented as a depth profile and mass-balance representation of the vertical flow conditions (Fig. 3).

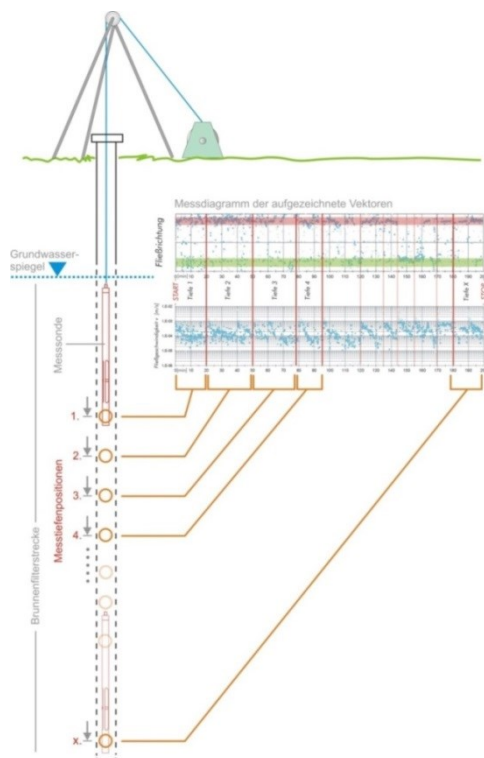


Abb. 1

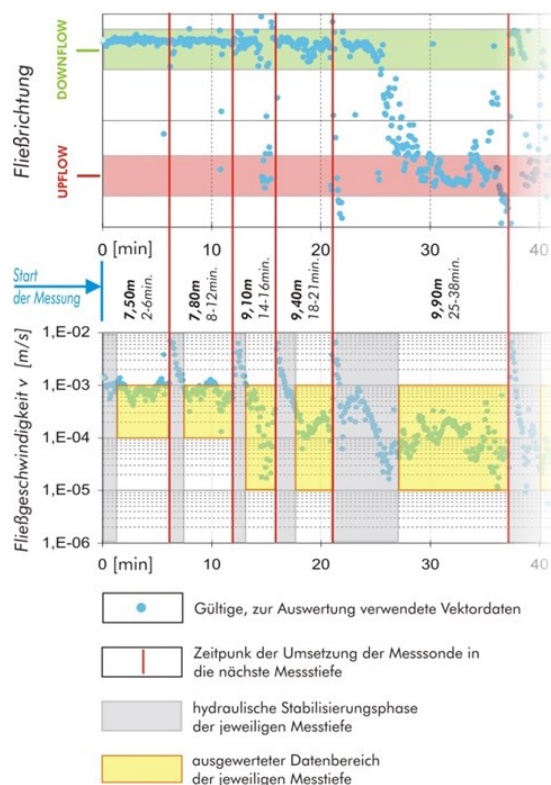
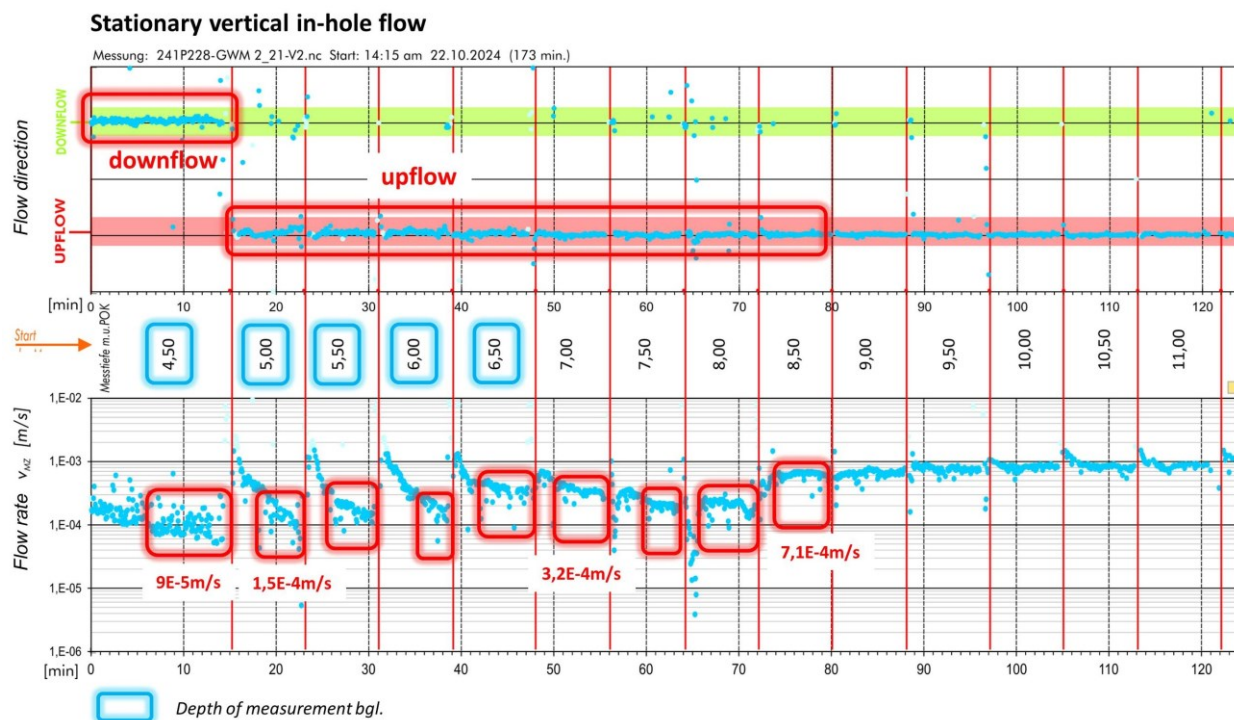


Abb.2



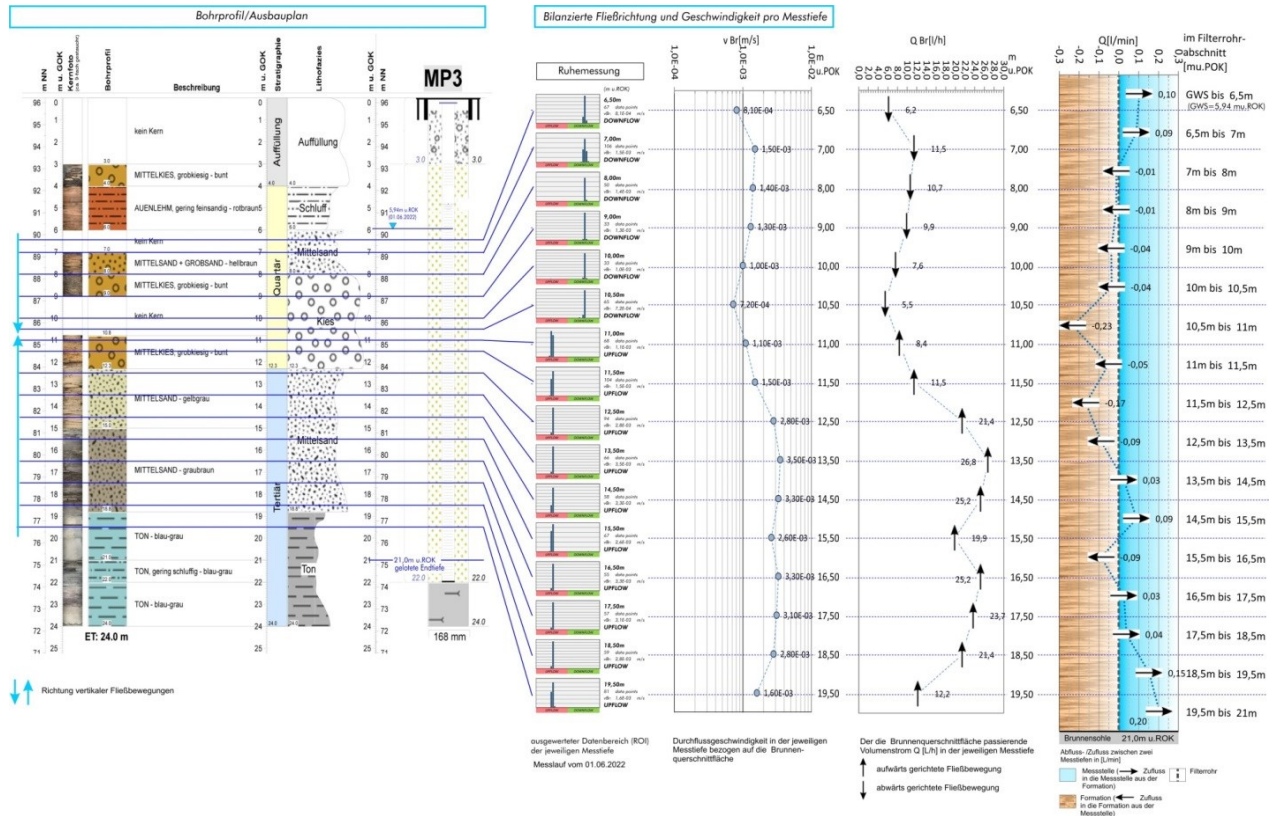
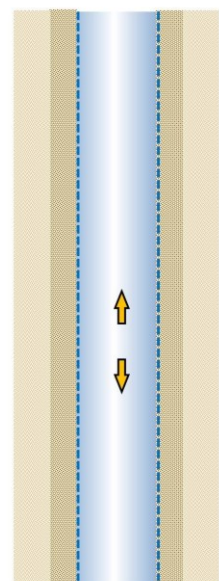


Abb.3

Detection of small transport volumes when measuring flow velocities below 1 mm/s.

- ➔ Annual transport volume under steady-state vertical flow in **5"** monitoring wells
 - @ 1mm/s ($1\text{E-}3\text{m/s}$) = 386 m³/a
 - @ 0,1mm/s ($1\text{E-}4\text{m/s}$) = 38 m³/a*
- ➔ Annual transport volume under steady-state vertical flow in **2"** monitoring wells
 - @ 1mm/s ($1\text{E-}3\text{m/s}$) = 62 m³/a
 - @ 0,1mm/s ($1\text{E-}4\text{m/s}$) = 6,2 m³/a*

* PHREALOG measurement range: 1×10^{-2} to less than 1×10^{-5} m/s





Flow measurement probe with a 100 m cable reel and MP1 equipment for measurements under hydraulically induced flow conditions.



Probe guidance in the well casing with centralizers



Field computer for analyzing the image data