Introduction to Groundwater Development and Management

Short Course at Water & Environment Centre, Sana'a

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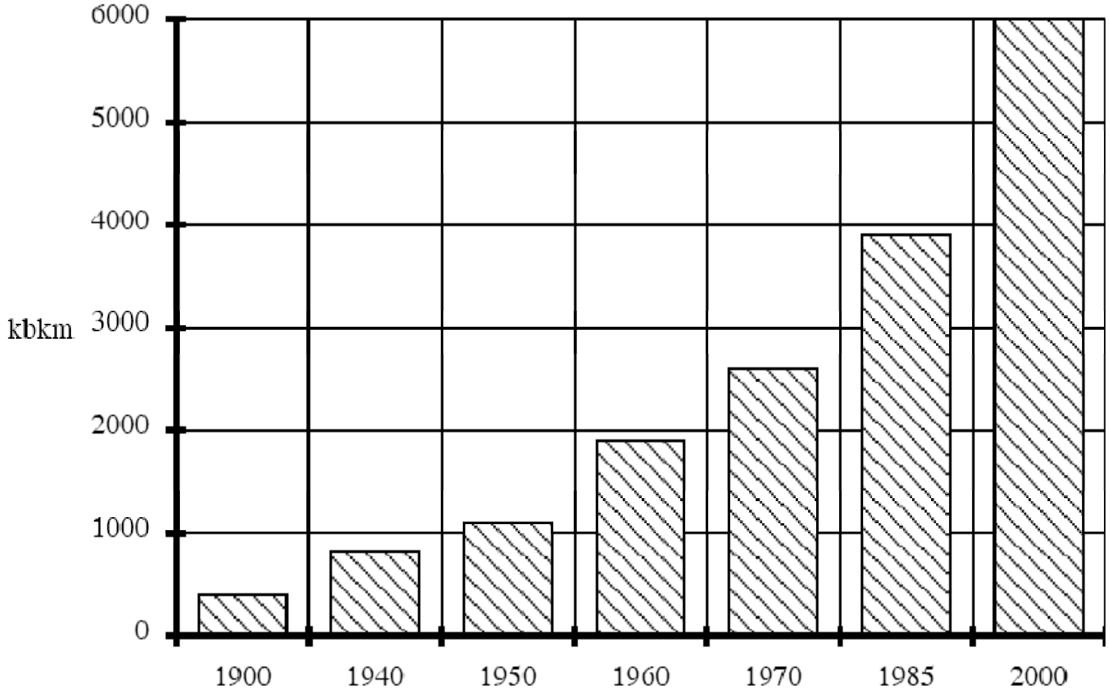
1. Introduction

Development of water demand, reasons and conflicts

➢ Development of world water demand in the 20th century

Today:

- more than 2 billion people suffer under unhygienic and insufficient water supply conditions.
- contaminated water is the main reason for more than 80% of world-wide diseases and epidemics.



from: WHO

Development of water demand, reasons and conflicts about resources:

➢ Reasons for increased water demands and potential conflicts about resources (global scale):

- increased world population, problems of urbanization
- increased energy requirements and economic expansion
- increased food demand and raised irrigation demand for agriculture
- over-stressing of agricultural areas > soil erosion > decrease of agricultural areas > change of groundwater-recharge rates

<u>Consequences</u>**:** rising conflicts about resources, political und social strains, struggle for resources:

water management **< >** exploration of mineral resources **< >** agriculture **< >** urbane regions **< >** industrial fields

Percentage of withdrawal in renewable groundwater resources

Region	Land	%
Nordafrika	Ägypten	97
	Libyen	374
	Tunesien	53
Karibik	Barbados	51
Südasien	Afghanistan	52
Naher Osten	Israel	88
	Jemen (nördl. Teil)	147
	Jemen (südl. Teil)	129
	Katar	174
	Saudi-Arabien	106
	Vereinigte Arabische Emirate	140
	Zypern	60
Südeuropa	Malta	92

Quelle: World Resources Institute, World Recources 1990 – 91, New York/Oxford 1990

Usage of ground water and surface water in Europe

Country	Groundwater (%)	Surface water (%)
Austria	99	1
Belgium	67	33
Denmark	99	1
Finland	49	51
France	65	35
Germany	72	28
Great Britain	28	72
Italy	87	13
Luxembourg	73	27
The Netherlands	70	30
Norway	5	95
Spain	22	78
Sweden	22	78
Switzerland	83	17

average value of EU: 65 % (groundwater)

Bavaria, Germany: 94% (2/3 without treatment)

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Advantages of groundwater management
(in comparison with surface water management):

- The quantity is mostly relative constant,
- The development is possible in the consumer's proximity,
- The composition is relative constant,
- during the flow are self-purification processes working,
- "Time for warning" in a case of accidents.

2. Hydrogeological analysis and exploration

- Fundamental questions in the context of groundwater exploitation and management:

1. How great is the demand for water?
2. What is the long term productivity of the aquifer?
3. Which impact has the groundwater withdrawal to the regional groundwater levels?
4. Are any negative side effects possible?
5. How many wells are needed; where is the best location for drilling; which is the best drilling method, drilling diameter and depth; how should the construction be done; what is the production rate?

- Determination of water demand:

  <u>Benchmark for hydrologic analysis:</u>

  average demand: annual requirement in kbm / 365 days / 86,4 = l/s

  <u>Benchmark for technical facilities:</u> peak demand

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Concept of groundwater yield

- Scale of considerations:
  - well yield
  - aquifer yield
  - basin yield

- Factors, which restrict/control abstraction rates:
  - hydrological / hydrogeological factors
  - efficiency: e.g. energy costs, investment costs
  - water quality: e.g. groundwater pollution, salt water intrusion
  - water rights

Hydrogeoical analysis for exploration of aquifers and aquifer systems:

1. Compilation and analysis of available data
   - literature, files, reports, expertise
   - thematic maps: geology, hydrogeology, soil, climate, topography
   - drilling profiles, pumping tests, groundwater level, water analysis

2. Remote sensing by satellite and aerial images (optional)
   - tectonics
   - geology, soil
   - land use, vegetation
   - drainage system

3. Fieldwork; geological / hydrogeological mapping
   - aquifer / aquitard
   - springs
   - discharge measurements, sampling
   - identification of recharge/discharge-areas; field observations

Hydrogeogical analysis for exploration of aquifers and aquifer systems:

4. Drillings, pumping tests, other analysis
    - Geological information from drilling profiles
    - Determination of groundwater levels, contour lines/flow direction
    - Identification of hydraulic characteristics (transmissivity, storage coefficient) by pumping tests
    - Composition of groundwater (chemical-physical, isotopic)
    - Water budget, rate of groundwater recharge

5. Geophysical measurements
    - Borehole geophysics
    - Surface geophysics

6. Analysis and evaluation of groundwater resource
   - Groundwater flow controlled by topography and geology:
     - Identification of recharge / discharge areas, water divides as well as local and regional flow systems
   - Quantitative interpretation: application of Darcy's law
   - Determination of optimal well locations
   - Arrangements for preventative groundwater protection

7. Determination of available groundwater

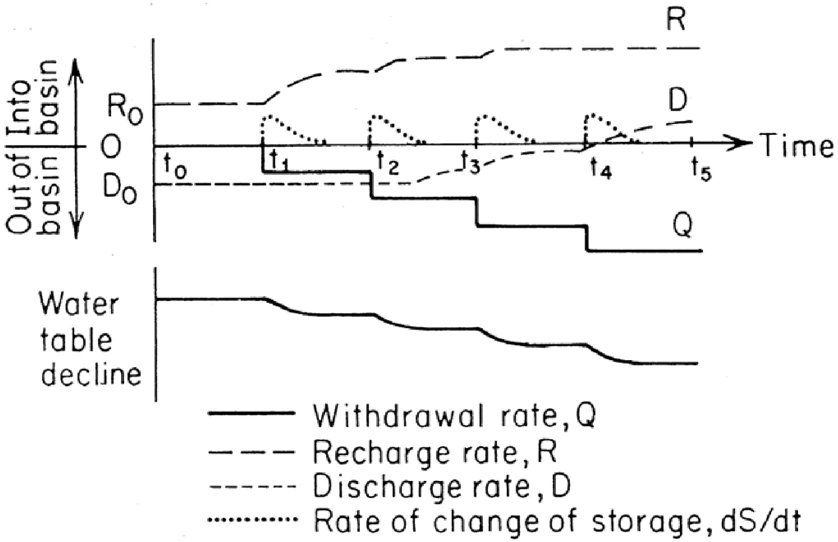
   Concept of "safe yield" (Todd 1952): Amount of water which can be withdrawn from a groundwater basin annually without producing an undesired result. Any draft in excess of safe yield is overdraft.

   Exception: Exploration of fossil groundwater resources

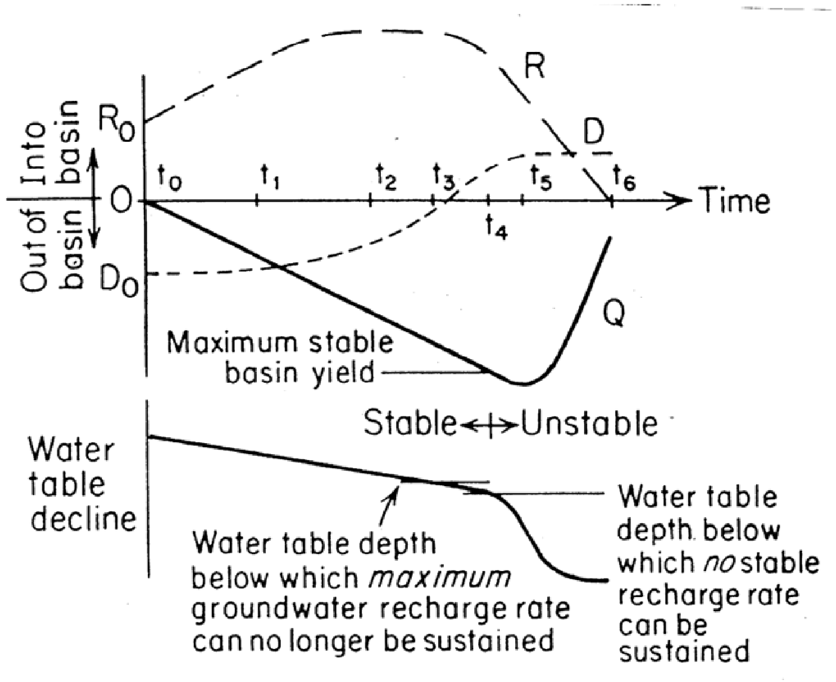
8. Arrangements for the enhancement of groundwater storage or recharge
   - Induced recharge of groundwater
   - Bank infiltration

Schematic diagram of transient relationships between recharge rates, discharge rates, and withdrawal rates

$$Q(t) = R(t) – D(t) + dS/dt$$



(a)



Freeze & Cherry 1979

(b)

Application of remote sensing in hydrogeology (1)

Type of Observation	Purpose of Observation
A. Water, or water features, at the land surface	Inference of ground-water conditions from surface-water conditions
1. Drainage density; subdivision of area on basis of drainage density	Classification of terrain on basis of relative permeability; differentiation of tracts of rather different permeability
2. Localized gain or loss of streamflow (e.g., springs and seeps along streams; sites or reaches of loss of water from channel)	Classification of streams as gaining or losing, and location of gaining and losing reaches; from this, inference of general nature of ground-water discharge, recharge, and circulation in near-surface rocks; together with geologic data, may permit inference of confined or unconfined aquifers, and of geologic controls on ground water
3. Seepage at land surface (commonly shown by character and distribution of vegetation)	Location of sites of ground-water discharge; areal form and areal and topographic distribution of these sites, together with geologic data, may permit inference of type of aquifer and of geologic controls on ground water
4. Presence and distribution of man-made water features (wells, improved springs, reservoirs, canals)	Show presence of water; with supplementary data, particularly relating to vegetation and land-surface drainage, may permit inference of effect of these water features on ground water in the area. (Photographs made before and after construction of features are particularly valuable)

from: HEATH & TRAINER, 1968
Introduction to Ground-Water Hydrology

Application of remote sensing in hydrogeology (2)

Type of Observation	Purpose of Observation
B. Character and areal distribution of rocks	Inference of broad geologic controls on the occurrence of ground water
1. Specific type(s) of rock(s) as inferred from such evidence as landforms; texture, color, or tone of land surface; vegetation	Broad classification of types of water-bearing material near the land surface, and hence inference of probable porosity and relative permeability of near-surface material; with data on climate, vegetation, and drainage, inference of chemical quality of ground water
2. Spatial form and interrelations of rock units (stratigraphy and structure)	Inference of size, shape, and boundaries (lithologic and hydrologic) of probable aquifers and aquicludes; inference of conditions of recharge and discharge of ground water
3. Spatial relation of rock units to surface-water bodies	Inference of hydrologic boundaries and recharge conditions

from: HEATH & TRAINER, 1968:
Introduction to Ground-Water Hydrology

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3. Construction and operation of wells
    1. Drilling methods for wells
    2. Well types
    3. Well design
    4. Well development and well performance tests
    5. Well recovery and well remediation, optimised management

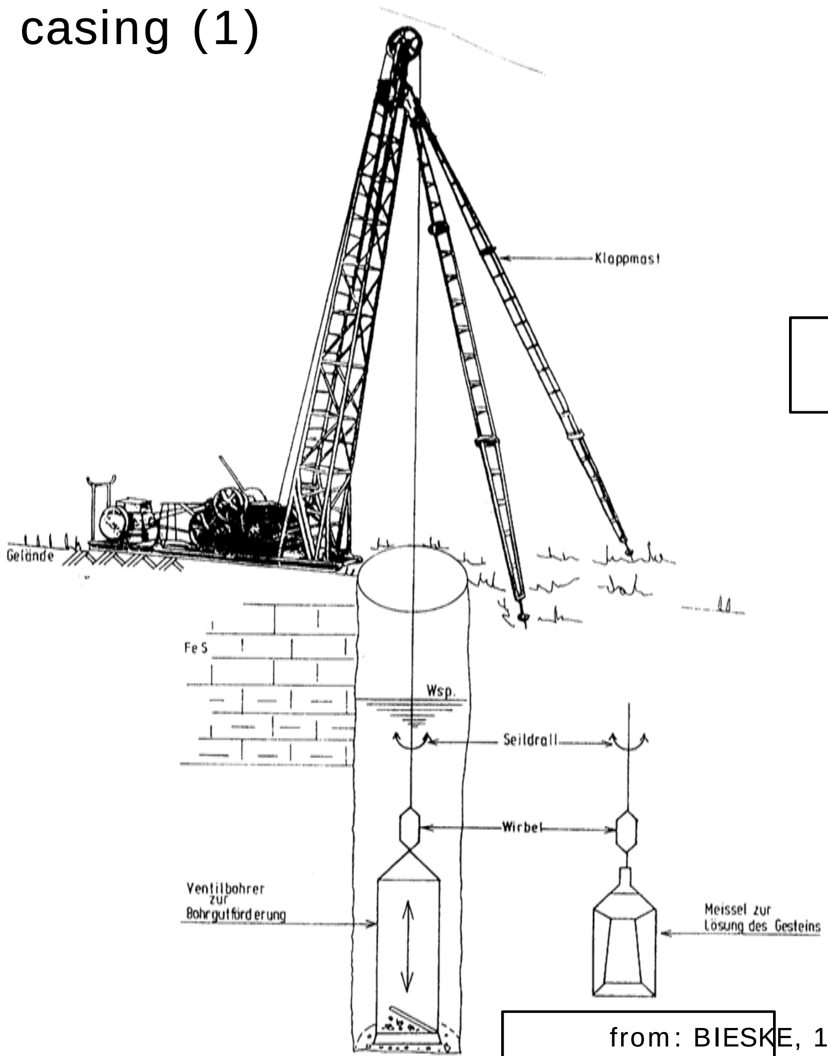
Drilling methods

- <u>Drilling without fluid</u>: with casing
    - applicable for low depths, low construction site effort
    - in case of greater depth: „telescoping“
    - accurate sampling
    - moderate impact on environment
    - convenient for the investigation of contaminated sites
- <u>Hydraulic-circulation drilling</u>: without casing (except very deep boreholes)
    - application of fluids or fluid additives
    - fast progress of drilling
    - applicable for great depths
    - applicable for the construction of observation wells and wells
    - not applicable for the investigation of contaminated sites

Classified to DVGW-bulletin W115: drillings for the development of groundwater

1. Criterion: Kind of drilling motion: rotary, percussive, and a combination of both
2. Criterion: Kind of removing the rock cuttings: continuous, discontinuous

Drilling without fluid, with casing (1)



Cable tool drilling

from: BIESKE, 1992, DVGW 1996

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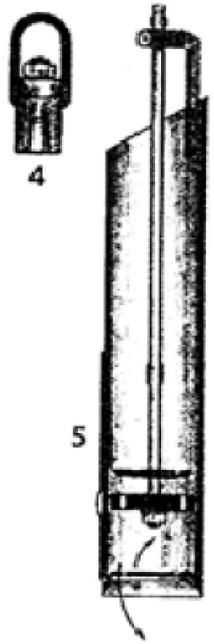
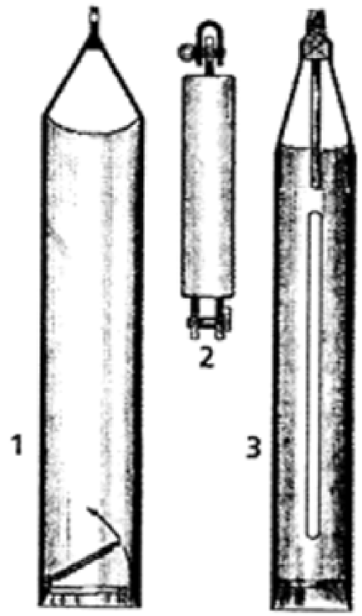
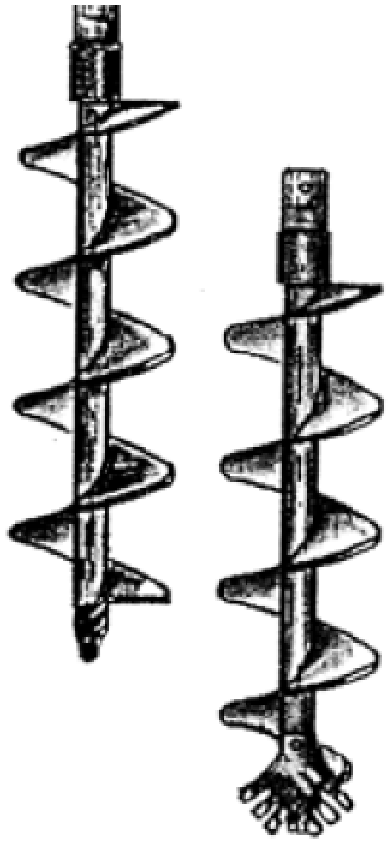
Drilling without fluid, with casing(2)

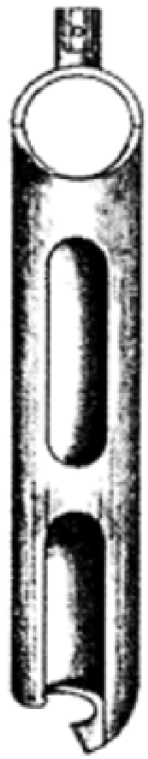


Seilwirbel (4) und
Kiespumpe (5)



Schlammbüchse (1),
Schwertstange (2)
Und Schlagbüchse (3)


Schneckenbohrer


Bohrschappe

from: BIESKE, 1992, DVGW 1996

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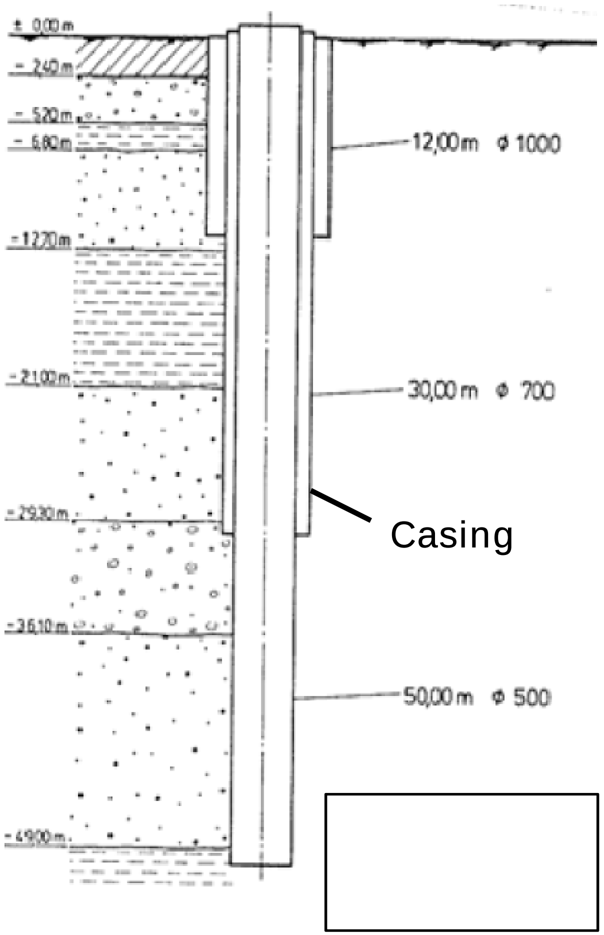
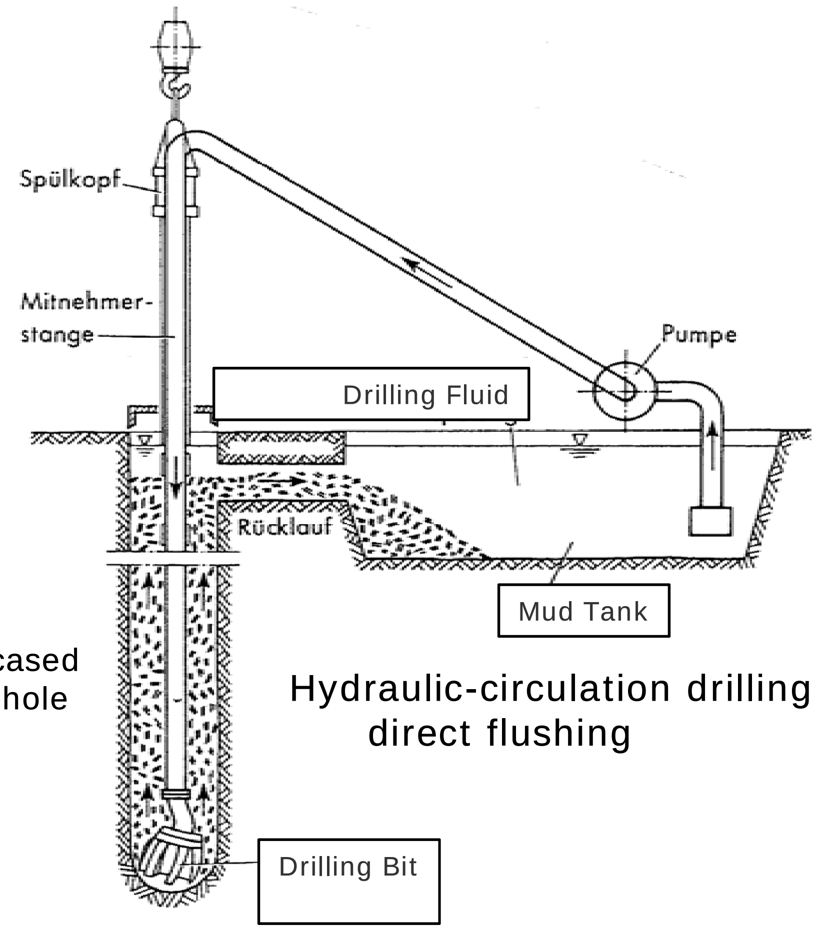
Drilling without fluid, with casing(3)

„telescoping“

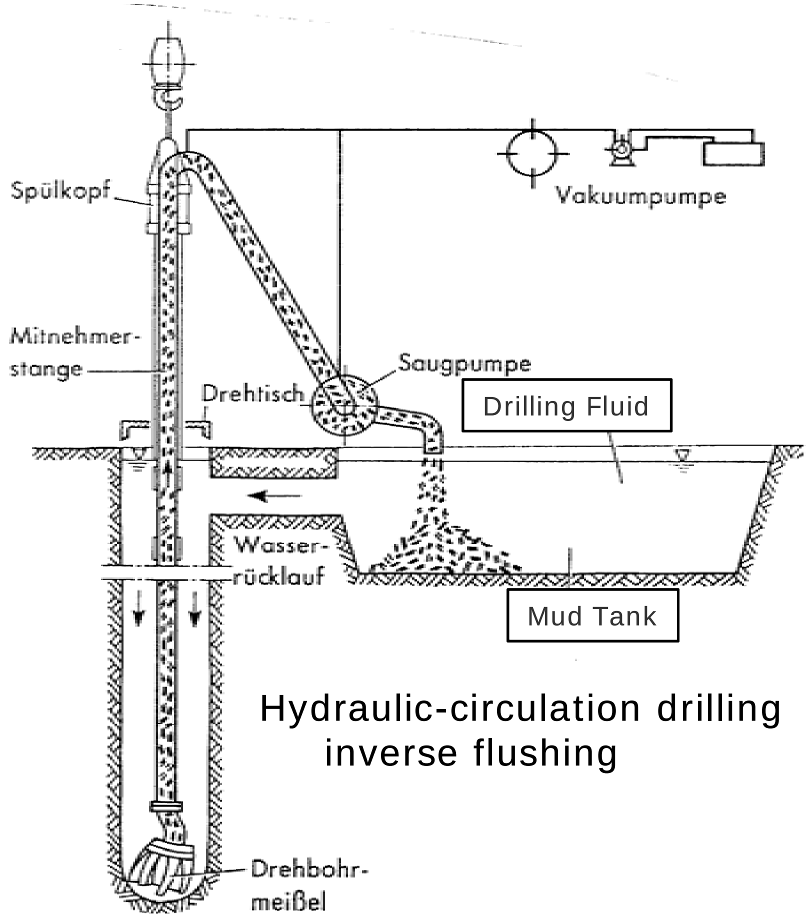


from: BIESKE, 1992, DVGW 1996

Rotary-Drilling (1)



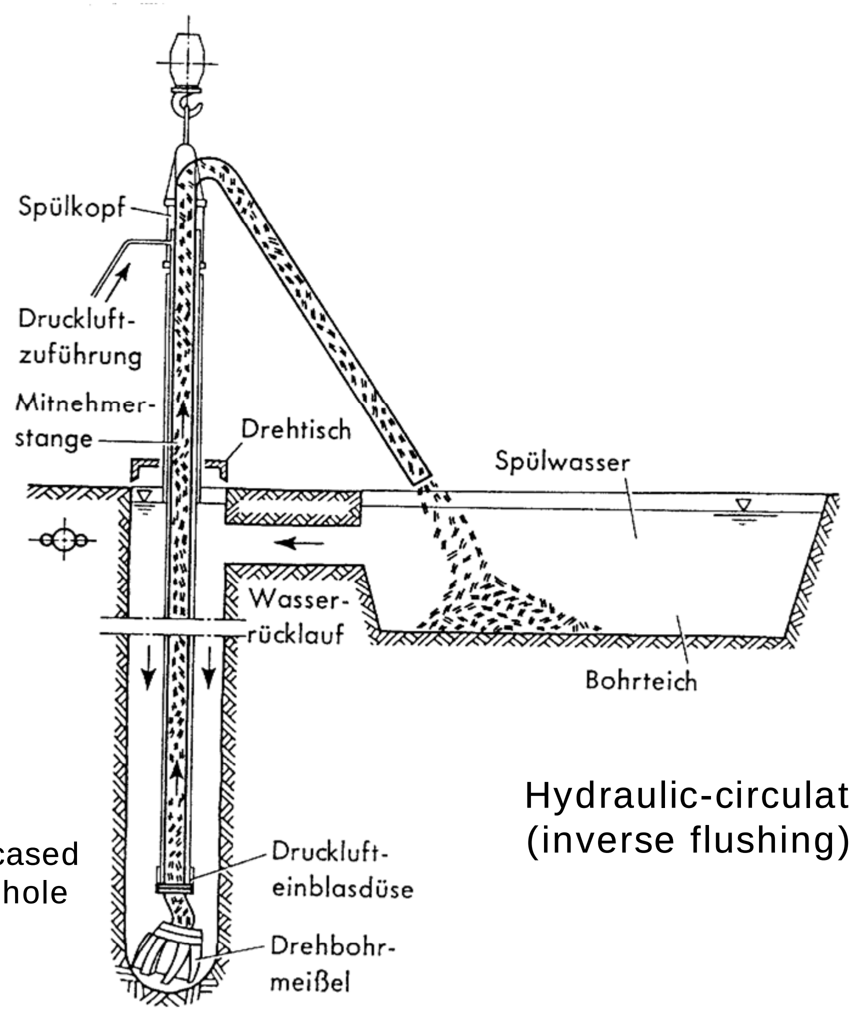
Hydraulic-circulation drilling
direct flushing



Hydraulic-circulation drilling
inverse flushing

from: BIESKE, 1992

Rotary-drilling (2)



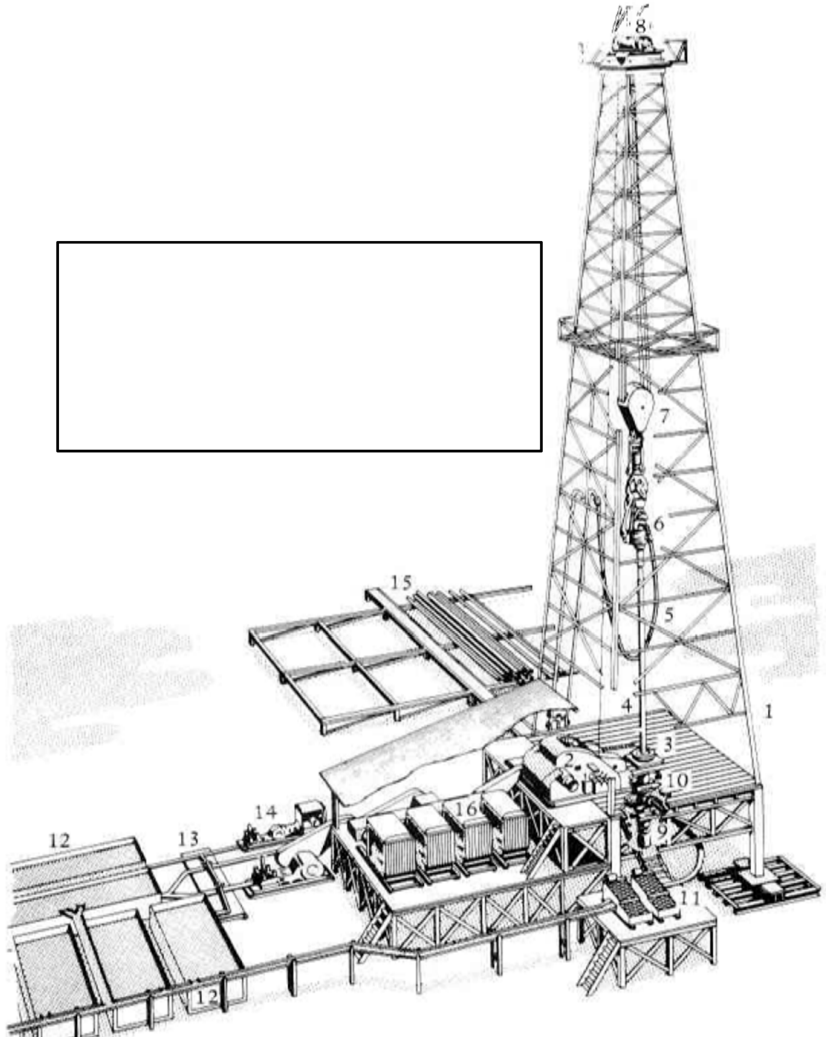
uncased borhole

Hydraulic-circulation drilling (inverse flushing)

from: BIESKE, 1992

Rotary Rig Equipment

1. Derrick
2. Drawworks
3. Rotary table
4. Kelly
5. Flexible hose
6. Rotary swivel
7. Travelling block
8. Crown block
9. Cellar
10. Blowout preventer
11. Vibrating screen
12. Mud tank
13. Mud manifolds
14. Mud pumps
15. Pipe rack
16. Power unit



Rotary Rig Equipment

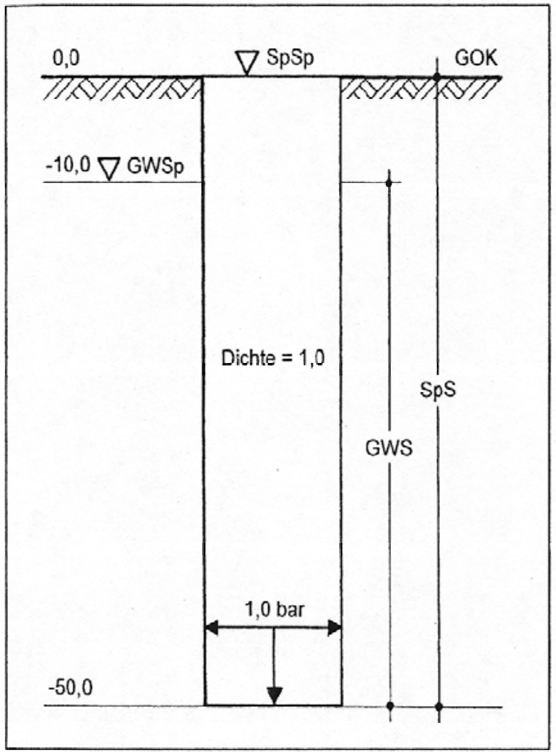
from: SELLEY (1998)

Drilling fluids

- Function of the drilling fluid
  - removes rock cuttings from the bit
  - stabilizes the borehole wall
  - cools drilling bits

- Fluid additives
  - **Bentonite:** main component is montmorillonite; Na-Bentonite: gel-like in the non-moveable state
  - **CMC-polymers** (carboxymethylcellulose): basic material: cellulose made of wood processing, restrict the inflow of drilling fluid into the bedrock, often combined with additives
  - **Polyacrylamids:** effectiveness like CMC, strong inhibited impact on swellable clays
  - **without additives:** fresh water flushing; pressure in the borehole mind. 4-5 m above RWS, high quantities of water have to be provide in a case of a pressure drop

Hydraulic methods for borehole stabilization (1)



Specific weight of drilling fluid = 1,0

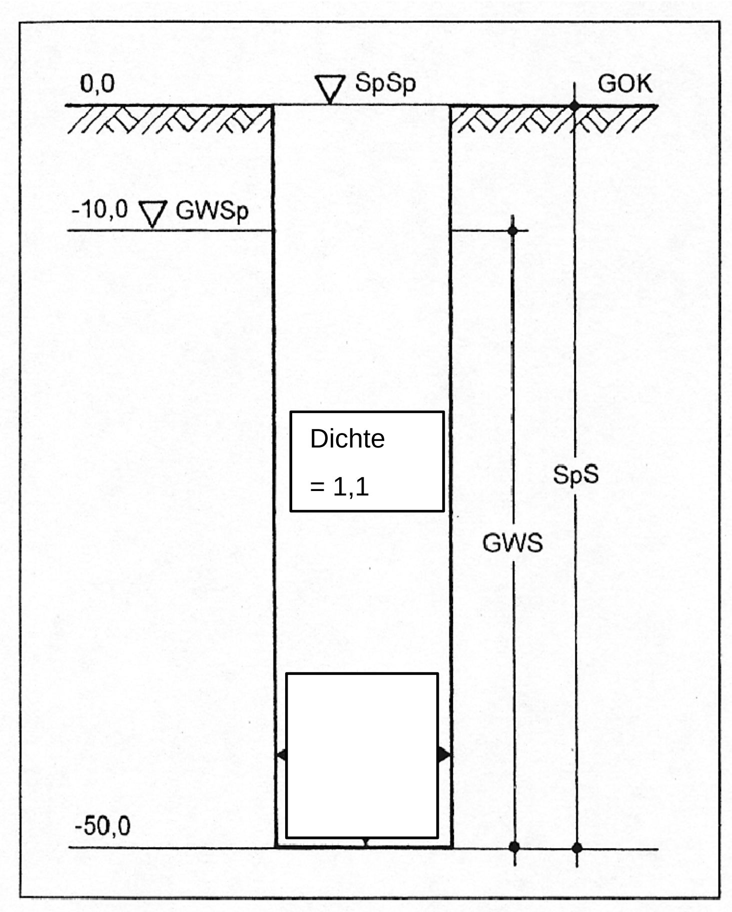
hydrostatic overpressure: 10 m Water column = 1,0 bar
(in all depths: SpSp – GWSp = hydrostatic overpressure)

GWS: Groundwater column
SpS: Drilling fluid column

- a hydrostatic overpressure is build up:
- by the groundwater head (GW-Sp), which increases the fluid level (SpSp) and
- because the density of the supporting fluid is higher than the groundwater density

from: URBAN, 2002

Hydraulic methods for borehole stabilization(2)



GWS: Groundwater column
SpS: Drilling fluid column

Hydrostatic overpressure at a depth of 50 m:

50 m SpS x 1,1 t/cbm specific weight = 55 m WS
-40 GWS x 1,0 t/cbm spec. Gw. = -40 m WS
----
15 m WS

Hydrostatic overpressure at a depth of 100 m:

100 m SpS x 1,1 t/cbm specific weight = 110 m WS
-90 GWS x 1,0 t/cbm spec. Gw. = -90 m WS
----
20 m WS

- fluid over pressure increases when the density of the drilling fluid raises and by running depth
- By an artesian confined groundwater increases the fluid pressure by loading agents: chalk (achievable density: 1,25-1,45) or heavy spar (<2, barite: 2-2,6)

from: URBAN, 2002

Type of drilling methods

- Construction by drilling without fluid, with casing:

1. Installation of a filter section / solid pipe section
2. Funnelling the filter sand / gravel
3. Extraction of the casing
4. Well development

- Construction by hydraulic-circulation drilling:

1. After reaching the final-depth: retention of the flushing circulation
2. Construction of the drilling tools
3. Geophysical measurements
4. Installation of a filter section / solid pipe section
5. Decreasing the flushing density
6. Funnelling the filter sand / gravel
7. well development

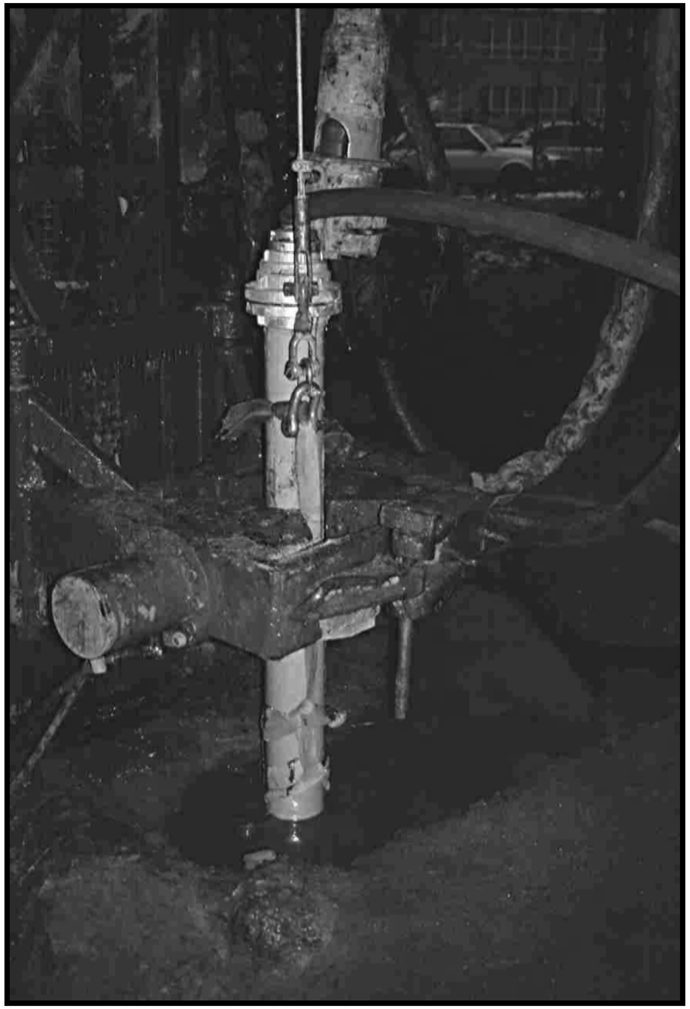
Example: hydraulic-circulation drilling(1)

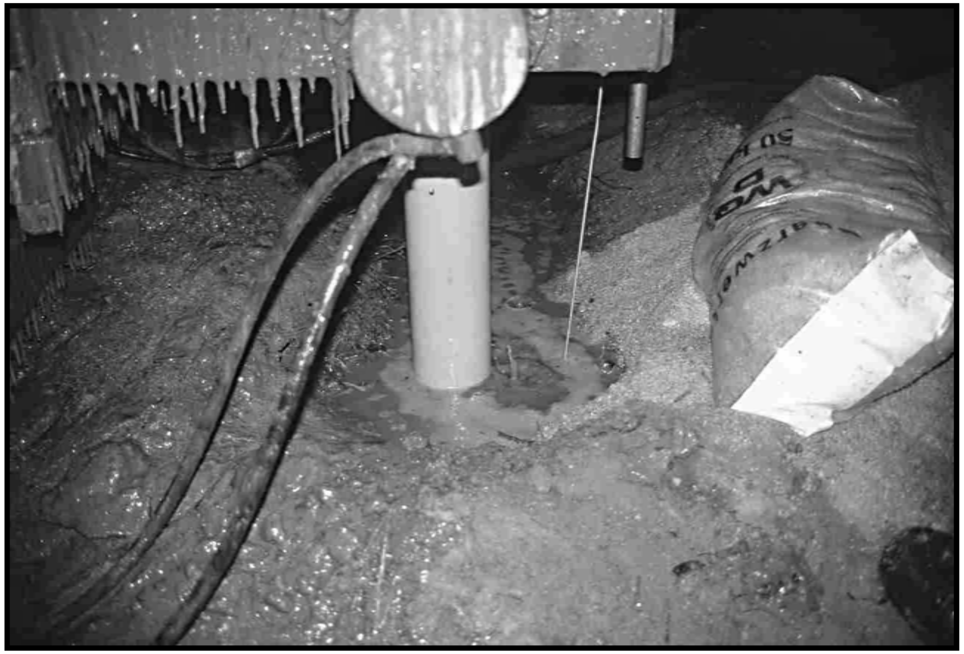
Construction of an observation well

Example: hydraulic-circulation drilling (2)

Example: hydraulic-circulation drilling (3)

Example: hydraulic-circulation drilling (4)





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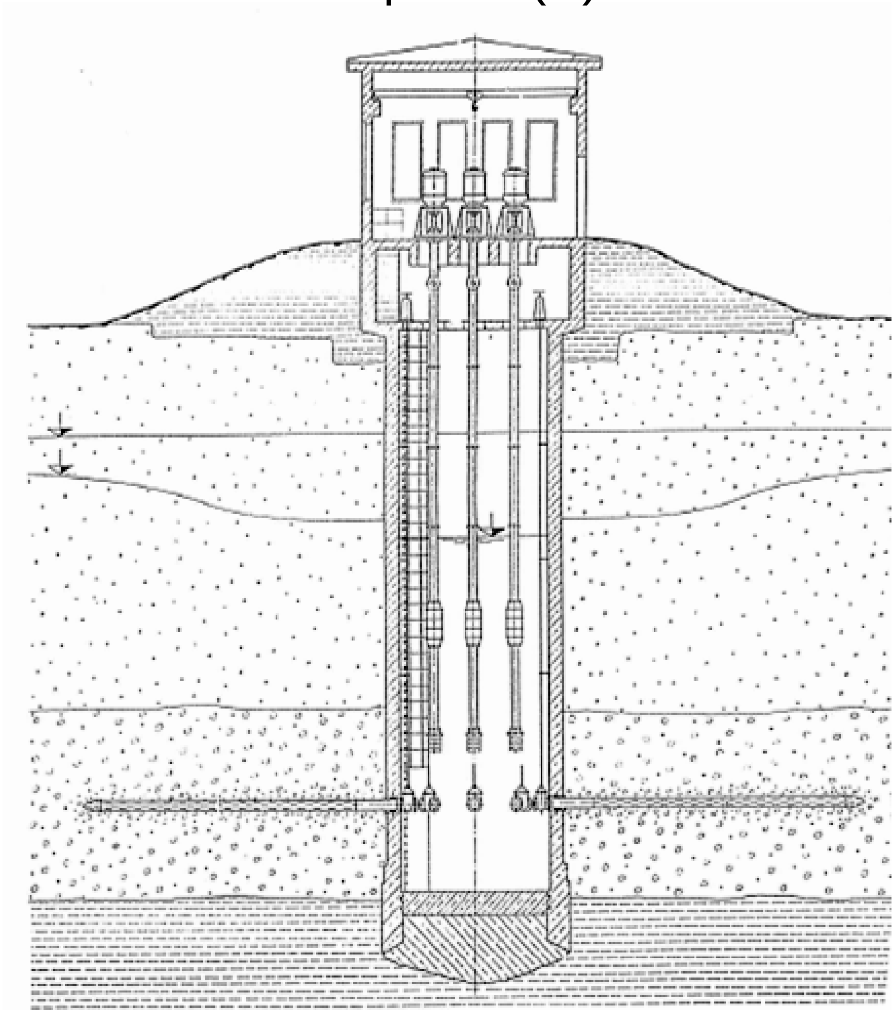
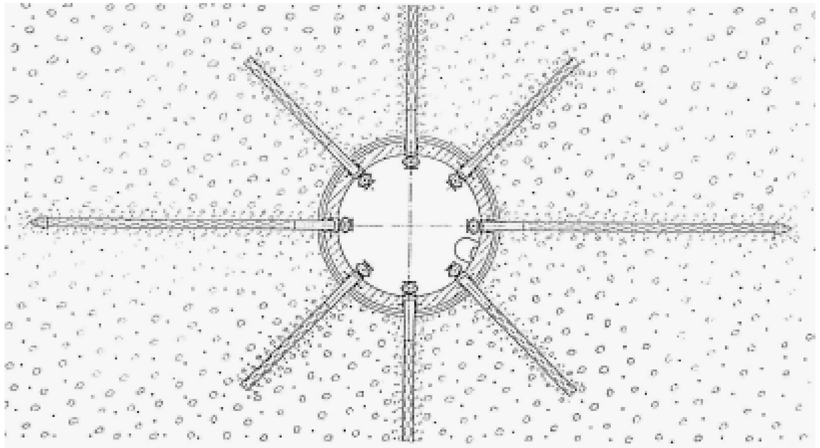
Groundwater capture (2): horizontal well



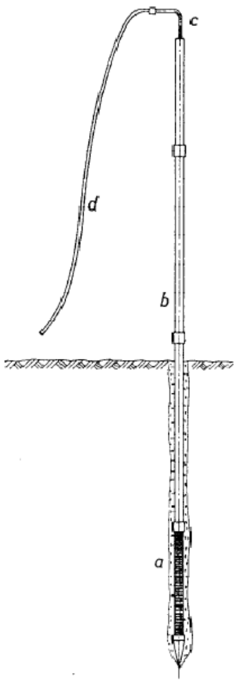


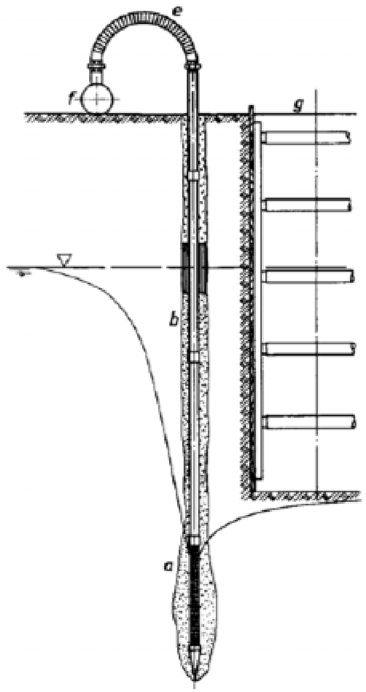
Proceeding by driving the filter drain (screen)

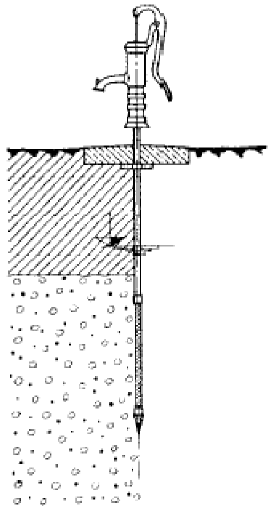
- Ranney-method
- Fehlmann-method
- Kiesmantel-method

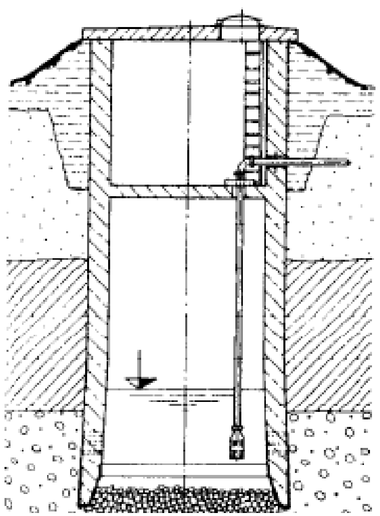
from: BIESKE, 1992

Groundwater capture (3)

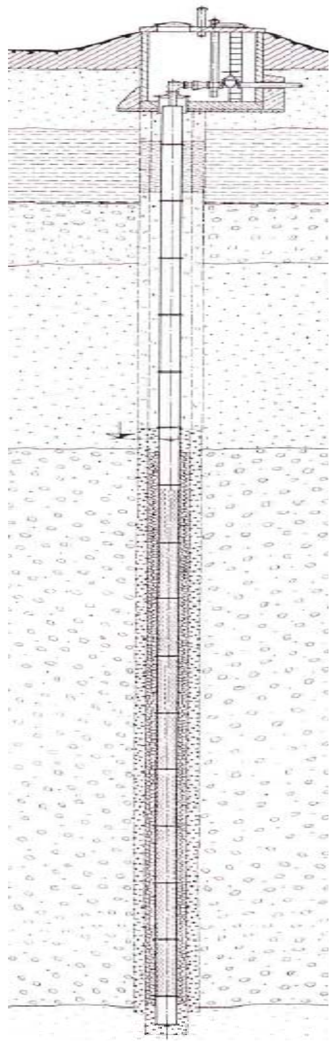






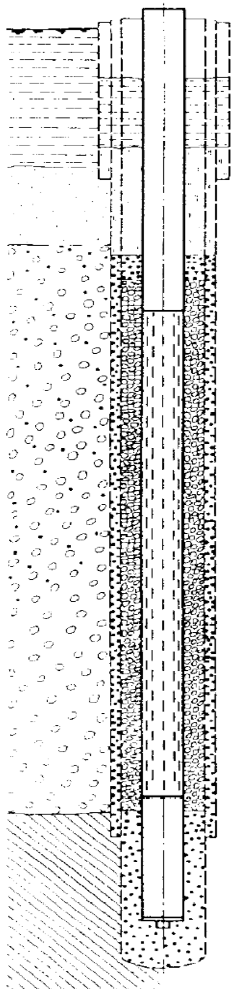


Shaft well (right)

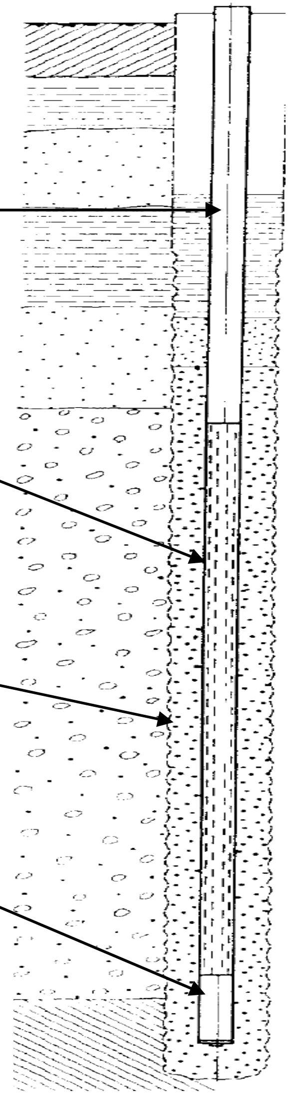


from: BIESKE, 1992

Construction of well bores



Drilling with casing



Drilling without casing

from: BIESKE (1992)

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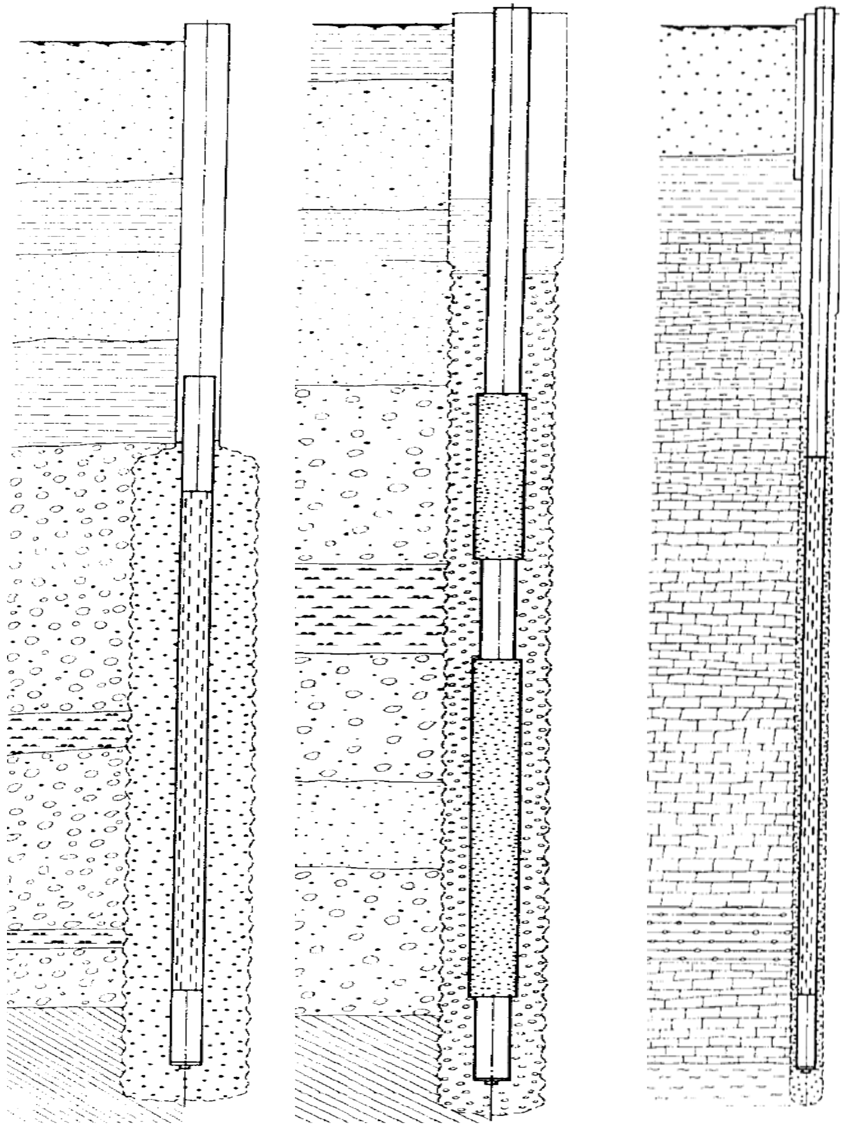
Adjustments of gravel packs

Selected gravel packs for different situations

- well with a extended gravel pack (left)
- well with “gravel pack tubes” (centre)
- construction in hard rock (right)



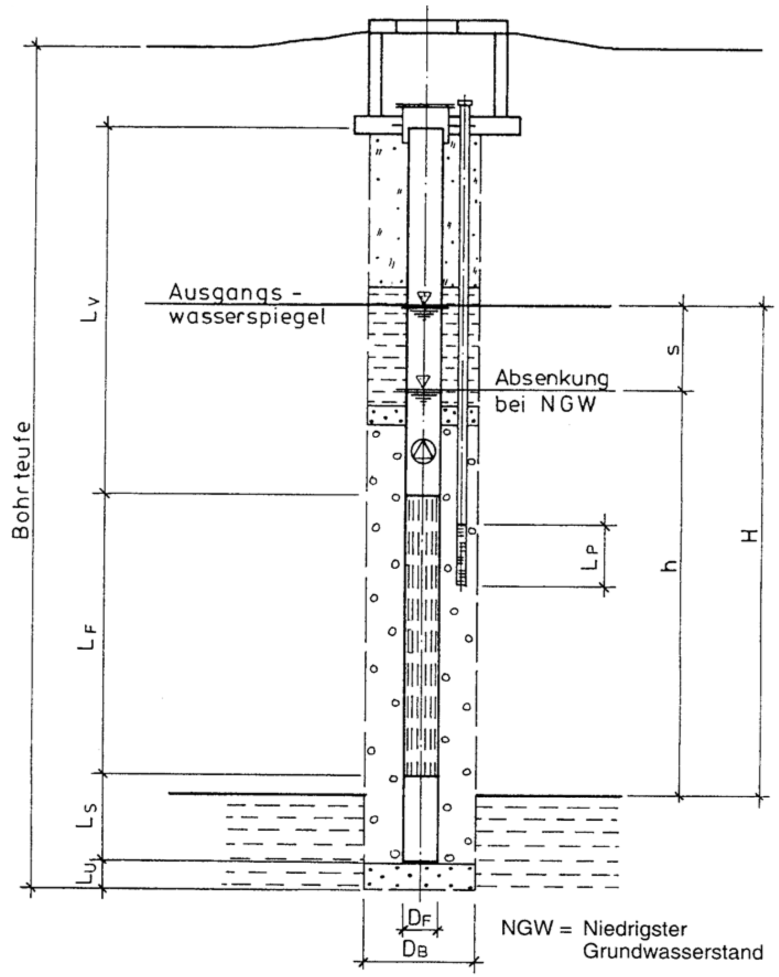
from: BIESKE (1992)

Design of a well

- Main dimensions:
  - well diameter (= final well diameter)
  - diameter of the filter pipe
  - length of the filter
  - well depth (= drilling depth)

- Additional information:
  Position of the static head and depression head

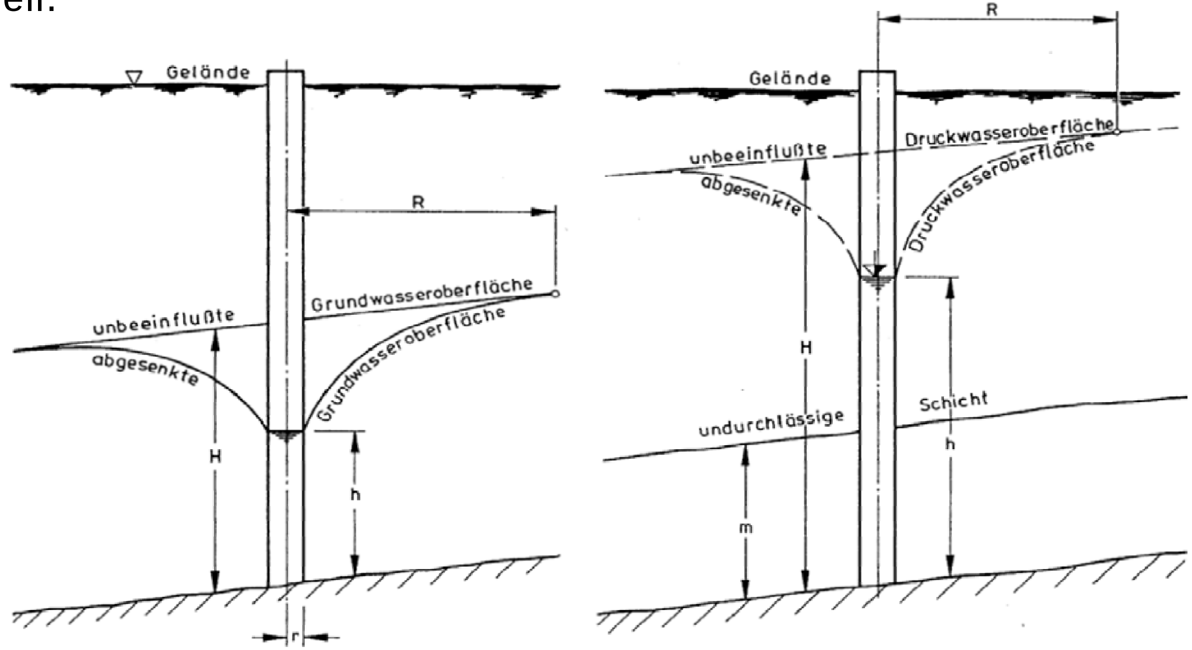
T_B:	drilling depth
D_B:	well diameter
D_F:	diameter of the filter pipe
L_F:	length of filter
A_F:	open screen area
D_a :	grain size of the filter gravel
s_W:	slot size
Q_a:	water rush
Q_F:	volume



from: TRESKATIS, in: DVGW (1996)

Well diameter

- **Ideal diameter** (offers the economical best well yield):
  capacity of the well (Q_F) has to accommodate the prevalent water rush (Q_a) to the well.



from: BIESKE, 1992

- **well diameter** = (end-) drilling diameter
- **minimum diameter:** Installation of pumps must be possible plus a safety margin of mini. 400 mm (i.e. filter diameter: ca. 200 mm).

Well dimension

- water rush: volume of water per unit of time, which flows out of the aquifer into the well. With an increased draw down, the water rush raises (increased entrance velocity).

confined aquifer:

$$Q_a = \frac{\pi \cdot k_f \cdot (H^2 - h^2)}{\ln R - \ln r}$$

unconfined aquifer:

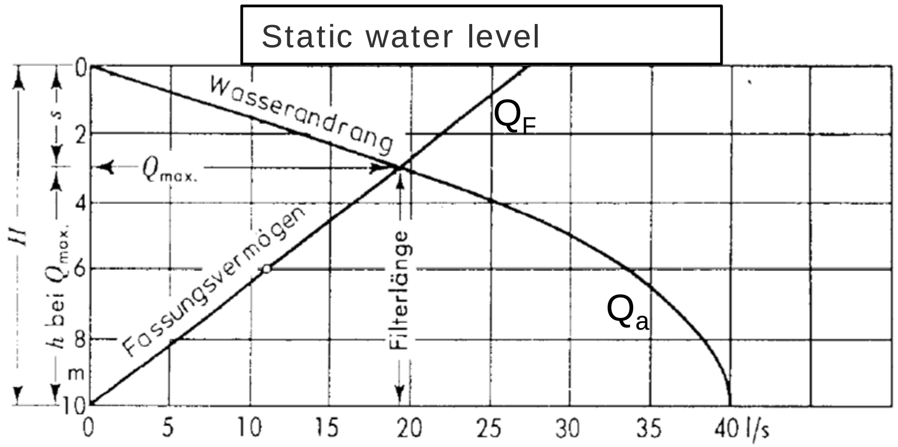
$$Q_a = \frac{2\pi \cdot m \cdot k_f \cdot (H - h)}{\ln R - \ln r}$$

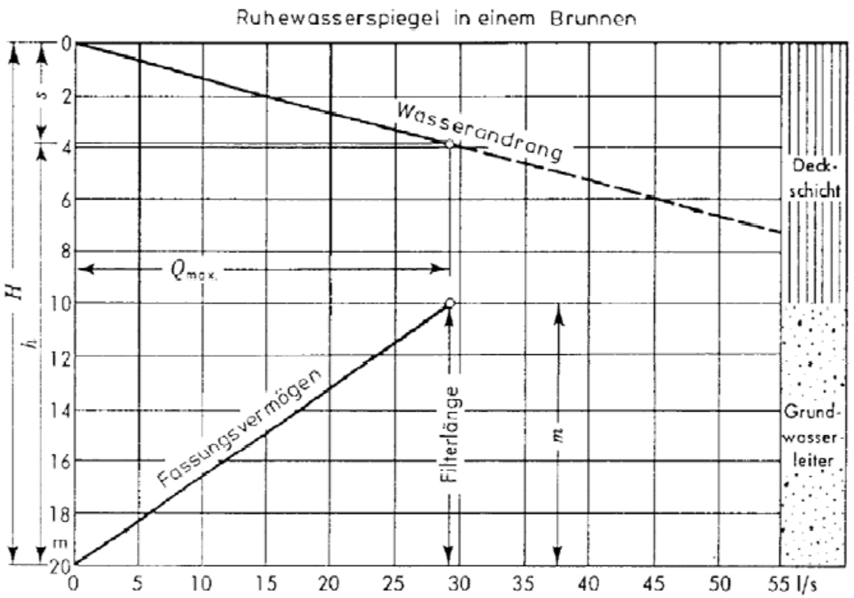
- well capacity: volume of water per unit of time, which the well can accommodate through the filter pipe. With an increased draw down the capacity decreases (reduction of area of inflow).

$$Q_F = 2\,r \cdot \pi \cdot h \cdot \frac{\sqrt{k_f}}{15}$$

Determination of the economical best well yield

- Capacity and water rush by unconfined ground-water ratios (**right**)





- Capacity and water rush by confined ground-water ratios (**left**)

from: BIESKE, 1992

Diameter of the filter pipe

- Empirical formula: diameter of the filter = diameter of the well x 0,5

  The diameter of the filter pipe has to be adjusted, so that the ground-water inflow into the filter is laminar (premature aging by turbulent flow).

mean reliable filter velocity in the gravel filter:

$$v_f = \frac{Re_k \cdot \nu}{\delta_{wk}} = \frac{6 \cdot 1{,}31 \cdot 10^{-6}}{\delta_{wk}} \qquad \text{(Truelsen)}$$

Re_k = REYNOLDsche Zahl für laminares Einströmen, obere Grenze: 6
δ_{wk} = Korngröße der inneren, am Filterrohr liegenden Kiesschüttung (m),
ν = temperaturabhängige kinematische Zähigkeit, im Mittel bei 10°C: $1{,}31 \cdot 10^{-6}$ m²/s,
v_f = mittlere zulässige Fließgeschwindigkeit (m/s) im Filterkies.

The adjustment of grain size at the external gravel pack depends on aquifer.

As a consequence of $\frac{\sqrt{kf}}{15}$ (= vmax = maximum velocity of well inflowing water) is vf degraded

Length of filter pipe

- Adjustments with the thickness of the aquifer
- The depression head has to be located one meter above the top of the filter pipe.
- Water inflow into the submersible pump should not occur within the length of filter pipe; unless there exists a 2-3 m long solid pipe

➢ Depth of wells:

- is generally geared to the lower boundary of the aquifer

Materials of filter pipes and types of construction

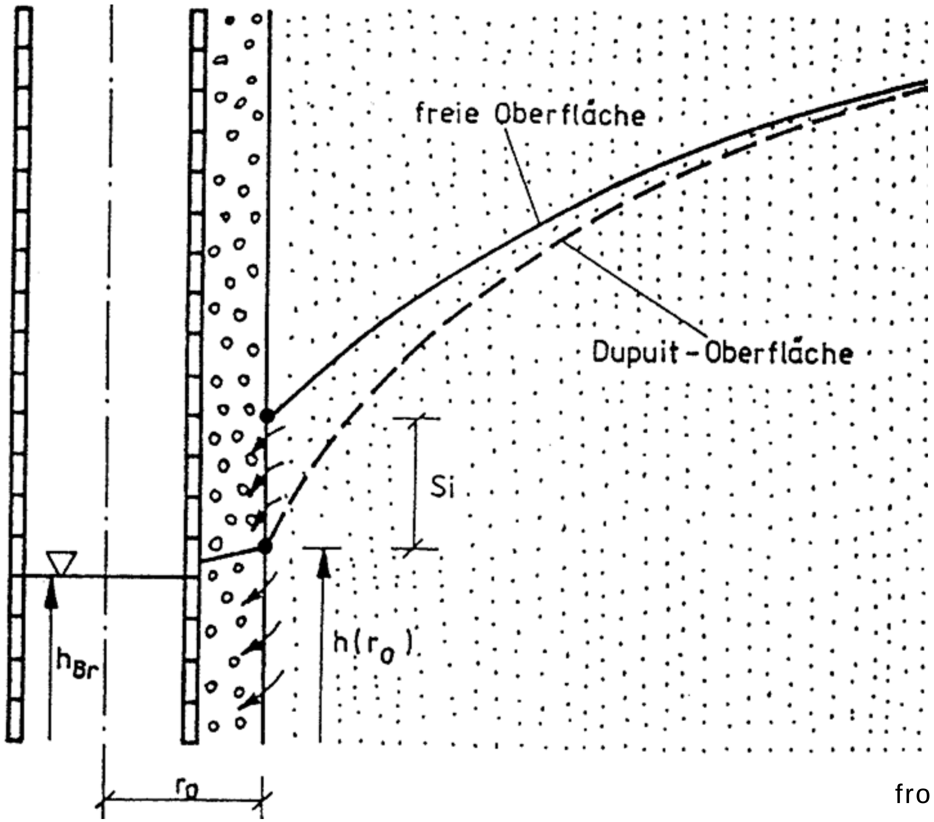
- Requirements:
  sand less water access, low filter access resistance, resistant to corrosion, high mechanical resistance, hygienic harmless, long durability

- Materials:
  cupper, iron- or steel plate (zincked or plastic-coated), stainless steel, wood (with melamine resin coated compressed wood), stoneware, concrete, synthetic materials, tightened fibre glass resin.

- Type of construction:
  Slot perforation lengthwise and crosswise (milled slots), slot pontine perforation (metal pipes), jalousie perforation (metal pipes), poultice filament filter (stainless steel), fins filter, filter made of circular elements (polystrole-die-casting), obo-filter (spiralled arranged filter segments made of compressed wood).

- Filter slots: Size of slots = lowest filter grain x 0,5

Seepage length (Si) and filter-access-resistance ($h_{(ro)}$-$h_{(Br)}$



from: BIESKE (1998)

- Si just for unconfined aquifers; accumulation according to SCHESTAKOW
- increased draw down = increased Si
- draw down under no circumstances >50% of ground-water thickness

Objectives and dimension of the gravel packing

- **Objectives of the gravel filter:**
  - Stabilization the well construction
  - Optimal well inflow
  - Minimizing the transport of sand in the delivered groundwater (< $1 g/m^3$)
- **Optimal filter grain size:**

First, the filter grain size has to be chosen so that the lowest friction of fine grains are transported into the well and can be delivered (removal of sand, time limited). In the following well operation: Minimizing the transport of sand; development of a permanent and steady gravel packing.

There exist a (empirical determined) relationship between a „characteristic grain“ of the aquifer and the suitable filter grain:

filter grain = characteristic grain x filter factor

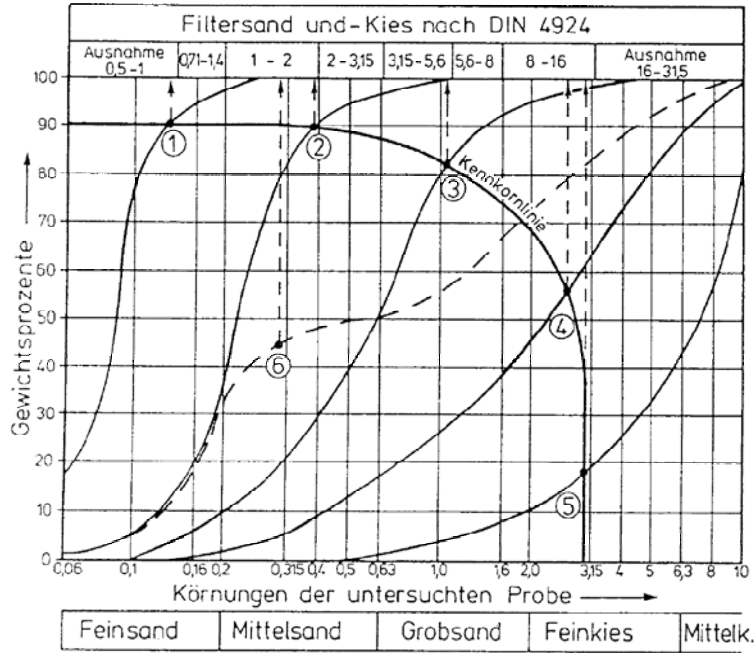
the characteristic grain determination is based on the grain size distribution (fractions >10mm are not be considered and get separated); characteristic grain is located in the upper part of the grain size distribution curve

Determination of the convenient filter grain size

1) Method according to <u>TRUELSEN</u>
   (TRUELSEN 1957, TRUELSEN & AHORNER 1960)
   with U < 3: filter grain size at 75%-cutting line of the sum curve
   with U = 3-5: filter grain size at 90%-cutting line of the sum curve

2) Method according to <u>NAHRGANG</u>
   (DVGW-bulletin W 113)

3) „*Characteristic grain method*"
   according to <u>BIESKE</u> (1961):
   filter grain size =
   characteristic grain x filter factor
   filter factor = ratio between the narrowest openings and filter grain size (SICHARDT 52); mostly 4-5



Filterkieskörnungen nach DIN 4924

	Körnungen in mm	Zusammengehörige Körnungen bei mehrfacher Abstufung für Brunnenfilter 2)					Unterkorn Zulässiger Höchstanteil in Gewichtsprozenten	Überkorn Zulässiger Höchstanteil in Gewichtsprozenten	Siebgutmenge für Probe g
Filtersand	0,25 bis 0,5 1)	×					15	15	500
	über 0,5 bis 1		×				10	10	500
	über 0,71 bis 1,4			×					1000
	über 1 bis 2	×			×				1000
Filterkies	über 2 bis 3,15		×			×			1000
	über 3,15 bis 5,6			×					1000
	über 5,6 bis 8	×			×				5000
	über 8 bis 16		×			×			5000
	über 16 bis 31,5			×	×	×			10 000

from: BIESKE (1998)

Example: Determination of filter grains

1. Step:
Determination according to the geological situation

Teufe	Kennkorn	Filterfaktor	Schüttkorn
5,00 - 8,50 m	1,05 mm	5	~ 5,3 mm
8,50 - 10,00 m	1,42 mm	5	~ 7,1 mm
10,00 - 16,00 m	2,1 mm	5	~10,5 mm

2. Step:
Adjustments according to DIN-standards

für	5,00 - 8,50 m	die Fraktion	3,15 - 5,6 mm
für	8,50 - 10,00 m	die Fraktion	5,6 - 8 mm
für	10,00 - 16,00 m	die Fraktion	8 - 16 mm.

3. Step: Compensation of two layers for the characteristic grain 1,42: filter factor 4; hence: filter grain 5,68

für	5,00 - 10,00 m	die Fraktion	3,15 – 5,6 mm
für	10,00 - 16,00 m	die Fraktion	8 - 16 mm.

4. Step:
layer boundaries calibration

Aquifereinheit	Verkiesung
5,00 - 10,00 m	bis 11,00 m: 3,15 – 5,6 mm
10,00 - 16,00 m	unter 11,00 m: 8 - 16 mm

from: LANGGUTH & VOIGT (1980); modified

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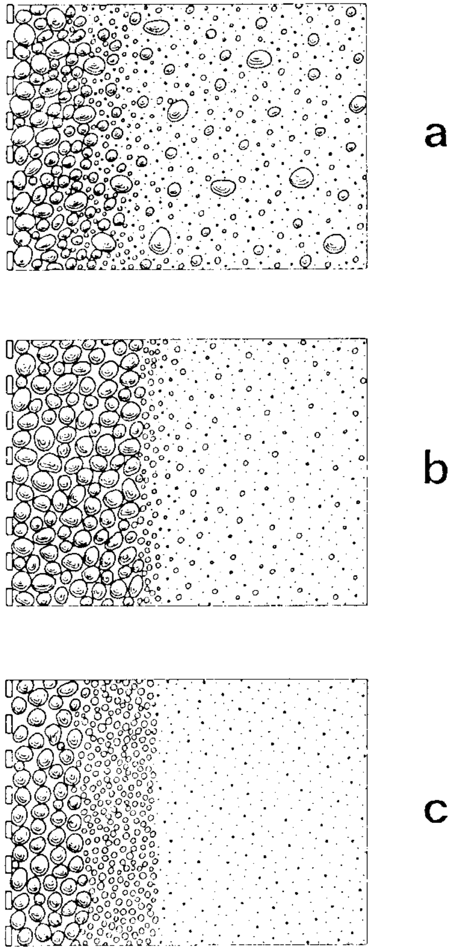
Well development („removal of sand“)
DVGW – bulletin W117, W119

- Objectives:
  - displacement of the finest grain frictions of the gravel packing
  - displacement of the fine grain friction from the adjacent part of the aquifer
  - stabilization of the grain structure in the environment of the well
  - disposal of flushing residuals

- Methods for well development:
  - well development (“Klarpumpen”)
  - intensive removal of sand with U-pumps and packer systems in selected sections
  - „shocking“
  - „*Entsandungskolben*“

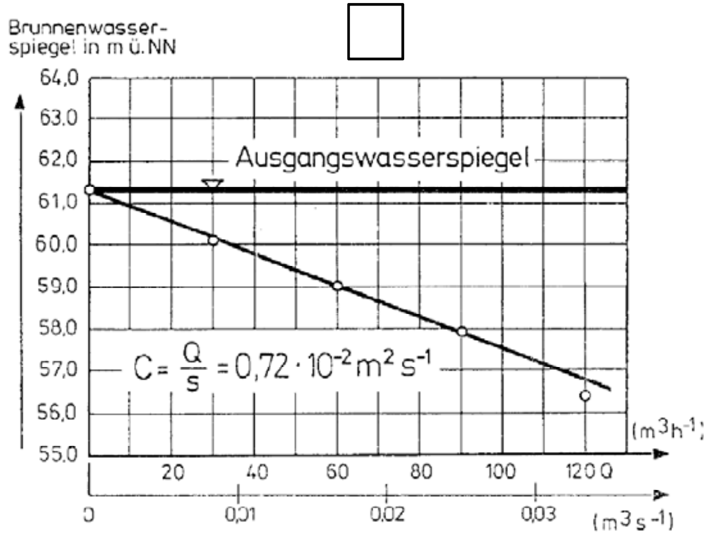


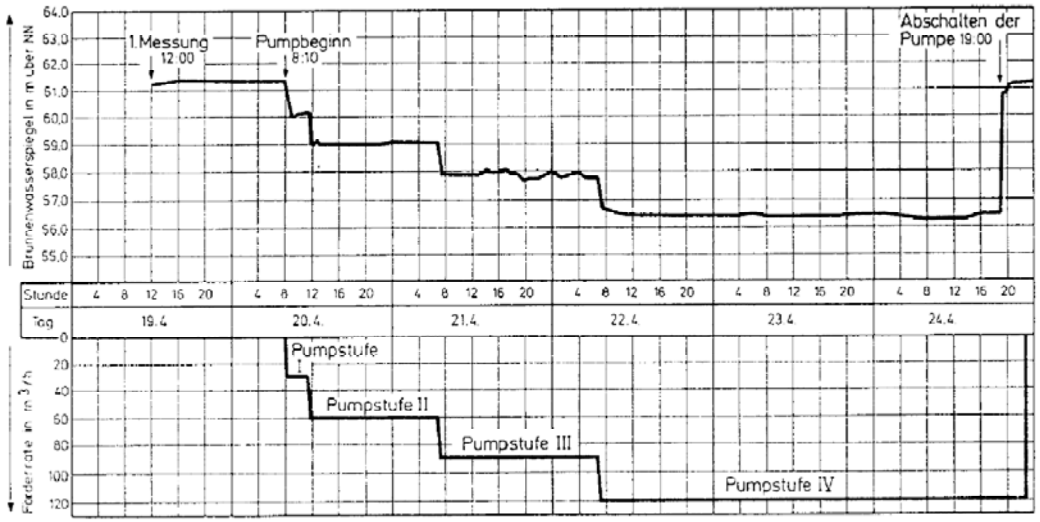
Grain structure as the result of the removal of sand
a) natural developed well
b) simple gravel packing
c) double gravel packing

from: LANGGUTH & VOIGT (1980)

Well performance tests

- Objectives:
  - Determination of specific yield
  - Extraction of data for the selection of the correct pump





from: LANGGUTH & VOIGT (1980)

Well regeneration and rehabilitation, optimised operation management
(from: DVGW-bulletins W 130: well regeneration)

The capacity of a well can considerably decrease by increasing operation time.

- Reasons for a decreased performance:

    - Sand fillings:
        - transport of sand in the delivered raw water
        - sand deposits within the well
        - self-sealing processes by mobilised particles in front of or inside the gravel packing (mechanical colmation)

    - Ferric incrustation: precipitation of Fe and/or Mn-compounds
        - chemical induced ferric incrustation
        - biological induced ferric incrustation

    - Sintering: chemical precipitation of carbonate-compounds due to the shift of the carbonate equilibrium

Well regeneration and rehabilitation, optimised operation management
(from: DVGW-bulletins W 130: well regeneration)

➢ Reasons for a decreased performance:

- Incrustation of screens (biologic fouling): reduction of permeability in the well surroundings due to population explosion by mud-producing bacteria and fungi. Especially important for bank filtration.
  possible reasons:
  - Supply of organic matter and N-compounds
  - not removed residuals of drilling fluids based on organic matter.
- Aluminium precipitation: precipitation of aluminium hydroxide (rare!). The precipitation occurs in an environment with high Al-values and acid pH-values.
- Corrosion: relevant just for the application of zincked construction materials: 10-15 times of bulking; damages are irreversible.

Methods for well regeneration:

- Chemical methods (license issued under water law is required)
- Mechanical and hydro mechanical methods
  - brushing
  - slices („piston“)
  - pumping performance
  - high pressure jetting by air or water
  - well surging
  - hydro fracturing

➢ Methods for well rehabilitation:

  - over drilling and re-filtering
  - reparation of selected sections (e.g. sealing by uncontrolled water inflow)
  - insertion of a new casing and regeneration