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HYDROGEOLOGY AND GEOHYDROLOGY

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FOREWORD

The present report is a summary of lectures on hydrogeology - geohydrology, given as a part of the Introductory Lecture Course of the Geothermal Training Programme. The aim of the lectures, and this report, is twofold: First, to give a short but comprehensive review of the fundamental factors in geothermal hydrogeology - geohydrology and their interactive connections. Second, to stress some principal aspects, usually not dealt with in standard textbooks, as the importance of the perspective of the objectives, how to proceed in view of the incompleteness of our information and the common misunderstandings in the use of scientific language. The report is thus complementary to the textbooks, and it is the author's hope, that it will help the reader to avoid a few of the dangers, luring at every footstep when dealing with this dynamic and vivid branch of the geothermal sciences.

The contents of the report are arranged as follows:
First, the hydrological definition of a geothermal system is elucidated (Section 1), then the hydrological regime and the basic rules of the groundwater flow are dealt with (Section 2 - 4), next the hydrological properties of the rocks are discussed (Section 5 - 8), followed by a short review of some aspects of various types of geothermal systems (Section 9), and finally the basic principles in geohydrological - hydrogeological investigations are briefly discussed (Section 10 - 11).

CONTENTS

1. GROUNDWATER AND GEOTHERMAL ENERGY

The role of the groundwater-flow in the geothermal sciences is very important, because of the physical nature of water and its over all presence. The groundwater is an energy-carrier. It has a relatively high specific heat capacity (kcal/l × grd or J/kg × grd), it is present in the rocks in a great quantity and it is highly mobile. It is thus able to transport energy with relatively slight losses for long distances, as well vertically, from deep sources to the surface (many high-temperature areas), as horizontally, from a distant source to an outlet on the surface (many low-temperature areas) (see Fig. 1).

The hydrogeological structures often channel the groundwater-flow, thus concentrating it, and with it, in geothermal cases, also the energy. The heat-energy from an areal source may thus be concentrated through hydrogeology and groundwater-flow into a single spot (natural thermes, drilled wells etc). The available quantity of water/energy depends on hydrogeological and geohydrological factors.

These factors result in a flow path of the geothermal water, composed of various elements (see Fig. 2). The most obvious one is the outlet, be it a natural or an artificial one (hot spring, borehole). In most cases the hot water has some vertical way of ascend to the surface from the depths of the reservoir. At the other end of the flow path the water must have some place of origin, where it enters the rocks and the groundwater circulation. This place is often unknown, but the water must be conducted from it via some flow channel towards the outlet. The location and nature of this flow channel is often much of a guesswork. Yet there is often enough a limited range of possible conditions or choices for the flow channel and the area of origin for the water so that by eliminations they can be approached with some notable degree of probability. The quantity of water infiltrating in the catchment area sets an upper limit for the quantity flowing out at the outlet. A similar limitation is present in the flow channel: The quantity passing it is dependent on the structure of the flow channel itself and the energy conditions of the water.

The quantity of energy that the geothermal system discharges is dependent on the groundwater flow (discharge) and the energy of the water in this flow. The groundwater flow again depends on the hydrogeological structure of the system and the conditions of the groundwater present in the system (see Fig. 3).

The importance of the various hydrological and hydrogeological factors varies with the perspective, or the size of the object (see Fig. 4). A single well (borehole) yields only a small part of the total groundwater flow of the system, and even the exploitable area, the reservoir, can not yield the total flow. On the other hand a borehole can yield so much water as can technically be pushed through it and the total yield from a reservoir can reach a high percentage of the total groundwater fluid stored in the reservoir although it is impossible to suck the last drop of hot water out of a geothermal system.

2. HYDROLOGY AS SCIENCE

Hydrology, in a broad sense, is the science of natural water, especially its movements and physical behaviour. As a natural science, hydrology may be divided into surface-hydrology and groundwater-hydrology. Other branches of hydrology are i.g. hydraulics and hydrochemistry (see Fig. 5).

The flow of the geothermal fluid is an object of the hydrological sciences. The concern of the groundwater-hydrology is primarily the groundwater-flow. The effect of the geological structures and the physical nature of the different types of rock-bodies on the groundwater-flow is the object of the hydrogeology. The quantitative aspects of the circulation of natural water in the hydrological cycle are the chief objects of the geohydrology (see Fig. 6).

3. GROUNDWATER-SUPPLY (DRAINAGE AREA)

Regarding only the water, not the energy, a geothermal field has a drainage area, a flow channel and an outlet. This path, which the water must follow, is illustrated in the hydrological cycle. The ultimate source of all geothermal waters, or practically all, is the evaporation from the oceans and the surface of the earth. This vapor condenses and falls in the drainage area as some kind of precipitation (rain, snow), depending on meteorological factors (see Fig. 7). There a part of it evaporates back into the air, part of it flows away at the surface as surfacial run-off, part of it infiltrates into the earth. Only this infiltration joins the groundwater. The infiltration can be expressed by a simple formula:

$$I = P - E - R; \qquad (1)$$

I: Infiltration (mm/time unit)
P: Precipitation (mm/time unit)
E: Evapotranspiration (mm/time unit)
R: Run-off (mm/time unit)

None of these parameters can be measured exactly. Often the infiltration is estimated from some kind of measurements of the other parametres. The precipitation is measured with a rain-gauge at some local stations. There is always some loss in the measurement, dependent on wind velocity, temperature and so on. A further error arises from the fact, that such a measurement is not truly representative, because it is local and punctual, whereas the precipitation on the drainage area is areal (1/sec. km^2). The evapotranspiration can not be measured directly and is normally computed from meteorological data. Similarily, the measurement of the run-off is often difficult, and obtainable with some exactness only where a river has an "ideal" river bed. The calculation of the infiltration can therefore at its best only be a good estimate. Yet it is very useful for establishing some limit-values for the water potential of the drainage area.

Of course no geothermal field can yield more water that it obtains through the flow-channels from the drainage area, without disturbing the natural balance in the ground-water. This again may be changeable with time, depending i.g. on the infiltration rate in the drainage area. All geohydrological parametres are more or less fluctuating with time.

4. GROUNDWATER FLOW

Not the total amount of water, that has been infiltrated into the earth in a drainage area, must return to the surface in a corresponding geothermal field. Some water may flow to some other places and some may flow subterranean through the geothermal field, without coming to the surface. The amount of water in the geothermal field can still be estimated, if the parametres of the groundwater-flow and the input (infiltration) in the drainage area are known, or can be estimated.

The relationship between the groundwater flow and its driving force changes with the conditions of the flow. When the flow is slow and the delaying effect of the friction against the walls of the conductor is considerable, as is in a porous media, the flow is laminar, i.e. the flowlines (the path of a single drop) are nearly parallel. If the flow is faster, or the space is wider (less wall effect) the flow becomes suddenly turbulent. Much of the energy of the flow is lost in the turbulence so that the efficiency of the driving force is strongly reduced (see Fig. 8).

The groundwater-flow in an aquifer is normally a laminar flow. In the vicinity of a pumped well or in big openings in the rocks (tectonic fissures, karstic caves etc), the flow may become turbulent. The velocity of the flow is then markedly less. For the natural groundwater-flow this case is seldom met.

The natural groundwater-flow can be looked on as the result of the physical interaction between the groundwater-body in the rocks and the different parts and structures of the rocks themselves. As a mass transfer of a fluid with an inner friction through a medium with a certain resistance (capillary forces, friction etc.) against the flow, the groundwater-flow must have some driving force. In almost all natural cases this driving force results from a potential gradient in the water-body itself, i.e. (somewhat simplified), a pressure difference along the flow-channel, resulting mainly from the height of the surface of the water body (the watertable), and the density of the water. This potential gradient and the viscosity of the water, are parametres of the groundwater-flow, that is inherent to the water body (see Fig. 9).

The mass velocity of a laminar groundwater-flow can be expressed through parametres of the water-body and the rock-body:

$$V = \frac{k \times \rho}{n \times \eta} \times I; \qquad (2)$$

- V: Mass velocity (not the true velocity of a single water particle:) (m/s)
- k: Intrinsic permeability of the rocks (Darcy) (1 darcy $\approx 10^{-8}$ cm^2)
- n: Porosity (Dimensionsless)
- ρ: Specific weight of water (g/cm^3)
- η: Dynamic viscosity of the water (Poise) ($1P = 100\ cP = 1\ g\ cm^{-1}s^{-1}$)
- I: Hydraulic gradient (Potential gradient) (Dimensionsless)

In most cases the mass velocity is not the most interesting feature of the groundwater-flow, but the specific discharge, i.e. the mass that flows per time unit through an areal unit of a cross-section of the flow-channel ($m^3s^{-1}/m^2 = m/s$). This parametre has the same dimension as the velocity. Their connection is:

$$q = v \times n = k \times \frac{\rho}{\eta} \times I; \qquad (3)$$

The total discharge through a flow-channel is then:

$$Q = q \times F; \qquad (4)$$

- q: specific discharge (m/s)
- Q: Total discharge; flow (m/s)

F: Area of the cross-section of the flow-channel (m^2)
K: Hydraulic conductivity (m/s)

Formula (3) may be simplified, if ρ and η remain constant:

$$q = K \times I; \qquad (5)$$

This is an expression of the <u>Darcy's</u> law, the basic formula for the groundwater-flow (see Fig. 10).
The most important hydrogeological parametres of the rocks are then:
1) The intrinsic (or specific) permeability: The specific ability of the rocks to conduct a fluid. This is a quality of the rocks alone. It can hardly be measured, in any case in the nature, but must be calculated from the hydraulic conductivity.
2) The hydraulic conductivity: The ability of the rocks to conduct a fluid with a certain viscosity. It is dependent on the properties of the rocks and the fluid together. It can be calculated from the transmissivity.
3) The transmissivity: The ability of rocks with certain dimensions (thickness) to conduct a certain quantity of fluid. It depends on the properties of the rocks and the fluid and the dimensions of the rock body. The transmissivity is the value measured or calculated directly from tests like pumping tests.

In geothermal hydrology there must be made a sharp distinction between the rock-parametre alone, the intrinsic permeability, and the rock-water-parametre, the hydraulic conductivity. This is as a rule not necessary in the "cold-water"-hydrology. This distinction appears therefore not always clearly in hydrological literature.

In "coldwater-hydrology" formula (5) is preferred, but in geothermal-hydrology neither the specific weight (ρ) nor the dynamic viscosity (η) remains constant, when the temperature of the water changes. At 20°C is ρ = 1,00 (g/cm^3) but at

100°C is ρ = 0,96 (g/cm^3) (see Fig. 11).
The changes in viscosity are much greater: at 20°C is η = 1,002 cP, at 100°C is η = 0,28 cP and at 370°C is η = 0,06 cP (liquid water) (see Fig. 12).

As the velocity and/or the discharge increases with decreasing viscosity, the hydraulic conductivity (K) in a geothermal aquifer can be one or two orders of magnitude (10-100 times) higher than in a "coldwater"-aquifer, although the intrinsic permeability (k) of both aquifers is the same.

5. AQUIFERS AND AQUICLUDES

Rock-bodies and geological structures may be classified according to their relative permeability:

High permeability:	<u>Aquifer</u>
Low permeability:	<u>Aquitard</u>
Very low permeability:	<u>Aquiclude</u>
No permeability:	<u>Aquifuge</u>

In most cases only the relative distinction between aquifers and aquicludes is relevant, and used. The aquifers represent then the flow channels with their relatively high permeability and the aquicludes the "walls" and barriers between the flow channels. In some cases this can be an oversimplification, i.e. where the tardy flow through a low-permeability aquiclude may contribute materially to the geothermal flow. In such cases the term "<u>semi- permeable</u> is often used.

In common use the aquifers are the groundwater-conductors, constituting the flow-channels, whereas the aquicludes (and aquifuges) constitute hydrological barriers, limiting the flow channels (see Fig. 13).

An aquifer, which is everywhere open to atmoshperic pressure, has a <u>free surface</u> and is <u>unconfined</u> (see Fig. 14). The potential gradient in such a water-body is approximately equal to the gradient of this surface, i.e. the gradient of the water-table. An aquifer, which is closed from the atmosphere by an aquiclude is a <u>confined</u> aquifer and has a <u>piezometric</u>

surface, i.e. the approximate elevation of the water table in wells, which were connected with the aquifer. The potential gradient is then approximately equal to the gradient of the piezometric surface. A water-body that lies above the groundwater-body (as a rule lying on a aquiclude) and is not connected with it is called perched water.

6. HYDROLOGICAL PROPERTIES OF ROCKS

The groundwater flows through the interconnected voids or openings in the rocks. The ratio of the total voids-volume and the total volume of the rock is the porosity of the rock. There is no simple relation between the porosity and the ability of the rocks to conduct or transmit water, i.e. their permeability (see below) (see Fig. 15).

The volume (space) of the interconnected voids and openings only is the effective porosity, which is always smaller than the total porosity. In lava, and other massive rocks, the vesicules in the rock-mass are ineffective. In clays, shale and other very fine grained clastic rock the adhesive forces in the finer pores rend them ineffective. In such cases the effective porosity is often only a small part of the total porosity. The inter-granular pores in clastic rocks are always small and even invisible. This porosity has therefore been termed microporosity. Tectonic fissures, shrinkage fissures, karstic cavities, openings in scoriae and at lava contacts on the other hand are normally of greater extent, and well visible, and have therefore been termed macroporosity. Porosity, genetically related to the rocks, (intergranular pores, shrinkage fissures etc.), can be termed primary porosity, whereas porosity obtained later on can be termed secondary porosity. The use of those scientific terms in literature is somewhat diffuse and individual. It must therefore in any case be clearly defined how they are used.

The water-conductivity of the rocks depends on the permeable voids. These are of two different kinds: Pores and fissures. Accordingly the rocks can be divided in porous rocks and jointed rocks: Most porous rocks are also jointed. Some fissures are of tectonic nature and younger than the rocks themeselves. The whole space in the voids can be termed porosity. Only interconnected voids, that allow an unbroken flow through the rocks have an effect on the groundwater-flow (see Fig. 16).

The flow of groundwater through the pores has a strong analogy to the flow through a cylindrical capillary:

$$Q = \frac{\pi}{8} \times \frac{1}{\pi} * I \times r^4; \qquad (7)$$

r: Radius (½ diametre) of the capillary (m)

Other signs see formulas (2) - (4)

The only parametre in this formula related to the rock is the width of the pores. As the number of pores generally increases proportional to the decrease of the width of the pores, the ratio of the number of pores in a cross section of two aquifers with different grain sizes is equal to:

$$N_1/N_2 = (R_2/R_1)^2; \qquad (8)$$
$$R_2 > R_1;$$

N_1, N_2: Number of pores
R_1, R_2: Radius of pores

By constant viscosity and hydraulic gradient, the discharge is then related only to the rock-parametre, it is the number and the width of the pores:

$$Q \propto r^2; \qquad (9)$$

There is as a rule a good correlation between the pore-size and the grain-size of a clastic rock. Their ratio is yet not direct proportional, the pore-size decreasing less than the grain-size, when the rocks are finer grained.

As the pores are no true cylindrical tubes, but more or less angular and twisted between and around the grains, the deviation from the cylindricality must be taken into account with a geometrical corrections-factor, C. This constant is varying from rock to rock, but is a rock-parametre of the permeability, that thus can be expressed approximately as:

$$k = c \times d^2 \qquad (10)$$

d: Mean diametre of the grains in the rocks (m)

c: Geometrical corrective

From formulas (7) - (9) it is then clear, that

$$Q \propto c \times d^2; \qquad (11)$$

The flow through a fissure has strong analogy to the flow between two plates:

$$Q = \frac{2}{3} \times \frac{1}{7} \times I \times D^3; \qquad (12)$$

D: Distance between the plates (m) (see Fig. 17).

If the total width of the fissures is the same percentage of the width of the flow-channel, then the discharge through the fissures is the greater the fewer - and wider - they are. The narrower the fissures are, the more numerous are they and the more fractured appears the rock to be. It is therefore somewhat paradoxical, at the first instance, that the rock is the less permeable. A coarse jointed lava or an intrusive (shrinkage fissures) can therefore easily be a far better aquifer than a fine jointed one; on a scale big enough, indeed.

Any metamorphization reduces as a rule the permeability of the rocks. Formation of clay or other secondary minerals can fill pores, cracks and fissures. Sedimentary and pyroclastic rocks are more prone to alteration than the massive igneous rocks, because of the much greater surface of the grains (see Fig. 18).

They can therefore form dense aquicludes in permeable strata. On the other hand, the available space is much greater in those rocks (see above), so that a fissure-filling of 1% total rock-volume may completely close a lava-bank, while a filling of 10% total rock-volume may reduce the permeability of a pyroclastic layer only 50-75%.

7. PERMEABILITY OF ROCK - TYPES

Clastic rocks are porous. Sedimentological parametres influencing their permeability are grain size, degree of sorting (distribution of grain sizes), angularity of the grains and the degree of consolidation and cementation. The higher the last named degree is, the less space is left for the intergranular voids and the less is the permeability. As the sedimentary/clastic rocks become the better consolidated the older they are and the deeper they have been buried, it is a general rule, that rocks of the same kind becomes less permeable with age and stratigraphical depth. Pores are bigger relative to the grains, when the grains are angular, than when they are well rounded. Many pyroclastics, fanglomerates etc. have a high angularity, while fluviatile and littoral sediments (sandstones, conglomerates etc.) have normally well rounded grains. The high angularity of the rock in the former group is as a rule upset by their low degree of sorting. The pores are then filled with finer particles, which are abundant. Clastic rocks with rounded grains are usually well sorted. There are, of course, exceptions from all rules.

The grain size is by far the most important factor. A coarse sandstone may have permeability ranging 10^{-3} - 10^{-6} m/s, while shales and siltstones may have permeability as low as 10^{-6} - 10^{-10} m/s. (The permeability is here corresponding to the hydraulic conductivity. The corresponding values for the "intrinsic permeability" would be 10^{2} - 10^{-1} darcy respectively 10^{-1} - 10^{-5} darcy) (see Fig. 19).

Igneous intrusives (plutonic rocks) and metamorphites are massive rocks, without a notable microporosity. They always have some macroporosity, often of secondary nature, in form of joints, shrinkage planes and deformation planes. Their permeability is very low, 10^{-8-} - 10^{-10} m/s, and they may generally be classified as aquicludes.

Of the volcanic rocks many acid and intermediate rocks resemble the plutonic ones in their primary porosity. They can also be strongly jointed and then have a much higher permeability. This is often of secondary nature. Basalts, especially in stratified lava-sequences, have often a very high permeability, resulting from high amount of scoria on both sides of the layer, and from intense jointing (shrinkage joints and tectonic fractures). The lavas are often intermingled with pyroclastics. These can be good aquifers, when well sorted and loose at the earth surface, but consolidated or in a strata-sequence they generally act as aquicludes. Despite their lack in permeability, they can be interesting because of their high storage coefficient (approximately corresponding to the effective porosity) compared with the massive lavas. The value for the former can be as high as 0,2-0,3 (20 - 30%), while the value for the latter is only 0,01-0,1 (1-10%).

Only few rocks are really homogeneous in composition and structure, but this is indeed a question of the scale. A cube of 1 m size might thus be quite homogeneous although a cube of 10 m size of the same rock could easily be heterogenous. This is especially important in clastic rocks, where sand lenses, conglomerate beds, clay horizons etc. may cause hydrological inhomogeneities. In strata sequences the thinning out of beds, unconformities etc. also cause inhomogeneities, a phenomenon that is often present in volcanic series (see Fig. 20).

All stratified rocks are to some degree anisotropic. The permeability in the strafification plane (bedding plane) is normally uniform and isotropic, but the permeability perpendicular to this plane is most often different, less, as a rule. The contact plane of different beds is often a physical discontinuity, i.e. a horizontal opening, with the effect of a narrow fissure, increasing the permeability of the rock in the stratification-plane. Beds or zones with low permeability are normally parallel to the stratification-plane. There is a certain analogy between the well-known laws about parallel and serial connected electrical conductances (: reciprocal value of a resistance) and similarily connected hydrological conductances. In that case the parallel connection is analog to the flow along the stratification plane and the serial one to the flow perpendicular to this plane. Then beds with low permeability reduce the parallel permeability (in regard to the stratifcation plane) only proportionate to the ratio of their thickness to the total thickness, whereas the decrease in the perpendicular permeability is much stronger and quite aproportionate to this ratio. The permeability along the stratification plane is often 10-100 times higher than the one perpendicular to this plane. The contact plane or contact zone between distinct rock-types or beds is normally a discontinuity, often with some open spaces. Such contacts are therefore often water conduits and the most active parts of an aquifer. This is especially important in volcanic sequences, where the contact zone is often scoriacous and the contact "planes" very rough. Of course, such anisotropies are not restricted to single rock-bodies or strata-sequences, but occur also on a regional scale (see also below).

8. TECTONIC HYDROGEOLOGY (SECONDARY PERMEABILITY)

Tectonics can influence the permeability of rock-formations very strongly, although the effect on the rocks themselves (as a grain -or mineral - assemblage) may be slight. The chief factors are fracturing and dislocations. The fractures are either tensional or compressional, the former ones leading to openings, and eventually some breccia - building, along the fracture plane or in the fracture zone, while the latter ones lead rather to closing of openings and formation of true mylonite, that is an aquifuge (see Fig. 21).

The most important dislocations are faults, tilting of the strata and folds. Faults are fractures and act in the same way. They also may cut off continous aquifers and thus act like a hydrological barrier. If a strata sequence, consisting of alternating aquifers and aquicludes is tilted in (or against) the direction of the groundwater-flow, the water may be diverted to the surface, or the strata sequence acts as a barrier (see also above). Tilting perpendicular to the flow-direction can lead to channeling of the flow. Folds act in a similar way. As the water flows most easily along the strata (the bedding planes etc) in a heterogeneous sequence, the direction of the fold-axis becomes a preferred flow-direction. The folds also can be "traps" for confined water, which can have a high pressure under such circumstances.

Tectonic features are regional phenomena as tectonic systems, and local as single features. Most tectonic systems are quasi-linear and can therefore create a strong hydrological anisotropy. The chief regional effects are thus channeling, chambering, through hydrological barriers and the anisotropy-effect. On a local scale, tectonics can also be very important. Open fractures or fracture systems are quasi-planar water-conduits normally with a predominant vertical direction. They can thus conduct confined or quasi-confined water to the surface. A hydrological barrier can have a similiar effect. Open fractures are indeed rare at greater depth than some hundred metres below the earth surface, except in regions of active tectonics, but in most cases a hydrological inhomogenity remains for a quite long time. In regions of active tensional tectonics some widening of joints may take place, although the effect is more often relatively slight. The compression of rocks (joints and other fissures) in corresponding areas is often of a somewhat more metastabile nature and can be preserved for a long time after the cessation of the tectonic activity.

The importance of the hydrogeological parametres changes with the perspective (see Fig. 22). For a good well (borehole) the permeability of the surrounding rocks is by far most important, regardless of the porosity and many other parametres. "Striking a vein" is a major aim in drilling a well. A good reservoir is characterised by a plentiful storage, i.e. a high storage coefficient and the corresponding volume. This is a parametre of the effective porosity, the extension of the reservoir and a sufficient total permeability of the system to conduct the required amount of water to the wells.

9. SOME ASPECTS OF GEOTHERMAL HYDROLOGY

Every geothermal system has a heat source (regional heat-flow, magmatism) and a groundwater source. Both are indispensable, but whereas the former one is primary and the ultimate cause of a geothermal systems, the latter one is always present in one way or other, its nature determining for a great part the nature of the geothermal system (see Fig. 23).

The heat content of the water may become so high, that it evaporates and ascends as steam the way of the least resistance to the surface. This is the case, when the heat/water ratio is especially high because of a strong heat-flow and/or a small amount of water. A "steaming ground" must therefore not necessarily mean a strong heat-source, it can also mean a lack of water. The pressure/density ratio is much higher in steam than in (liquid) water. The steam can therefore arise for greater vertical distances and against greater resistance (narrower channels etc.) than the water, but it is also much more strongly confined to the open channels (macroporosity) than the water. It appears at greater topographical heights than the water-outlets, but is also more indicative of fractures and similar hydrological inhomogeneities.

From the hydrological balance and flow path structure the geothermal systems can be classified as local or regional and with or without an offlow channel (see Fig. 24). These distinctions are based on various degrees of coincidence of the energy area, the catchment area of the water and the outlet area. In the local systems the water and the energy are originated from the same area, while the energy is accumulated into the flow channel in the regional ones.

In the cases of regional heat-flow the hydrological conditions are, that the vadose groundwater must be able to descend to such depths, that it can accumulate enough heat and then ascend to the surface without to great a loss of energy (see Fig. 25). Volcanotectonics and volcanism are hydrologically important.

Dykes and subvolcanic plugs can form hydrological barriers (dense rocks, small jointing or perpendicular to the flow) as well as flow channels (intense, open jointing, parallel "creeping-planes" in dykes). Calderas can form closed, or semi-closed, hydrological basins. In almost any case their strongly faulted boundary zones act as vertical channels and/or hydrological barriers. The heaping up of volcanic materials, as strata-volcanoes, mountain-clusters or ridges, results in topographic heights, commonly with a higher precipitation than the surroundings and a relatively high water-table, diverting the flow outwards.

Topographic features are also important, where the heat-source is connected with volcanic acitvity. Volcanic mountains generally have a higher rate of precipitation than their surrounding. The rocks at the surface are generally young and often highly permeable, so that infiltration can be strong, although the run-off is so also, because of the steep topopraphic gradients on the mountain-sides. Such a mountain-system can therefore have a relatively high groundwater-table and an outwards directed hydraulic gradient. Natural outlets of hot water normally lie in topographic depressions or on the lower slopes, except where hydrogeological structures (fractures, aquifers) direct the water to a higher lying outlet.

Such conditions are i.g. present in the big tectonic grabens (Rhine-graben, etc.), where the graben is filled with relatively young and little consolidated sediments, allowing a slow descendance of the ground-water, and where the fracture-zones on both sides enable the hot water to ascend in semi-closed channels, the reduced density of the hot water being the driving force of the ascendance (see Fig. 26).

In Iceland the situation is somewhat different. The hydraulic gradient of the country-wide groundwater body is generally directed away from the central region of the island towards the coast, thus adding a strong force to the groundwater-flow at depth. The Tertiary and Lower-Quaternary volcanics are generally well stratified with a strong vertical/horizontal anisotropy, resulting in confined or semi-confined aquifers reaching for long distances. The dip of the strata may lead to channeling of the flow, thus governing the flow-direction. Similar effects have the numerous quasi-linear fault systems and volcanic dykes, that create a very strong anisotropy and/or flow-channels. The same forces are essentially at work in the active volcanic zones, with the difference that the permeability of the aquifers is generally much higher and the anisotropical effect of the tectonics and volcanotectonics stronger, although the high permeability of the aquifers may upset this effect, at least partially (see Fig. 27). The location of natural outlets (hot springs) are, at least partially, influenced by topographical features, the deep incisions of lowlands, valleys and fjords cutting the piezometric surface of the confined or semi-confined hot water system (see Fig. 28).

The thermal water or steam intended for utilization is generally obtained from drilled wells, i.e. boreholes, as they concentrate the natural output and also allow for geothermal mining. Such a borehole is a spatial figure of quasi-linear dimension. Cutting through a punctual, linear or planar spatial figure and aquifer, or the boundary plane of an aquiclude (above) and aquifer (below) the cut always appears on this (quasi-) linear borehole as a (quasi-) point. This has led to the common phrase of "striking a vein" in analogy to medical remedies of the middle ages. "Vein" as a quasi-linear spatial aquifer is indeed very rare in the bedrock. This expression is thus a physical nonsense and a phrase, that has caused much confusion and innumerable errors in borehole hydrology, but it is very common in use, and does not need to bother anybody, if its real and true meaning is known. The most common "veins" are in reality (quasi-) planar conduits or boundary-planes between aquicludes/aquifers.

A pumped well is an artificial feature, superposed on the natural groundwater-body (see Fig. 29). It is in some sense a punctual and negative potential source. Its potential gradient is very steep near to the pump (and along the flow channel of the borehole) although declining rapidly with distance into the rock-bodies. The flow towards the pump is wholly unnatural and neither in harmony nor in phase with the natural ground water flow. The flow lines are totally changed and the response of the aquifer on the flow can be totally different to the natural flow. Drill mud and cuttings can change the conditions of the rocks in the walls of the borehole. A fine-grained aquifer, or one with narrow fissures, can be totally tightened off in the course of drilling. On the other hand an open channel can appear as a big "vein" for a time, although of limited extensions, especially because of the extra pressure on the water while drilling.

Thus artificial as well as natural factors can limit the exploitation of a geothermal field (see Fig. 30). The permeability of the rocks surrounding a well is limiting as is the quantity of the available water. The same applies to the construction of the well itself. The yield of a reservoir is limited by its storage, the present quantity of water and by the structure of the flow channels. The optimal efficiency of its exploitation is dependant of the siting of wells, their construction and the pumping. In the long run the hydrological balance of the whole geothermal system may be a limiting factor.

The perspective is also dominant in the differing aspects of the geothermal - hydrological objectives (see Fig. 31). The economically dominant aspect of a well is its yield (energy and water), the potential of the reservoir and the long-time balance of the whole system. This can be tested in the case of the well, must be calculated for the reservoir but can only be evaluated for the system. Correspondingly the mode of information changes from descriptive to theoretical.

10. HYDROLOGICAL SURVEYING

The aim of geothermal exploitation is to get as much water/energy as possible, of the best quality, at the optimal site and at the lowest costs.

This necessitates always a thorough research of the natural conditions, including a hydrological survey. The question of such a research is a quantitative one, in regard of utilization. This means, that all parametres must be brought as far as possible on a quantitative form, although their nature is a qualitative one. This transformation of parametres is a delicate action, necessitates a thorough understanding of the involved facts and sciences and is absolutely a task for the hydrological/hydrogeological specialist.

The mode of investigation (observation) changes with the perspective of the objectives. The parametres vary (transmissivity, storage, balance) as do also the available investigation methods and the mode of the presentation of the results (see Fig. 32).

The same applies to the observability of the hydrological and hydrogeological factors, they vary with the perspective (see Fig. 33). It is therefore very important to make sure that the scientists are communicating in the same "language," i.e. that they put the same meaning into the same term and are regarding the present problems from the same perspective.

This is perhaps most clear, when regarding the objectives from a regional and a local point of view. The methods are different, the parametres sought are also different, the presentation of objects is different but the terms used are the same and the ultimate goal of the investigation also (see Fig. 34).

The obtainable hydrological/hydrogeological informations are principally the shape of the groundwater-body, the distribution of potential in it, hydrogeological structure, flow-directions of the groundwater, hydrological balance in the form of an output - input relationsship (see Fig. 35). Further hydrological research and testing is possible, when some wells have been drilled, with the help of pumping tests, well-logging etc., but this will not be dealt with here.

The first step in the hydrological/hydrogeological survey is to establish the height of the piezometric surface. For this purpose a reconnaissance of all accessible surface water and water levels in wells must be done, as complete as possible. Perched water, and other occurences of a false water- or temporary water, must be identified as such. Then it must be taken into account, that the potential distribution in a confined (hot water-) aquifer at greater depths can be another than in the surficial groundwater. Surficial information of this kind is normally very scant. In connection with this water-table survey the input (infiltration) and output (run-off, outflow) of the areas in question must be estimated or calculated. When necessary, the water-table can be surveyed indirectly with geophysical methods, especially geoelectrical methods.

Chemistry, temperature and other physical properties of the surface/well-water can give valuable indications regarding its origin and flow patterns. Of course this is especially important for the surficial thermal water, but a survey of the "cold" water in the region is usually necessary for the correct understanding of the regional hydrology.

Geological mapping and profiling is necessary. The basic maps and profiles are done in the usual stratigraphical - lithological tectonic way. It is then the task of the hydrogeologist to transform this map into a hydrogeological one; usually inclusive some amount of field-work. Also here geophysical exploration can be of great value, although there informations are always indirect and interpretative and depend very much on the geophysicist's knowledge and understanding of geology and geological thought and to a not less degree on the experience of the geologists in physics and formular thought (see Fig. 36).

When these informations have been compiled, and the necessary results from the other fields of the geothermal research are also available, the research team can start trying to reconstruct the most probable water-supply-areas and flow-channels for the geothermal field, at this moment in a qualitative/semi-quantitative way (see Fig 37 and Fig. 38). These qualitative models or working-images must then be transformed into quantitative models. With them it is possible to evaluate the hydrological balance and the groundwater-flow in a quantitative way, to compare the different qualitative models and the many assumptions and estimates on which they are founded. Finally, such models enable the scientists to predict with some probability the effects of pumping from a well of certain dimensions at a certain location, and aid essentially to the election of a convenient site for the drilling of the bore-holes. Testing and logging of the boreholes always yield substantial information about the hydrological/hydrogeological system, although the aquiferial response may differ from natural conditions for various reasons and always must be interpretated carefully and in common by the hydrologist and the borehole-specialist. This new information can make a review of the hydrological model necessary. The same can happen in the course of exploitation.

11. THE HYDROLOGICAL - HYDROGEOLOGICAL MODELS

The role of the hydrological model is to represent at any time the current ideas (the human reflexion on the sensed and measured nature, in an abstracted form) about the geothermal system and the corresponding image of its hydrodynamic and hydrogeological structure. The model must be reviewed and corrected at intervals, as well during the stage of exploration as during the much longer stage of exploitation. How all various responses of the geothermal field/system to exploration and exploitation and how this model inevitably influences engineering and executive decisions in the adminstration of the geothermal field, will not be discussed here, but only reminded of.

A hydrological model of this kind can be said to consists of the interactive "hydrological bodies," as spatial rock-water-elements of the system, and the "hydrological field potential," as the driving force of groundwater movements (see Fig. 39).

The hydrologcial bodies have as properties a shape, permeability coefficients, anisotropy of permeability, storage coefficient, viscosity of fluid and the nature of their boundaries (hydrological boundaries etc.). Their theoretical (often hypothetical), construction is for the greatest part the work of the hydrogeologist, while the construction of the hydrological potential field is mainly the work of the hydrologist and the hydraulic engineer operating the model (see Fig. 40).

While in construction, such a model must incessantly be compared with the known (or assumed) data: piezometric surface, flow direction, quantity of flow, input-output etc. In the course of this comparisons the unknown or inaccurate data can be corrected on the base of the limits set by the model. This method leads of course not to the aim when a pair of parametres are formally interactive ($Q = f(k)$ etc.), but it must be kept in mind, that the model is never anything like reality, it is just an image of our opinions on the natural object, based on our incomplete knowledge and understanding. Nevertheless, a carefully constructed model usually represents the optimal quantitative approximation of the scientists ideas to the real nature (see Fig. 41).

From this brief description of the hydrological/hydrogeological survey and the construction of the corresponding hydrological model it should be clear, that the hydrologist/hydrogeologist in charge not only must know his own job well, but must also have a thorough knowledge of and some experience in quite many other fields of science: physics, geology, meteorology, mathematics, chemistry and geophysics. His is not an easy task, because he must communicate with the scientists from the other fields in terms and "language," that both sides really understand and on a reasonable scientific basis. Lacking this scientific all-round back-ground, there is only one way to get some grasp of complicated hydrological/hydrogeological problems: consult the specialist(s).

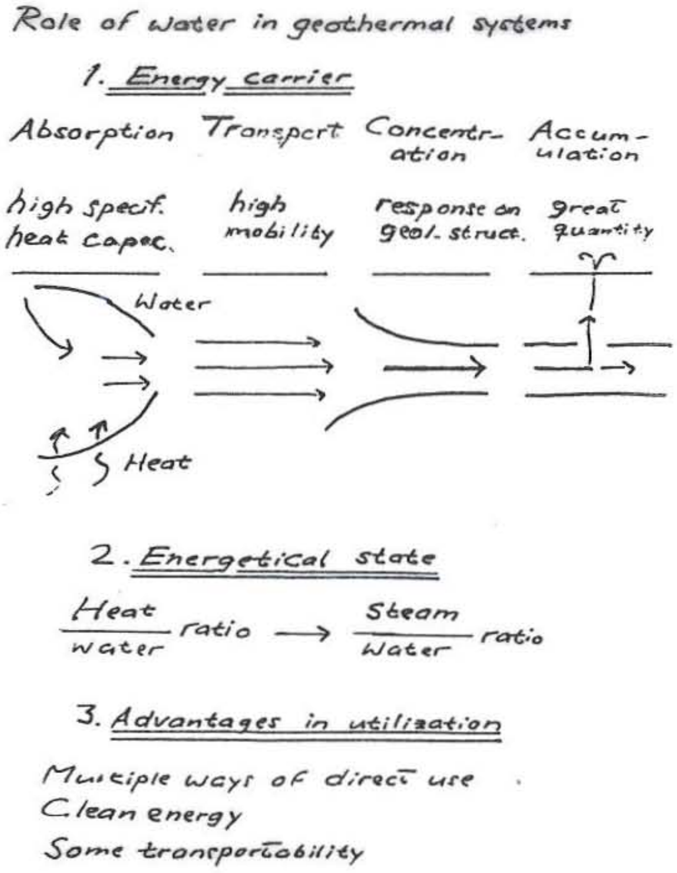


Fig. 1: Role of water in geothermal systems.
The physical properties of water distinguish it as an efficient medium for the transport of geothermal energy and its exploitation.

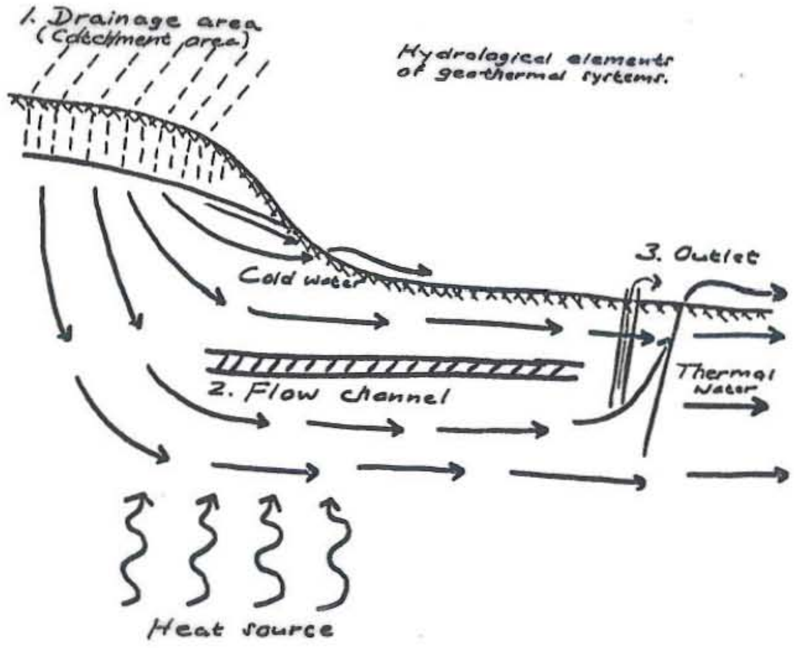


Fig. 2: Hydrological elements of geothermal systems.
Every geothermal system has a drainage area as source of water, a flow channel and an outlet to the surface.

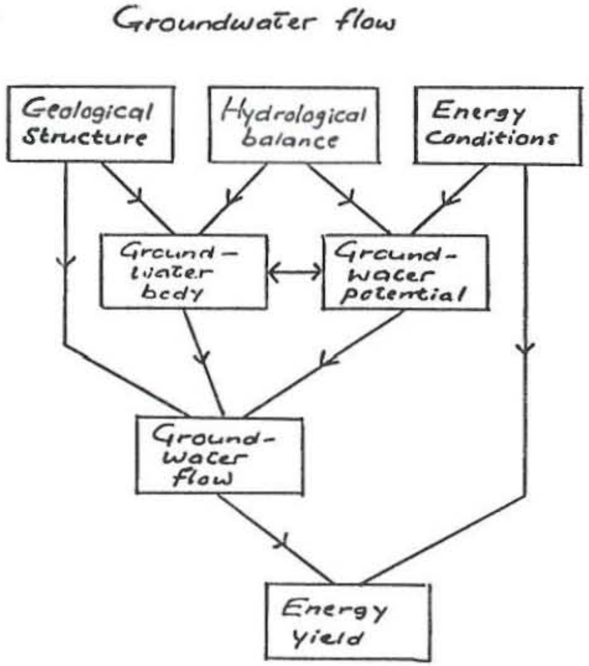


Fig. 3: Groundwater flow.
The groundwater flow depends on the geological structure, the hydrological regime and the energy conditions.

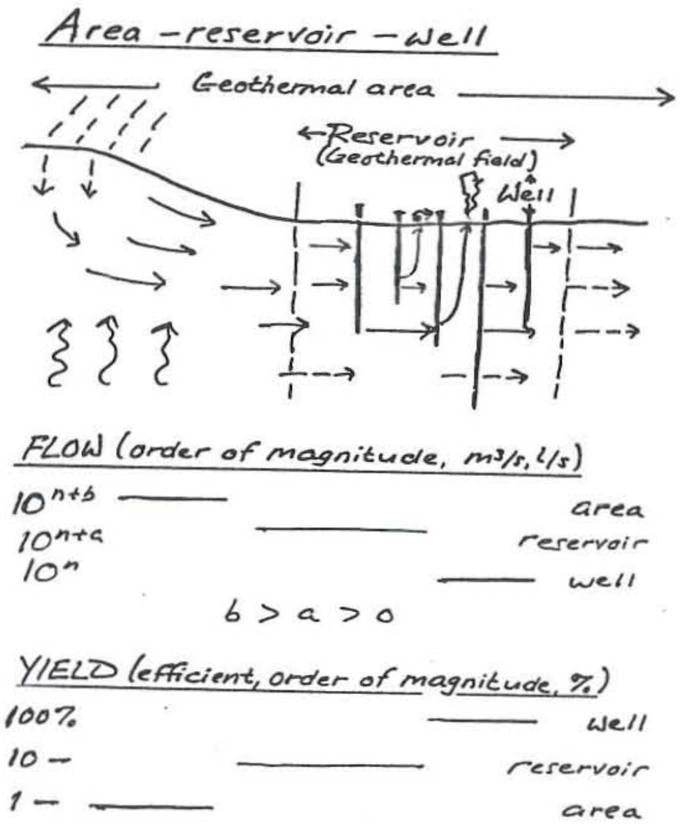


Fig. 4: Area - reservoir - well.
The importance of the various hydrogeological - hydrological factors varies with the perspective of the objectives.

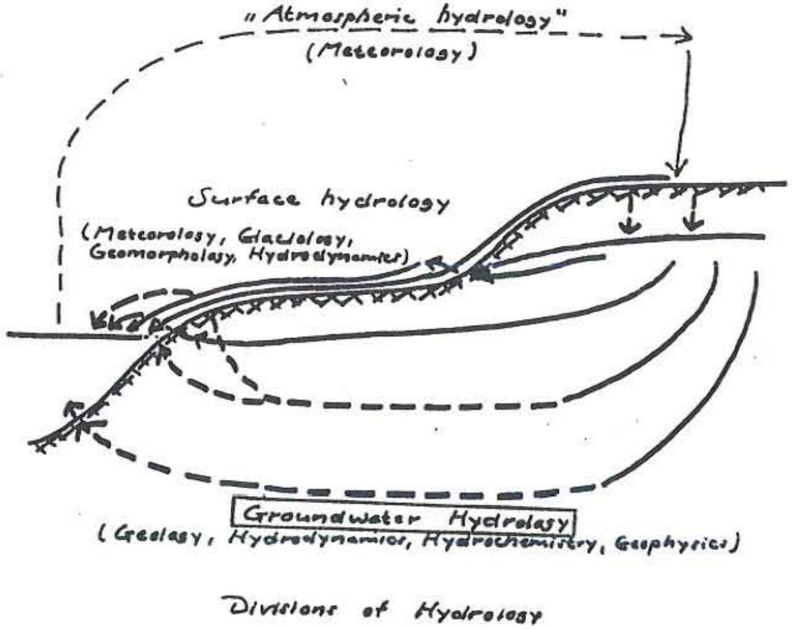


Fig. 5: Divisions of hydrology.
The groundwater hydrology is the most important branch of hydrology in the geothermal sciences.

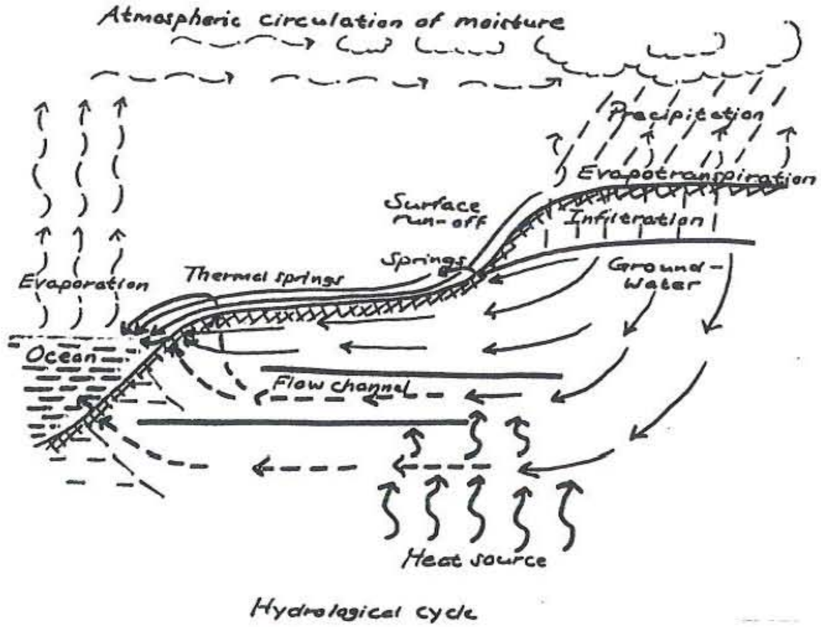


Fig. 6: Hydrological cycle.
The groundwater flow is the subterrean part of the hydrological cycle.

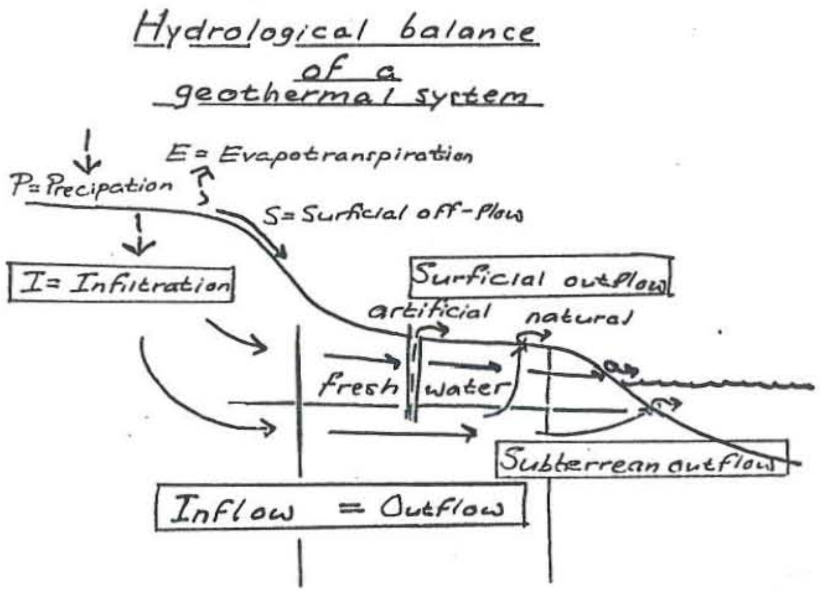


Fig. 7: Hydrological balance of a geothermal system.
The surficial outflow is the only observable part of the hydrological balance. The other parts must be calculated or estimated.

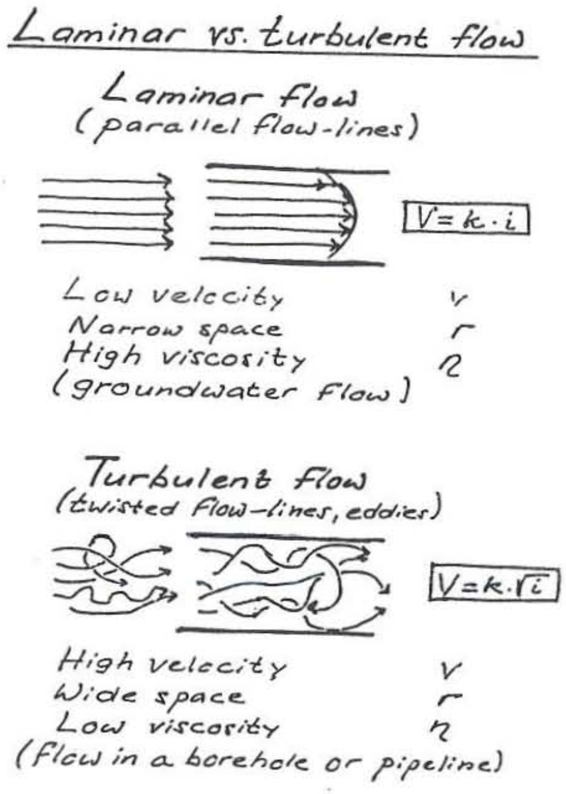
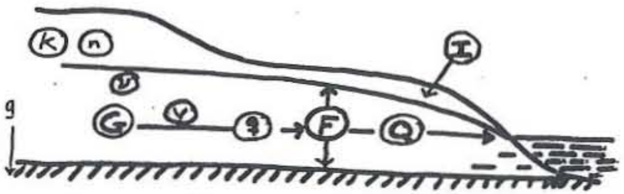


Fig. 8: Laminar and turbulent flow.
The natural groundwater flow is usually laminar but the artificial flow in a pumped wells is in most cases turbulent.

Laminar ground water flow:



$$q = k \cdot \frac{1}{\nu} \cdot I\, g; \qquad (1)$$

q : Specific discharge [m/s]
k : Intrinsic permeability [darcy; ≈ (m²)]
ν : Kinematic viscosity [St; (m²/s)]
I : Hydraulic gradient [–]
g : Gravitational acceleration [m/s²]

$$\nu = \frac{\eta}{\rho}; \qquad (2)$$

η : Dynamic viscosity [P; (g/cm·s)]
ρ : Density [g/cm³]

$$\rho = f_1(T); \qquad (3)$$
$$\eta = f_2(T); \qquad (4)$$
$$k \neq f(T); \qquad (5)$$
$$I = f(k, \nu, G); \qquad (6)$$

G : Rock and water conditions.

$$V = \frac{q}{n}; \qquad (7)$$

V: Mass velocity [m/s]
n: Effective porosity [–], always < 1.

$$Q = q \cdot F; \qquad (8)$$

Q : Discharge [m³/s]
F : Profile area of flow-channel [m²]

$$q = K \cdot I; \qquad (9)$$

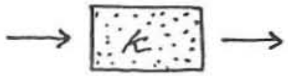
if (ρ, ν) are constant

K: („Permeability") Hydraulic conductivity [m/s]

Fig. 9: Laminar groundwater flow.
The viscosity of the water, the permeability of the bedrock and the potential gradient in the water are the fundamentals of the groundwater flow.

Intrinsic permeability (k)

is the ability of a rock to conduct fluid.



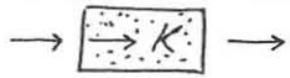
k : [d, darcy; md, millidarcy] ≙ 10^{-8} cm²

Hydraulic conductivity (K)

is the ability of a rock to conduct a certain fluid

$$K = g \cdot \nu \cdot k;$$

g : gravity acceleration

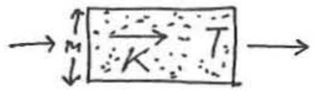


K : [m/s, cm/s];

Transmissivity (T)

is the ability of a rock/strata with certain dimensions to conduct a certain fluid.

$T = m \cdot K$; m: thickness, depth.



T : [m²/s];

Fig. 10: Hydrogeological parametres of the rocks.
The intrinsic permeability is a rock parameter alone, the hydraulic conductivity depends also on the fluid and the transmissivity then also on the dimensions of the aquifer.

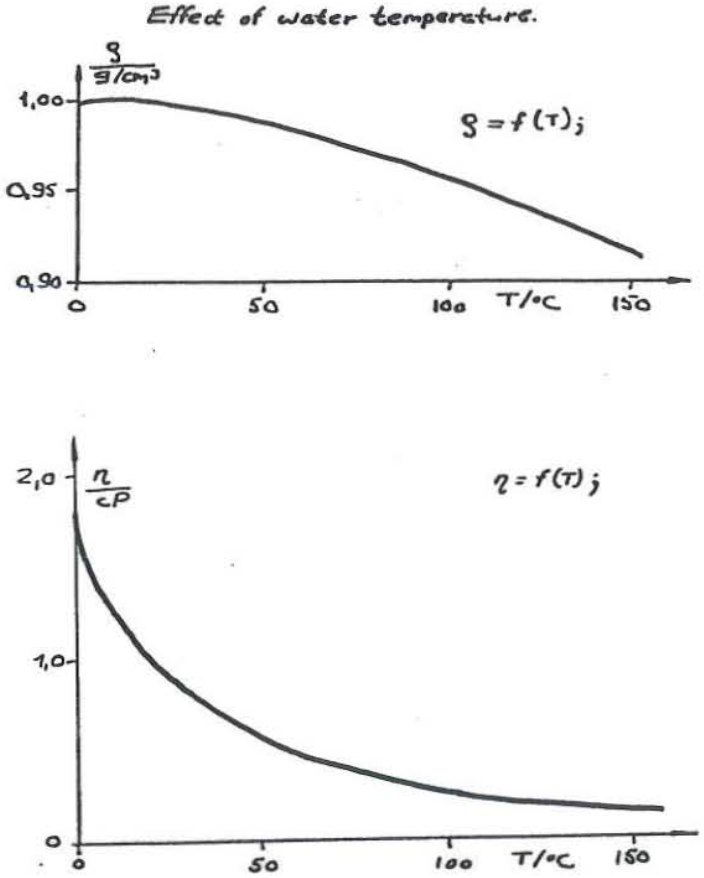
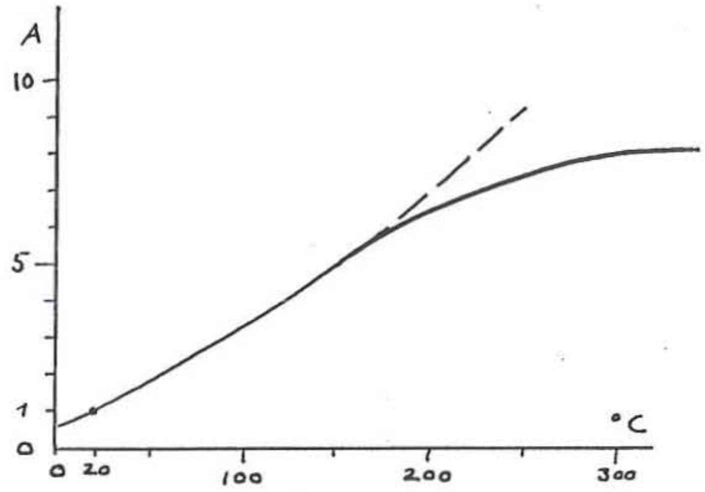


Fig. 11: Effect of water temperature.
The viscosity of the water decreases with rising temperature but the hydraulic conductivity increases accordingly.



$K = A \cdot 10^5 \cdot k;$

$K = \frac{\gamma \cdot g}{\eta} \cdot k; \quad \frac{\gamma \cdot g}{\eta} = A \cdot 10^5;$

K: Hydraulic conductivity [m/s];
γ: Density of water [g/cm^3] $\leq 1,0$;
g: Gravitational acceleration [m/s^2] $\approx 9,8$;
η: Dynamic viscosity [cP = 1/100 P]: $< 0,1 - 1,8$;
k: Intrinsic permeability [darcy];

1 darcy = 10^3 mdarcy $\approx 1,02 \cdot 10^{-8}$ cm^2;
1 d
1 darcy $\triangleq 10^{-5}$ m/s (20°C);

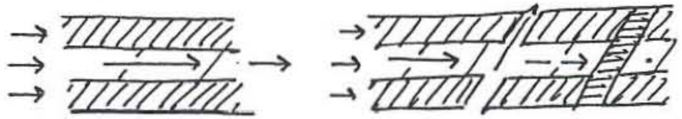
Fig. 12: Hydraulic conductivity as function of temperature.
The intrinsic permeability is a constant of the rocks, but the hydraulic conductivity depends also on the temperature of the water.

Aquifers vs. aquicludes

Aquifers are water conductors for groundwater flow.

Aquicludes are barriers for groundwater flow.

Flow-channels and reservoirs are systems of aquifers and aquicludes



„Veins" in boreholes are high-permeable aquifers

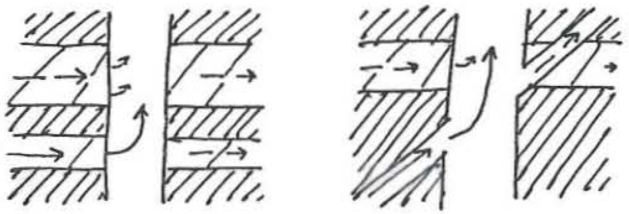


Fig. 13: Aquifers and aquicludes.
Aquifers transmit water, aquicludes close the groundwater flow off.

Types of aquifers

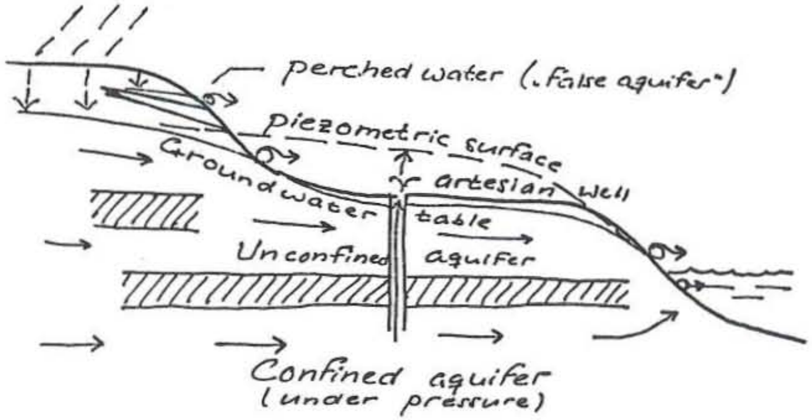
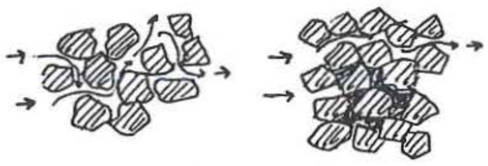


Fig. 14: Types of aquifers.
Aquifers open to atmospheric pressure are unconfined, closed aquifers are confined and usually with over- or underpressure.

Porosity and permeability

The water flows through the interconnected voids in the rocks, not through massive rocks or unconnected voids (pores).



All voids (pores) : Total porosity

Interconnected voids: Effective porosity

Permeability depends on

- effective porosity
- size of connected pores

not on

- total porosity
- size of unconnected pores (closed cavities)

Fig. 15: Porosity and permeability.
There is no direct connection between porosity and permeability.

Permeability of porous rocks.

Flow through a capillary:

$$Q = \frac{\pi}{8} \cdot \frac{1}{\eta} \cdot I \cdot r^4 ; \qquad (1)$$

Q: Flow (discharge) $[m^3/s]$
η: Dynamic viscosity $[m^2/s]$
I: Hydraulic gradient $[-]$
r: Radius of capillary $[m]$

$$\frac{N_1}{N_2} = \frac{R_2^2}{R_1^2} ; \qquad (2)$$

$$Q_1 \triangleq N_1 \cdot R_1^4 ; \quad Q_2 \triangleq N_2 \cdot R_2^4 ; \qquad (3,4)$$

$$\frac{Q_1}{Q_2} \triangleq \frac{N_1 \cdot R_1^4}{N_2 \cdot R_2^4} = \frac{R_2^2}{R_1^2} \cdot \frac{R_1^4}{R_2^4} = \frac{R_1^2}{R_2^2} ; \qquad (5)$$

$$Q \triangleq r^2 ; \qquad (6)$$

$$Q \triangleq c \cdot d^2 ; \qquad (7)$$

c: Geometrical corrective $[-]$
d: Diametre of grains $[m]$

Fig. 16: Permeability of porous rocks.
The width and wall resistance of the pores is the dominant factor in the permeability of the porous rocks.

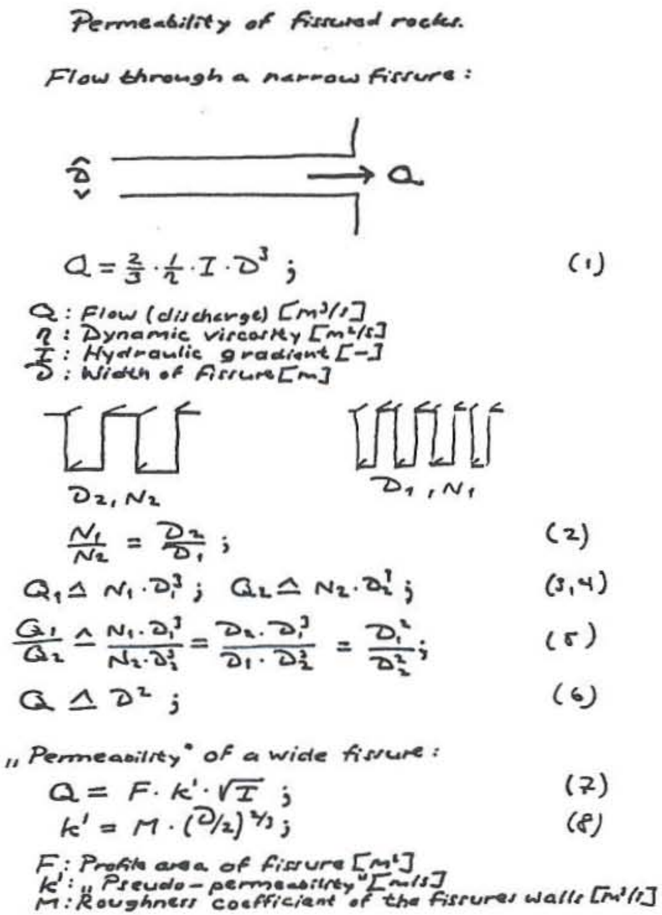


Fig. 17: Permeability of fissured rocks.
The width of the fissures and the roughness of their walls is the dominant factor of the permeability of the fissured rocks.

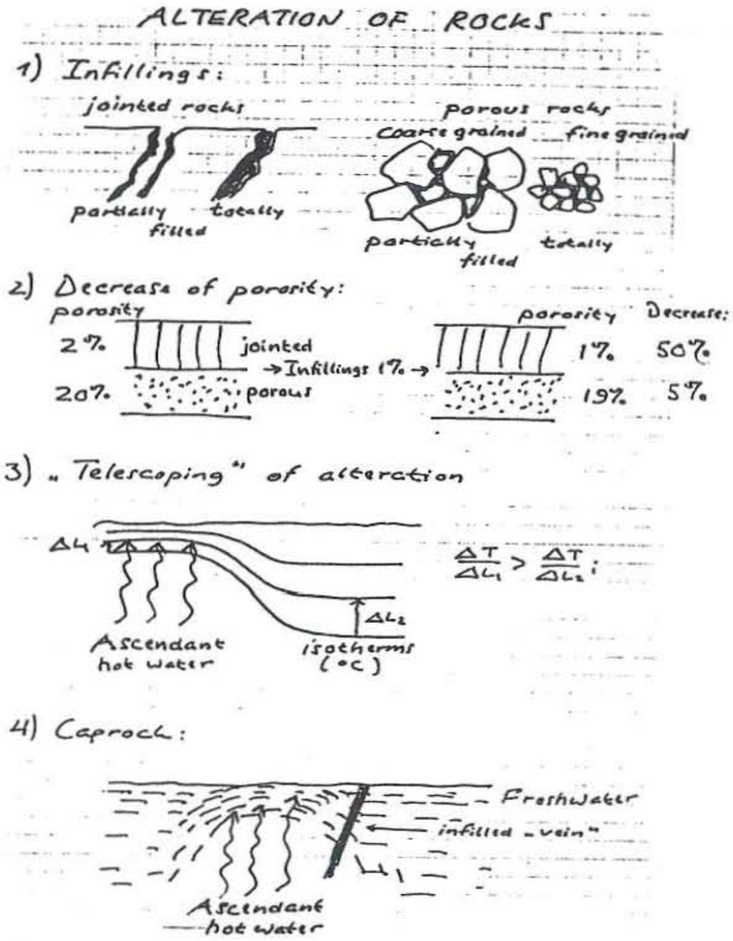


Fig. 18: Alteration of rocks.
Alteration reduces the permeability and the storage coefficient of the rocks.

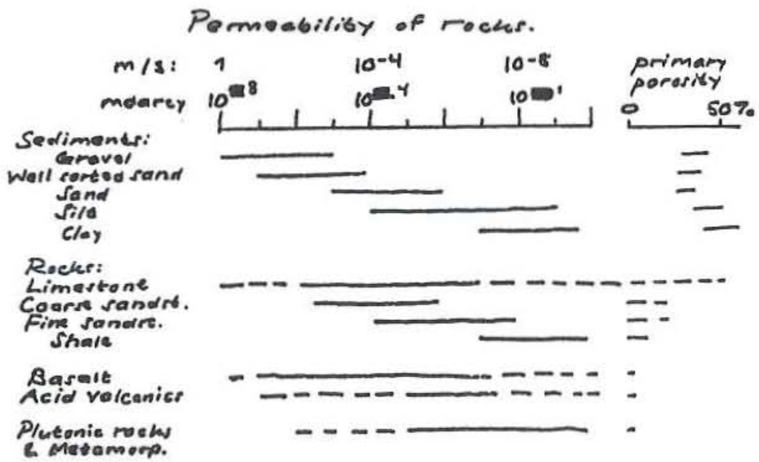


Fig. 19: Permeability of rock types.
The permeability of rocks of a certain lithological rock type is varying with facies, alteration, fracturing, structure and other factors.

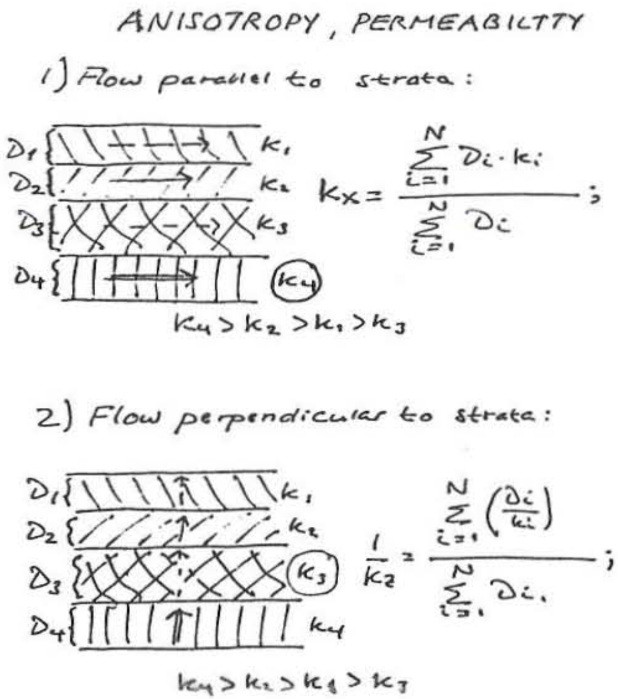


Fig. 20: Anisotropy of permeability.
The permeability is usually higher along the bedding planes than perpendicular to them.

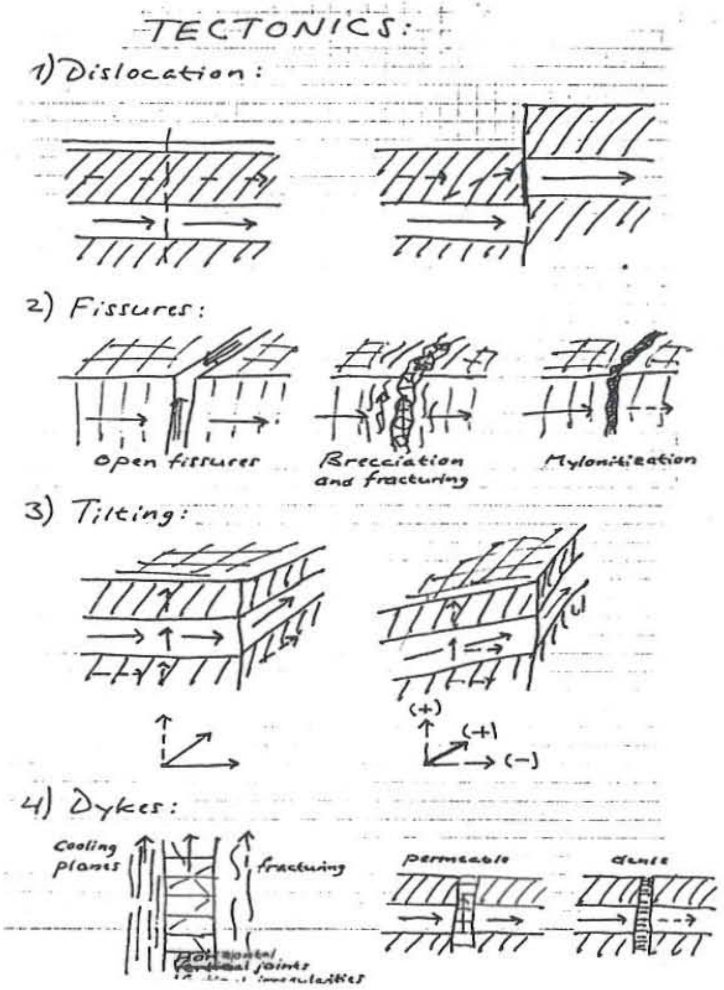


Fig. 21: Tectonic permeability.
Tectonics usually channel the groundwater flow and create an anisotropy, as well as providing for many "veins" in the aquifer.

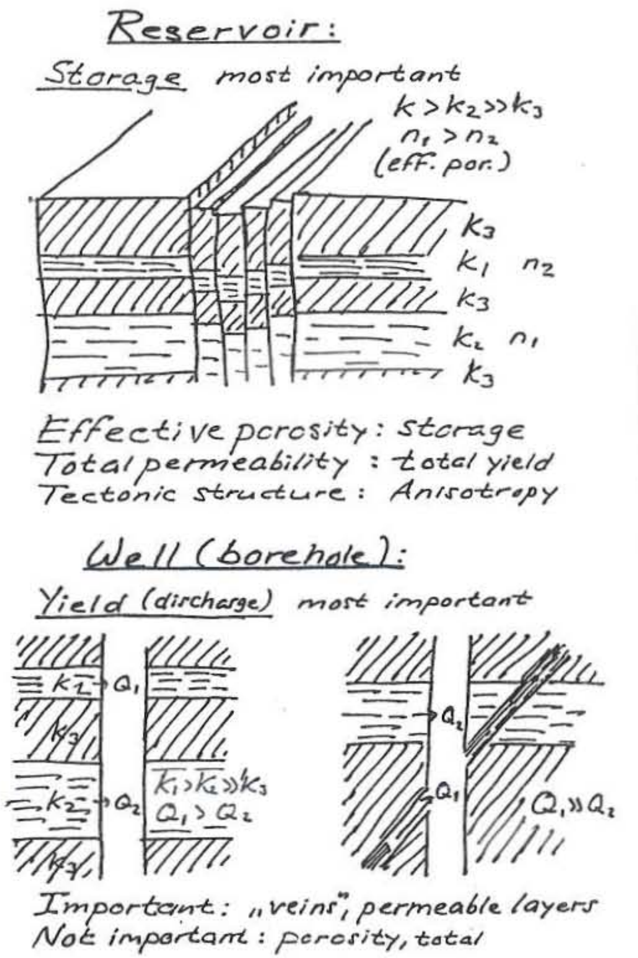


Fig. 22: Reservoirs and wells.
The storage is the most important parameter of the reservoir and sufficient permeable "veins" the one of the wells.

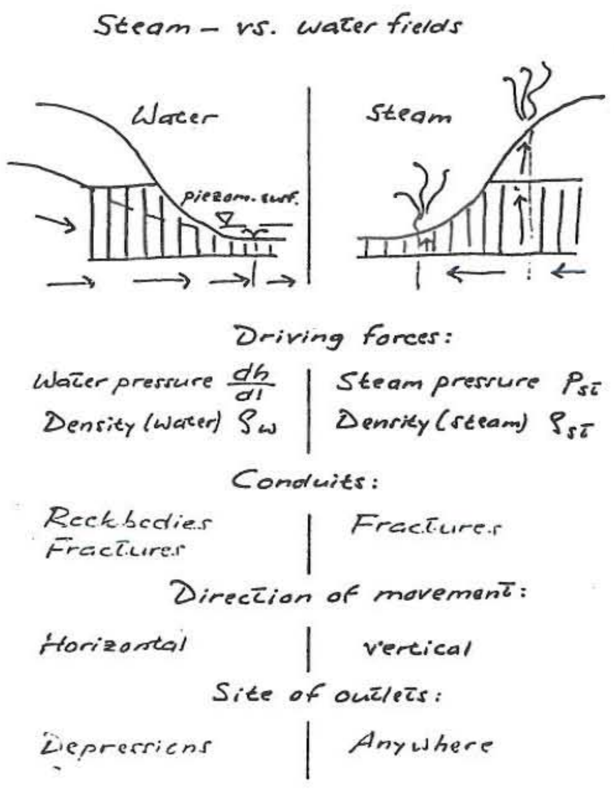


Fig. 23: Steam versus water fields.
The natural movement of the steam is essentially vertically but that of the water is more horizontally.

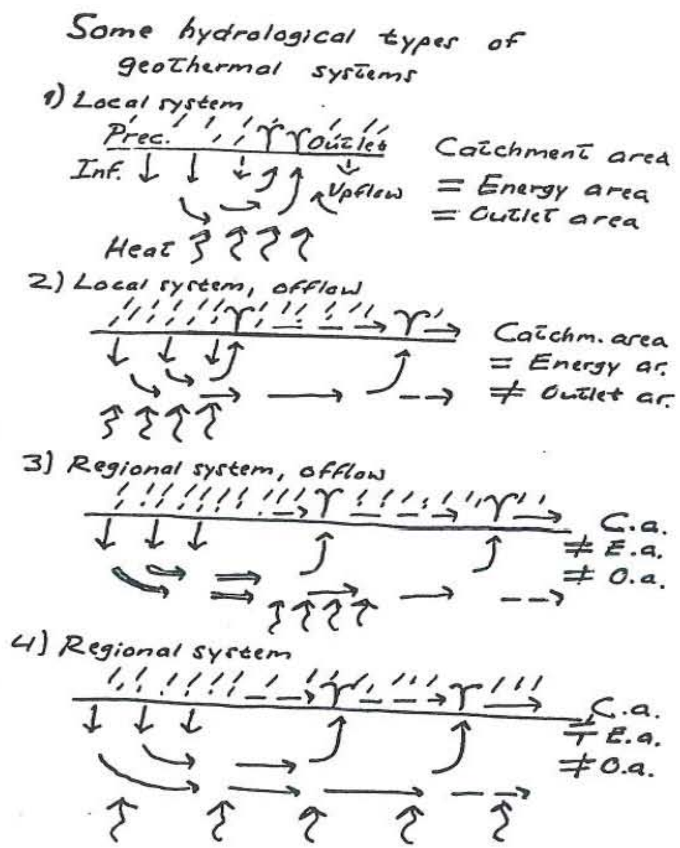


Fig. 24: Hydrological types of geothermal systems.
The coincidence of the catchment area, the energy supply area and the outlet area is varying.

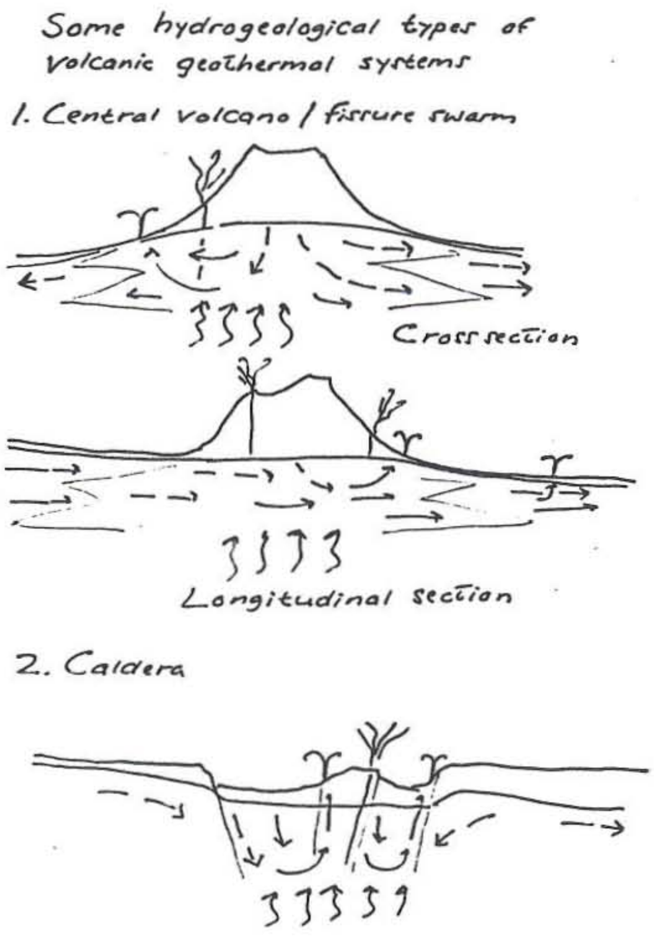


Fig. 25: Hydrological types of volcanic geothermal systems. The immediate presence of a magmatic heat source and the young volcanic rocks and tectonics characterize the volcanic geothermal systems.

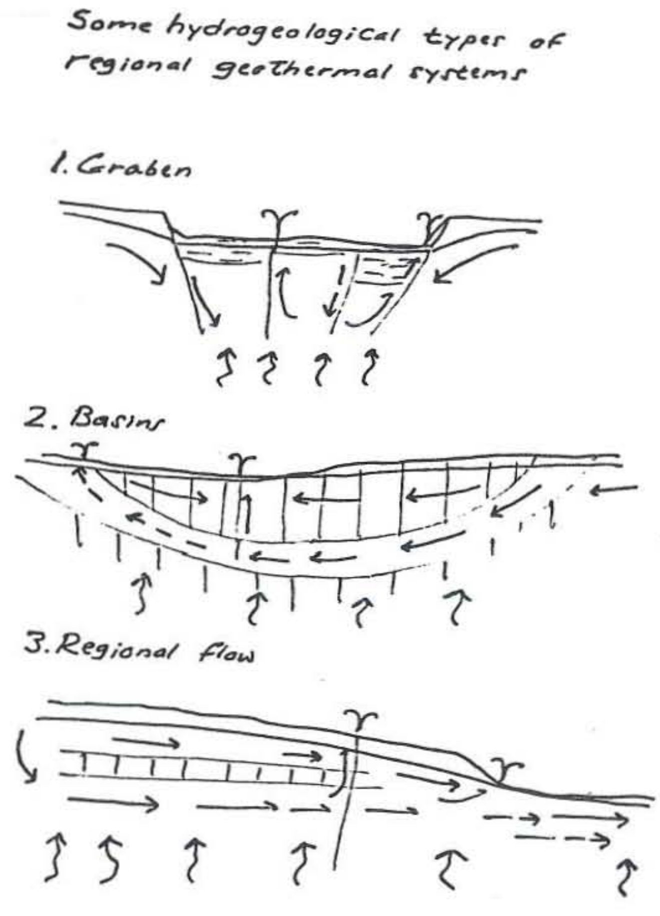


Fig. 26: Hydrological types of regional geothermal systems. A widely distributed regional heat flow and the great extension of the hydrogeological structures characterize the regional geothermal systems.

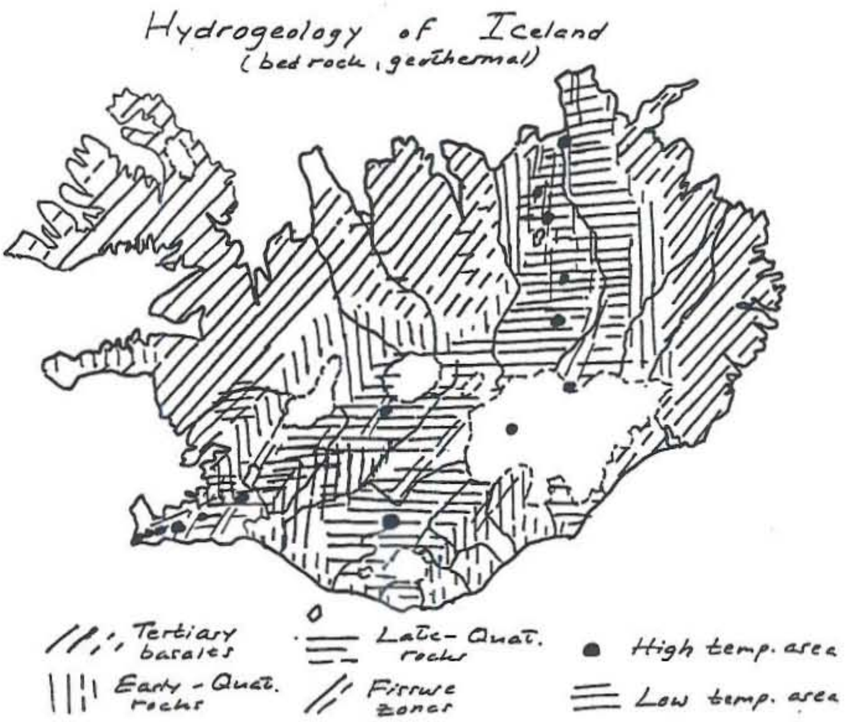


Fig. 27: Hydrogeology of Iceland.
Low temperature fields are prevailing in the Tertiary - Early Quaternary zones but high temperature fields in the volcanically active Late Quaternary zones.

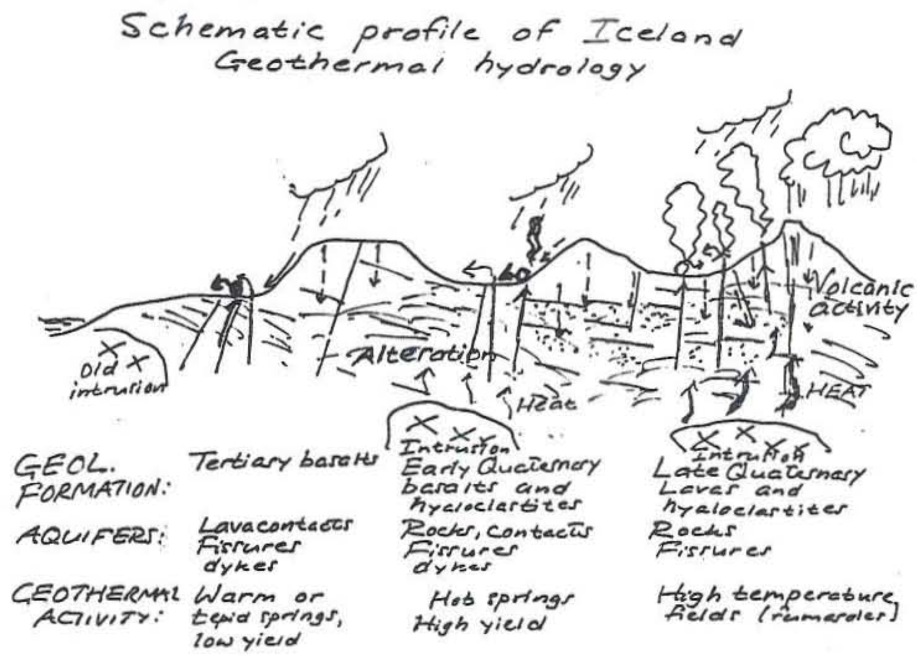


Fig. 28: Geothermal - hydrological profile of Iceland.
The intensity of the geothermal activity increases towards the volcanically active zones.

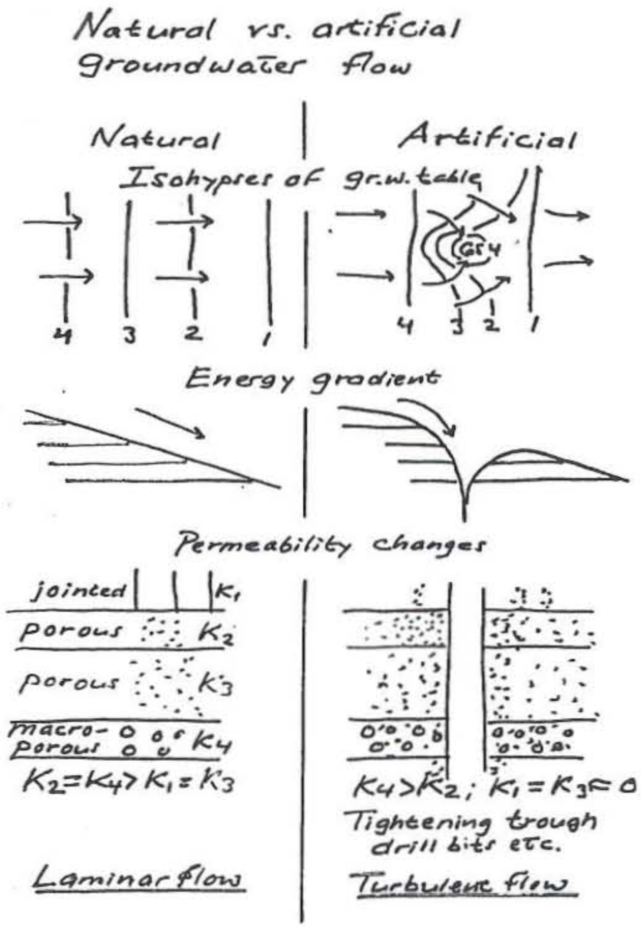


Fig. 29: Natural versus artificial groundwater flow. The drilling and pumping of wells is a drastic disturbance of the natural conditions.

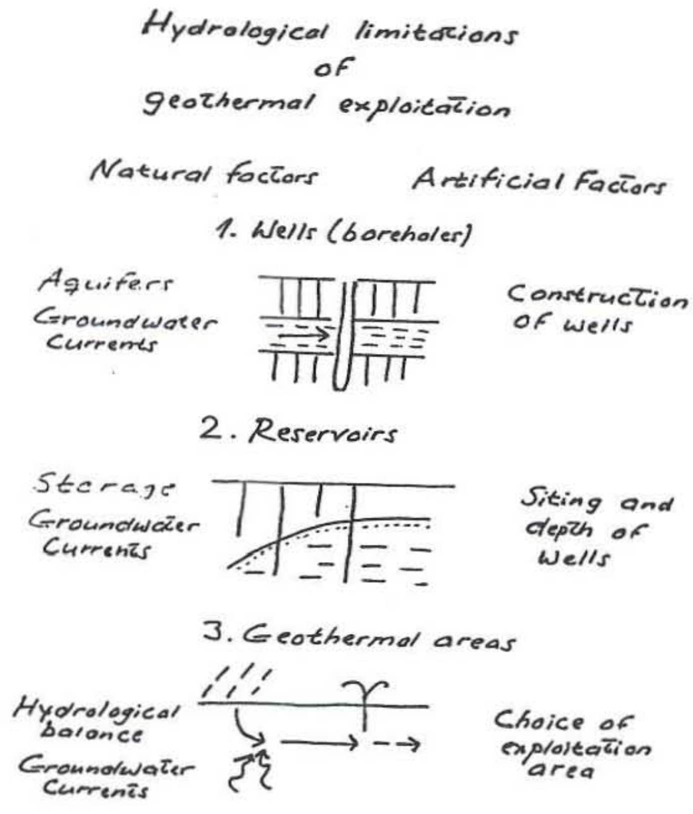


Fig. 30: Hydrological limitations of geothermal exploitations.
In addition to the natural limitations man-made constructions and decisions can have a limiting effect on the extraction from geothermal fields.

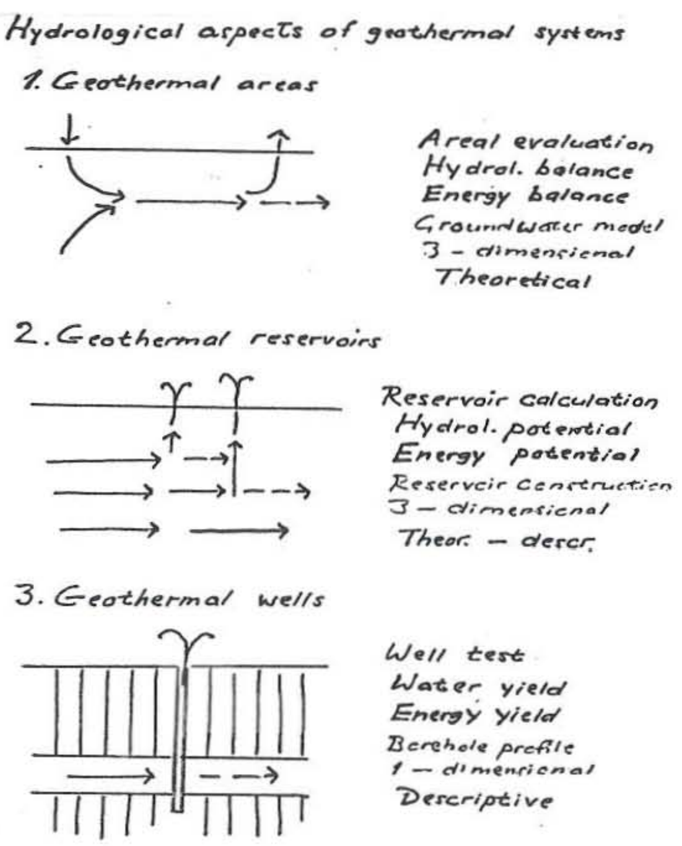


Fig. 31: Hydrological aspects of geothermal systems. A different perspective and scientific approach are necessary for the investigation of geothermal areas, reservoirs and wells.

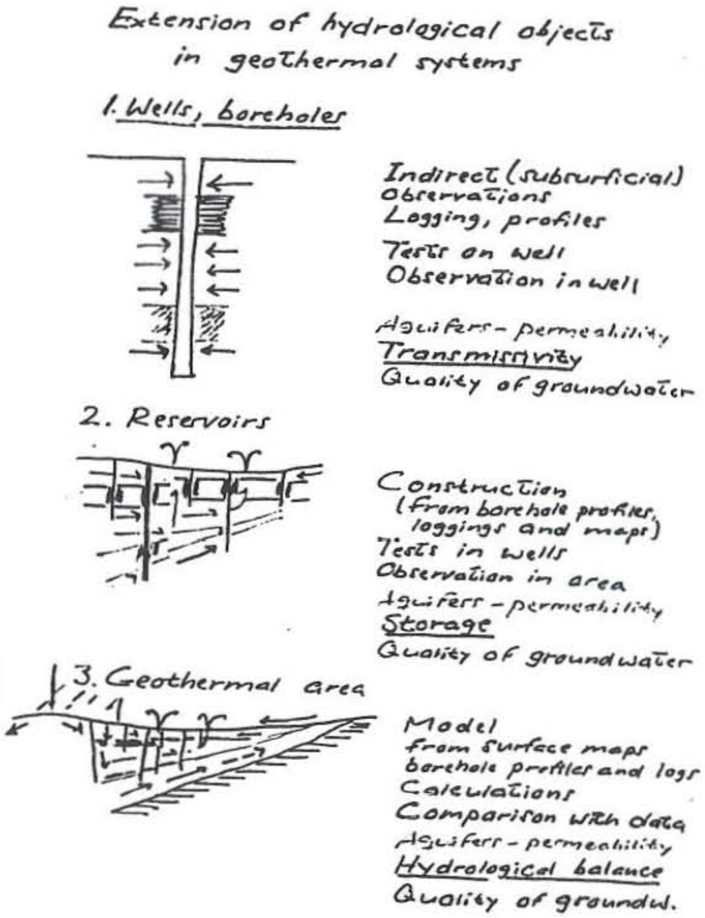


Fig. 32: Extensions of hydrological objectives. The desired information and the methods of investigation are different for wells, reservoirs and areas.

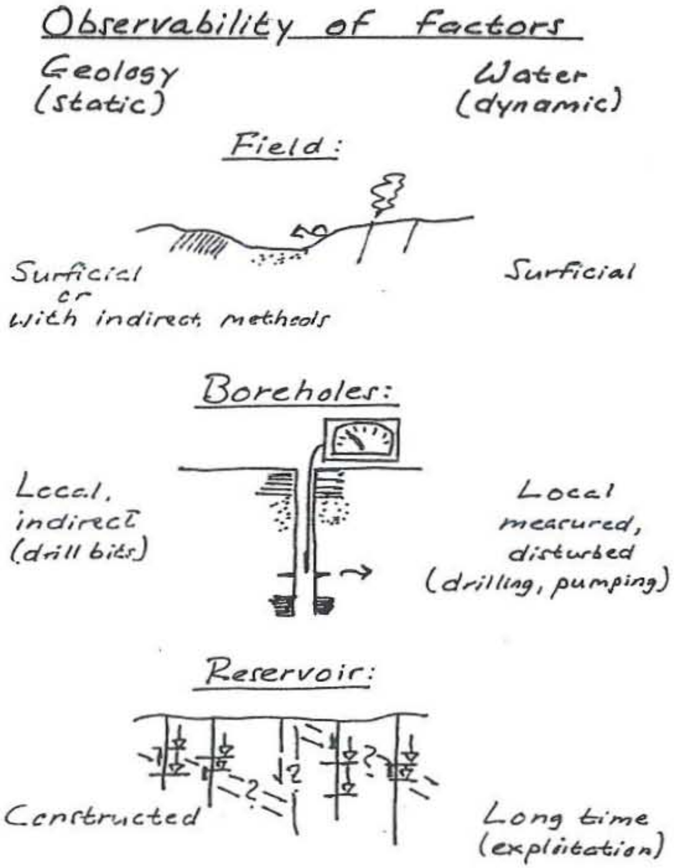


Fig. 33: Observability of factors.
The mode of access to the information is different for the different ways of scientific approach.

Regional vs. local investigation

	Regional	Local
	Extension	
	Area – reservoir	Borehole – reservoir
	Objects	
Site Hydrology Geology Conditions	Surface regime systems natural	Sub-surface yield Conduits artificial
	Methods	
Investigation Trial Description	Survey model maps	Logging tests profiles
	Scientists	
Hydrology Geology Geophysics	(field-) hydrologist field - geolog. field - geoph.	hydraulic engineer borehole - geolog. logging - geoph.
etc.	etc.	

Fig. 34: Regional and local investigation.
The regional survey mainly takes place on the nearly horizontal plane of the surface and the depths of space must be calculated or constructed, but the local tests and measurements are performed on the linear depth of the wells.

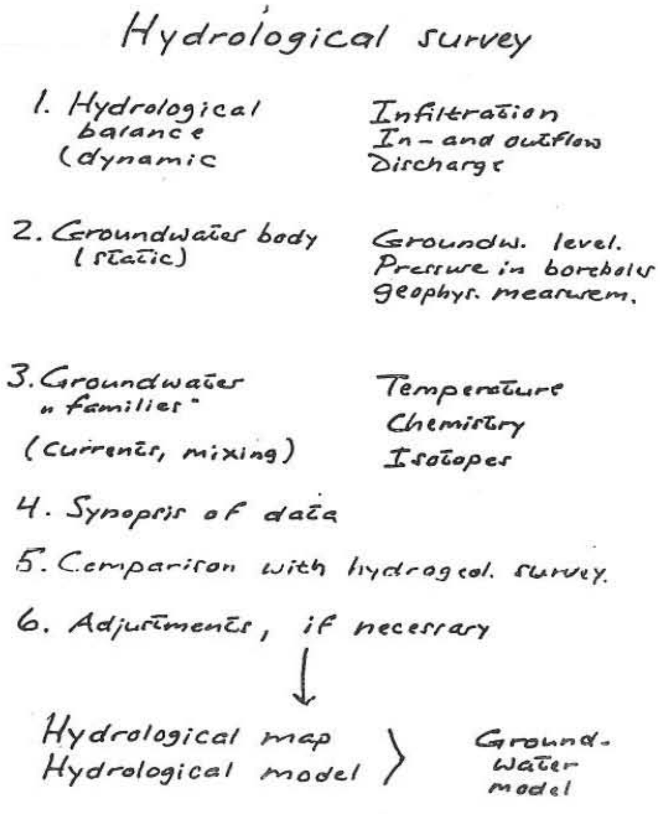


Fig. 35: Hydrological survey.
The objective of the hydrological survey is the shape and conditions of the groundwater body and its movements.

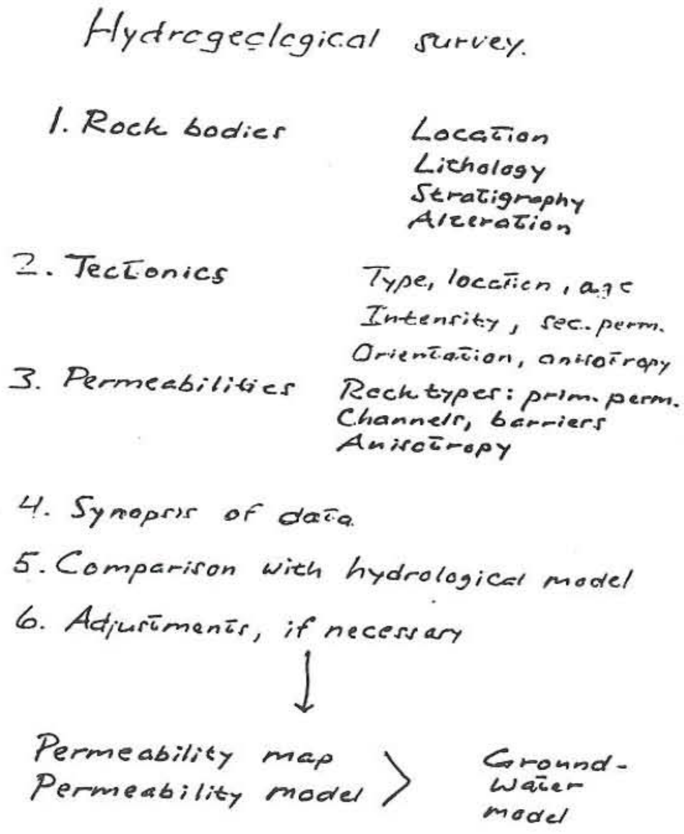


Fig. 36: Hydrogeological survey.
The objective of the hydrogeological survey is the natural arrangement of the rock bodies and the structure and nature of the flow channels.

Hydrological data:

Object:	Parameter:	Mode of observation:
Lakes, springs	Water level (Elevation)	Measured
Boreholes	Water level pressure	Measured
Climate	Infiltration (Precipation)	Calculated (Measured)
Rivers, wells	Discharge	Measured
All water (properties)	Temperature Chemistry	Measured Analysed

Presentation of hydrol. data:

Hydrological maps
— profiles
Profiles of boreholes
(temperature, chemistry
pressure, water level etc.)
Seasonal variations (diagrams)
Long time changes (—)
Tables

Fig. 37: Hydrological data.
The hydrological data represents the dynamic groundwater body.

Hydrogeological data:

Objects:	Parameter:	Mode of observation:
Aquifers, aquicludes	Permeability Porosity	Classified Measured
Alteration	Reduction of permeability	Analysed Classified
Tectonics	Secondary permeability, Anisotropy	Measured classified
Groundwater currents	Direction discharge	Estimated measured, calculated

Presentation of hydrogeol. data.

Hydregeological maps
— profiles
Profiles of boreholes
(rock types, permeabilities
porosities, alteration etc.)
Descriptions, classifications
Tables

Fig. 38: Hydrogeological data.
The hydrogeological data represents the more static rock bodies and structures.

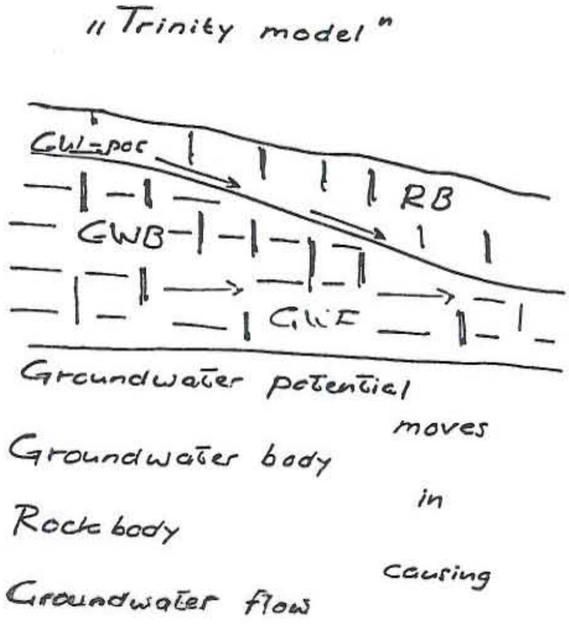


Fig. 39: The "Trinity model."
The groundwater potential is the result of the interaction between the rocks and the groundwater and supplies the driving force for the groundwater in the rocks.

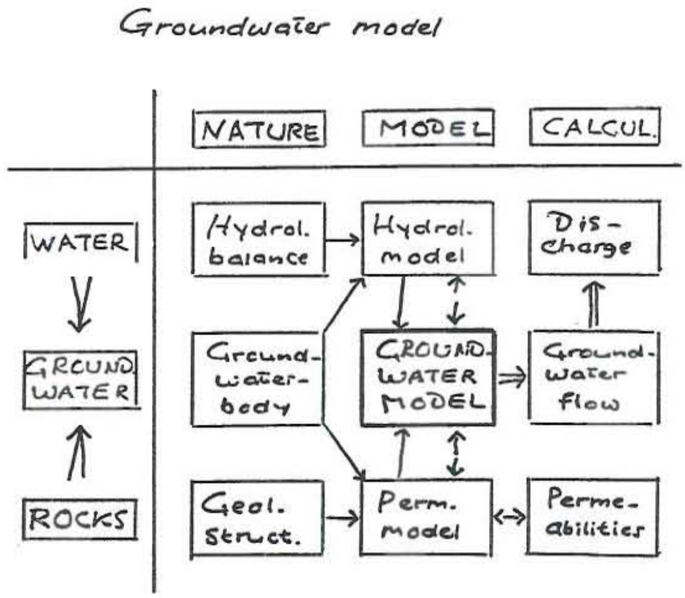


Fig. 40: Groundwater models.
A groundwater model is a simplified image of selected natural factors and a convenient tool to calculate the quantitative response of the qualitative nature on natural or man-made changes.

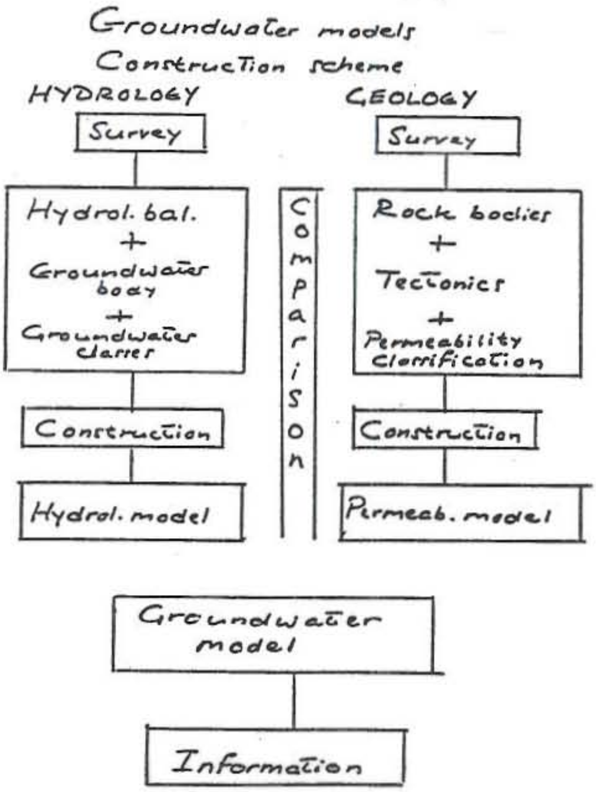


Fig. 41: Construction of groundwater models. The construction of the models is essentially the transformation of classified or qualitative data into quantitative ones and an approximation with measured or calculated data to obtain results on a quantitative form.