8. AQUIFER THERMAL ENERGY STORAGE (ATES)

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Abstract. Storage of renewable energy in the underground will reduce the usage of fossil fuels and electricity. Hence, these systems will benefit to CO_2 reduction as well as the reduction of other environmentally harmful gas emissions, like SO_X and NO_X. ATES, BTES and CTES are three options of Underground Thermal Energy Storage (UTES) systems. ATES and BTES are widely used in some countries. Relevant properties and different aspects of design and construction of ATES systems is discussed in this article.

Keywords: Underground Thermal Energy Storage, Aquifer, Borehole

8.1. Introduction to Underground Thermal Energy Storage (UTES)

There are several concepts as to how the underground can be used for underground thermal energy storage (UTES) depending on geological, hydrogeological and other site conditions. In Figure 28 some different options are schematically illustrated.

The two most promising options are storage in aquifers (ATES) and storage through borehole heat exchangers (BTES). These concepts have already been introduced as commercial systems on the energy market in several countries. Another option is to use underground cavities (CTES), but this concept is so far rarely applied commercially.

In ATES (Aquifer Thermal Energy Storage) systems groundwater is used to carry the thermal energy into and out of an aquifer. For the connection to the aquifer water wells are used. However, these wells are normally designed with double functions, both as production and infiltration wells, see Figure 29.

The energy is partly stored in the ground water itself but partly also in the grains (or rocks mass) that form the aquifer. The latter storage process takes place when the ground water is passing the grains and will result in the development of a thermal front with different temperatures. This front will move in a radial direction from the well during charging of the store and then turn back while discharging.

There are several hundreds of these systems in operation, with the Netherlands and Sweden as dominating countries of implementation. Practically all

H. Ö. Paksoy (ed.), Thermal Energy Storage for Sustainable Energy Consumption, 155–176.

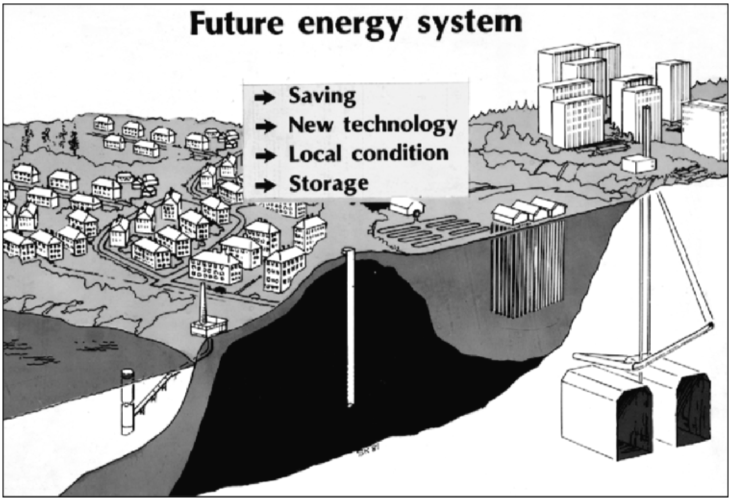


Figure 28. Different options using the underground for storage of thermal energy

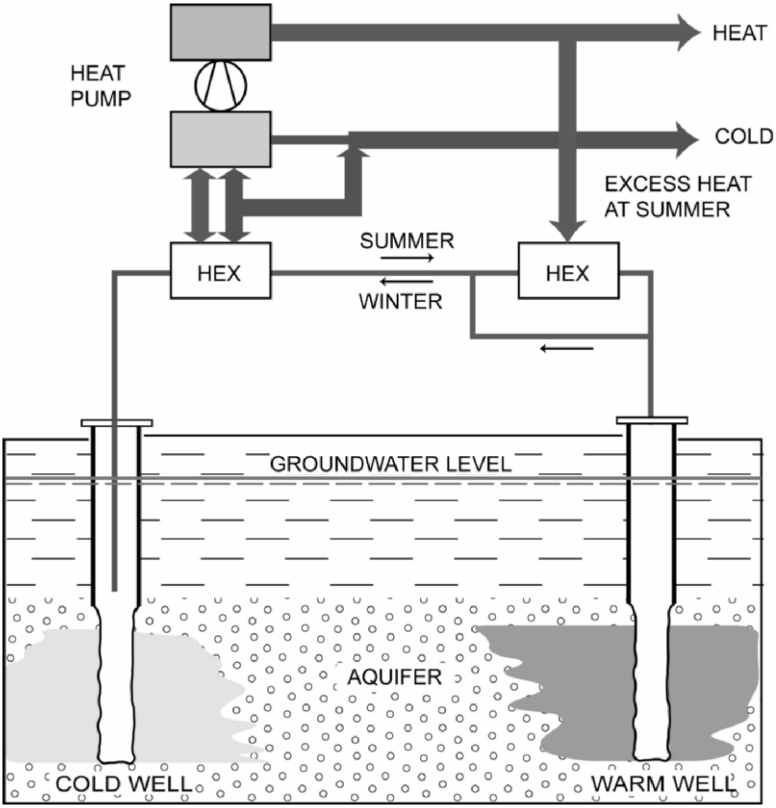


Figure 29. Principal ATES configuration

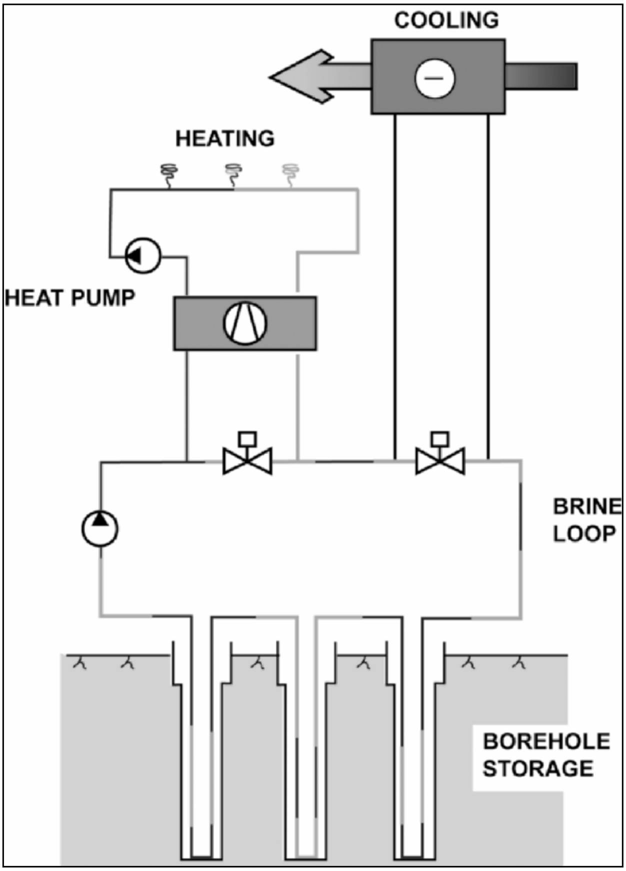


Figure 30. Principal BTES configuration

systems are designed for low temperature applications where both heat and cold are seasonally stored. However, the systems are some times also applied for short-term storage.

BTES (Borehole Thermal Energy Storage) systems consist of a number of closely spaced boreholes, normally 50–200 m deep. These are serving as heat exchangers to the underground. For this reason they are equipped with Borehole Heat Exchangers (BHE), typically a single U-pipe, see Figure 30.

In some countries the boreholes are grouted after the BHE installation, in others no backfill at all is being used. Instead the boreholes are naturally filled with groundwater. Using grout will normally decrease the thermal efficiency but on the other hand the groundwater will be protected.

In the U-pipe a heat (or cold) carrier is circulated to store or discharge thermal energy into or out of the underground. The storing process is mainly conductive and the temperature change of the rock will be restricted to only a few meters around each of the boreholes.

These systems have been implemented in many countries with thousands of systems in operation. The numbers of plants are steadily growing and new countries are gradually starting to use these systems. They are typically applied for combined heating and cooling, normally supported with heat pumps for a better usage of the low temperature heat from the storage.

8.2. Optional Configurations

Depending on type of application there are several different system configurations to consider. The four main systems are principally illustrated in Figure 31.

The simplest system (A) is based upon that ground water is directly used for preheating of ventilation air during the winter and for cooling during the summer season. In this case heat and cold from ambient air is seasonally stored

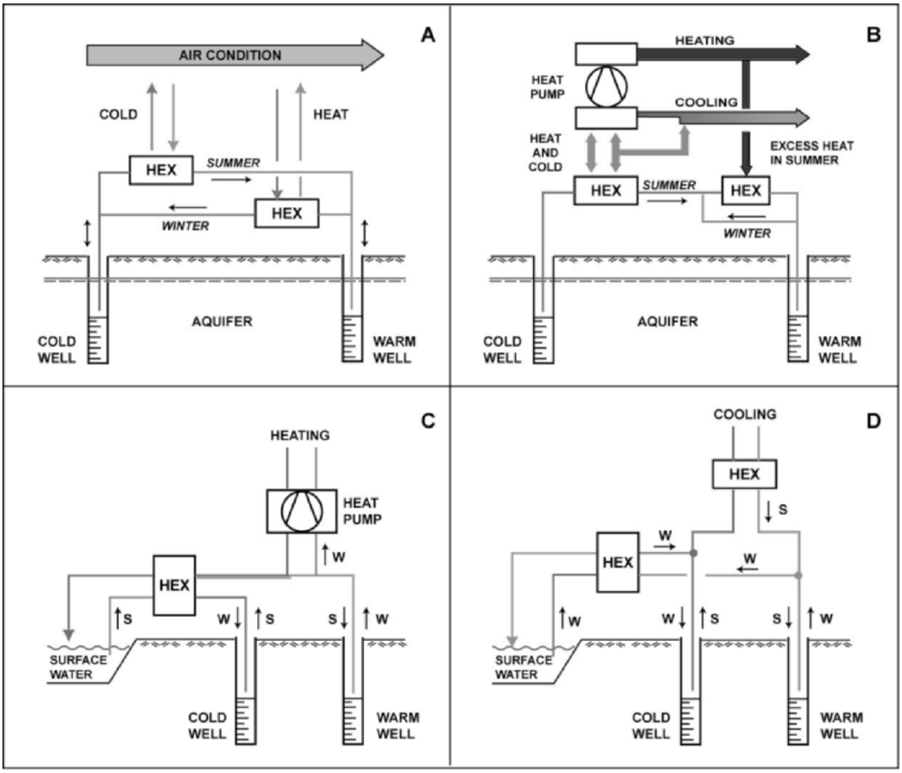


Figure 31. The main ATES configurations

in the aquifer at a temperature level of approx. +5 °C (winter) and +15 °C (summer). More commonly used is the heat pump supported system (B) that works the same way as system A. However, the production of heat is much larger and the temperature change is somewhat greater. System C represents an early type of ATES applications where surface water is used as a source of energy for the heat pump. This heat, at a temperature of 15–20 °C, is stored during the summer and used during the heating season. The fourth system (D) is similar, but in this case cold from the winter is stored to be used for district cooling.

Of these systems, heat pump supported combined heating and cooling applications (system B) are dominating. However, in recent years, there is a growing interest for storage of natural cold (system D), which is used for district cooling applications or for industrial process cooling.

8.3. Application Statistics and Experiences

In Table 9 the recent statistics of ATES utilisations in Sweden are presented. As can be seen the technology is so far preferably used for commercial and institutional buildings with small or medium sized applications. Large-scale plants are applied for some district heating and cooling systems while the industry sector only has a couple of systems applied for manufacturing industries. The rest represents cooling in the telecom sector.

In the Netherlands the number of applications is much larger (approx. 200 plants in 2004). In this country the use for industrial process cooling has a dominant portion of applications as well as for green house heating and cooling.

Some 20 years of experiences has reviled that a significant number of ATES plants have had or have operational problems or failures. The major part of these has been solved by fairly simple measures. However, a few plants have continued difficulties with the well capacities.

The dominating reason behind the problems is clogging of the wells mainly caused by iron precipitation. For this reason the research on ATES is focused on how to collect geological, hydrogeological and hydrochemical data in a proper way in order to design functional systems and wells.

Accurate site investigation data with test drillings and pumping tests are also of importance for modelling and simulations to be used for permit applications. The simulations are used to predict the thermal and hydraulic influences and are used for environmental assessment issues as well as for prediction of potential physical damages caused by the pumping of ground water.

TABLE 9. Statistics of ATES plants in Sweden

UTES system (for illustration, see Figure 31)	Number of plants	Average storage capacity (MW)		Utilisation sector (number of plants)				
		Heat	Cold	Com/Ins building	District heating	Combined DC/DH	District cooling	Industry[a]
Direct heating and cooling	1	0.3	0.3	1	—	—	—	—
Heat pump supported heating and cooling	25	1.30	1.45	15		4		6
Heat pump supported heating only	5	1.9	—	1	4	—	—	—
D. Cooling only	7	—	6.9	—	—	—	4	3
Total	38	—	—	17	4	4	4	9

[a] Process cooling of telecommunication stations included.

TABLE 10. Economics and potential energy savings by ATES

System application (see Figure 31)	PF	Energy saving (%)	Payback (years)
A. Direct heating and cooling	20–40	90–95	0–2
B. HP supported heating and cooling	5–7	80–87	1–3
C. HP supported heating only	3–4	60–75	4–8
D. Direct cooling only	20–60	90–97	0–2

8.4. Economics and Environmental Benefits

In general, the investment in an ATES system will not bee significantly higher than the investment for a conventional system. In some cases it may even be less. Since the operational cost is much less due to the energy savings, the ATES system is normally quickly paid. However, the experienced pay back time will differ with type of system. This is clearly shown in Table 10 which illustrate the performance factor (PF), the resulting energy savings compared to conventional systems and the calculated pay back time. The figures are derived from the same Swedish applications that are shown in former Table 9. Conventional systems in these cases consist of fossil fuels or electricity for heating and chillers or district cooling for air conditioning.

The environmental benefits are related to energy savings and will in most cases support the usage of ATES in any country. The obvious benefit is the reduction of CO_2 by using a large portion of natural renewable heat and cold in the systems. Besides the reduction of CO_2, there are also fewer emissions of NO_X and acidity (acid rain) to the atmosphere.

In the coming chapters fundamental issues for understanding the underground requirements for developing ATES systems are described.

8.5. Types of Aquifers

To be able to construct an ATES systems a proper aquifer has to at hand at or close to the site where the ATES user is located.

By definition groundwater can be found almost anywhere. The groundwater table is defined as the level under which all pores or fractures are water saturated, see Figure 32.

An aquifer is in practice defined to be a limited geological formation from which ground water can be pumped by using water wells.

There are two kinds of aquifers. If the groundwater stands in direct contact with the atmosphere as in the figure above, the aquifer is regarded as unconfined. If, on the other hand a permeable formation below the groundwater table is covered by a less permeable layer, the aquifer is regarded as confined, see Figure 33.

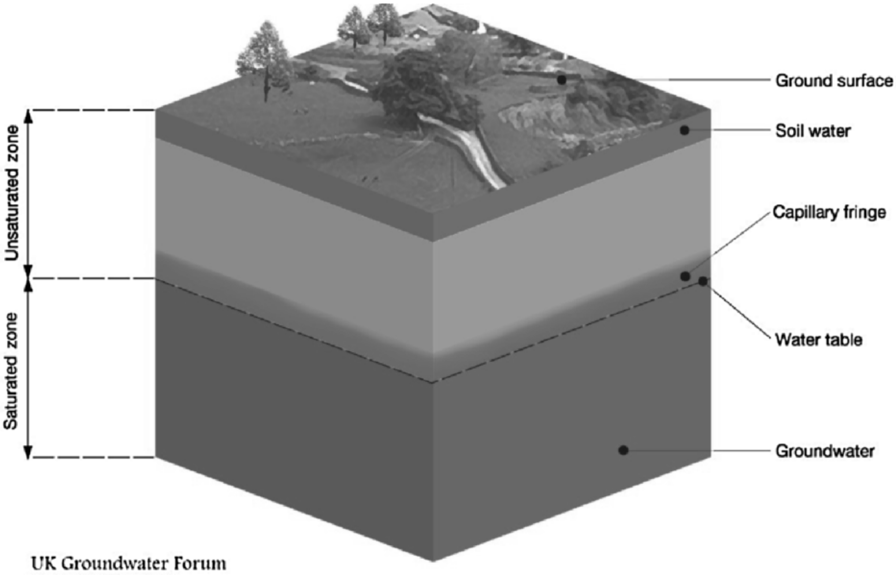


Figure 32. The saturated zone defines the groundwater table

The confined type of aquifer has a hydraulic pressure (static head) that is on a higher level than the top of the aquifer. This artesian pressure can sometimes reach above the surface level resulting in self flowing wells (artesian wells).

In nature, the groundwater is a part of the hydrological cycle. Hence, groundwater is naturally recharged and drained. Sometimes the draining is shown up as springs, but more common it flows out to a lake or a river as shown in Figure 34.

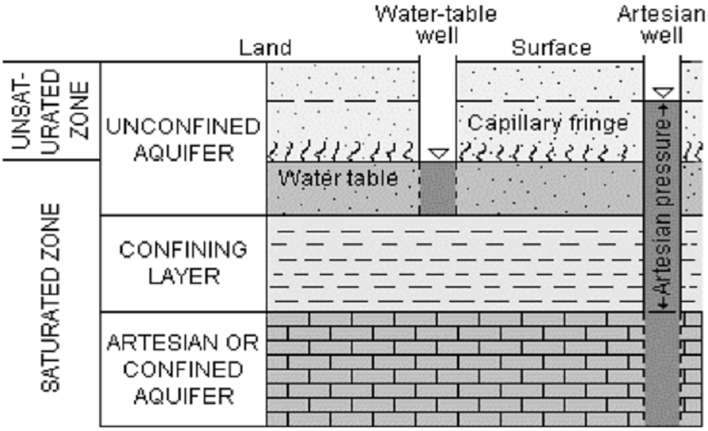


Figure 33. Confined and unconfined aquifers

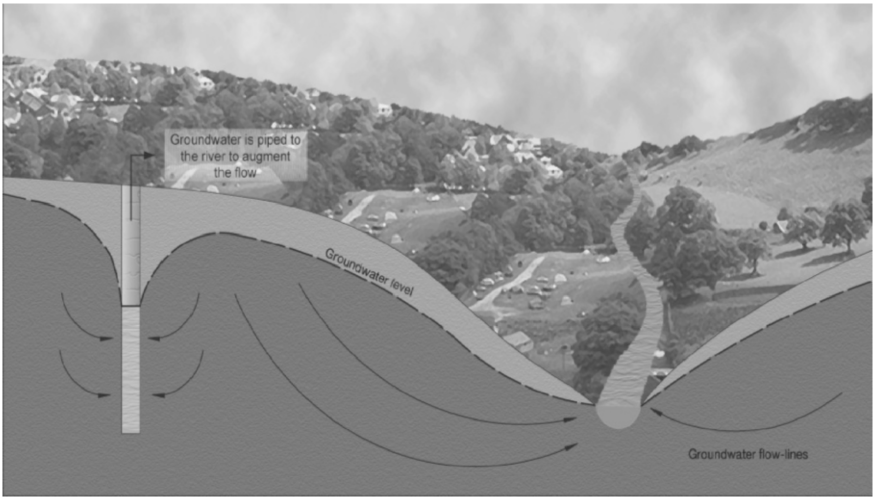


Figure 34. Flow of groundwater from an unconfined aquifer, drained by a river and by pumping from a water well

The figure also show how pumping of groundwater will create a cone of depression around the well. The size and shape of this cone is mainly related to the pumping rate and the hydraulic conductivity of the aquifer.

In the case of confined aquifers, the natural recharge and flow is more restrained, and as illustrated in Figure 35, the flow distance will normally be significantly longer and more time consuming.

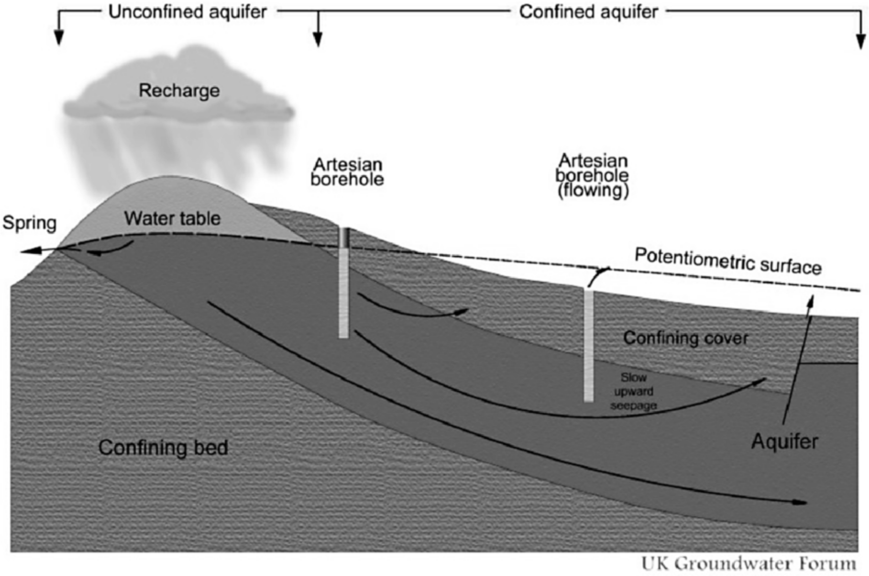


Figure 35. Flow of groundwater in an confined aquifer with potential artesian wells

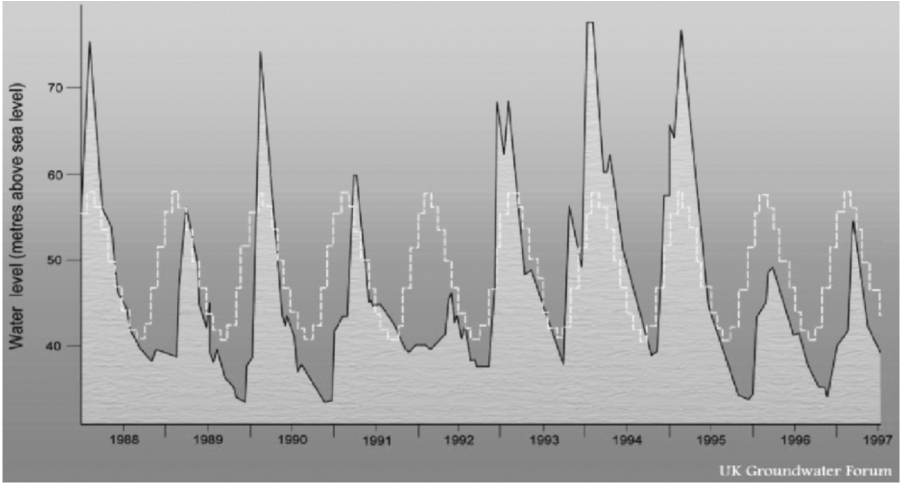


Figure 36. Variations of the groundwater table in UK, compared to “normal” values

Another difference is that the cone of depression will be larger since it only reflects a drop of hydraulic pressure around the well and the recharge area of the groundwater is restricted to the unconfined part of the aquifer. Still, if the wells in the figure should be pumped it is important to recognize that some recharge will take place also through the confining bed. This may create consolidation of this bed followed by potential damages to buildings.

The principal variation of the undisturbed groundwater table over a series of years is shown in Figure 36. This natural variation is mainly climate dependent. Most important is the precipitation and under what season the precipitation occurs. Normally, most of the recharge take place under non growing seasons in west European climate zones. In arid climate zones the recharge take place more occasionally and then combined with temporary “cold and rainy” conditions.

8.6. Aquifer Properties

Any ATES application will require a good knowledge of the aquifer being the target to use.

The most important properties are

- Geometry (surface area and thickness).
- Stratigraphy (different layers of strata).

- Static head (groundwater or pressure level).
- Groundwater table gradient (natural flow direction).
- Hydraulic conductivity (permeability).
- Transmissivity (hydraulic conductivity × thickness).
- Storage coefficient (yield as a function of volume).
- Leakage factor (vertical leakage to the aquifer).
- Boundary conditions (surrounding limits, positive or negative).

The first four items are studied by using topographical, geological and hydrogeological maps and descriptions, data from existing wells and older site investigations. The latter ones may contain geophysical data as well as older pumping tests and so forth. Any information on groundwater chemistry is of importance as well as information of the natural groundwater temperature.

This material will give the first picture of the aquifer and will be the basis for complementary site investigations. These may include test drillings, geophysical logs and pumping tests with water chemistry in order to fully understand the aquifer conditions.

The latter five bullets are obtained by using different forms of pumping tests. Such a test is normally done with a pumping well and a number of observation wells or pipes placed at certain distances from the well and in different directions. The duration varies but is commonly 1–2 weeks.

During the test the groundwater table is monitored and the drawdown cone around the pumping well is established. From these drawdown data the hydraulic properties of the aquifer can be analyzed as shown in Figure 37.

The most important parameter is the *permeability* (or *hydraulic conductivity*) is defined as the resistance for water to flow in the aquifer material and it is expressed as a flow rate (m/s) when it is affected by the gravity (gradient 1.0).

In an unconfined aquifer the permeability relates to the specific yield. This term express the ability for the aquifer to be drained and is clearly related to the grain size. The specific retention reflects the capillary forces that tend to retain water close to the grains. How these parameters relate to each other is shown in Figure 38.

From a pumping test the permeability is evaluated as *Transmissivity* (m^2/s). This parameter express the added permeability's meter by meter. By dividing the transmissivity with the thickness of the aquifer an average permeability is given.

If the test has proceeded till a steady state (cone of depression fully developed), the leakage factor as well as the storage coefficient can be determined. These factors are less important but may be critical when it comes to modelling

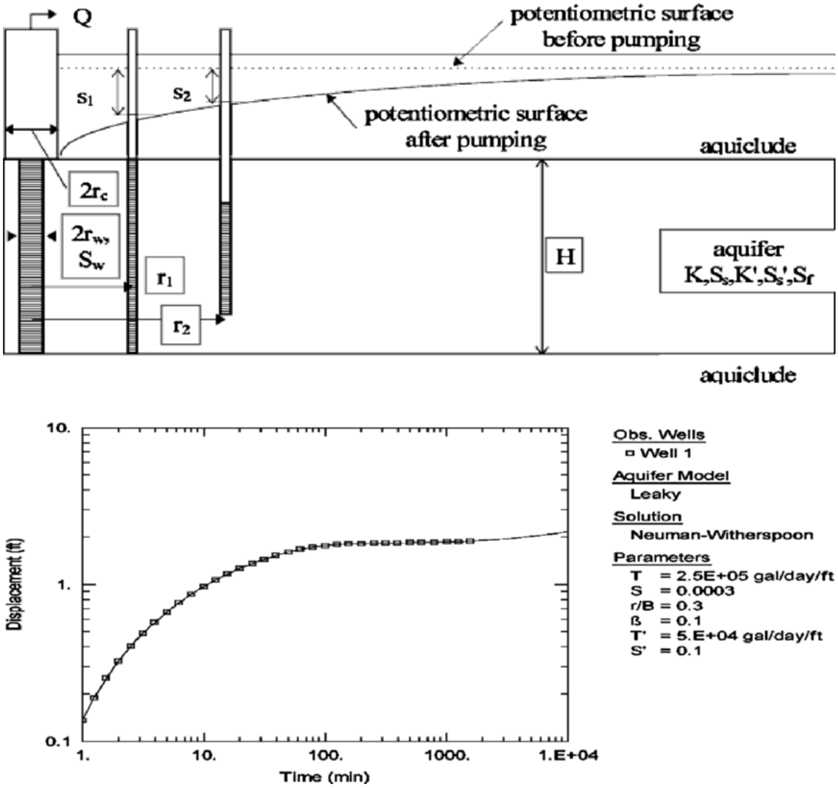
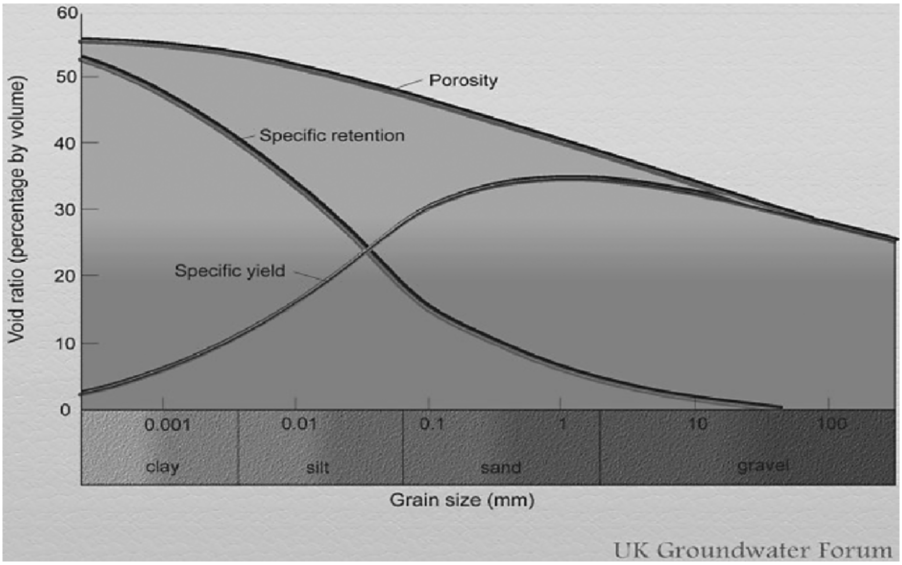


Figure 37. A pumping test is used to evaluate the hydraulic properties of the aquifer



UK Groundwater Forum

Figure 38. The relation of porosity, specific yield, specific retention and grain size in an unconfined aquifer

and simulations. Also positive and negative the boundary conditions may be essential for modelling, especially if they occur close to the well sites.

8.7. Ground Water Chemistry

8.7.1. PROBLEMS RELATED TO WATER CHEMISTRY

As stated earlier, the chemical composition of the groundwater is of uttermost importance when it comes to the design of any ATES system. The reason is the potential risks for functional problems with wells and other components in the system.

Potential problems with an ATES loop are illustrated in Figure 39 and encounter a number of events that are related to the chemical behaviour of the system. However, the figure also illustrates problems connected to a general system design, such as aeration and sand production. These types of problems may also have secondary damaging impacts on surroundings buildings and the environment.

8.7.2. HOW TO TRACE WELL PROBLEMS

The most common technical problem is clogging of wells. Clogging is defined as an increased flow resistance for water to enter the well (or be disposed

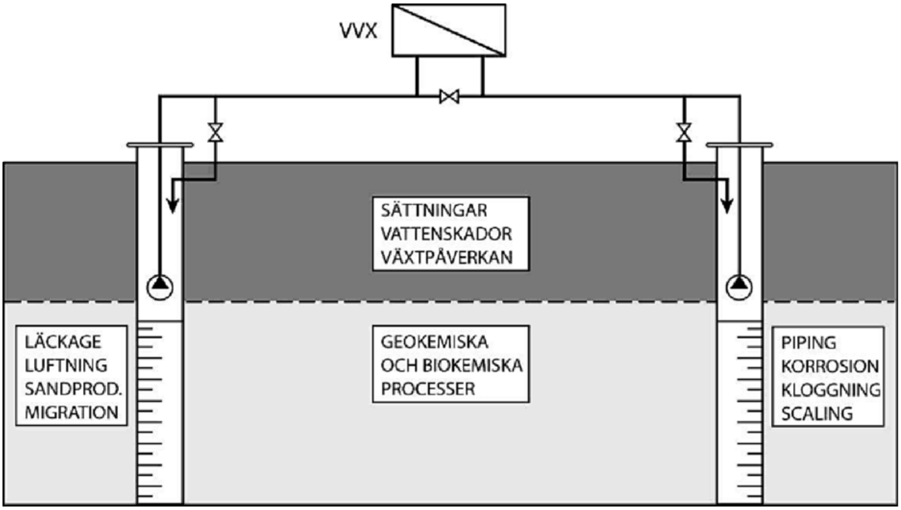
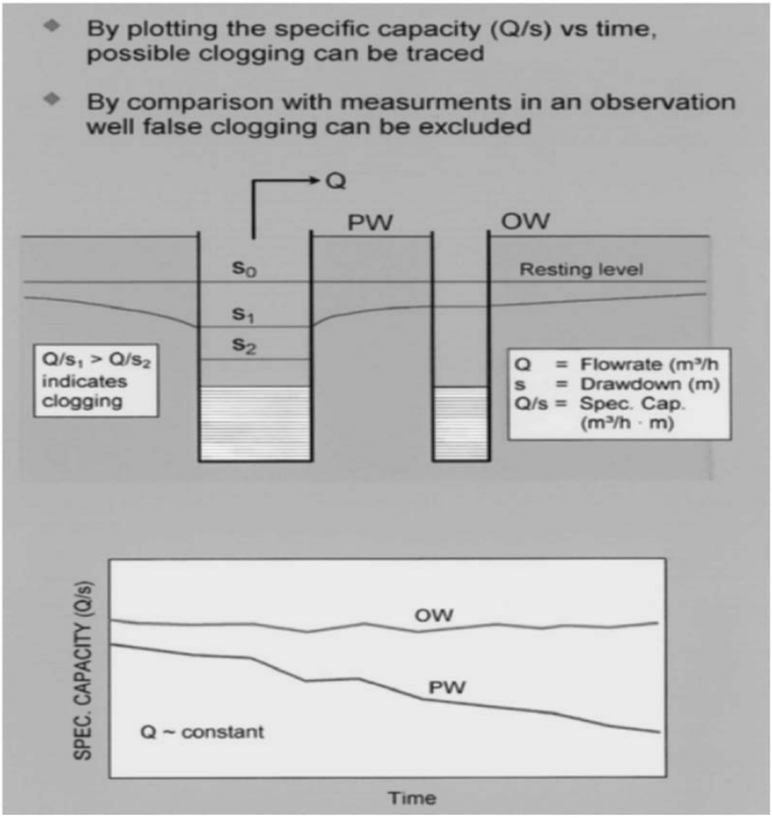


Figure 39. Potential technical problems in an ATES loop. Secondary impacts on the surrounding environment may occur



- By plotting the specific capacity (Q/s) vs time, possible clogging can be traced
- By comparison with measurments in an observation well false clogging can be excluded

Figure 40. By using a monitoring program clogging can easily be traced in an early stage

through the well). The clogging process normally gets more and more evident with time and will result in a lower and lower well capacity.

Clogging can easily be traced and dealt with in an early stage by monitoring flow rates and drawdown as shown in Figure 40.

The figure illustration shows occurrence of clogging by plotting data from an observation well (OW) and compare that to the production well (PW). In this case the production well shows a decreased specific capacity while the observation well shows a steady level versus time. The only explanation is then that the resistance for water to enter the production well is increasing. The increased resistance will lower the drawdown inside the well, while the groundwater table outside the well is kept constant. This will increase the hydraulic gradient (the driving force) between the well and the aquifer and hence maintain a constant flow rate.

"False clogging" sometimes occurs. Such events are either explained by a general lowering of the groundwater table or by failure of the submersible pumps cutting down the flow rate. However, by monitoring both the production wells and the aquifer in observation wells or pipes such events can be excluded as a result of clogging.

8.7.3. CLOGGING PROCESSES

There are three main clogging processes

- Clogging by fines.
- Hydro-chemical clogging.
- Biochemical clogging.

Already during drilling and well construction there are certain risks for clogging of the aquifer porosity. As illustrated in Figure 41, fines may invade into permeable beds decrease the yield capacity. A well known such clogging additive to the drilling mud is bentonite, which ones invaded is very difficult to clean out. For this reason it is much better to use polymers in the mud.

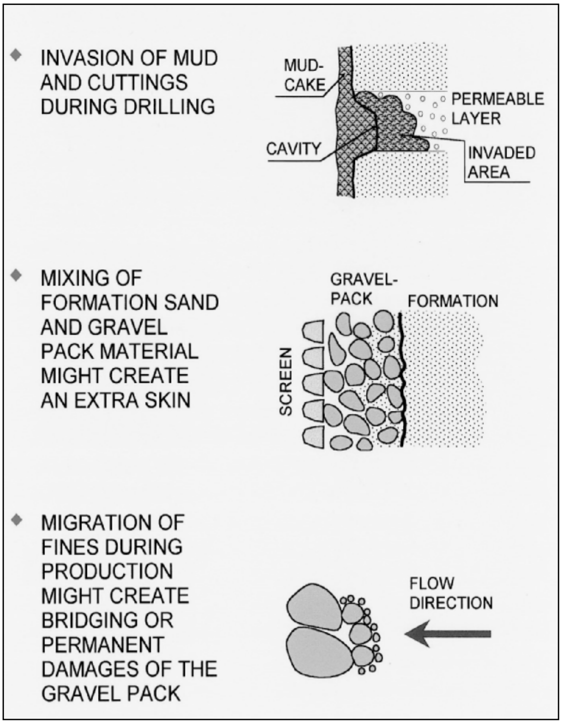


Figure 41. Different forms of clogging by fine particles during drilling, well construction and later on, production

During the construction of gravel packed wells a critical stage is the placement of the gravel pack. As shown in the figure this procedure should be carried out in a way that the gravel is not mixed with formation sand. For this reason its better to pump down the gravel through a tremie pipe rather than to poor it down and let it sink by gravity forces.

Even if a well has been properly designed and constructed, there is always a certain risk for a gradually clogging process cased by migration of fine grained formation particles. Typically, these fine particles will form bridges in the well vicinity which will increase the flow resistance. However, these bridges can be broken down by a reversed flow and the fines may be flushed to the surface by a further well development. For this reason wells with potential bridging should be constructed so they easily can be flushed.

8.7.4. HYDRO CHEMICAL CLOGGING

Under certain conditions the wells may be clogged by solid chemical precipitates. Most common of these are iron and calcium compounds.

The main processes behind these types of clogging are illustrated in Figure 42.

In general the processes are initiated by changes of pH and the redox potential (Eh) of the water.

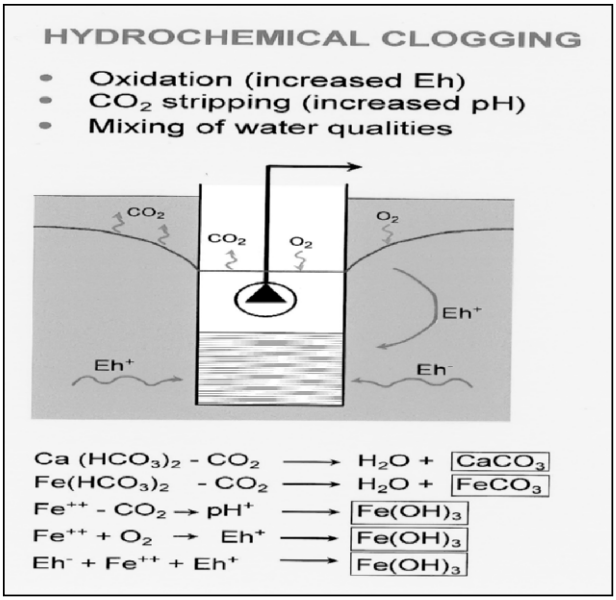


Figure 42. Hydro-chemical well clogging processes

Precipitation of carbonates (often referred to as scaling) may take place if carbon dioxide is allowed to be stripped out from the water. This happens if the draw down in the well exceeds the bubble point for CO_2. For this reason large draw downs should be avoided for scaling sensitive waters.

Stripping of CO_2 may also cause iron to precipitate, normally as iron hydroxide. That type of precipitation will also occur if an reduced type of water is entering the well from one side and an oxidized type from the other side. A third and obvious iron oxidation process will take place if reduced water gets in contact with oxygen.

To prevent from hydro-chemical clogging the systems should be designed so there is no entrance of air to the ground water loop. Hence, the loop should be perfectly air tight and constantly under pressure.

8.8. Design and Construction

8.8.1. DESIGNING STEPS AND PERMIT PROCEDURE

Any ATES realization is a quite complex procedure and has to follow a certain pattern to be proper developed. Typical designing steps are as follows:

- Pre feasibility studies (describes the principal issues).
- Feasibility study (tells the technical and economical feasibility and environmental impact compared to one or several reference systems).
- The first permit applications (local authorities).
- Definition of hydro-geological conditions by means of complementary site investigations and measurements of loads and temperatures, etc on the user side.
- Evaluation of results and modeling (used for both technical, legal and environmental purposes).
- Final design (used for tender documents).
- Final permit application (for court procedures).

The technical issues are general, but the permit procedure may vary from country to country. However, in most countries the use of ground water for energy purposes will be restricted and will be an issue for application according to different kind of acts.

8.8.2. FIELD INVESTIGATIONS

One essential part in developing an ATES project is to perform site investigations. The more knowledge that is obtained of the underground properties, the better basis for design is achieved.

The site investigations will most commonly cover the following procedure:

1. Geological mapping.
2. Geophysical investigations.
3. Test drillings.
4. Pumping tests.

The test drillings will define the stratigraphical units in the area while the geophysics and geological mapping are used for extrapolation of the layers and for definition of geometry, see Figure 43.

Test drillings may like in the figure be a part of the final system and can be looked upon as an early investment in system. However, more commonly they are drilled in a small dimension and do not fit into the final system after design. In these cases they still can serve as observation wells.

For shallow aquifers in the overburden it is common to drive slim steel pipes that are perforated in the lower meter or so. This method has proven to be an excellent way of taking samples for the design of screened production wells.

Based on the results a conceptual model is created and the hydraulic properties of the aquifer and its surrounding layers are derived from the pumping test.

The final outcome will be a geological model that is more or less accurate and that can be used for the final design using simulation models.

To be able to make model simulations the load of heat and cold have to known. For this reason it is common to perform measurements on how the loads are varied at different out door temperatures.

Such investigations that also covers supply and return temperatures in the distribution systems are often done prior to or in parallel with the underground site investigations. The results are key factors as basis for design in order to calculate flow rates and size of the ATES storage. In Figure 44 an example of heating and cooling load for an ATES application in workshop factory is given.

8.8.3. MODEL SIMULATIONS

Simulations are used for several reasons, but preferably to study how different flow rates and different number and distances between the wells are functioning. The results will then guide the decision where to place the wells and with what flow rate they should be operated.

The outcomes of such simulations are of two kinds, namely

1. The hydraulic impact shown as cones of depression and uplift around the wells.
2. Configuration of the thermal front around the wells.

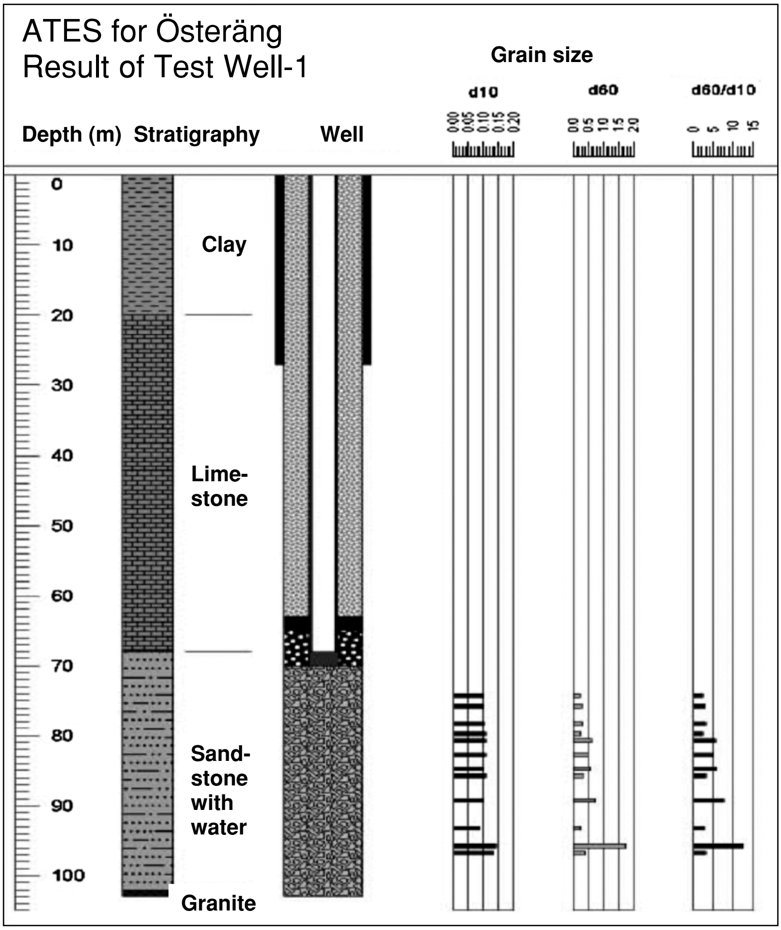


Figure 43. Example of results from a test drilling

The hydraulic impact will be more or less extensive depending on the distance between the groups of wells. With a long distance the impacted area will be larger than for a shorter distance. In Figure 45 an example from a simulation at Bo 01 in Malmö, Sweden is shown.

As can be seen, the impact area, defined as a change of static head with 0, 3 m or more, reach quite a distance.

In Figure 46 the corresponding thermal front is illustrated. As can be seen the thermally impacted area is much less. As a matter of fact, in this case the warm and cold fronts are somewhat overlapping one each other. This will to some extent be a disadvantage for the production temperature, but due to restricted surface availability this was accepted.

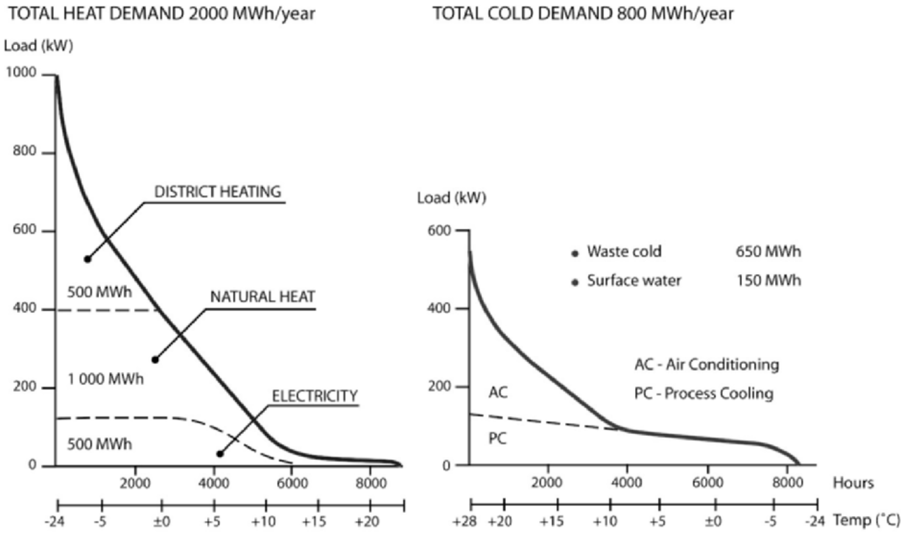


Figure 44. Example of heat and cold load duration diagrams

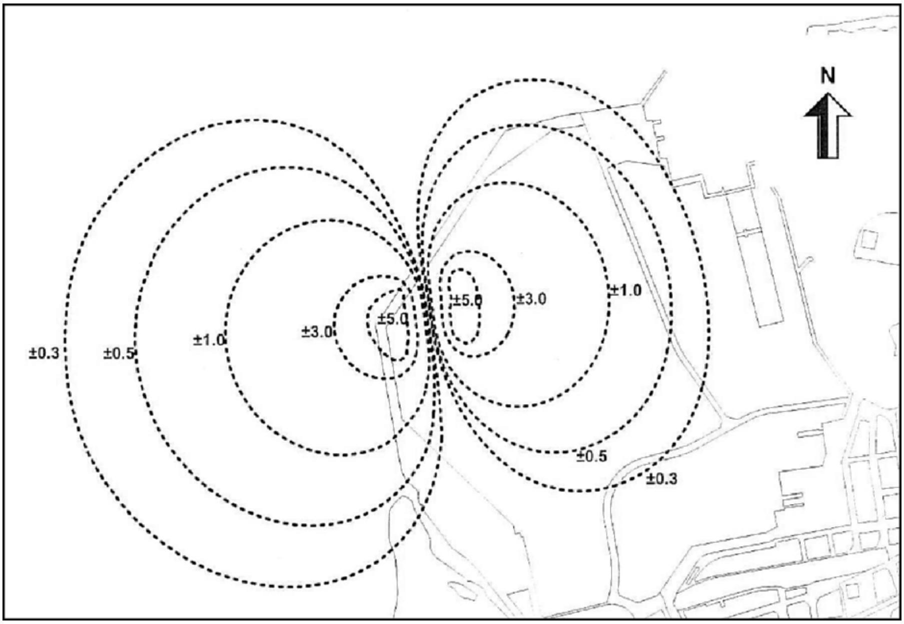


Figure 45. Example of a hydraulic simulation with 2 groups of wells, 7 warm and 7 cold, run with a flow rate of 32 l/s. The simulation is done with MODFLOW. Figures in meter. The distance between the well groups are 150 m (see also Figure 46)

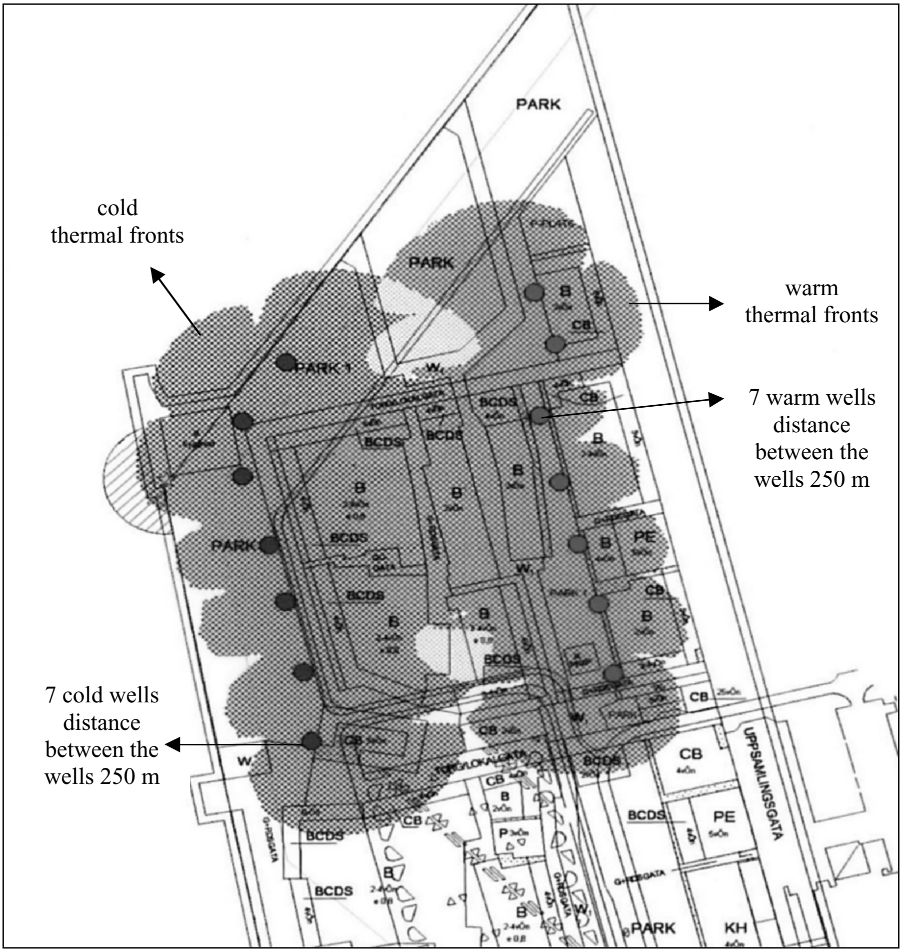
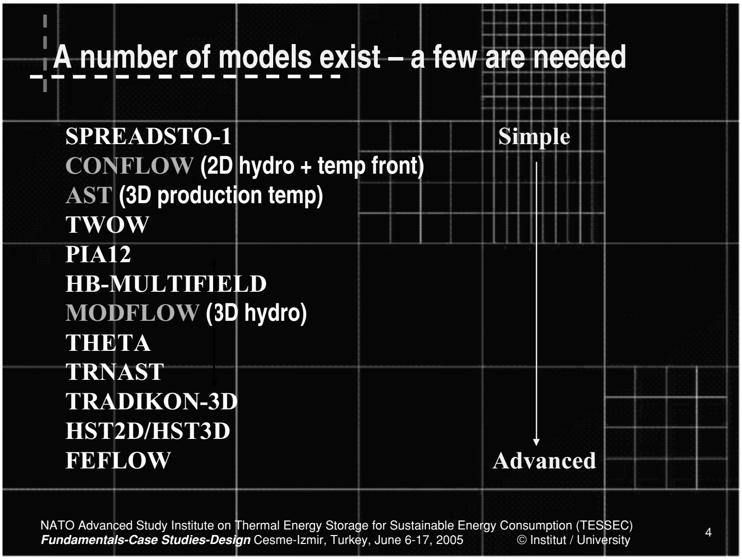


Figure 46. Warm and cold thermal fronts as they have been simulated with CONFLOW for the Bo 01 plant

There are a number of simulation models available on the market. Some are user friendly and quite easy to use, while others are more advanced. In Figure 47 some of the models are listed.

There are a lot of aspects that can be addressed when it comes to model simulations. However, most of these can be summarized with these bullets:

- Model simulations are necessary for design and for ATES impact studies.
- Some user friendly models are available on the market at a fairly low cost.



A number of models exist – a few are needed

SPREADSTO-1
CONFLOW (2D hydro + temp front)
AST (3D production temp)
TWOW
PIA12
HB-MULTIFIELD
MODFLOW (3D hydro)
THETA
TRNAST
TRADIKON-3D
HST2D/HST3D
FEFLOW

Simple

Advanced

NATO Advanced Study Institute on Thermal Energy Storage for Sustainable Energy Consumption (TESSEC)
Fundamentals-Case Studies-Design Cesme-Izmir, Turkey, June 6-17, 2005 © Institut / University

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Figure 47. Models for hydraulic and thermal simulations. Market ones is commonly used in commercial ATES projects

- The accuracy of the model and hence the simulation results will increase with the number of data input and the quality of these.
- Still, models are always simplifications of real conditions. Simulated results may differ significantly from operational results.