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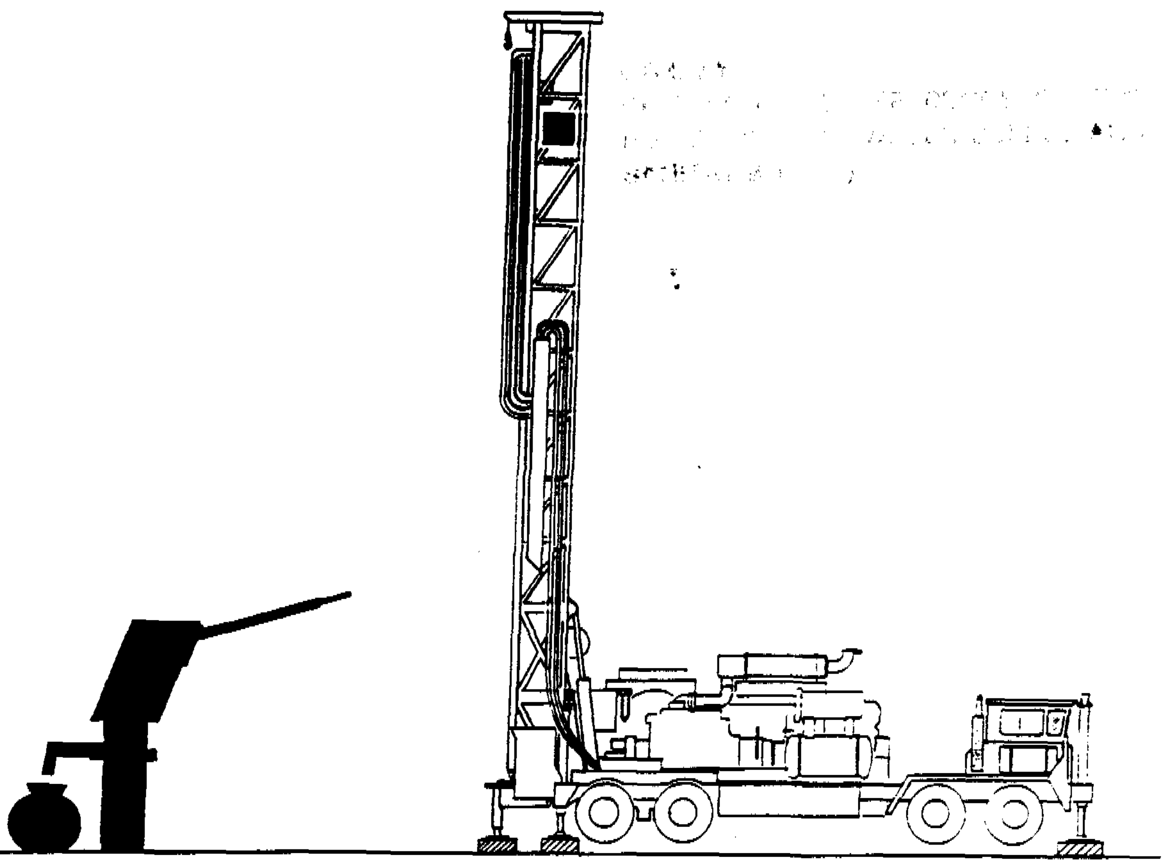

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STEP DRAW-DOWN PUMPING TEST

by Mr. Bjorn Hydbom, Hydrogeologist

Optimal discharge from the aquifer?
Choice of pump and accessories?
Optimal depth of installation?

To answer these questions, it is necessary to have information about the properties of the well and the aquifer transmissivity.

This may be obtained by doing a step draw-down pumping test (SDT), a method developed by Jacob.

The theories of a SDT and how to carry out a test is briefly described below.

DRAW-DOWN THEORY

In ground water engineering, changes in potentiometric surface or water table due to pumping is called draw-down. Draw-down is commonly expressed in feet or in meter, and it is a measure of the force needed to get ground water in the aquifer to flow into the well, i.e. the yield is related to draw-down.

Aquifer test (constant-rate) and well test (step draw-down) pumping tests offer the most powerful methods for analyzing the hydrogeologic and the hydraulic character of an aquifer and a well.

By use of the Theis equation (1935), draw-down measurements made during an aquifer test permits calculation of the hydraulic boundaries and the aquifer's storage capacity. However, to solve the equations, measurements from at least one observation well is requirements.

In a step-down test, the draw-down data from the pumped well are normally too distributed by well properties to permit an evaluation of the aquifer's storage capacity. Conversely, a constant-rate test can not be used to determine well properties.

Well properties and aquifer transmissivity can be calculated if one uses a step draw-down pumping test, SDT. Moreover, a SDT can be used to determine the momentaneous specific capacity of a well. It can also be used to determine the short-term specific capacity at various discharge rates. The information obtained from the SDT can be used to select an optimum well discharge rate.

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The duration of a SDT is of crucial importance for the prognosis of the well's long-term specific capacity due to that the radius of the influence-zone by the test is approximately proportional to the square-root of the time. To double the radius of influence, the pumping time has to be prolong by a factor of four.

Thus, if the duration of the final pumping step of a SDT is prolonged, distant aquifer behaviour may be estimated and taken into consideration in the prognosis of the well's long-term specific capacity.

THE STEP DRAW-DOWN TEST

The step draw-down test has been developed by Jacob (1946) to examine the performance of a well.

If the flow into a well is laminar, draw-down is directly proportional to the discharge rate,

$S_W=B*Q$

S_w=draw-down in well (length)
B=factor for all laminal flow (length*time/volume)
Q=discharge rate (volume/time)

The B-factor depends on all parameters that governs laminar flow in the aquifer and the well and it is time dependent.

In SI-units B is defined as,

$B=(0.183/T)*(\log[(2.25*T)/r_w^2*S])+\log(t)+0.8697*\partial)$

T=transmissivity (volume/time/length)
r_w=nominal borehole radius (length)
S=storage coefficient (-)
t=elapsed pumping time (time)
∂=skin factor (-)

T and S are thought of as constant aquifer properties, while r_w and are bore-hole parameters depending on the hole size and the bore-hole's adaptation to the aquifer.

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Turbulent flow will occur in some wells when pumped with a higher rate. Under turbulent conditions, the linear relationship between draw-down and pumping rate no longer holds, and part of the draw-down is generally related to the pumping rate.

$S_W=B*Q+C*Q^n$

C=factor for all turbulent flow [length*(time/volume)^n
n=exponent for turbulent flow

When turbulent flow occurs, the specific capacity will decline, often dramatically, as the discharge rate is increased. When this happens, it is useful to have a means of computing the turbulent and laminar draw-down components in order to make proper judgments of the optimum discharge rate and installation depth of the pump.

A SDT can be executed in different ways. Usually three to five pumping steps (rates) are used, each lasting 30 minutes to 2 hours. The entire test is usually conducted in one day.

The ordinary way to evaluate a SDT is time consuming because the aquifer behaviour can not be fully evaluated unless the effective time of influence is taken into consideration i.e. full recovery after every concluded step.

This time consuming procedure can be avoided if a computer system for registration and evaluation of the draw-down data is used. Systems such as the Atlas Copco Well Monitor System will effectively register the draw-down and give a detailed and fast graphical evaluation of the SDT data. These systems are a tool-box of great help to the engineering hydrogeologist.

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PRINCIPLES OF EVALUATION

For evaluation of well performance and transmissivity a short step draw-down tests are in many ways as useful as the much longer constant-rate tests.

As mentioned earlier, a typical series of step draw-down data for the pumped well do not fully conform to a laminar draw-down pattern. In the following we address the principal reasons for this lack of conformity which includes:

- Well losses
- Well is developing
- Hydraulic conditions that violate the Thesian assumptions
- Other factors

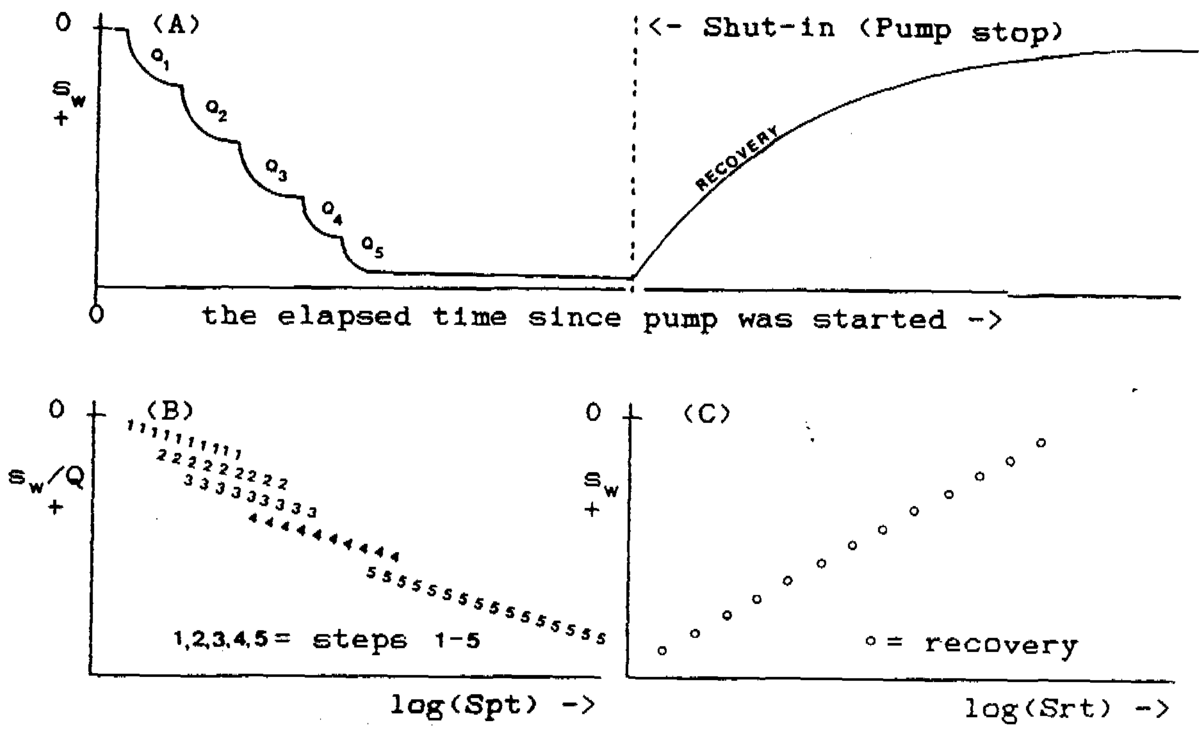

Figure 1 A Draw-down pattern during a conventional SDT. The figure shows four pumping steps followed by a recovery in a linear time scale.

B Pattern of specific draw-down plotted versus the logarithm of the adjusted pumping time, Spt.

C Pattern of residual draw-down plotted versus the logarithm of the adjusted non dimensional recovery time, Srt.

<u>Well losses</u>

The plots A, B and C in figure 1 illustrate a typical series of data obtained from a pumped well during a SDT. Instead of falling on the same straight line during the pumping period, the data falls on parallel lines as shown in plot B. The residual draw-down data in plot C forms a straight line of recovery.

The logarithmic time scale in figure 1, plot B and C., take the change in discharge rate into consideration. The adjusted time in plot B can be called specific pumping time (Spt) and the adjusted non-dimensional recovery time in plot C can be called specific recovery time (Srt). The reason for calculating the weighted values Spt and Srt, is to be able to plot all steps in one diagram instead of using different diagrams for each step.

The parallel lines of the specific draw-downs in plot B occurs due to that the well itself imposes head losses. These head losses are partly laminar and partly turbulent and they may be written as:

$s =(Q*\partial)/(2\ T)$ [laminar head loss]

$s_C=C*Q^n$ [turbulent head loss]

For a well that has a complete developmentt, the data series of a SDT presents itself as in figure 1, plot B. Such a data series can readily be evaluated by using the step's characteristic specific draw-down $(s_w/Q)^o$ - data plotted versus the discharge rates in a so called Jacob plot.

The B-factor is evaluated from the fitted straight lines intercept of the y-axis line. The C-factor is the slope slope of the line.

If $n \neq 2m$ then the well performance is probably more complicated, nd a closer analysis of the present conditions for the test is required prior to any further evaluation.

Developing well

If a well that is developing while it is submitted to a SDT will give a poor data series. In such a case the assumption that C^n is constant will not anymore be valid.

An example of a poor data series is shown in plot B in figure 2. This data series can not be used to evaluate the aquifer transmissivity or the well properties. Tests giving poor data, due to well development, should be rerun when the development is completed.

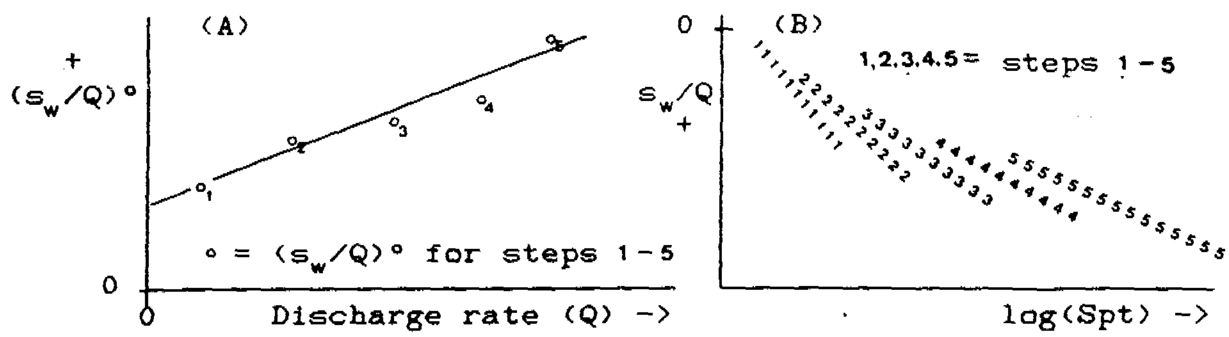

Figure 2 A A Jacob plot $(s_w/Q)^o$ versus Q for a developed will.
B Pattern of (s_w/Q) - data for a well developing during pumping.

Hydraulic conditions and other factors

In figure 3, plot A and B, common variations in the pattern of test data are shown. Although the lines are straight they are not all of equal slope as the lines in plot B of figure 1.

The lines in figure 3 represent a more complex flow system than stated by the equations above.

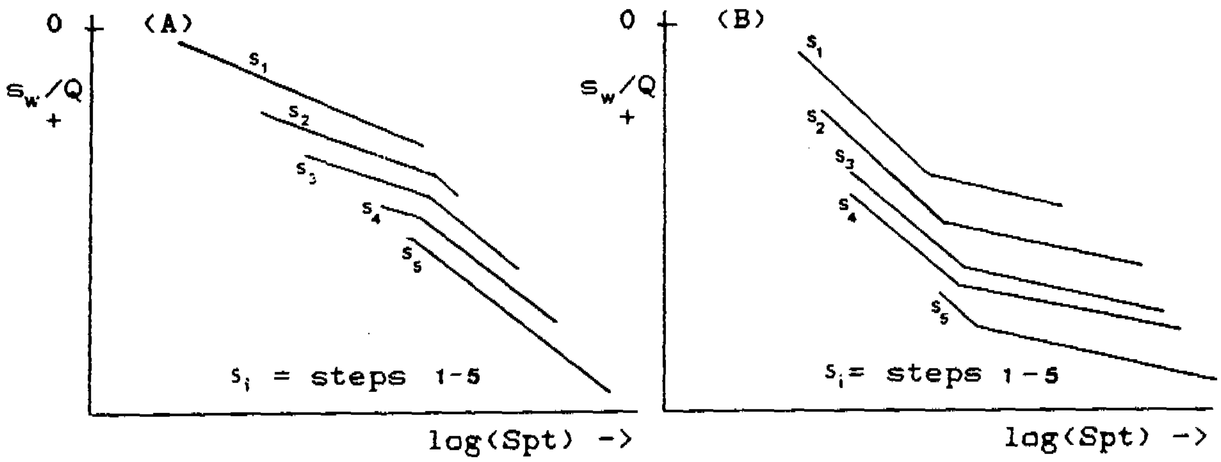

Figure 3

A Pattern of (s_w/Q) - data versus Spt for pumping a well near a negative hydraulic boundary, or when the aquifer's transmissivity is varying.

B Patter of s_w/Q) - data versus Spt for pumping a well near a positive hydraulic boundary, or, when in a leaky system, water table conditions etc.

In plot A, figure 3, the slope of draw-down increases. A no-flow boundary (negative) can give this kind of deviation. Other reasons for the deviation could be a variation of the transmissivity in the aquifer or partial penetration in granular aquifer or, quite often, a fractured aquifer.

Plot B illustrates a pattern of a constant-head boundaries (positive) caused by e.g. inter-layer leakage conditions or slow drainage of water table aquifers.

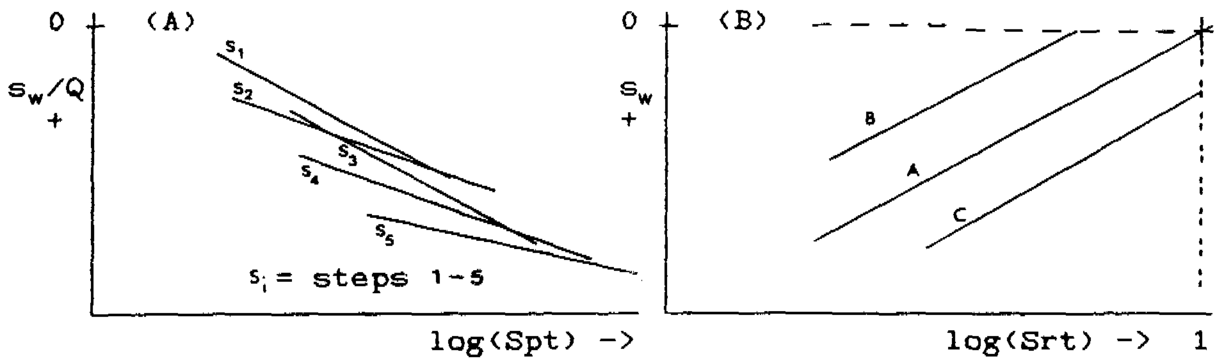

Figure 4

A Patter of (s_w/Q) - data versus Spt where discharge or draw-down measurements are not accurate.

B Pattern of residual draw-down versus Srt for pumping well when:

a) An infinite aquifer is present.

b) Water derives from sources other than intrinsic aquifer storage.

c) A dewatered (limited) aquifer is present, or more water from storage was discharged than merely from pumped well.

Plot A of figure 4 illustrates the effect of poor measurements. The lines are straight but not parallel. Usually this pattern reflects inaccuracies in the discharge measurements taken during the test. The arithmetic average of the slopes of the straight lines could be used to estimate T, but B, C and n will be very difficult to obtain from a test like this.

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Plot B of figure 4 illustrates common variations in recovery data. The recovery data for ideal (infinite) aquifer conditions should approach $S_w=0$ as Srt=>1. In some cases the line is displaced upward (line B), in other words it is displaced downwards (line C). Two reasons for these displacements are:

- The draw-down and recovery data were not adequately corrected for precedent water-level trends.

- The assumptions that all water instantaneously came from storage may be violated.

Line (B) will occur if there is a local recharge, line (C) will if water from a nearby storage is discharging or if a dewatering.

The use of the specific draw-down plot and the recovery plot can render a lot of important information about the flow system. However, it must be stressed that neither of these plots can give information about the flow system beyond the shut-in time of the SDT. After the shut-in time every statement is a prognosis, and a sound hydrogeological concept should be applied by the engineering hydrogeologist.

CONDUCTING A PUMPING TEST

To run a good pumping test on a well all available information about the well and the current aquifer conditions should be used.

A pumping test will not give an accurate prognosis unless the test is carried out methodically, carefully recording time, discharge and draw-down.

The test can be carried out with the means of a bucket, stop-watch and a lead. With only these devices it is possible to measure the three parameters in a pumping test, though for a qualitative evaluation it might not give a sufficient accuracy in the measurements.

Computer systems, such as the "Well Monitor", are today commonly used to facilitate the registration and evaluation of test pumping data giving a better and more accurate prognosis of the well behaviour.

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Below is given a suggestion for how to make a good step draw-down test.

FIELD PROCEDURE

The field procedure of a complete well test can be divided into four parts:

- The air-lift pumping test
- The 1-hour discharge test
- The SDT with three to five steps
- The recovery test

The air-lift pumping test

To facilitate the choice of pump for the SDT, an air-lift pumping test is normally carried out by the driller at completion of the well. The air-lift yield is usually measured at the end of the test while the well is emptied, i.e. at maximum draw-down. If the well can not be emptied, the accomplished draw-down should be measured prior to the shut-in of the air-lift. The specific capacity of the air-lift (SCal) is calculated as follows:

$SCal=Q/s_w$

Q=the air-lift yield
s_w=the accomplished draw-down

The choice of submersible pump

The submersible pump that will be used during the 1-hour test and the SDT should be chosen with respect to the air-lift yield and the well's total depth. The data from the air-lift are quickly plotted in a pump curve chart, and a pump with suitable discharge rate and total pressure head is readily chosen.

The change of discharge rate during the pumping tests is controlled by the means of a restriction valve.

The pump setting depth

The pump setting depth of the submersible pump should always be as deep as possible in order to have a large draw-down during the pumping tests.

The 1-hour discharge test

The main purpose of the 1-hour test is to determine the highest discharge rate that will be used during the SDT. The discharge rate might not be constant throughout the 1-hour test, but never the less should the initial 1-hour discharge rate ($Q1^o$) be:

$Q1^o=(PL-SH)*SCal$

PL=the distance from the well-head to the pump level
SH=the distance from the well-head to the static water level
SCal-the specific capacity of the air-lift pumping test

During the 1-hour discharge test, the discharge rate (Q) and the draw-down (s_w) are measured every five minutes, while the test is running.

The resulting specific capacity (Q/s_w) is calculated and plotted versus the logarithm of the elapsed time.

In figure 5, the interpretation of a (Q/s_w) - plot is exemplified. The idea is to extrapolate the decrease in the (Q/s_w) - ratio to the planned shut-in time (x) of the SDT. This will make it possible to calculate the maximum discharge rate (Q_{max}) for the SDT.

Q_{max}=(PL-SH)*SCx
PL and SH as above
SCx=the extrapolated specific capacity at planned shut-in time

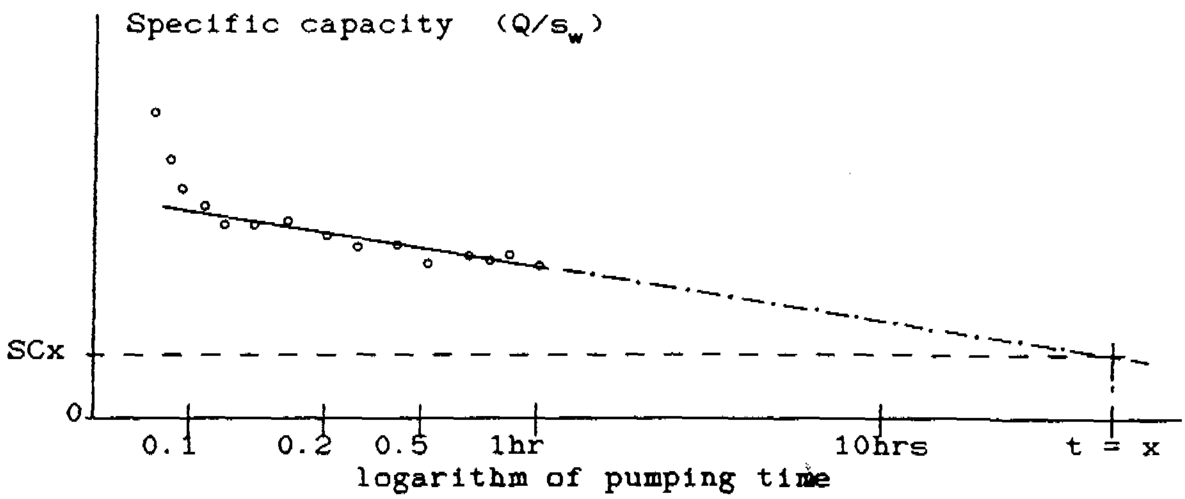

Figure 5 The figure shows how the (Q/s_w) - ratios are plotted versus the log(t), and how the extrapolation of the data is made to find the SCx.

The step draw-down test

After the 1-hour test the groundwater level should recover for at least two hours before the SDT is begun.

If there is a difference in static head when the SDT is started, this should be registered.

The number of pumping steps (N) to make a good SDT is normally four or five. Under no condition can the number of steps be less than three as this is the least required for the calculations.

The discharge rate of each step (Qi) should be:

$Qi=i/N*Q_{max}$; i=1,2,3,..,N

i-the number of order of pumping steps
N=the total number of pumping steps
Q_{max}=the maximum discharge rate

The length of any step should not be shorter than 30 minutes, though the different steps do not have to be equally long in time.

If a water table condition is present, the length of each pumping-step must exceed the duration of slow drainage in order to avoid an erroneous interpretation.

It is recommended to prolong the duration of the final step if an investigation of aquifer boundaries is desired.

A typical SDT could consist of five pumping steps, with each step, but for the final one, lasting for 30-120 minutes. The final step should be anywhere between 4-24 hours. The shifting of discharge from one rate to the next should be made without interruption.

The recovery test

The recovery test is an extremely important test. It is easy to execute and is used to confirm the results from the pumping period. Ideally, the recovery period should last until the water level has fully recovered. In some cases is this is very time-consuming or even impossible. As a rule-of-thumb, it is recommended to measure the recovery for a period of at least half the time of the pumping period.

If the submersible pump does not have a non-return valve, the water in the riser pipe will be released upon shut-in and the returning volume can cause erroneous recovery measurements if the transmissivity of the aquifer is small compared to the well-bore storage. In most cases this behaviour is quite transient and can be readily seen and avoided in the evaluation.

COMPUTER AIDED PUMPING TEST

Using a computer system will greatly facilitate registration and interpretation of a pumping test. The draw-down, recovery and time is automatically registered by the computer. The same computer is then used to do the interpretation and evaluation of the test. Figure 6 shows the prognosis plot of a pumping test made with the Atlas Copco Well Monitor System. The plot gives all information needed for a pump installation, i.e. installation depth (head), discharge rate (pump capacity) and pumping time. It also shows the part of the draw-down caused by the turbulent flow.

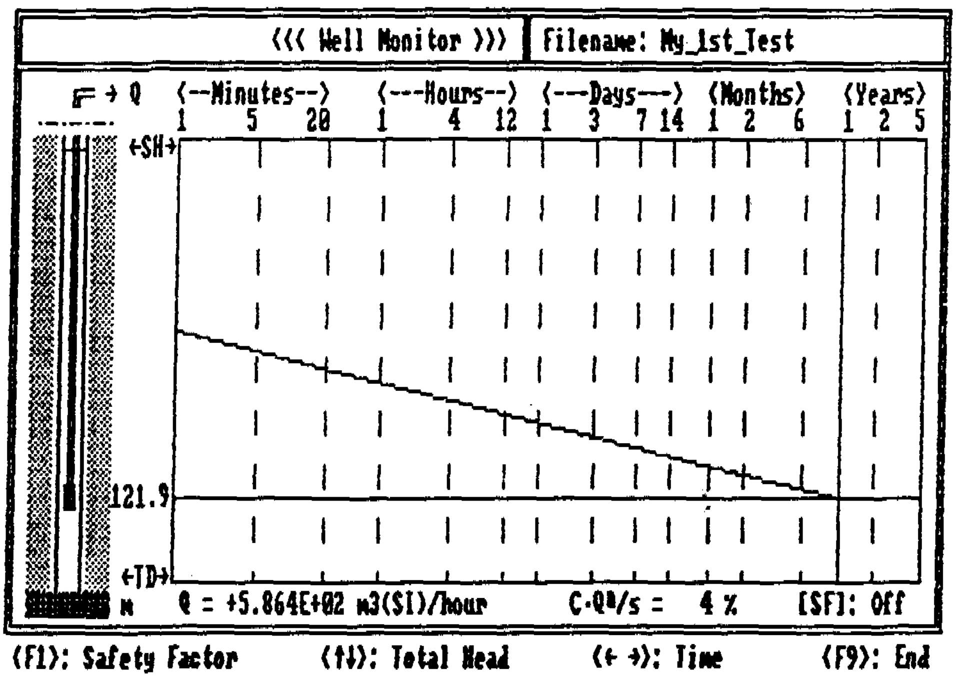

Figure 6 Prognosis plot from computer interpretation of a pumping test.