SATEM: Selected Aquifer Test Evaluation Methods

A microcomputer program

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Preface

Estimating the hydraulic characteristics of waterbearing layers is an essential part of groundwater studies. One of the most effective ways of determining these characteristics is to conduct and analyze aquifer tests. All the methods used in such analyses involve the manual processing and interpretation of test data. This can be quite time-consuming, especially if the data are numerous or the aquifer conditions are complex.

In recent years, many computer codes have been written which automatically adjust the values of hydraulic characteristics to match the field data. There are serious doubts, however, whether these 'black-box' methods yield reliable results – the consensus being that, in the analysis of aquifer test data, a 'diagnostic' plot of the field data is an absolute must.

With this in mind, I have written the program SATEM, which presents a diagnostic plot of the field data on the monitor. It also enables the user to check his analysis by presenting a match between the drawdowns observed in the field and the theoretical drawdowns found from the analysis. Hence, the analysis itself is still being done by the user. This approach combines the advantages of manual analysis (i.e. professional judgement and a 'feel' for the local hydrogeological conditions) with the advantages of the computer (i.e. data can be analyzed quickly and accurately, sensitivity analyses that represent possible combinations of aquifer and well conditions are easily made, and hard copies of the data curve and the best-fitting theoretical curve can be produced and used directly as report-ready figures).

SATEM allows the analysis of tests in unconsolidated aquifers that are confined, leaky, or unconfined, provided that the pumped well fully penetrates the aquifer. It can also be used for confined and unconfined aquifers with partially penetrating wells. SATEM can evaluate the drawdown data observed during pumping and the residual-drawdown data observed during recovery. The data can be taken from observation wells and/or from the pumped well itself.

The book has been written for professionals, but is also intended for students. For them I have included not only the computer-aided analyses, but also the manual procedures. In addition, the book offers both professionals and students the opportunity to deepen their insight by making their own sets of test data with the auxiliary program SCAL and solving them with the program package SATEM.

In making the book suitable for students, I could not avoid certain overlaps with ILRI's 'Analysis and Evaluation of Pumping Test Data' by Kruseman and de Ridder. I also make many references to that book for more detailed information. In some ways, the present book can be regarded as a follow-up to the work of Kruseman and de Ridder.

Included with this book is a copy of the compiled version of the program; it is given on a 5-1/4-inch floppy disc in MS-DOS format. The program can be run on any IBM-compatible microcomputer, provided it is equipped with a CGA, EGA, or Hercules graphics card and corresponding monitor. A numerical co-processor will ensure really short response times.

As a service to users, a copy of the program is also available on a 3-1/2-inch floppy disc. Requests for this disc should be made separately when the book is being ordered. Orders can be addressed to the International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands.

The author

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1 Introduction

There are numerous examples of groundwater-flow problems whose solution requires a knowledge of the hydraulic characteristics of the waterbearing layers. The problem may be that of predicting the future watertable when one or more wells are to be pumped for domestic water supplies or for irrigation. Or, the problem may be a more regional one of determining the quantity of water that can be withdrawn from a large groundwater basin, or it may be one of determining the seepage flow into a waterlogged area, as in a groundwater balance study.

Performing an aquifer test is one of the most effective ways of determining the hydraulic characteristics of waterbearing layers. The procedure is simple: for a certain time and at a certain rate, water is pumped from a well in the aquifer, and the effect of this pumping on the watertable is regularly measured, in the well itself and in a number of piezometers in the vicinity.

In most studies of regional groundwater resources, the number of aquifer tests that can be performed must be restricted owing to their high costs. One can, however, perform an aquifer test without using piezometers, thereby cutting costs. Of course, one must then accept a certain, sometimes appreciable, error. To distinguish such tests from the normal aquifer test, they are often called single-well tests.

To determine the hydraulic characteristics of waterbearing layers after a single-well or an aquifer test, the data collected during the test are substituted into an appropriate well-flow equation. In this book, only the basic well-flow equations will be discussed. For well-flow equations that cover a wider range of conditions, see Kruseman and de Ridder (1989).

2 Basic concepts and definitions

This chapter summarizes some basic concepts and definitions of terms relevant to the subject and the discussions which follows.

2.1 Types of waterbearing layers

Waterbearing layers are classified as aquifers, aquitards or aquicludes, according to their water-transmitting properties. With regard to the flow to pumped wells the following definitions are commonly used.

An aquifer is a waterbearing layer in which the vertical flow component with respect to the horizontal flow component is so small that it can be neglected. In an aquifer the groundwater flow is assumed to be predominantly horizontal.

An aquitard is a waterbearing layer in which the horizontal flow component with respect to the vertical flow component is so small that it can be neglected. In an aquitard the groundwater flow is assumed to be predominantly vertical.

An aquiclude is a waterbearing layer in which both the horizontal and vertical flow components are so small that they can be neglected. In an aquiclude the groundwater flow is assumed to be zero.

Common aquifers are geological formations of unconsolidated sand and gravel, sandstone, limestone, and heavily fractured volcanic and crystalline rocks. Common aquitards are, for example, clays, shales, loam, and silt.

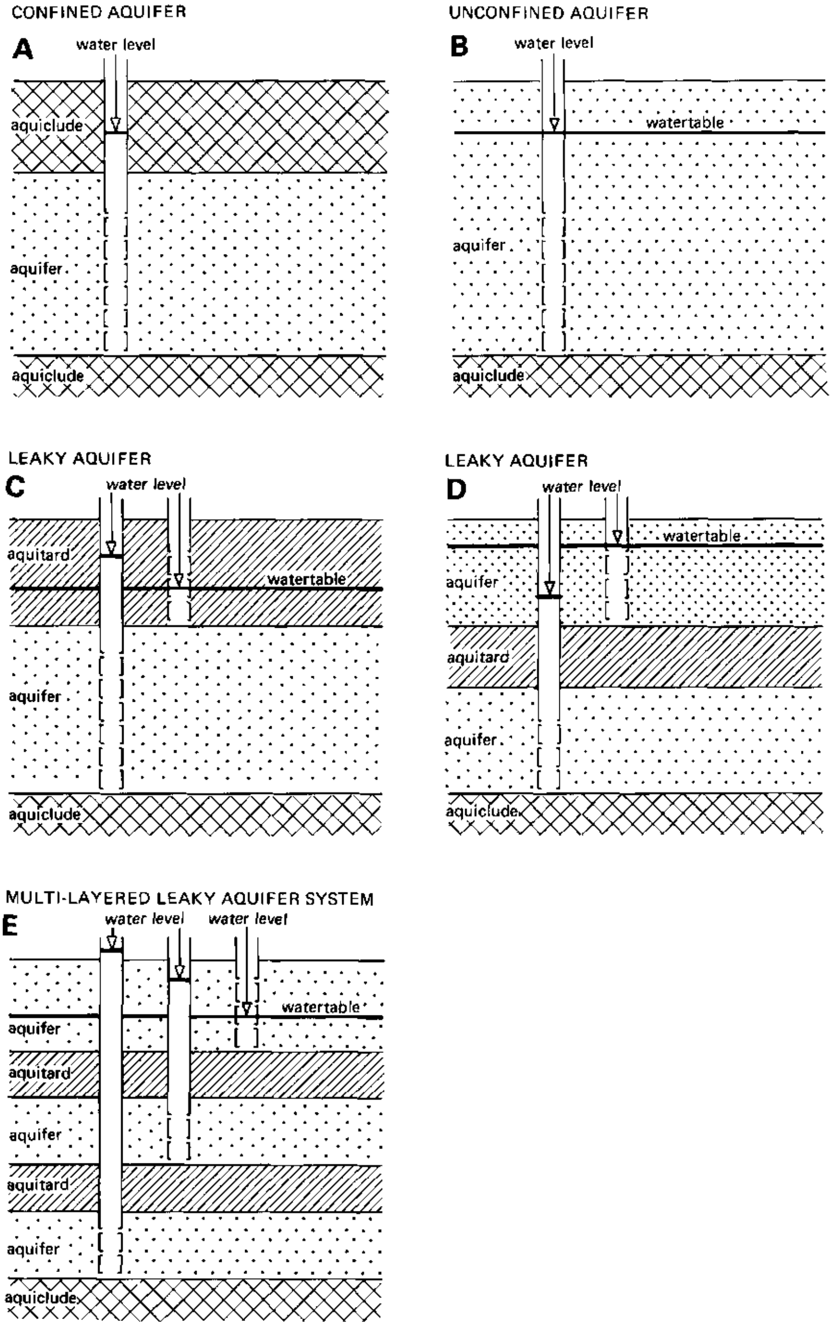
2.2 Aquifer types

Different types of aquifer may be distinguished (Figure 2.1). The four main types are the confined aquifer, the unconfined aquifer, the leaky aquifer, and the multi-layered aquifer.

A confined aquifer is a completely saturated aquifer whose upper and lower boundaries are aquicludes. In confined aquifers the pressure of the water is usually higher than that of the atmosphere and the water level in wells tapping such aquifers stands above the top of the aquifer (see Figure 2.1.A). By piezometric surface is meant the imaginary surface through all the points to which the water will rise in wells penetrating the aquifer. When the water level in wells tapping such aquifers stands above the ground surface, they are called free-flowing wells or artesian wells.

An unconfined aquifer is a partly saturated aquifer bounded below by an aquiclude and above by the free watertable or phreatic surface (see Figure 2.1.B). At the free watertable, the pressure of the groundwater equals that of the atmosphere. The water level in a well penetrating an unconfined aquifer does not, in general, rise above the watertable, except when there is vertical flow.

A leaky aquifer, also known as a semi-confined aquifer, is a completely saturated aquifer that is bounded below by an aquiclude and above by an aquitard. The overlying


CONFINED AQUIFER

UNCONFINED AQUIFER

LEAKY AQUIFER

LEAKY AQUIFER

MULTI-LAYERED LEAKY AQUIFER SYSTEM

Figure 2.1 Different types of aquifers

aquitard may be partly saturated when it extends to the land surface (see Figure 2.1.C) or is fully saturated when it is overlain by an unconfined aquifer that is bounded above by the watertable (see Figure 2.1.D). The piezometric level in a well tapping a leaky aquifer may coincide with the watertable if there is a hydrologic equilibrium; it may rise or fall below the watertable in areas with upward or downward flow, in other words, in discharge or recharge areas.

A multi-layered aquifer is a succession of leaky aquifers separated from each other by aquitards rather than a representative of a main aquifer type (see Figure 2.1.E). In deep sedimentary basins such an interbedded system of permeable and less permeable layers is very common.

2.3 Hydraulic head

Groundwater moves from levels of higher energy to levels of lower energy, whereby its energy level is essentially the result of elevation and pressure. The energy level of groundwater at a certain point in the waterbearing layer corresponds with the elevation – as measured from an arbitrary plane of reference – to which the groundwater will rise in a blank pipe that is open at the point in question (Figure 2.2). The length of the water column, h, represents this energy level and is called the hydraulic head.

Such a pipe, driven or placed in the subsoil so that there is no leakage around the pipe and all entrance of water into the pipe is through the open bottom, is called a piezometer. When a pipe contains slots or perforations over its lower part (screen), it is called an observation well.

In aquifers vertical flow components are usually lacking or of such minor importance that they can be neglected. Hence at any depth in an aquifer, the hydraulic head corresponds to the watertable height, in other words, in measuring the water level it does not make any difference how far the piezometer penetrates into the aquifer as Figures 2.3.A to 2.3.D show.

In aquitards, the flow of groundwater is mainly vertical. When such a flow exists, the water level in a piezometer which penetrates into the aquitard, is a function of its depth of penetration (Figures 2.3.C and 2.3.D).

In a confined or unconfined aquifer it is sufficient to install a single piezometer or observation well at a certain location, while in a leaky or multi-layered aquifer several piezometers should be installed at the same location with different penetration depths.

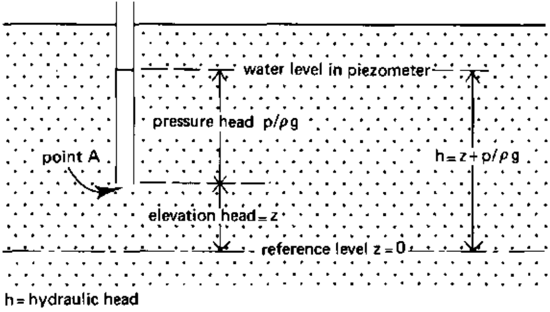


Figure 2.2 Hydraulic head

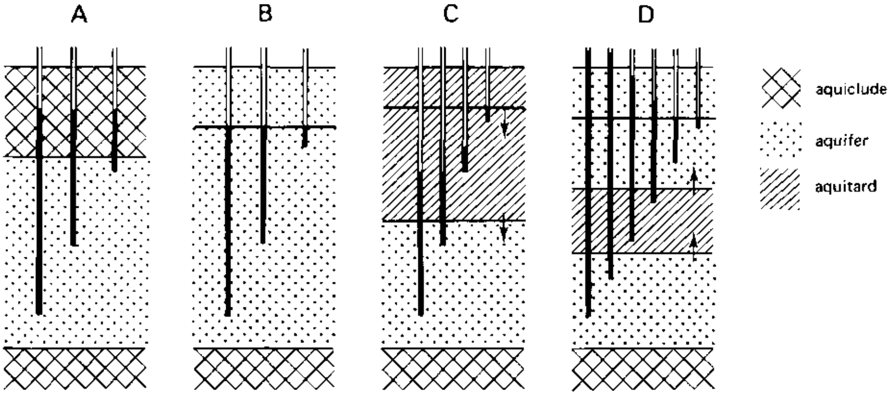


Figure 2.3 Examples of water levels observed in piezometers

2.4 Darcy's law

Darcy's law states that the rate of flow through a porous medium is proportional to the loss of head and inversely proportional to the length of the flow path, or

$$v = -K\frac{\Delta h}{\Delta l} = -K\,i \tag{2.1}$$

where

v = specific discharge or Darcy velocity (Length/Time)
K = hydraulic conductivity (Length/Time)
Δh = head loss (Length)
Δl = length of flow path (Length)
i = hydraulic gradient (dimensionless)

Darcy's law can alternatively be written as

$$Q = -K\frac{\Delta h}{\Delta l}A = -K\,i\,A \tag{2.2}$$

where
Q = volume rate of flow (Length^3/Time)
A = cross-sectional area normal to flow direction (Length^2)

The hydraulic conductivity K is a parameter depending on both the properties of the porous medium and of the fluid. It is the amount of flow per unit cross-sectional area under influence of a unit gradient. The hydraulic conductivity K should not be confused with the intrinsic permeability, k. The relation between these two parameters is

$$K = k\frac{\rho g}{\mu} \qquad (2.3)$$

where

k = intrinsic permeability of the porous medium (Length^2)
ρ = density of the fluid, i.e. the water (Mass/Length^3)
g = acceleration due to gravity (Length/Time^2)
μ = dynamic viscosity of the fluid, i.e. water (Mass/Length × Time)

In using Darcy's law it is important to know the range of its validity. After all Darcy (1856) conducted his experiments on sand samples in the laboratory. Darcy's law is valid for laminar flow, but it is not valid when the flow is turbulent, as may happen in cavernous limestone, or fractured basalt. In case of doubt, the Reynolds number serves as a criterion to distinguish between laminar and turbulent flow. The Reynolds number is expressed as

$$N_R = \rho\frac{vd}{\mu} \qquad (2.4)$$

where d is a representative length dimension of the porous medium usually taken as a mean grain diameter or a mean pore diameter.
Several experiments have shown that Darcy's law is valid for $N_R < 1$ and does not create severe errors up to $N_R = 10$. This value thus represents an upper limit to the validity of Darcy's law. It should, however, not be considered as a unique limit, because turbulence occurs gradually. At full turbulence the head loss varies approximately with the second power of the velocity rather than linearly. Fortunately, most groundwater flow occurs with $N_R < 1$ so that Darcy's law applies. Only in exceptional situations, where the rock contains wide openings, or in the near vicinity of a pumped well will the criterion of laminar flow remain unsatisfied and Darcy's law is then not valid.

2.5 Anisotropy and heterogeneity

The well-flow equations presented in this book are based on several assumptions. Amongst them that aquifers and aquitards are homogeneous and isotropic. This means that the hydraulic conductivity is independent of where it is measured within the formation and also independent of the direction of measurement (Figure 2.4.A). The individual particles of geological formations are seldom spherical so that when deposited underwater they tend to settle on their flat sides. Such a formation can still be homogeneous, but the hydraulic conductivity varies with the direction of measurement (Figure 2.4.B). In this particular case the hydraulic conductivity K_h measured in the horizontal direction is significantly greater than the hydraulic conductivity K_v measured in the vertical direction. This phenomenon is called anisotropy. In alluvial formations the K_h/K_v ratios range from 2 to 10, but values as high as 100 do occur.

The lithology of geological formations generally varies, however, significantly in both horizontal and vertical directions. Consequently, the hydraulic conductivity now

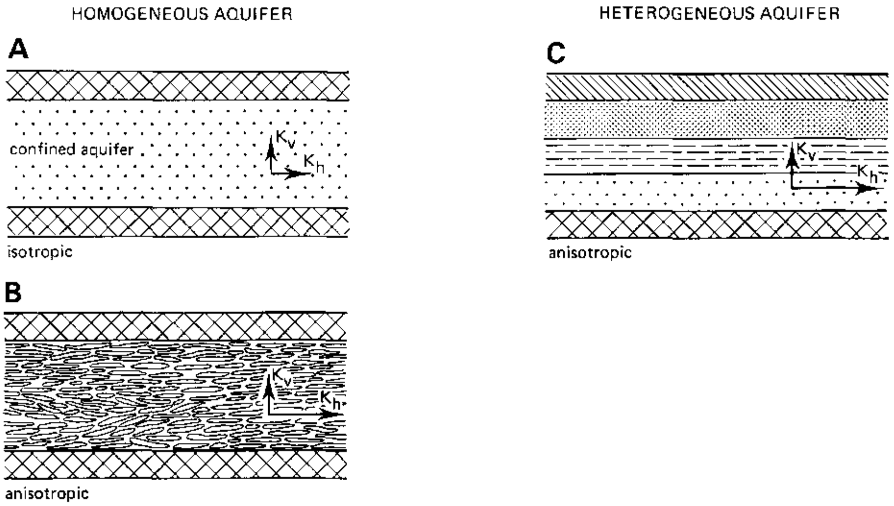


Figure 2.4 Homogeneous isotropic aquifer, homogeneous anisotropic aquifer, and heterogeneous anisotropic aquifer

depends on the position within the formation. Such a formation is called heterogeneous. Figure 2.4.C is an example of layered heterogeneity. If the hydraulic conductivity of the individual layers also varies in the direction of measurement, the formation is moreover anisotropic. Heterogeneity appears not only in the form as shown in Figure 2.4.C. Individual layers may pinch out, their grain size may vary in horizontal direction, they may contain lenses of other grain sizes or may be discontinuous by faulting.

2.6 Physical properties

This section summarizes the physical properties and derived parameters of aquifers and aquitards which appear in the various equations that describe the flow to a pumped well.

2.6.1 Hydraulic conductivity (K)

The hydraulic conductivity is the constant of proportionality in Darcy's law (Equation 2.1) and is defined as the volume of water that will move through a porous medium in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow. Hydraulic conductivity can have any units of Length/Time, for example m/day. Table 2.1 shows orders of magnitude of the hydraulic conductivities for different materials.

Table 2.1 Order of magnitude of the hydraulic conductivity for different materials in m/day (from Bouwer, 1978)

Geologic classification		K	
clay	10^{8}	–	10^{-2}
fine sand	1	–	5
medium sand	5	–	20
coarse sand	20	–	100
gravel	100	–	1000
sand and gravel mixes	5	–	100
clay, sand, gravel mixes (till)	10^{-3}	–	10^{-1}
sandstone, carbonate rock	10^{-3}	–	10^{0}
shale		10^{-7}	
dense solid rock		$< 10^{-5}$	
fractured or weathered rock (core samples)	almost 0	–	3.10^{2}
volcanic rock	almost 0	–	1.10^{3}

The hydraulic conductivity of a waterbearing layer is affected by the density and viscosity of the groundwater (Equation 2.3). In turn, the density of the water may vary with pressure, temperature and concentration of dissolved solids. For instance, saline water is of higher density than fresh water and will thus increase the hydraulic conductivity of a waterbearing layer. The viscosity is strongly influenced by the water temperature.

The higher the temperature, the lower the viscosity of the water will be and the easier it will be for the water to move through the pores of a waterbearing layer, thus resulting in a higher value for hydraulic conductivity. Values of K are normally expressed for a temperature of 20 °C. K_t values calculated for other temperatures (t) can be converted as follows

$$K_{20^\circ} = \frac{\mu_t}{\mu_{20^\circ}} K_t \tag{2.5}$$

The hydraulic conductivity values presented in Table 2.1 are expressed for a temperature of 20 °C.

2.6.2 Saturated thickness (H, D')

For confined aquifers, the saturated thickness is equal to the physical thickness of the aquifer between the aquicludes above and below it (see Figure 2.1.A). The same is true for the confined parts of a leaky aquifer bounded by an aquitard and an aquiclude (see Figures 2.1.C and 2.1.D). In both these cases, the saturated thickness is a constant.

For unconfined aquifers, the saturated thickness is equal to the difference between the free watertable and the aquiclude (see Figure 2.1.B). Because the watertable changes its position with time, the saturated thickness of an unconfined aquifer is not constant, but variable.

Whether constant or variable, the saturated thickness of an aquifer is denoted by the symbol H. Its order of magnitude can range from several metres to hundreds or even thousands of metres.

For aquitards in leaky aquifers, the saturated thickness can be variable or constant. In Figure 2.1.C, the aquitard is partly saturated and has a free watertable. Its saturated thickness depends upon the position of the watertable. In Figure 2.1.D, the aquitard is bounded by two aquifers and is fully saturated. Its saturated thickness is physically determined and thus constant.

The saturated thickness of an aquitard is denoted by the symbol D'. It may ranges from a few metres to tens of metres.

2.6.3 Transmissivity (KH or T)

The transmissivity is the product of the average hydraulic conductivity (K) and the saturated thickness of the aquifer (H). Consequently, the transmissivity is the rate of flow under a hydraulic gradient equal to unity through a cross-section of unit width over the whole saturated thickness of the waterbearing layer. It has the dimensions of $Length^2/Time$ and is, for example, expressed in m^2/day. Its range of order of magnitude can be derived from those of K and H.

2.6.4 Specific storage (S_s) and storativity (S)

The specific storage S_s of a saturated confined aquifer is the volume of water that a unit volume of aquifer releases from storage under a unit decline in head. This release of water under conditions of decreasing hydraulic head stems from the compaction of the aquifer due to increasing effective stress and from the expansion of the water due to decreasing water pressure. The specific storage S_s depends on the elasticity of both the aquifer material and the water. For a certain location it can be regarded as a constant. Its order of magnitude is 10^{-4} to 10^{-6}; it has the dimension of $Length^{-1}$.

The storativity S of a saturated confined aquifer of thickness H is defined as the volume of water released from storage per unit surface area of the aquifer per unit decline in the component of hydraulic head normal to that surface. In a vertical column of unit area extending through the confined aquifer, the storativity S equals the volume of water released from the aquifer when the piezometric surface drops over a unit distance. Storativity is thus defined as

$$S = S_s H \qquad (2.6)$$

The storativity of a saturated aquifer is a function of its thickness. Storativity is a dimensionless quantity, as it involves a volume of water per volume of aquifer. Its values in confined aquifers range from 5×10^{-5} to 5×10^{-3}.

2.6.5 Specific yield (S_Y)

The specific yield is the volume of water that an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline of the watertable. In unconfined aquifers, the effects of the elasticity of the aquifer material and the water are negligible, except for a short time after the start of pumping. Values of the specific yield are much higher than the storativities of confined aquifers. Table 2.2 shows orders of magnitude of the specific yield for different materials.

Table 2.2. Order of magnitude of the specific yield for different materials in percentages (from Boonstra and de Ridder, 1981)

Geological classification	S_Y
clay	1–18
fine sand, silt	1–46
medium and coarse sand	16–46
gravel	13–44
sandstone	2–41
siltstone	1–33
volcanic rock	2–47

Specific yield is sometimes called effective porosity, unconfined storativity, or drainable pore space. Small interstices do not contribute to the effective porosity, because the retention forces in them are greater than the weight of water. Hence, no groundwater will be released from these small interstices by gravity drainage.

2.6.6 Hydraulic resistance (c)

The hydraulic resistance characterizes the resistance of an aquitard to vertical flow, either upward or downward. It is the ratio of the saturated thickness of the aquitard D' and its hydraulic conductivity for vertical flow K' and is thus defined as

$$c = D'/K' \tag{2.7}$$

The dimension of the hydraulic resistance is Time and is, for example, expressed in days. Its order of magnitude may range from a few to thousands of days. Aquitards having c-values of 1000 to 1500 days or more, are regarded to act as aquicludes, although theoretically an aquiclude has an infinitely high c-value.

2.6.7 Leakage factor (L)

The leakage factor describes the spatial distribution of leakage through one or two aquitards into a leaky aquifer or vice versa. It is defined as

$$L = \sqrt{KHc} \tag{2.8}$$

Large values of L originate from a high transmissivity of the aquifer and/or a high hydraulic resistance of the aquitard. In both cases the influence of leakage will be small and the area over which leakage takes place, large. The leakage factor has the dimension of Length, and it may be expressed in metres.

3 Performance of an aquifer test

3.1 General

An aquifer test is performed to determine one or more of the hydraulic characteristics of an aquifer. The principle of an aquifer test is that a well is pumped and the effect of this pumping on the aquifer's hydraulic head is measured in the well itself and in a number of piezometers or observation wells in the vicinity. The change in water level induced by the pumping is known as the drawdown. These drawdowns simultaneously measured in the pumped well and the piezometers gives an indication of the cone of depression. Figure 3.1.A shows such a distance-drawdown relationship.

In the literature, aquifer tests based on the analysis of drawdowns during pumping, are commonly referred to as 'pumping tests'. The hydraulic characteristics can also

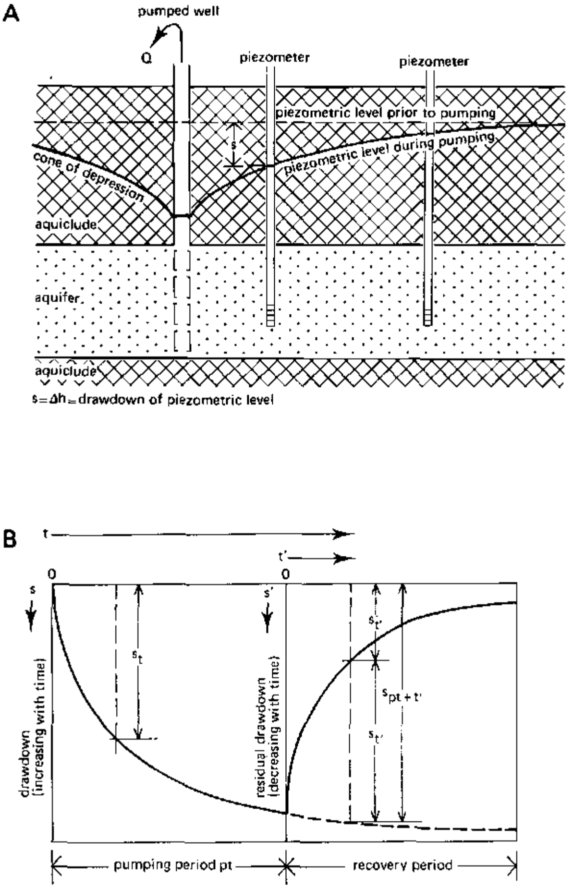


Figure 3.1 Distance-drawndown and time-drawndown behaviour during pumping and recovery tests

be found from a recovery test. In such a test, a well that has been discharging for some time is shut down, and thereafter the recovery of the aquifer's hydraulic head is measured in the well and in piezometers in the vicinity. Figure 3.1.B gives an example of the time-drawdown relationship for the pumped well or a piezometer during a pumping test followed by a recovery test.

The question of how many piezometers should be employed depends not only on the amount of information desired and the required degree of accuracy, but also on the funds available for the test. In the following chapters, it will be shown that drawdown data obtained from a single piezometer or observation well are sufficient to calculate the hydraulic characteristics of an aquifer. By placing two or more piezometers it is possible however, to make separate analyses based on the drawdown data of each individual piezometer and compare their results. Obviously, the results of such an analysis will be more accurate than the results obtained with a single piezometer, and they will also be representative of a larger volume of the aquifer. It is always best to have as many piezometers as conditions permit and to place them in various directions and distances from the pumped well.

Although no fixed rule can be given, placing piezometers at distances of between 10 and 100 m from the well will usually give reliable data. For thick or stratified confined aquifers, these distances must be greater, say between 100 to 250 m or more. In case of partially penetrating wells, the observation wells should have a short screen of 1 to 3 m length. An optimum result in determining the hydraulic characteristics of the aquifer can be obtained by placing the screen of the observation well at half the depth of the screen of the pumped well.

The site selection, and the design and construction of the pumped well and the piezometers are beyond the scope of this book. For information on these subjects reference is made to Driscoll (1986), Genetier (1984), Kruseman and de Ridder (1989), and Groundwater Manual (1981).

3.2 Measurements

Ideally, an aquifer test should be performed under the natural conditions of a stable watertable. This is, however, not always possible. Watertables rise and fall due to natural recharge and discharge of the groundwater reservoir (precipitation and evaporation), manmade recharge and discharge of the groundwater reservoir (irrigation losses and pumping from wells), changes in barometric pressure, and/or tidal movements in coastal aquifers.

Such short-term variations of the watertable have an adverse effect on the drawdown and recovery of the watertable during testing. Hence, for some days prior to the actual test, the water levels in the well and the piezometers should be measured, say twice a day. For each observation point, a time-versus-water-level curve, or hydrograph, should be drawn. From these, the trend and rate of water-level changes can be read. At the end of the test, i.e. after complete recovery, water-level readings should be continued at the observation points for one or two days. With these data, the hydrographs can be completed and the rate of water-level change during the test can be determined. This information can then be used to correct the drawdowns observed during the test itself (trend correction).

The water-level measurements must be taken many times during the course of a test, and with as much accuracy as possible. Because water levels are dropping fast during the first hour or two of the test, readings should first be taken at brief intervals. These intervals are gradually increased as pumping continues. Since in all the analysis procedures the time is plotted on a logarithmic scale, it is recommended to have ten values in each log cycle of time. For observation wells far from the well and for those in aquitards above or below the aquifer, the brief time intervals in the first minutes of the pumping test can be disregarded.

After the pump has been shut down, the water levels in the well and the piezometers will start to rise. In the first hour, they will rise rapidly, but as time goes on the rate of rise decreases. These rises can be measured in what is called a recovery test. If the yield of the well was not constant throughout the pumping test, recovery-test data are more reliable than the drawdown data collected during pumping. Recovery-test data can thus be used as a check on the calculations that are based on the drawdown data. The schedule for recovery measurements is the same as that for the pumping period.

Water-level measurements can be taken in various ways, i.e. wetted-tape method, mechanical sounder, electric water-level indicator, floating-level indicator or recorder, pressure gauge, or pressure logger. For detailed information on these devices, reference is made to Kruseman and de Ridder (1989) and Driscoll (1986).

Fairly accurate measurements of water levels can be made manually, but then the instant of each reading should be recorded with a chronometer. Experience has shown that it is possible to measure the depth to water within two millimetres. For piezometers close to the well, the wetted-tape method and the mechanical sounder cannot be used due to the rapid water-level changes and the noise of the pump, respectively.

Although the pressure-gauge method is less accurate than the other methods (within 6 cm), it is the most practical method for measuring water levels in a pumped well. It should, however, not be used for measuring water levels in observation wells.

Among the arrangements to be made for a pumping test is the control of the discharge rate. To avoid complicated calculations later, the discharge rate should preferably be kept constant throughout the test. The discharge should be kept constant by manipulating a valve in the discharge pipe. This gives more accurate control than changing the speed of the pump. During pumping tests, the discharge rate should be measured at least once every hour, and adjustments necessary to keep it constant should be made.

The discharge rate can be measured with various devices, i.e. commercial water meter, flume, container, orifice weir, orifice bucket, or jet-stream method. For detailed information on these devices, reference is also made to Kruseman and de Ridder (1989).

The water delivered by the well should be prevented from returning to the aquifer. This can be done by conveying the water through a large-diameter pipe over a convenient distance, at least 300 m, depending on the location of the piezometers, and then discharging it into a canal or natural channel. Preferably, the water should be discharged away from the line of piezometers. The pumped water can also be conveyed through a shallow ditch, but precautionary measures should be taken to seal the bottom of the ditch with clay or plastic sheets to prevent leakage.

3.3 Duration of a pumping test

The question of how long a pumping test should last is difficult to answer because the period of pumping depends on the type of aquifer and the degree of accuracy desired in establishing its hydraulic characteristics. Economizing on the pumping period is not recommended because the costs of running the pump a few extra hours are low compared with the total costs of the test. Moreover, better and more reliable data are obtained if pumping continues until the cone of depression has stabilized and does not seem to be expanding further as pumping continues. At the beginning of the test, the cone develops quickly because the pumped water is initially derived from the aquifer storage immediately around the well. But, as pumping continues, the cone expands and deepens more slowly because, with each additional metre of horizontal expansion, a larger volume of stored water becomes available. This may often lead inexperienced observers to conclude that the cone has stabilized, or in other words that steady state has been reached. Inaccurate measurements in the piezometers – additional drawdowns that are becoming smaller and smaller as pumping continues – can also lead to this wrong conclusion. In reality, the depression cone will continue to expand until the recharge of the aquifer, if any, equals the discharge.

The unsteady-state flow, also known as non-equilibrium flow, is time dependent, i.e. the water level as observed in piezometers, changes with time. During a pumping test, the unsteady-state flow condition occurs from the moment pumping starts till the steady state is reached. Theoretically, in an infinite, horizontal, completely confined aquifer of constant thickness which is pumped at a constant rate, there will always be an unsteady state, as such an aquifer is not recharged by an outside source. In practice, well flow is considered to be in unsteady state as long as the changes of the water level in the piezometers are measurable, or as long as the hydraulic gradient changes in a measurable way.

The steady-state flow, also known as equilibrium flow, is independent of time, i.e. the water level, as observed in piezometers, does not change with time. It occurs, for instance, when there is equilibrium between the discharge of a pumped well and the recharge of the pumped aquifer by an outside source. Such outside sources may be recharge from surface water of nearby rivers, canals, or lakes, or recharge from groundwater of an unconfined aquifer with constant watertable overlying an aquitard which covers a pumped leaky aquifer. Because real steady-state conditions seldom occurs, it is said in practice that a steady-state condition is reached when the changes of the water level as observed in piezometers are negligibly small, or when the hydraulic gradient has become constant.

To establish whether unsteady or steady-state conditions prevail, the changes in head during the pumping test should be plotted. Figure 3.2 shows the different plots and their interpretations.

In some wells, a steady state occurs a few hours after the start of pumping; in others, it does not occur until after a few days or weeks, whereas in yet other wells it never occurs, even though pumping continues for years. Kruseman and de Ridder (1989) suggest that, under average conditions, steady-state flow is generally reached in leaky aquifers after 15 to 20 hours of pumping, and in a confined aquifer, after 24 hours. In an unconfined aquifer, the cone of depression expands more slowly, so a longer period of pumping is required, say, three days.

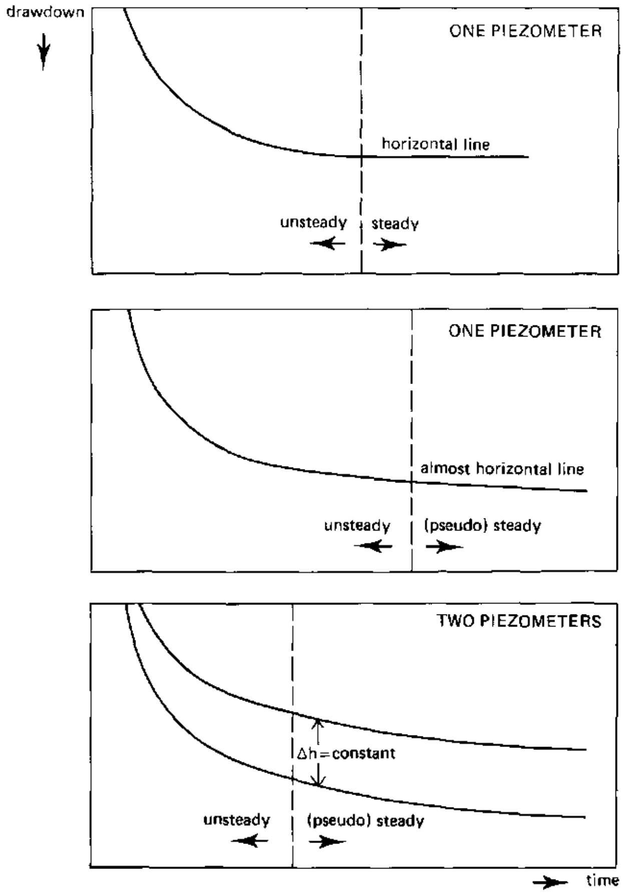


Figure 3.2 Plots showing the changes in drawdown during a pumping test and their interpretations

Preliminary plotting of drawdown data during the test will often show what is happening and may indicate whether or not a test should be continued.

3.4 Processing the data

All measurements of the water level, time, and discharge of the pump should preferably be noted on pre-printed forms. After some hours of pumping, sufficient time will become available in the field to draw the time-drawdown curves of each observation point. These graphs will be helpful in checking whether the test is running well and in deciding on the time that the pump can be shut down when steady or pseudo-steady state flow has been reached.

Most well-flow equations require drawdown data. The depth to the water level data should therefore be converted to drawdown data, in other words, the initial depth to the water level must be subtracted from the depth to the water level data during the test.

It may be necessary to correct the observed drawdowns for external influences, i.e. influences independent of the test (trend correction). If, during the post-recovery period, the same constant water level is observed as during the pre-testing period, it can be assumed that no external forces influenced the hydraulic head in the aquifer during the test. If, however, the water level is subject to unidirectional or rhythmic changes, the observed drawdowns will have to be corrected before being used in the analysis. Such phenomena are likely to occur during pumping tests of long duration.

When the evaluation of the test data has been completed, a report on the results should be written. For more information on the details of what such a report should contain, reference is made to Kruseman and de Ridder (1989).

A copy of the report should be kept on file for further reference and later studies. Samples of the different layers penetrated by the borings should be stored too, because they may be needed for other studies in a later phase of investigations. The basic field measurements of the test should be put on file as well. The conclusions drawn from the test may become obsolete in the light of new insights, but the hard facts, carefully collected in the field, remain facts and can always be re-evaluated.

4 Application of analysis methods

In this chapter methods for evaluating aquifer and single-well tests conducted in confined, leaky, and unconfined aquifers are presented. These methods have been incorporated in the program package SATEM.
All the presented methods were developed under the following common assumptions and conditions:

- The aquifer has a seemingly infinite areal extent;
- The aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by the test;
- Prior to pumping, the hydraulic head is (nearly) horizontal over the area influenced by the test;
- The aquifer is pumped at a constant-discharge rate;
- The flow to the well is in unsteady state;
- The water removed from storage is discharged instantaneously with decline of head;
- The diameter of the pumped well is small, i.e. the storage inside the well can be neglected.

Additional assumptions and limiting conditions are mentioned where the individual methods are discussed separately.

4.1 Analysis methods drawdown data

4.1.1 Confined aquifers

Theis (1935) was the first to develop a formula for unsteady-state flow that introduces the time factor and the storativity. He noted that when a well penetrating an extensive confined aquifer is pumped at a constant rate, the influence of the discharge extends outward with time. The rate of decline of head, multiplied by the storativity and summed over the area of influence, equals the discharge.

The Theis equation, which was derived from the analogy between the flow of groundwater and the conduction of heat, is written as

$$s = \frac{Q}{4\pi KH} \int_u^\infty \frac{1}{y} \exp(-y)\,dy = \frac{Q}{4\pi KH} W(u) \qquad (4.1)$$

and

$$u = \frac{r^2 S}{4KHt} \qquad (4.2)$$

where

s = drawdown measured in a well (m)
Q = constant well discharge (m^3/d)

KH = transmissivity of the aquifer (m^2/d)
r = distance from the pumped well (m)
S = storativity of the aquifer (–)
t = time since pumping started (d)

The exponential integral is written symbolically as W(u), which in this usage is generally read as well function of u or Theis well function. Values of this function can be found in Appendix A.

Jacob's modification of the Theis method

In Figure 4.1 the Theis well function W(u) is plotted versus 1/u on semi-log paper. Figure 4.1 shows that, for values of 1/u larger than 100, the Theis well function exhibits a straight-line segment. The Jacob method is based on this phenomenon. Cooper and Jacob (1946) showed that, for the straight-line segment, Equation 4.1 can be approximated by

$$s = \frac{2.30Q}{4\pi KH} \log \frac{2.25KHt}{r^2S} \tag{4.3}$$

If the time of pumping is long enough, a plot of the drawdown s observed at a particular distance r from the pumped well versus the logarithm of time t, will show a straight line. If the slope of this straight-line segment is expressed as the drawdown difference ($\Delta s = s_1 - s_2$) per log cycle of time ($\log t_2/t_1 = 1$), rearranging Equation 4.3 gives

$$KH = \frac{2.30Q}{4\pi\Delta s} \tag{4.4}$$

If the straight line is extended until it intercepts the time-axis where s = 0, the interception point has the coordinates s = 0 and $t = t_o$. Substituting these values into Equation 4.3 gives $\log [2.25KHt_o/r^2S] = 0$ or $[2.25KHt_o/r^2S] = 1$ or

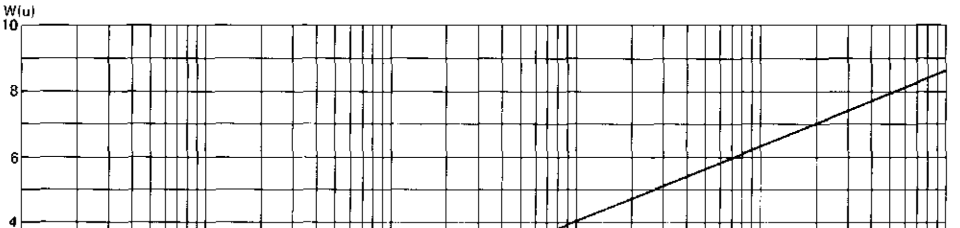


Figure 4.1 Theis well function W(u) versus 1/u for fully penetrating wells in confined aquifers

$$S = \frac{2.25KHt_o}{r^2} \tag{4.5}$$

Jacob's straight-line method is based on the assumptions listed at the beginning of this chapter and on the following limiting conditions:

- The pumped well penetrates the entire thickness of the aquifer and thus receives water by horizontal flow;
- The pumping time is sufficiently long that a straight-line segment can be distinguished from a time-drawdown plot on semi-log paper.

Procedure

- For one of the wells, plot the drawdown values s versus the corresponding time t on semi-log paper (t on logarithmic scale);
- Select a time range and draw a best fitting straight line through that part of the plotted points;
- Determine the slope of the straight line, i.e. the drawdown difference Δs per log cycle of time;
- Substitute the values of Q and Δs into Equation 4.4 and solve for KH;
- Extend the straight line until it intercepts the time axis where $s = 0$, and read the value of t_o;
- Substitute the values of KH, t_o, and r into Equation 4.5 and solve for S;
- Substitute the values of KH, S, and r into Equation 4.2 together with $1/u = 100$ and solve for t. This t value should be less than the time range for which the straight-line segment was selected;
- If drawdown values are available for more than one well, apply above procedure to the other wells also.

Hantush's modification of the Jacob method

Some aquifers are so thick that it is not justified to install a fully penetrating well. Instead, the aquifer has to be pumped by a partially penetrating well. Because partial penetration induces vertical flow components in the vicinity of the pumped well, the assumption that the well receives water from horizontal flow is not valid. Hence, the standard methods of analysis cannot be used unless allowance is made for partial penetration.

Partial penetration causes the flow velocity in the immediate vicinity of the well to be higher than it would be otherwise, leading to an extra loss of head. This effect is strongest at the well face, and decreases with increasing distance from the well. It is negligible if measured at a distance that is one to two times greater than the saturated thickness of the aquifer, depending on the amount of penetration.

According to Hantush (1962) the drawdown due to pumping in a confined aquifer can be described by the following formula

$$s = \frac{Q}{4\pi KH}[W(u) + f_s] \tag{4.6}$$

where W(u) is the Theis well function, and

$$f_s = \frac{2H^2}{\pi^2(b-d)(b'-d')} \sum_{n=1}^{\infty} \left(\frac{1}{n^2}\right) W\left(u, \frac{n\pi r}{H}\right)$$

$$\times \left[\sin\left(\frac{n\pi b}{H}\right) - \sin\left(\frac{n\pi d}{H}\right)\right]\left[\sin\left(\frac{n\pi b'}{H}\right) - \sin\left(\frac{n\pi d'}{H}\right)\right] \quad (4.7)$$

where

$$W\left(u, \frac{n\pi r}{H}\right) = \int_u^{\infty} \frac{1}{y} \exp\left(-y - n^2\pi^2 r^2/4H^2 y\right) dy$$

This integral is known as the Hantush well function. Values of this function can be found in Appendix B.

Note: The angles are expressed in radians. For an explanation of the symbols, see Figure 4.2.

When the difference between b′ and d′ is small ($b'-d' < 0.05$ H), Equation 4.7 can be replaced by

$$f_s = \frac{2H}{\pi(b-d)} \sum_{n=1}^{\infty} \left(\frac{1}{n}\right) W\left(u, \frac{n\pi r}{H}\right)$$

$$\times \left[\sin\left(\frac{n\pi b}{H}\right) - \sin\left(\frac{n\pi d}{H}\right)\right]\left(\cos \frac{n\pi z}{H}\right) \quad (4.8)$$

This equation should be used when piezometers instead of observation wells have been installed.

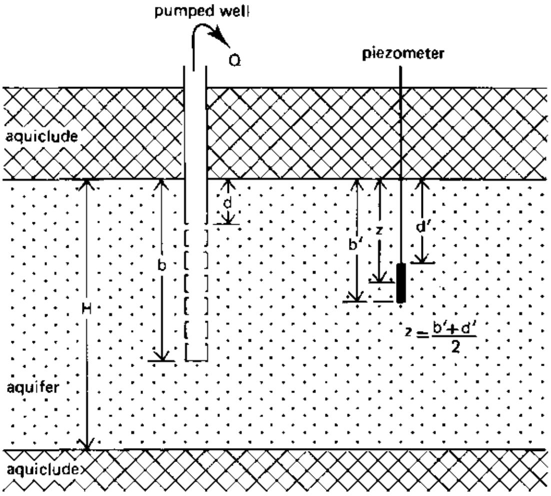


Figure 4.2 Schematic illustration of the parameters of the Hantush modification of the Jacob method for partial penetration

In Figure 4.3 the expression W(u) + f_s is plotted versus 1/u on semi-log paper. Figure 4.3 shows that this expression exhibits a straight-line segment. It can be shown that this straight-line segment will develop under the following conditions

$$1/u > 100, \text{ i.e. } t > 25\, r^2S/KH \tag{4.9}$$

$$f_s \text{ constant, i.e. } t > H^2S/2KH \tag{4.10}$$

If the latter condition is fulfilled, Equations 4.7 and 4.8 reduce to

$$f_s = \frac{4H^2}{\pi^2(b-d)(b'-d')} \sum_{n=1}^{\infty} \left(\frac{1}{n^2}\right) K_o\left(\frac{n\pi r}{H}\right) \times \left[\sin\left(\frac{n\pi b}{H}\right) - \sin\left(\frac{n\pi d}{H}\right)\right]\left[\sin\left(\frac{n\pi b'}{H}\right) - \sin\left(\frac{n\pi d'}{H}\right)\right] \tag{4.11}$$

and

$$f_s = \frac{4H}{\pi(b-d)} \sum_{n=1}^{\infty} \left(\frac{1}{n}\right) K_o\left(\frac{n\pi r}{H}\right) \left[\sin\left(\frac{n\pi b}{H}\right) - \sin\left(\frac{n\pi d}{H}\right)\right]\left[\cos\left(\frac{n\pi z}{H}\right)\right] \tag{4.12}$$

where

$$K_o\left(\frac{n\pi r}{H}\right) = \int_o^{\infty} \cos\left(\frac{n\pi r}{H}\sinh y\right) dy$$

This integral is known as the modified Bessel function of the second kind and zero order. Values of this function can be found in Appendix C.

It can be seen that for a given set of parameters Equations 4.11 and 4.12 yield constant values. On this phenomenon the Hantush's modification of the Jacob method was based. Hantush (1962) showed that for the straight-line segment Equation 4.6 can be approximated by

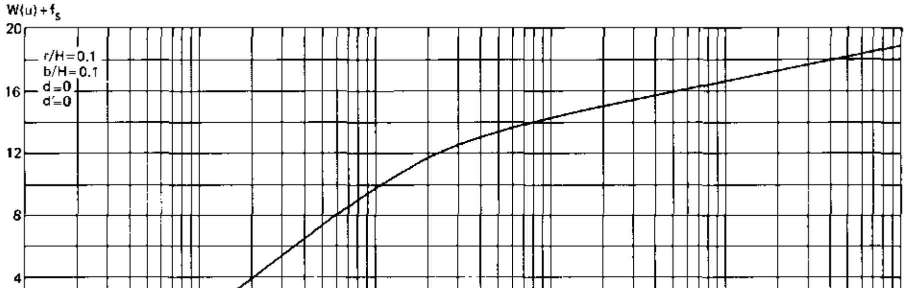


Figure 4.3 Hantush well function W(u) + f_s versus 1/u for partially penetrating wells in confined aquifers

$$s = \frac{2.30Q}{4\pi KH} \log \frac{2.25KHt}{r^2S} \times e^{f_s} \qquad (4.13)$$

If we use drawdown observations at a particular distance r from the pumped well, a plot of drawdown s versus the logarithm of time t will show a straight line, provided that the time of pumping t was long enough. If the slope of this straight-line segment is expressed as the drawdown difference ($\Delta s = s_1 - s_2$) per log cycle of time ($\log t_2/t_1 = 1$), rearranging Equation 4.13 gives

$$KH = \frac{2.30Q}{4\pi\Delta s} \qquad (4.14)$$

If the straight line is extended until it intercepts the time-axis where $s = 0$, the interception point has the coordinates $s = 0$ and $t = t_o$. Substituting these values into Equation 4.13 gives $\log [2.25KHt_oe^{f_s}/r^2S] = 0$ or $[2.25KHt_oe^{f_s}/r^2S] = 1$ or

$$S = \frac{2.25KHt_o}{r^2} e^{f_s} \qquad (4.15)$$

Hantush's modification of the Jacob method is based on the assumptions listed at the beginning of this chapter and on the following limiting conditions:

- The pumped well does not necessarily penetrate the entire thickness of the aquifer;
- The pumping time is long enough for a straight-line segment to be distinguished from a time-drawdown plot on semi-log paper.

Procedure

- For one of the wells, plot the drawdown values s versus the corresponding time t on semi-log paper (t on the logarithmic scale);
- Select a time range and draw a best fitting straight line through that part of the plotted points;
- Determine the slope of the straight-line, i.e. the drawdown difference Δs per log cycle of time;
- Substitute the values of Q and Δs into Equation 4.14 and solve for KH;
- Extend the straight line until it intercepts the time axis where $s = 0$, and read the value of t_o;
- Calculate f_s from Equation 4.11 or 4.12 as is applicable; a limited number of the series involved is generally sufficient;
- Substitute the values of KH, t_o, f_s, and r into Equation 4.15 and solve for S;
- Substitute the appropriate values into Equations 4.9 and 4.10 and solve for t. The largest t value should be less than the time range for which the straight-line segment was selected;
- If drawdown values are available for more than one well, apply above procedure to the other wells also.

Remarks

In Figure 4.3 the expression $W(u) + f_s$ exhibits apart from a straight-line segment an inflection point. Whether a time-drawdown plot shows such an inflection point, depends on the ratio of screen length and total thickness of the aquifer and on the ratio of distance to the pumped well and total thickness of the aquifer.

With increasing screen length compared to the total thickness of the aquifer, the value of f_s is decreasing resulting in a straight-line segment running parallel to the one as depicted in Figure 4.3, but at a lower position. With a screen length of 75 per cent of the total thickness of the aquifer, the inflection point cannot be determined any more from visual inspection. If the screen length is increased even further, the value of f_s approaches to zero, resulting in a type curve of W(u) as depicted in Figure 4.1.

The same phenomenon takes place when increasing the distance from the pumped well with respect to the total thickness of the aquifer. Depending upon the other parameters, the type curve as shown in Figure 4.3 reduces to the Theis well function W(u) for ratios of distance to the pumped well and total thickness in the range of one to two and beyond.

Finally, it must be noted that the Hantush modification of the Jacob method can also be applied to drawdown data of unconfined aquifers. It is then assumed that due to partial penetration the drawdowns will be small compared with the initial saturated thickness of the aquifer.

4.1.2 Leaky aquifers

When a leaky aquifer, as shown in Figure 4.4, is pumped, the piezometric level of the aquifer at the well is lowered, and this lowering spreads radially outward as pumping continues creating a difference in hydraulic head between the aquifer and the aqui-

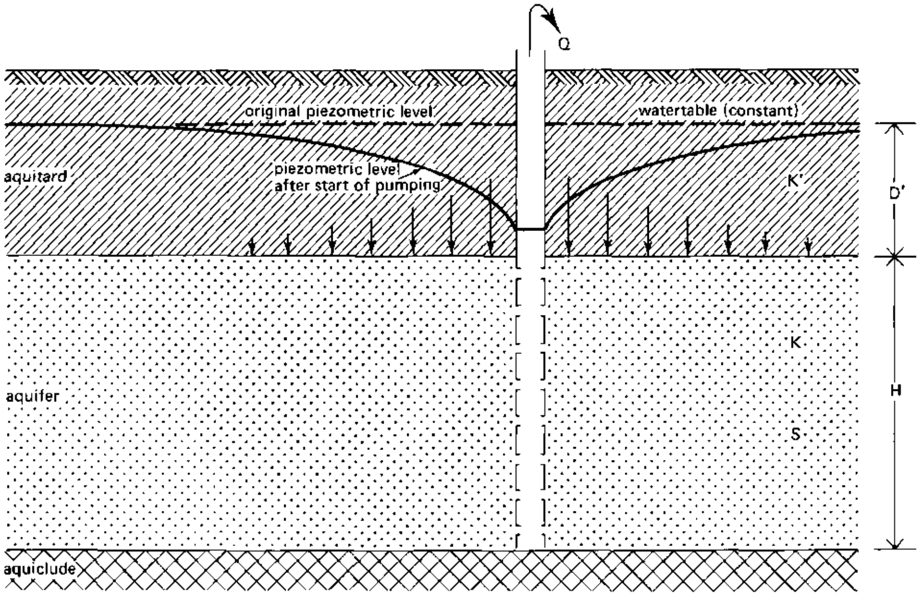


Figure 4.4 Schematic cross-section of a pumped leaky aquifer

tard. Consequently, the groundwater in this aquitard will start moving downward in a vertical direction to join the water in the aquifer. The aquifer is thus recharged by downward percolation from the aquitard. As pumping continues, the percentage of the total discharge derived from this percolation increases. After a certain period of pumping an equilibrium between the discharge rate of the pump and the recharge rate by vertical flow through the aquitard will be established. This steady state will be maintained as long as the phreatic level in the aquitard is kept constant.

Attention is drawn to the assumption that the leakage from the aquitard is proportional to the drawdown of the piezometric level of the aquifer. A consequence of this assumption is that the phreatic level in the aquitard should be constant or in practice that the drawdown of the phreatic level is less than five per cent of the thickness of the saturated part of the aquitard. When pumping tests of long duration are performed this assumption is generally not satisfied unless the phreatic level is recharged, for example by shallow ditches.

According to Hantush and Jacob (1955) the drawdown due to pumping a leaky aquifer can be described by the following formula

$$s = \frac{Q}{4\pi KH} \int_u^\infty \frac{1}{y} \exp\left(-y - \frac{r^2}{4L^2y}\right) dy = \frac{Q}{4\pi KH} W(u,r/L) \qquad (4.16)$$

and

$$u = \frac{r^2S}{4KHt} \qquad (4.17)$$

where

$L = \sqrt{KHc}$ = leakage factor (m)
$c = D'/K'$ = hydraulic resistance of the aquitard (d)
$W(u,r/L)$ = Hantush well function (Appendix B)

Equation 4.16 has the same form as the Theis equation (Equation 4.1), but there are two parameters in the integral: u and r/L. Equation 4.16 approaches the Theis equation for large values of L, when the exponential term $r^2/4L^2y$ approaches zero.

In Figure 4.5 the Hantush well function W(u,r/L) is plotted versus 1/u on semi-log paper for an arbitrarily value of r/L. Figure 4.5 shows that the Hantush well function exhibits an inflection point and for large values of 1/u a horizontal straight-line segment indicating steady-state flow. On these phenomena the inflection point method was based. Hantush (1956) showed that for the inflection point the following relationships hold

a.

$$s_p = 0.5\, s_m = \frac{Q}{4\pi KH} K_o\left(\frac{r}{L}\right) \qquad (4.18)$$

where K_o (r/L) is the modified Bessel function of the second kind and zero order and s_m is the steady-state drawdown;

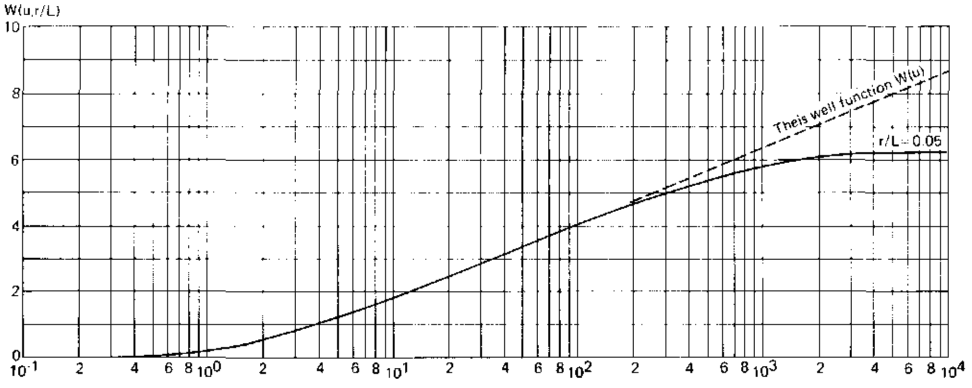


Figure 4.5 Hantush well function W(u,r/L) versus 1/u for fully penetrating wells in leaky aquifers

b.

$$u_p = \frac{r^2S}{4KHt_p} = \frac{r}{2L} \tag{4.19}$$

c. The slope of the curve at the inflection point Δs_p is given by

$$\Delta s_p = \frac{2.30Q}{4\pi KH} e^{-r/L} \tag{4.20}$$

d. At the inflection point, the relation between the drawdown and the slope of the curve is given by

$$2.30 \frac{s_p}{\Delta s_p} = e^{r/L} K_o(r/L) \tag{4.21}$$

In Equations 4.18 to 4.21, the index p means 'at the inflection point'. Further, Δs stands for the slope of a straight line.

Hantush inflection-point method is based on the assumptions listed at the beginning of this chapter and on the following limiting conditions

- The pumped well penetrates the entire thickness of the aquifer and thus receives water by horizontal flow;
- The phreatic level remains constant so that leakage through the covering layer takes place in proportion to the drawdown of the piezometric level;
- The pumping time is sufficiently long such that the steady-state drawdown can be estimated from extrapolation of a time-drawdown curve plotted on semi-log paper.

Procedure

- For one of the wells, plot the drawdown values s versus the corresponding time t on semi-log paper (t on logarithmic scale) and draw a curve that best fits through the plotted points;

- Determine from this plot the value of the steady-state drawdown s_m;
- Substitute the value of s_m into Equation 4.18 and solve for s_p. The value of s_p on the curve locates the inflection point p;
- Read the value of t_p at the inflection point from the time-axis;
- Determine the slope Δs_p of the curve at the inflection point. This can be closely approximated by reading the drawdown difference per log cycle of time over the straight portion of the curve on which the inflection point lies, or over the tangent to the curve at the inflection point;
- Substitute the values of s_p and Δs_p into Equation 4.21 and solve for $e^{r/L} K_0(r/L)$; by interpolation from values of this product which can be found numerically, find the value of r/L (see Appendix C);
- Calculate L from this r/L value and the r value of the well;
- Substitute Q, Δs_p, and r/L into Equation 4.20 and solve for KH;
- Substitute r, KH, t_p and L into Equation 4.19 and solve for S;
- Calculate c from the relation $c = L^2/KH$;
- If drawdown values are available for more than one well, apply above procedure to the other wells also.

Remarks

The accuracy of the calculated hydraulic characteristics depends on the accuracy of the value of the (extrapolated) steady-state drawdown s_m. The calculations should therefore be checked by substituting the different values into Equations 4.16 and 4.17. Calculations of s should be made for the observed values of t. If the values of t are not too small, the values of s should fall on the observed data curve. If the calculated data deviate from the observed data, the (extrapolated) value of s_m should be adjusted. Sometimes, the observed data curve can be drawn somewhat steeper or flatter through the plotted points, and so Δs_p can be adjusted too. With the new values of s_m and/or Δs_p, the calculation is repeated.

4.1.3 Unconfined aquifers

Figure 4.6 shows a pumped unconfined aquifer underlain by an aquiclude. There are the following basic differences between unconfined and confined aquifers when they are pumped:

- First, an unconfined aquifer is partly dewatered during pumping, whereas a confined aquifer remains fully saturated;
- Second, the water produced by a well in an unconfined aquifer comes from the physical dewatering of the aquifer, whereas in a confined aquifer it comes from the expansion of the water in the aquifer due to a reduction of the water pressure, and from the compaction of the aquifer due to increased effective stresses;
- Third, the flow towards the well in an unconfined aquifer has clear vertical components near the pumped well, whereas there are no such vertical flow components in a confined aquifer, provided, of course, that the well is fully penetrating.

Jacob (1950) showed that if the drawdowns in an unconfined aquifer are small compared with the initial saturated thickness of the aquifer, the condition of horizontal

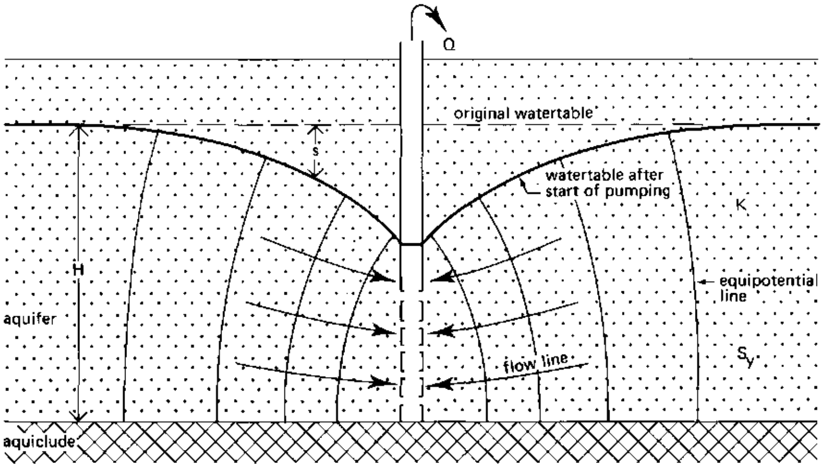


Figure 4.6 Schematic cross-section of a pumped unconfined aquifer

flow towards the well is approximately satisfied, so that the Theis equation (Equations 4.1 and 4.2) can be applied to determine the hydraulic characteristics. The only changes required are that the storativity S in the argument of the Theis well function be replaced by the specific yield S_y of the unconfined aquifer, and that the transmissivity KH be defined as the transmissivity of the initial saturated thickness of the aquifer.

When the drawdowns in an unconfined aquifer are large compared with the aquifer's original saturated thickness, the analysis as described in Section 4.1.1 should be based on corrected drawdown data. Jacob (1944) proposed the following correction

$$s_c = s - (s^2/2H) \tag{4.22}$$

where

s_c = corrected drawdown (m)
s = observed drawdown (m)
H = original saturated aquifer thickness (m)

It should be noted that the drawdown data in an unconfined aquifer usually shows a 'delayed yield' effect. The delayed yield is caused by a time lag between the early elastic response of the aquifer and the subsequent downward movement of the watertable due to gravity drainage. When the time-drawdown curve is plotted on semi-log paper, it shows then a typical S shape: a relatively steep early-time segment, a flat intermediate segment, and a relatively steep segment again at later times (see Figure 4.7).

During the early stage of an aquifer test – a stage that may last for only a few minutes – the discharge of the pumped well is derived uniquely from the elastic storage within the aquifer. Hence, the reaction of the unconfined aquifer immediately after the start of pumping is similar to the reaction of a confined aquifer as described by the flow equation of Theis.

Only after some time the watertable starts to fall and the effect of the delayed yield

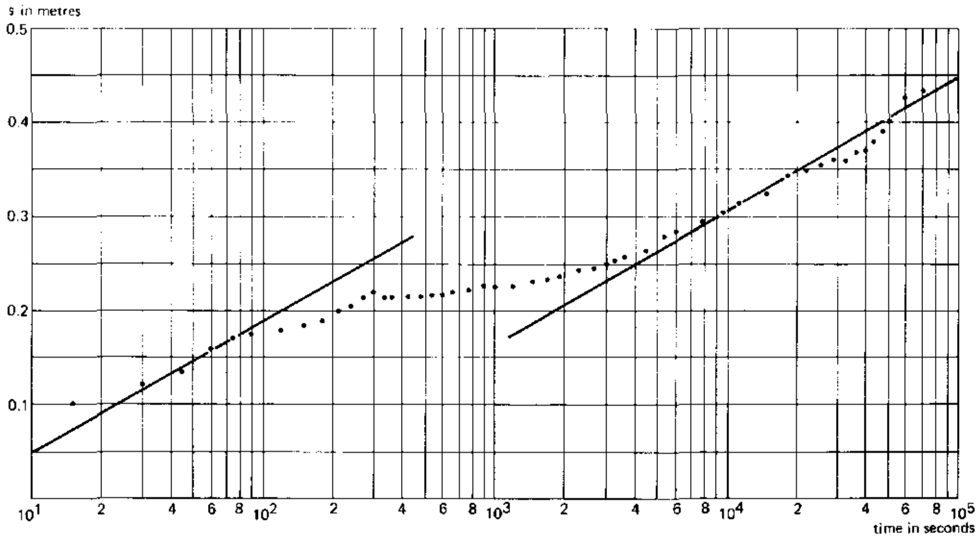


Figure 4.7 Time-drawdown plot in an unconfined aquifer showing delayed yield

becomes apparent. The influence of the delayed yield is comparable to that of leakage: the average drawdown slows down with time and no longer conforms to the Theis curve. After a few minutes to a few hours of pumping, the time-drawdown curve approaches a horizontal position.

The late-time segment of the time-drawdown curve may start from several minutes to several days after the start of pumping. The declining watertable can now keep pace with the increase in the average drawdown. The flow in the aquifer is essentially horizontal again and as in the early pumping time the time-drawdown curve approaches the Theis curve.

Neuman (1975) showed that using the method of analysis discussed in Section 4.1.1 the different hydraulic characteristics including the anisotropy in hydraulic conductivity may be determined. He outlined the following procedure:

1. A straight line is fitted to the late portion of the time-drawdown data, yielding values of the transmissivity and specific yield of the aquifer by applying Jacob's method;
2. A horizontal line is fitted to the intermediate portion of the time-drawdown data. The value of t_β corresponding to the intersection of this horizontal line with the straight-line passing through the late data is then determined. The dimensionless time $t_{y\beta}$ is calculated according to the following equation

$$t_{y\beta} = \frac{KHt_\beta}{r^2S_y} \qquad (4.23)$$

For the relationship between β and $t_{y\beta}$ Neuman presented Table 4.1.

Table 4.1 Values of $1/\beta$ and $t_{y\beta}$

$1/\beta$	$t_{y\beta}$	$1/\beta$	$t_{y\beta}$	$1/\beta$	$t_{y\beta}$
0.250	0.452	0.67	0.545	16.7	3.10
0.167	0.455	1.00	0.611	33.3	5.42
0.200	0.459	1.25	0.660	100.0	14.20
0.250	0.467	1.67	0.739	250.0	32.20
0.333	0.481	2.50	0.893	1000.0	123.00
0.400	0.494	5.00	1.310		
0.500	0.513	1.00	2.100		

He stated that a good approximation for this relationship within the range $4 < t_{y\beta} < 100$ is given by the equation

$$\beta = \frac{0.195}{t_{y\beta}^{1.1053}} \tag{4.24}$$

Using either the values of Table 4.1 or Equation 4.24 the value of β can now be calculated. The ratio between the horizontal and vertical hydraulic conductivity is given by

$$\frac{K_V}{K_H} = \beta \frac{H^2}{r^2} \tag{4.25}$$

3. A straight-line is fitted to the portion of the early time-drawdown data, yielding values of the transmissivity and storativity of the aquifer. If the transmissivity obtained from this step differs markedly from that of Step 1, the results of Step 3 should be discarded.

Neuman also showed that the drawdown correction as given in Equation 4.22 is strictly applicable only to the late drawdown data and is not applicable to the early and intermediate data. He therefore recommended that Equation 4.22 be used only in the determination of the KH and S_y from the late drawdown data and not in the determination of β, KH, and S from the early and intermediate data.

It must be noted that Step 2 of the analysis method as outlined by Neuman has not been incorporated in the computer program package.

4.2 Analysis methods recovery data

After a well has been pumped for a certain period of time pt and is shut down, the water level in the pumped well and in the piezometers – if present – will stop falling and start to rise again to its original position. This recovery of the water level can be measured as residual drawdown s′, i.e. as the difference between the original water level prior to pumping and the actual water level measured at a certain moment t′ since pumping stopped (see Figure 4.8).

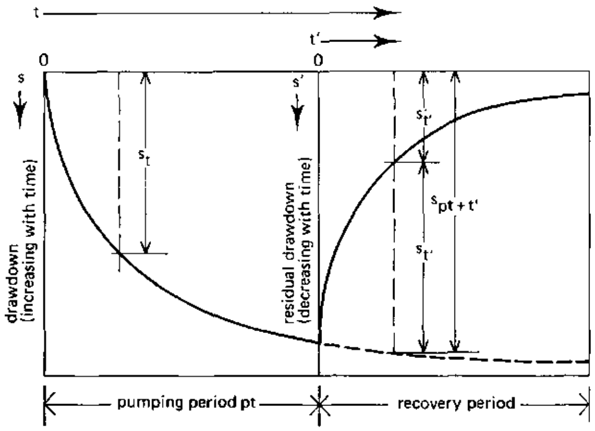


Figure 4.8 Time-drawdown behaviour during a pumping and recovery test

This residual drawdown s′ at time t′ is also equal to the difference between the drawdown caused by pumping the well with a discharge Q during the hypothetical time pt + t′ and the recovery caused by injecting water at the same point at the same rate Q by a hypothetical injection well during time t′

$$s'(t') = s(pt+t') - s(t') \tag{4.26}$$

Based on this principle, the recovery values s(t′) can be calculated if the hypothetical drawdown values s(pt + t′) can be estimated. This can be done when the drawdown data during pumping were analyzed using one of the methods given in Section 4.1. By back-substituting the obtained hydraulic characteristics into the appropiate equations, hypothetical values of s(pt + t′) are calculated. When from these the observed residual-drawdown data s′(t′) are subtracted, synthetic recovery values s(t′) are obtained. An analysis based on recovery data is identical to that of drawdown data. So, any of the methods discussed in Section 4.1 can also be used to analyze the recovery data.

Instead of using synthetic recovery data, residual-drawdown data can be used directly in the analysis. The so-called Theis recovery method is also based on the principle as written in Equation 4.26. With this method only the transmissivity value can be determined.

4.2.1 Confined aquifers

The residual drawdown s′, during the recovery period after a constant rate pumping test, is according to Theis (1935) given by

$$s' = \frac{Q}{4\pi KH}\{W(u) - W(u')\} \tag{4.27}$$

and

$$u = \frac{r^2S}{4KHt} \text{ or } u' = \frac{r^2S'}{4KHt'} \tag{4.28}$$

where
s' = residual drawdown (m)
S' = storativity during recovery (–)
t = pt + t' = time since pumping started (d)
t' = time since pumping stopped (d)

In Figure 4.9 the expression W(u)-W(u′) is plotted versus u′/u on semi-log paper. Figure 4.9 shows that this expression exhibits a straight-line segment. It can be shown that this straight-line segment will develop for u′ values smaller than 0.01. This results in the following limiting condition

$$u'/u = \frac{S't}{S\,t'} < \frac{S'}{S}\left(1 + \frac{4\,KH}{r^2S'}\,\frac{pt}{100}\right) \tag{4.29}$$

If S′/S is assumed to be unity and when the value of $4KH/r^2S' = 1440$, Equation 4.29 reduces then to that u′/u or t/t′ should be smaller than 1 + pt/100, where pt is the pumping time in minutes. In drawing Figure 4.9 the pt value was taken as 7900 min.

When u′ is sufficiently small ($u' < 0.01$) – the value of u is then also smaller than 0.01 provided that S′/S = 1 – Equation 4.27 may be approximated by

$$s' = \frac{2.30Q}{4\pi KH} \log \frac{S't}{S\,t'} \tag{4.30}$$

If we use residual-drawdown observations at a particular distance r from the pumped well, a plot of residual drawdown s′ versus the logarithm of the time ratio t/t′ will

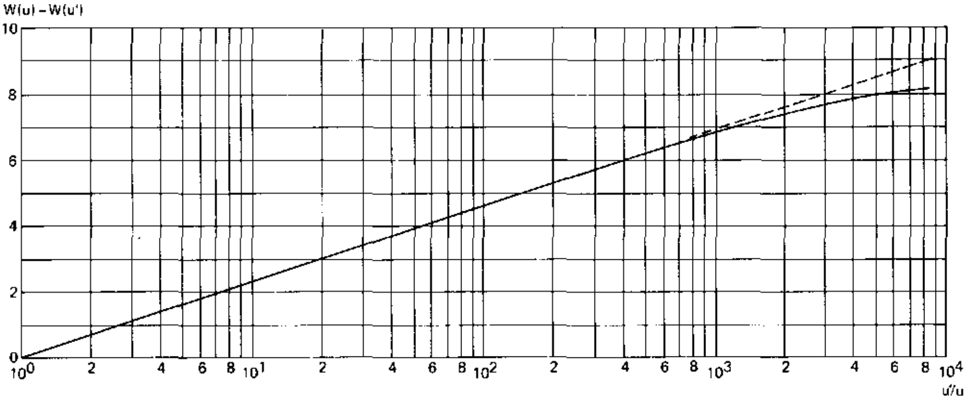


Figure 4.9 Theis recovery well function W(u) – W(u') versus u'/u for fully penetrating wells in confined aquifers

show a straight line, provided that the time of pumping pt was long enough. If the slope of this straight-line segment is expressed as the drawdown difference ($\Delta s' = s'_1 - s'_2$) per log cycle of the time ratio, rearranging Equation 4.30 gives

$$KH = \frac{2.30Q}{4\pi\Delta s'} \tag{4.31}$$

If the straight line is extended until it intercepts the time-axis where $s' = 0$, the interception point has the coordinates $s = 0$ and $t/t' = (t/t')_o$. Substituting these values into Equation 4.30 gives $\log [S't/St'] = 0$ or $[S't/St'] = 1$ or

$$S' = S\,(t/t')_o \tag{4.32}$$

The Theis recovery method is based on the assumptions listed at the beginning of this chapter and on the following limiting conditions:

- The pumped well penetrates the entire thickness of the aquifer and thus receives water by horizontal flow;
- The pumping time is sufficiently long that a straight-line segment can be distinguished from a time-residual drawdown plot on semi-log paper.

Procedure

- For one of the wells, plot the residual-drawdown values s' versus the corresponding time ratio t/t' on semi-log paper (t/t' on logarithmic scale);
- Select a time-ratio range and draw a best fitting straight line through that part of the plotted points;
- Determine the slope of the straight line, i.e. the drawdown difference $\Delta s'$ per log cycle of time ratio t/t';
- Substitute the values of Q and $\Delta s'$ into Equation 4.31 and solve for KH;
- Extend the straight line until it intercepts the time-ratio axis where $s' = 0$, and read the value of $(t/t')_o$;
- Substitute this value and the value of the storativity obtained from analyzing the drawdown data into Equation 4.32 and solve for S';
- Substitute the values of pt, KH, r, and S' into Equation 4.29 and solve for t/t'. This t/t' value should be greater than the time-ratio range for which the straight-line segment was selected;
- If residual-drawdown values are available for more than one well, apply above procedure to the other wells also.

Remarks

When for a leaky aquifer the residual-drawdown data are plotted versus t/t' on semi-log paper, the plot will usually show an S curve like the one as depicted in Figure 4.5. If these data are analyzed with the Theis recovery method using the slope of the inflection point, the transmissivity value will be overestimated (compare Equations 4.4 and 4.20) and the storativity value S' underestimated, because the $(t/t')_o$ value is greater than one. The Theis recovery method can only be used for leaky aquifers when the r/L value is small. This is usually the case when the residual-drawdown data of the pumped well itself are being analyzed.

5 Program package SATEM

Once the microcomputer has been loaded with the appropriate operating system, the actual program package is initialized by typing SATEM and pressing the carriage return key. This key will be marked with either an angle arrow, the word ENTER, or the word RETURN. From here on, this key will be referred to as the ENTER key.

The screen first displays general information regarding the program package SATEM followed by a main menu showing the different analysis programs. From this menu the user can select the appropriate program.

5.1 Program features

The program package SATEM consists of four different programs for the analysis and evaluation of aquifer and single-well test data. These programs are based on the different theories and corresponding analysis methods as were discussed in Chapter 4. Table 5.1 gives an overview of the main characteristics of these programs.

Table 5.1. Overview of the main characteristics of different programs

	JACOB	HANTUSH	PARTIAL	RECOVERY
aquifer test	+	+	+	+
single-well test	+	+	+	+
fully penetrating	+	+	+	+
partially penetrating	–	–	+	–
confined	+	+	+	+
leaky	–	+	–	–
unconfined	+	–	+	+
drawdown	+	+	+	–
recovery	+	+	+	–
residual	–	–	–	+

The presented programs have the following features in common.
They are fully interactive. The input to the programs is in the form of keybord entries. During the interactive session the user is confronted with basically two types of questions:

- Questions that require a yes or no answer. These are followed by (Y/N)? or (N/Y)? If the question ends with (Y/N)? and the answer is yes, type Y (or y) and press the ENTER key, or simply press the ENTER key. If the question ends with (N/Y)? and the answer is no, type N (or n) and press the ENTER key, or simply press the ENTER key;

- Questions about the displayed values of the input data. These are followed by a question mark only. If the value displayed is correct, simply press the ENTER key. If not, type in the correct value after the question mark and then press the ENTER key.

The above conventions keep to a minimum the steps that the user must complete.

In each program a standard set of relevant input data concerning an aquifer test is build in. These sets of input data can be used either to get acquainted with the programs or to change them according to the actual data the user would like to analyze. These new data can be stored in files to be used later for other analyses.

The programs always display the results of the analyses on the screen, both in a graphical and in a tabular form. While the programs give the user the option of printing the results of the analysis, a line printer is not needed to run the programs.

5.2 General structure

The four programs have an identical structure, except for the actual analysis. After selecting the appropriate analysis program, the user is confronted with the following sequence of screen information.

Screen 1

This screen deals with the data to be used for the analysis. The user has basically three options: to use the standard data to get acquainted with the program, to change the standard data into his own data, or to use data which he already stored in a file during a previous session. In the latter case, the user should specify the name of that file.

Each program has as option that all file names already stored in previous sessions will appear in the top of the screen, allowing the user to select the proper one. These displayed file names are followed by an extension. It must be noted that in specifying an existing file name, the extension should be omitted.

Each of the four programs automatically adds an extension to the file name whenever the user stores the data of a particular test. This is done to identify which file names can be used later on for a particular program. File names with the extension FTW can be analyzed with the programs JACOB, HANTUSH, and PARTIAL, while file names with the extension REC can be analyzed with the program RESIDUAL only.

Screen 2

This screen shows the relevant data of the test site. The displayed values are either the standard data or the previously stored data. The user can change them or keep them as they are. For all four programs the discharge of the pumped well in m^3/day, the pumping time in min, and the total number of wells for which observations are available, are being required.

For the program JACOB the type of aquifer is also being required. The user has the option to choose between confined and unconfined. To change the displayed aquifer type, type N (or n) and press the ENTER key, otherwise simply press the ENTER key. When unconfined is selected, the saturated thickness of the aquifer prior to pumping should be given. For unconfined aquifers the program JACOB adjusts the observed drawdown values according to Equation 4.22. It must be noted that these adjustments are only made within the analysis. The stored drawdown data remain unaffected.

For the program PARTIAL the length over which the pumped borehole penetrates the aquifer and the screen length of the pumped borehole is also required.

Screen 3

This screen shows the relevant data for each well for which observations are available. Four all four programs the distance of each well to the pumped well in m and the total number of observations for each well are required. For all the programs the observations in the pumped well itself can be used in the analysis. The effective radius of the pumped well should then be given in stead of the distance.

For the programs JACOB, HANTUSH, and PARTIAL the type of observations is also required. The user has the option of choosing between drawdown data during pumping or residual-drawdown data during recovery. To change from 'drawdown' to 'residual' or vice versa, type N (or n) and press the ENTER key, otherwise simply press the ENTER key. When residual-drawdown data are selected, these programs convert them to recovery data. This is being done in the following way. Using the hydraulic characteristics which were found from the analysis of the drawdown data, the programs calculate hypothetical drawdown values under the assumption that pumping continues during the recovery. From these the observed residual-drawdown data are subtracted yielding synthetic recovery data. The analysis based on recovery data is identical to that of drawdown data as was discussed in Chapter 4, Section 1.

It must be noted that for each well the available residual-drawdown data during recovery are prescribed directly after the drawdown data of the same well during pumping. Otherwise the above calculation procedure based on residual-drawdown data will yield erroneous results.

For the program PARTIAL the length over which the observation well penetrates the aquifer and the screen length of this observation well is also required. It must be noted that for piezometers the screen length should be equal to zero.

Screen 4

This screen shows for each well the actual drawdown values in cm as function of time in min since pumping started. For residual-drawdown values the time since the pump was shut down should be prescribed.

When ten time and (residual) drawdown values are displayed, the user is asked if the above values are correct. If so, the next ten pair values are successively being displayed. This is being repeated till the total number of observed (residual) drawdown values as specified in Screen 3 for that well have been displayed.

The next screen, if any, shows for the next well the time-(residual) drawdown data. This is repeated till the total number of wells as specified in Screen 2 have been displayed.

If the user would like to remove a certain drawdown value which was stored in a file during a previous session, he can do so by prescribing a negative value for the corresponding time.

When above data are not available as (residual) drawdown values in cm versus time in min, use can be made of the auxiliary program INPUT. For more information, the user is referred to Appendix D.

Screen 5
This screen allows the user to store the data in a file for later use. The user should type a particular name to identify the file. The name should contain less than nine characters. The actual program will automatically add its extension to this name. The programs JACOB, HANTUSH, and PARTIAL add FTW to the file name as extension, while the program RESIDUAL adds REC as extension.

Screen 6
This screen displays a semi-log plot of the time-drawdown data for the first well. The actual analysis is based on visual inspection of this plot. Each program poses questions which the user can answer in a trial and error fashion. These questions are different for each program and will be discussed when dealing with the individual programs.

The next screen, if any, shows the time-recovery data for the same well or the time-drawdown data for the next well. This is being repeated till the total number of wells as specified in Screen 2 have been displayed.

Screen 7
This screen displays the final results of all the different wells used in the analysis. The screen also allows the user either to use the same analysis program to re-evaluate the same data or to evaluate data from another test, or to return to the main menu of SATEM. The user can then either select another analysis program or terminate SATEM.

5.3 Individual programs

In the previous section the general structure of all the four programs was discussed, i.e. the seven types of screen information. Here, only the information presented in Screen 6 is dealt with. This is the information used to make the analysis. For each of the four programs, guidelines are given on how to use the information presented in Screen 6. This is done by using theoretical data to show the particular features of the different solutions. In each program these theoretical data sets are included for educational purposes.

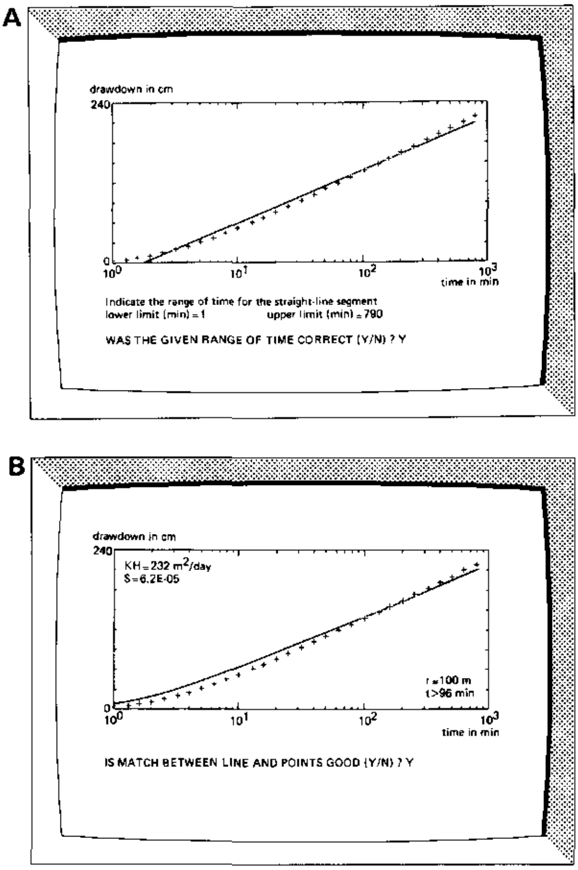
The user is advised to read this section completely before selecting a specific program. Features common to the four programs are not illustrated repeatedly in every program but are distributed over the different programs.

5.3.1 Program JACOB

The analysis method used in JACOB is based on the procedure as described in Chapter 4, Section 1.1 based on the Jacob's modification of the Theis method. The theoretical data set for JACOB consists of both drawdown data during pumping and residual-drawdown data during recovery of an observation well at a distance of 100 m from the pumped well. These drawdowns were calculated using the following hydraulic characteristics: KH = 200 m^2/day and S = 0.0001.

Screen 6 starts with a semi-log plot of the time-drawdown data of this well. From visual inspection the user is requested to prescribe the range of time for which the data plot exhibits a straight-line segment. The program shows as initial estimate for the lower limit the time that the first observation was made, and as initial estimate for the upper limit the time that the last observation was made. Suppose they do not have to be changed.

The next screen shows the same plot, but now with the selected straight-line segment. The program calculates this straight-line segment using linear regression and takes into account only that part of the drawdown data within the prescribed time range. Figure 5.1.A shows this screen. The option now exists to change the time range, if it is not satisfactory, or to continue. Although it is clear that the initial time range is not correct, the supposition is made that the user continues.



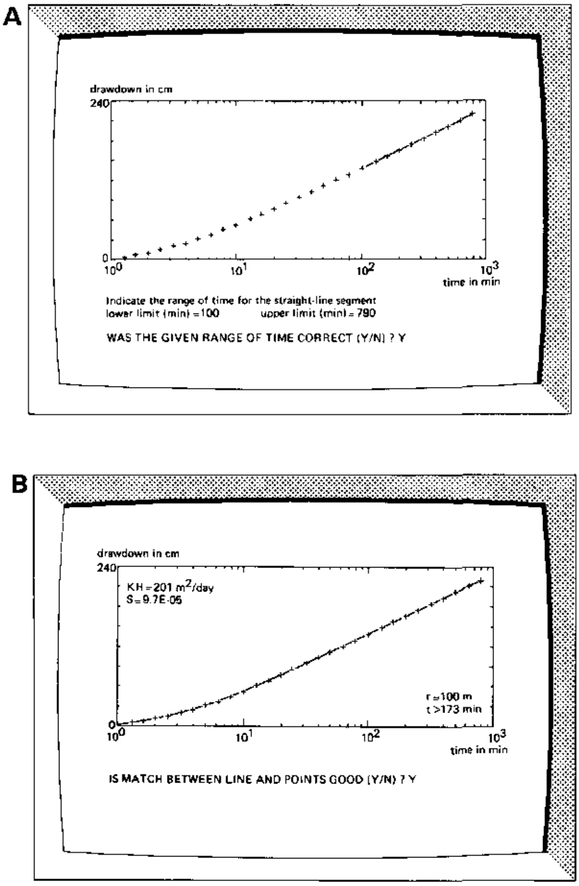
```
Indicate the range of time for the straight-line segment
lower limit (min) = 1              upper limit (min) = 790

WAS THE GIVEN RANGE OF TIME CORRECT (Y/N) ? Y
```

```
IS MATCH BETWEEN LINE AND POINTS GOOD (Y/N) ? Y
```

Figure 5.1 Screen 6 of the program JACOB
A: not correct determination of the straight-line segment
B: match of drawdown data with theoretical curve

The program now calculates the hydraulic characteristics according to the position of the straight-line segment selected. The transmissivity is calculated according to Equation 4.4 and the storativity according to Equation 4.5. In addition, the program calculates the time for which the 1/u value is 100, substituting in Equation 4.2 the hydraulic characteristic values from the analysis and the distance from the pumped well. These values are displayed on the next screen together with a line representing the calculated drawdowns. The program calculates these drawdowns according to Equations 4.1 and 4.2. Figure 5.1.B shows this screen. The option now exists of continuing or going back. From Figure 5.1.B it is clear that the match is not good, both from visual inspection and the indicated critical time value (96 min). The user must go back.

The lower limit is now changed from 1 to 100. Figure 5.2.A shows a different straight-line segment. From visual inspection it now proves satisfactory and the user can continue. Figure 5.2.B shows the new results of the analysis together with the



```
Indicate the range of time for the straight-line segment
lower limit (min) =100          upper limit (min) = 790

WAS THE GIVEN RANGE OF TIME CORRECT (Y/N) ? Y
```

```
KH = 201 m2/day
S = 9.7E-05

r = 100 m
t >173 min

IS MATCH BETWEEN LINE AND POINTS GOOD (Y/N) ? Y
```

Figure 5.2 Screen 6 of the program JACOB
A: correct determination of the straight-line segment
B: match of drawdown data with theoretical curve

calculated drawdowns. The match is now very good, although the critical time value (173 min) is higher than the lower time limit prescribed (100 min). The change of critical time value is due to the change in the transmissivity and storativity values. By returning once more and changing the lower time limit from 100 to 200, it will be seen that the new values are almost identical to the ones shown in Figure 5.2.B. This is not so surprising because the restriction that the value of 1/u should be greater than 100, is only a relative indication as can be seen from Figure 4.1. It can be shown that numerically, for instance, for a 1/u value of 10 the drawdown according to Equation 4.1 is only 5 per cent different from the one according to Equation 4.3. This slight deviation from the straight-line segment can hardly be seen from visual inspection.

If the user is satisfied with the analysis the option exists of putting the results as presented in Figure 5.2.B on paper.

The program now repeats the above procedure for the data of the next well. In this case they are residual-drawdown data of the same well observed during recovery. For the analysis of residual-drawdown data the program converts these into synthetic recovery values. These recovery values are calculated as the difference between the hypothetical drawdown values as if pumping continues and the observed residual-drawdown data. For the calculation of these hypothetical drawdown values the hydraulic characteristics found in the previous analysis are used. So, it must be noted that the synthetic recovery values are influenced by the analysis of the drawdown data of the same well.

Screen 6 shows a semi-log plot of these time-recovery data. In Chapter 4, Section 2 it has already been shown that the analysis based on recovery data is identical to that of drawdown data. Changing the lower time limit from 1 to 100 will give almost identical results as with the analysis of the drawdown data of this well. This is no surprise because the residual-drawdown data are also theoretical.

In applying the program JACOB to unconfined aquifers, the user should follow a somewhat different procedure. Firstly JACOB should be applied to the late-time data specifying an unconfined aquifer. The late-time data are then corrected according to Equation 4.22 yielding values of the transmissivity and specific yield of the aquifer. Next, if the early-time data also show a straight-line segment, JACOB should be applied again but now specifying a confined aquifer. The late-time data are then not corrected, yielding, according to Neuman (1975), the proper values of the transmissivity and elastic storativity of the aquifer.

5.3.2 Program HANTUSH

The analysis method used in HANTUSH is based on the procedure as described in Chapter 4, Section 1.2. The theoretical data set for HANTUSH consists of drawdown data of an observation well at a distance of 100 m from the pumped well and of the pumped well itself. These drawdowns were calculated using the following hydraulic characteristics: $KH = 200\ m^2/day$, $S = 0.0001$, and $c = 300$ days.

Screen 6 starts again with a semi-log plot of the time-drawdown data of the observation well. From visual inspection the user is requested to prescribe the (extrapolated) steady-state drawdown. The program shows as initial estimate the drawdown of the last observation. Suppose, it does not have to be changed.

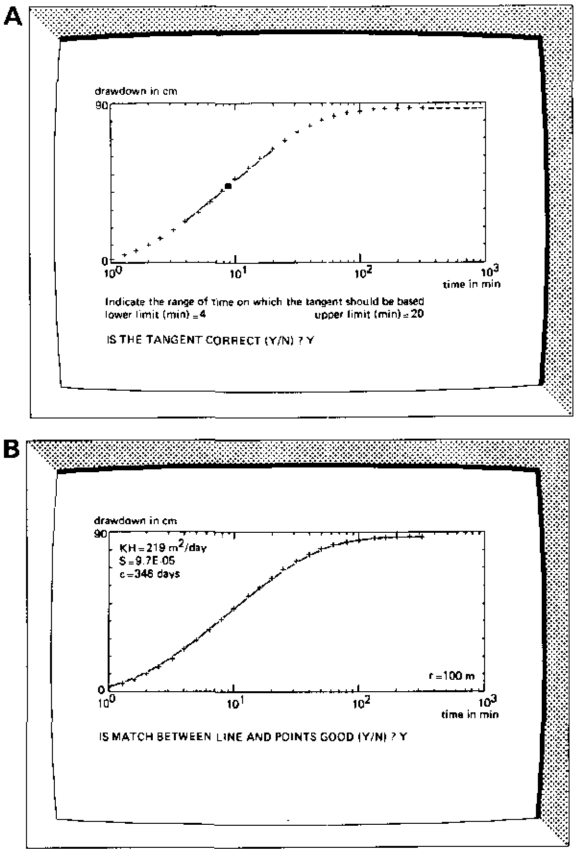
The next screen shows the same plot, but now with the level of the selected steady-state drawdown (dotted straight line) and with the location of the inflection point (filled-in square). Again from visual inspection the user is requested to prescribe the range of time for which the data plot exhibits a straight-line segment around this inflection point. When a straight-line segment is not present, the range of time to determine the tangent around the inflection point should be indicated. The program shows as initial estimate for the lower limit the time that the first observation was made, and as initial estimate for the upper limit the time that the last observation was made. Suppose they are changed as follows: lower limit = 4 min. and upper limit = 20 min.

The screen shows now in addition the selected straight-line segment. The program calculates this straight-line segment using linear regression and takes into account only that part of the drawdown data within the prescribed time range. Figure 5.3.A shows this screen. There is now the option of changing the time range, if the user is not satisfied, or continuing. Suppose the user continues.

The program now calculates the hydraulic characteristics according to the location of the inflection point and the slope selected, substituting the appropriate values into Equations 4.18 to 4.21. These values are displayed on the next screen together with a line representing the calculated drawdowns. The program calculates these drawdowns according to Equations 4.16 and 4.17. Figure 5.3.B shows this screen. Again there is the option of continuing or going back. Although the match is satisfactory, the calculated hydraulic characteristics differ some 10 per cent from the ones which were used to calculate the theoretical drawdowns. Suppose the user is not satisfied and goes back.

When the lower limit is changed from 4 to 7.5 min. and the upper limit from 20 to 10 min., the match is almost perfect and the hydraulic characteristics obtained from the analysis are now almost identical to the ones which were used to calculate the theoretical drawdowns. The conclusion from this is that for the determination of the slope of the inflection point the smallest possible time range around the inflection point should be selected, provided that the plotted data show a smooth distribution.

The program now repeats the above procedure for the data on the next well. In this case they are drawdown data of the pumped well itself. Figure 5.4 shows the semi-log plot together with the dotted straight line representing the steady-state drawdown, if the last observation is selected as representing this level. From Figure 5.4 it can be seen that the location of the inflection point is not indicated. The reason for this is that it falls outside the plot. In fact, it can not be located because its time coordinate cannot be fixed. In these situations, which are typical for time-drawdown data of the pumped well itself, the user is advised to take the first two or three observations as time range for determining the slope. Suppose lower limit 1 is taken and as upper limit 1.5 min. The program now determines internally the location of the inflection point by extrapolating the selected slope through the observation which was selected as the lower limit, till it intersects the horizontal line representing half the steady-state drawdown value. The resulting match is fairly good and the transmissivity value is close to the correct one. No values are given for the storativity of the tested aquifer and for the hydraulic resistance of the aquitard. The reason for this will be explained in Chapter 6, Section 3.4.



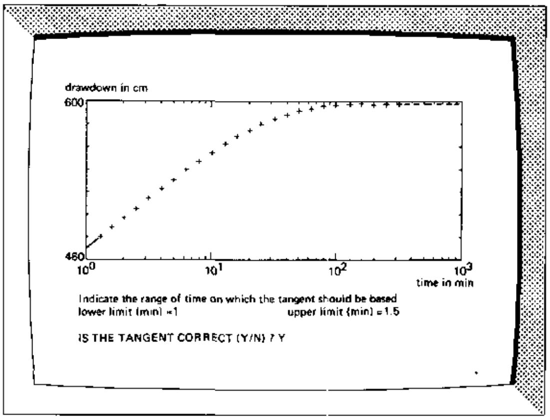
```
Indicate the range of time on which the tangent should be based
lower limit (min) =4                         upper limit (min)=20

IS THE TANGENT CORRECT (Y/N) ? Y
```

```
KH=219 m2/day
S=9.7E-05
c=346 days
r=100 m

IS MATCH BETWEEN LINE AND POINTS GOOD (Y/N) ? Y
```

Figure 5.3 Screen 6 of the program HANTUSH

A: correct determination of steady-state drawdown and slope of inflection point

B: match of drawdown data with theoretical curve



```
Indicate the range of time on which the tangent should be based
lower limit (min) =1                         upper limit (min) =1.5

IS THE TANGENT CORRECT (Y/N) ? Y
```

Figure 5.4 Screen 6 of the program HANTUSH: correct determination of steady-state drawdown and slope of inflection point

5.3.3 Program PARTIAL

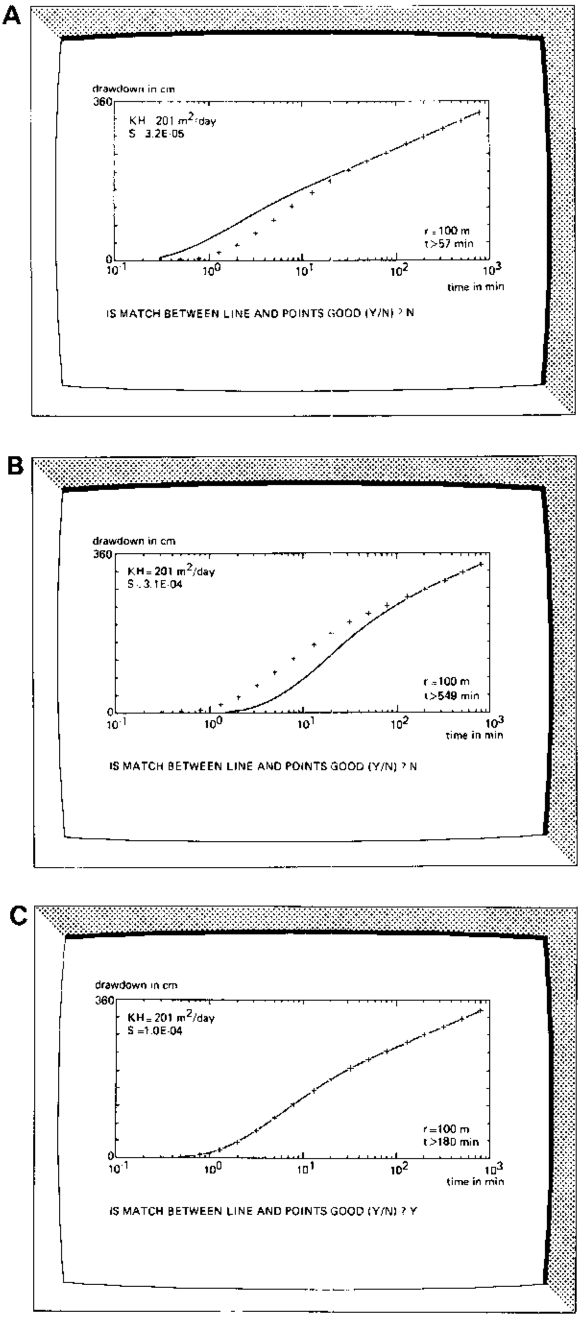
The analysis method used in PARTIAL is based on the procedure as described in Chapter 4, Section 1.1 based on the Hantush's modification of the Jacob method. The theoretical data set for PARTIAL consists of drawdown data of an observation well at a distance of 100 m from the pumped well. These drawdowns were calculated using the following hydraulic characteristics: $K = 0.4$ m/day, $H = 500$ m, and $S = 0.0001$. Both the pumped well as the observation well penetrated the aquifer to a depth of 100 m; the lower 50 m of these wells were screened. Apart from the partial penetration, the data set is identical to that used in the program JACOB.

With Screen 6 the user is confronted with a semi-log plot of the time-drawdown data of the observation well. From visual inspection the range of time for which the data plot exhibits a straight-line segment must be prescribed. The program shows as initial estimate for the lower limit the time that the first observation was made, and as initial estimate for the upper limit the time that the last observation was made. Suppose, the lower limit is changed from 0.32 to 100.

Now the screen shows in addition the selected straight-line segment. The program calculates this straight-line segment using linear regression and takes into account only that part of the drawdown data within the prescribed time range.

The thickness of the aquifer must now be prescribed. Suppose it is kept as 400 m. The program now calculates the hydraulic characteristics according to the position of the straight-line segment selected. The transmissivity value is calculated according to Equation 4.14 and the storativity value according to Equation 4.15. In addition, the program calculates both the time for which the u value is 0.01, substituting the appropriate values into Equation 4.9, and the time for which the f_s value has reached its maximum value and is constant, substituting the appropriate values into Equation 4.10. The largest value of these two and the values of the hydraulic characteristics are displayed on the next screen together with a line representing the calculated drawdowns. The program calculates these drawdowns according to Equations 4.6 to 4.8. Figure 5.5.A shows this screen. The option exists of continuing or going back. The match is clearly very poor in the early-time data. So the user goes back.

The time range describing the straight-line segment is not changed because the match for the later-time data was good. Instead, the thickness of the aquifer is changed from 400 to 600 m. Figure 5.5.B shows the results. The match is again very poor for the early-time data, but now the calculated drawdowns lie at the opposite site with respect to Figure 5.5.A. The thickness of the aquifer apparently lies between 400 and 600 m. The thickness of the aquifer is again changed from 600 to 505 m. Figure 5.5.C shows the results. The match is now perfect and the hydraulic characteristics obtained from the analysis are now almost identical to the ones which were used to calculate the theoretical drawdowns. Although the match is good, the critical time (180 min.) is higher than the lower time limit prescribed (100 min.). If the lower time limit is changed from 100 to 200, it will be seen that the values are almost identical to the ones shown in Figure 5.5.C. The reason for this is the same as was discussed for the critical time with the program JACOB. With the program PARTIAL the thickness of the aquifer can also be determined, in a trial and error fashion. This is not mentioned in the procedure as discussed in Chapter 4, Section 1.1 because of the very time-consuming manual calculations which are then required.



A

```
KH = 201 m2/day
S = 3.2E-05
r = 100 m
t>57 min
IS MATCH BETWEEN LINE AND POINTS GOOD (Y/N) ? N
```

B

```
KH = 201 m2/day
S = 3.1E-04
r = 100 m
t>549 min
IS MATCH BETWEEN LINE AND POINTS GOOD (Y/N) ? N
```

C

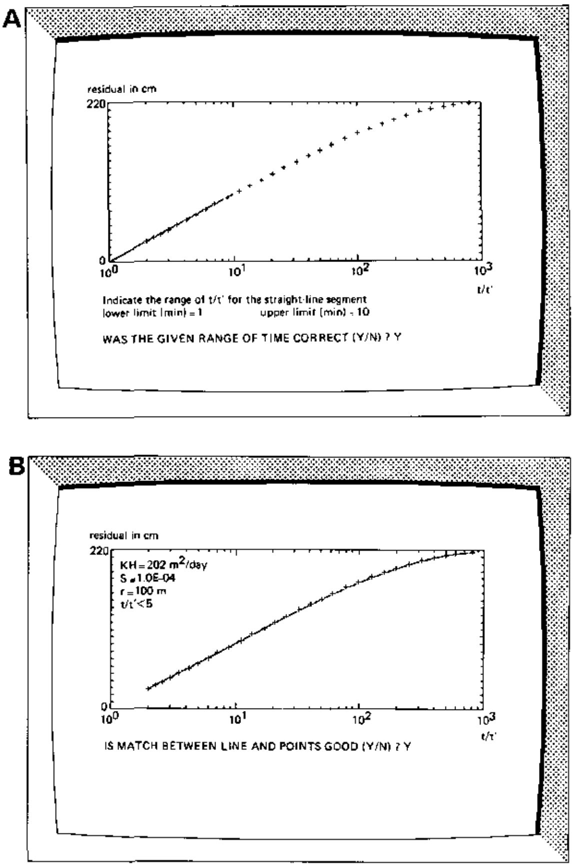
```
KH = 201 m2/day
S =1.0E-04
r =100 m
t>180 min
IS MATCH BETWEEN LINE AND POINTS GOOD (Y/N) ? Y
```

Figure 5.5 Screen 6 of the program PARTIAL showing match of drawdown data with theoretical curve
A: aquifer thickness 400 m
B: aquifer thickness 600 m
C: aquifer thickness 505 m

5.3.4 Program RESIDUAL

The method of analysis used in RESIDUAL is based on the procedure as described in Chapter 4, Section 2.1. The theoretical data set for RESIDUAL consists of residual-drawdown data during recovery of an observation well at a distance of 100 m from the pumped well. These residual drawdowns were calculated using the following hydraulic characteristics: KH = 200 m^2/day and S = 0.0001. The data set is identical to that used in the program JACOB.

With Screen 6 the user is confronted with a semi-log plot of the residual-drawdown data versus the time ratio t/t′ of the observation well. From visual inspection the range of time ratio for which the data plot exhibits a straight-line segment must be prescribed. The program shows as initial estimate for the lower limit the time ratio that the last observation was made, and as initial estimate for the upper limit the time ratio that the first observation was made. Suppose they are changed as follows: lower limit = 1 and upper limit = 10.



```
Indicate the range of t/t' for the straight-line segment
lower limit (min) = 1             upper limit (min) = 10

WAS THE GIVEN RANGE OF TIME CORRECT (Y/N) ? Y
```

```
KH = 202 m2/day
S = 1.0E-04
r = 100 m
t/t'<5

IS MATCH BETWEEN LINE AND POINTS GOOD (Y/N) ? Y
```

Figure 5.6 Screen 6 of the program RESIDUAL
A: correct determination of the straight-line segment
B: match of residual-drawdown data with theoretical curve

The screen now also shows the selected straight-line segment. The program calculates this straight-line segment using linear regression and takes into account only that part of the drawdown data within the prescribed time range. Figure 5.6.A shows this screen. From Figure 5.6.A it can be seen that the straight-line is intersecting the time ratio axis at $t/t' = 1$. This implies that the storativity values during pumping and recovery are the same. The option now exists of changing the time range, if the user is not satisfied, or continuing. Suppose the user continues.

The value of the storativity during pumping which was found from a previous analysis of drawdown data must now be prescribed. The user changes it to 0.0001. The program now calculates the hydraulic characteristics according to the position of the straight-line segment selected. The transmissivity value is calculated according to Equation 4.31 and the storativity value according to Equation 4.32. In addition, the program calculates the time ratio for which the u′ value is 0.01, substituting the appropriate values into Equation 4.29. These values are displayed on the next screen together with a line representing the calculated drawdowns. The program calculates these drawdowns according to Equations 4.27 and 4.28. Figure 5.6.B shows this screen. The option again appears of continuing or going back. Although the match is good, the critical time ratio (5) is lower than the upper time ratio prescribed (10). If the user goes back and changes the upper time ratio from 10 to 5, it will be seen that the values are almost identical to the ones shown in Figure 5.6.B. The reason for this is the same as was discussed for the critical time with the program JACOB.

When a value of the storativity is unknown, i.e. no drawdown values are available to determine the storativity during pumping, the user can make it unity. This has the following consequences. In Figure 5.6.B the calculated drawdowns will lie outside the graph and the displayed value under the symbol S′ does not represent the value of the storativity during the recovery, but in fact represents the ratio of the storativity during recovery and during pumping.

Finally, it must be noted, that the user should not use different values of the storativity during pumping to make a best match. Either the value which was found from a time-drawdown analysis must be prescribed or unity.

6 Guidelines

In this chapter guidelines will be given on how to select an appropriate method of analysis for a particular test. First, so-called diagnostic plots are discussed which correspond to theoretical drawdown behaviour. Next, it will be shown what the range of applicability is for each of the presented methods/programs. Finally, some deviations from the theory under field conditions are presented together with guidelines on how to interpret them.

To gain more insight in the theoretical features which are discussed in the first two sections, an auxiliary program has been added. With the program SCAL the user can make his own theoretical single-well or aquifer test. The relevant data are stored in a file TEST which has either the extension FTW or REC. The user can then analyze the file TEST.FTW with the programs JACOB, HANTUSH, or PARTIAL, or analyze the file TEST.REC with the program RESIDUAL. For more information, the user is referred to Appendix E.

6.1 Diagnostic plots

In Figure 4.1, 4.3, and 4.5 diagnostic plots are presented of theoretical solutions of the unsteady-state drawdowns in a confined aquifer with fully penetrating well, a confined aquifer with a partially penetrating well, and a leaky aquifer with a fully penetrating well. From these figures it can be seen that all the curves are functions of $1/u$, being equal to $4KHt/r^2S$. Assuming for an arbitrarily test constant values of KH, r, and S, the $1/u$ value varies only with the t value. Taking a test duration of a few days and assuming that drawdown values are recorded starting somewhere during the first ten minutes, the user will have drawdown values during two to three log cycles of time. From inspection of the curves in the above figures it will be clear that in an arbitrarily time-drawdown plot only part of these various curves will be present. Which part of the curve is present, depends on the actual ratio of transmissivity and storativity of the aquifer, KH/S, and on the actual distance from the pumped well, r. This distance will usually be in the range of 10 to 300 m. The first depends on the aquifer being tested and is for a particular site a constant but unknown factor, whereas the latter can be selected by the user and is known. In the following a distinction is made between the diagnostic plots of the pumped well and of piezometers or observation wells.

6.1.1 Pumped well

In single-well tests no piezometers or observation wells are present, so only drawdown data of the pumped well itself are available. As r value the outer diameter of the well screen is then taken.

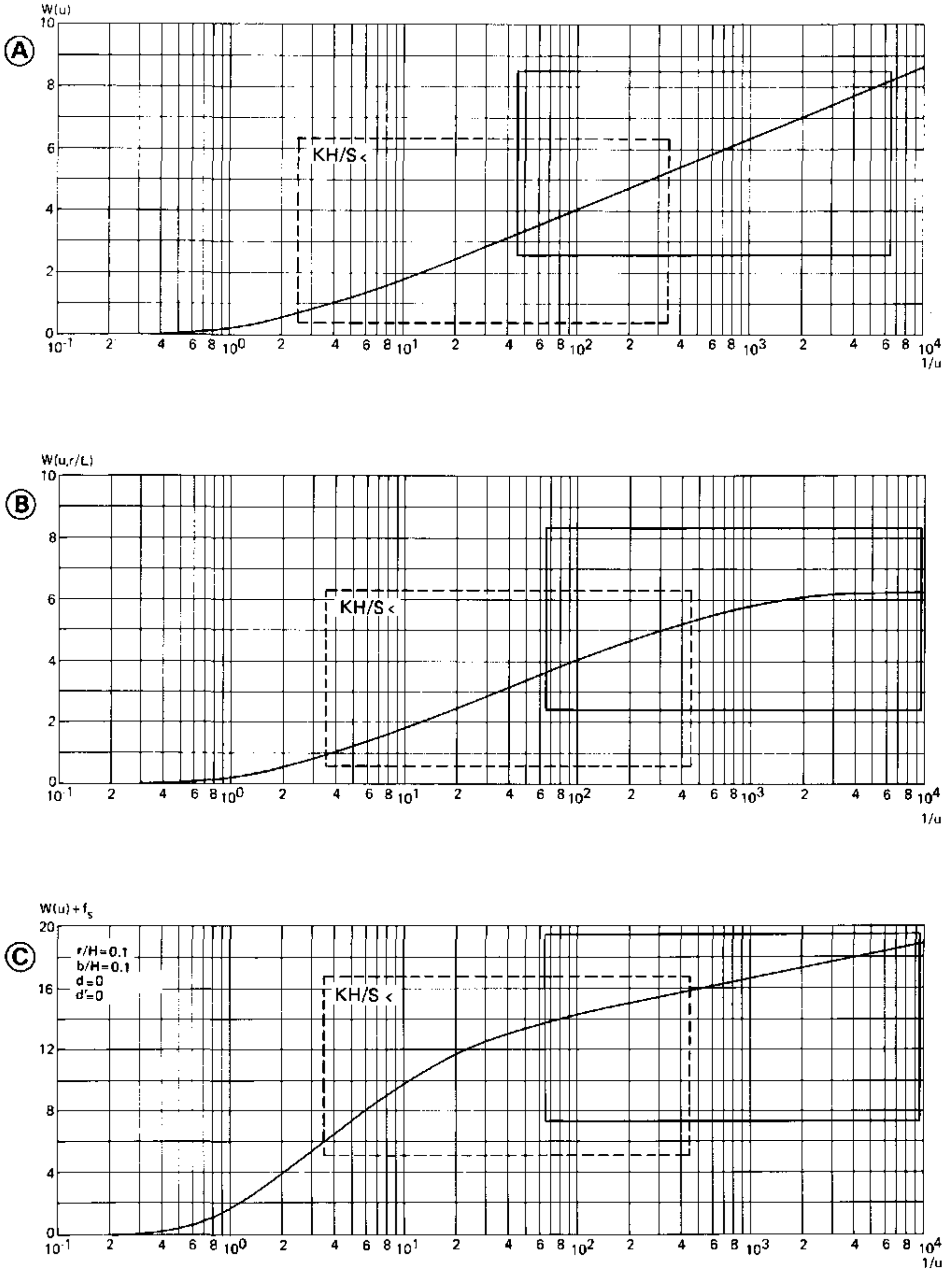


Figure 6.1 Diagnostic plots for the pumped well
A: (un)confined aquifers, fully penetrating wells
B: leaky aquifers, fully penetrating wells
C: (un)confined aquifers, partially penetrating wells

In Figure 6.1.A the diagnostic plot of the pumped well in a confined or unconfined aquifer is presented. According to Jacob's modification of the Theis method the time-drawdown curve will only exhibit a straight line under a slope for 1/u values greater than 100. This is a very rigid limitation and it can be shown that, in practice, a straight line occurs already from 1/u values being greater than 10. Taking as test duration one day, the radius of the well screen is so small that irrespective of the KH/S ratio in time-drawdown plots a straight line will be present. In addition, it can be stated that for confined aquifers no part of the preceding curve will be present yielding only a straight line. For unconfined aquifers however, a part of the preceding curve will be present for very low ratios of KH/S.

In Figure 6.1.B the diagnostic plot of the pumped well in a leaky aquifer is presented. Usually such a time-drawdown plot will exhibit a straight-line segment under a slope followed by a curved-line segment and ending in a horizontal straight-line segment. Two extreme situations can take place. For small ratios of KH/S the time-drawdown plots will only exhibit the straight-line segment under a slope, more or less irrespective of the hydraulic resistance value of the aquitard(s). This can occur when the tested aquifer is relatively thin with a low hydraulic conductivity value. For large ratios of KH/S the time-drawdown plots will exhibit a curved-line segment followed by a horizontal straight-line segment. This can occur when the tested aquifer is relatively thick with a high hydraulic conductivity value. When in such a situation the hydraulic resistance value of the aquitard(s) is also low, this preceding curved-line segment is missing and the plot will only exhibit the horizontal straight-line segment.

In Figure 6.1.C the diagnostic plot of the pumped well where the pumped well partially penetrates a confined aquifer, is presented. Usually, such a time-drawdown plot will only exhibit a straight line under a slope. Only for low ratios of KH/S combined with a small penetration depth compared to the thickness of the aquifer, the preceding curved line will also be present.

6.1.2 Piezometers or observation wells

In Figure 6.2.A the diagnostic plot of a piezometer or observation well in a confined or unconfined aquifer is presented. Such a time-drawdown plot will usually exhibit the curved-line segment, followed by a part of the straight-line segment under a slope. A larger part of the straight-line segment will be present for relatively high ratios of KH/S unless the distance from the piezometer to the pumped well is large. In addition, it can be stated that for unconfined aquifers the ratio of KH/S can be so small that even a piezometer close to the pumped well will not give a straight line under a slope. The only remedy is then to increase the pumping time.

In Figure 6.2.B the diagnostic plot of a piezometer or observation well in a leaky aquifer is presented. Usually, such a time-drawdown plot will exhibit the first curved-line segment, followed by a straight-line segment under a slope and ending in the second curved-line segment. Two extreme situations can take place.

For small ratios of KH/S the time-drawdown plots will only exhibit the first curved-line segment followed by a straight-line segment under a slope. In addition, it can be stated that for relatively high hydraulic resistance values the straight-line segment will not be present unless the distance from the piezometer to the pumped well is small.

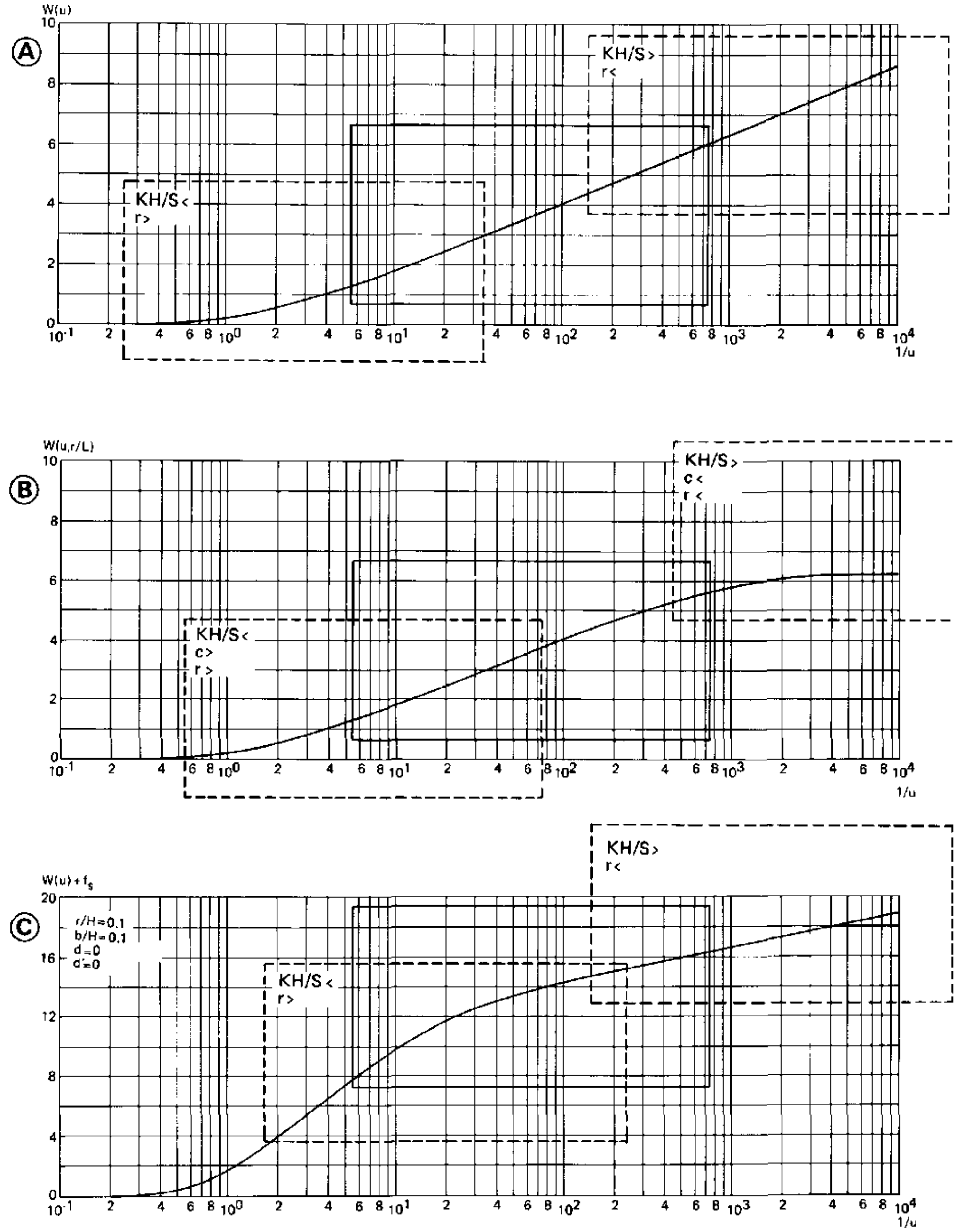


Figure 6.2 Diagnostic plots for an observation well
A: (un)confined aquifers, fully penetrating wells
B: leaky aquifers, fully penetrating wells
C: (un)confined aquifers, partially penetrating wells

For large ratios of KH/S the time-drawdown plots will only exhibit the second curved-line segment followed by a horizontal straight-line segment. This can occur when the tested aquifer is relatively thick with a high hydraulic conductivity value. When in such a situation the hydraulic resistance value of the aquitard(s) is also low, the second curved-line segment is missing unless the distance from the piezometer to the pumped well is large.

In Figure 6.2.C the diagnostic plot of a piezometer or observation well where the pumped well partially penetrates a confined aquifer, is presented. Such a time-drawdown plot will usually exhibit the second curved-line segment followed by a straight-line segment under a slope. This characteristic shape will only occur for penetration depth ratios less than 70 per cent and distances from the piezometer to the pumped well less than the thickness of the tested aquifer. If one of the above conditions is not fulfilled, the characteristic plot will be similar to that of a piezometer or observation well where the pumped well fully penetrates a confined aquifer.

Two extreme situations with a partially penetrating pumped well can take place. For small ratios of KH/S the time-drawdown plots will usually exhibit the second curved-line segment, followed by a straight line segment under a slope. When the distance from the piezometer to the pumped well is not too small, it will also exhibit the first curved-line segment and the inflection point. For large ratios of KH/S the time-drawdown plots will only exhibit the straight-line segment under a slope. This can occur when the tested aquifer is relatively thick with a high hydraulic conductivity value.

6.2 Applicability and limiting conditions

In this section the theoretical conditions are discussed for each of the separate programs under which an analysis can yield reliable results. The user can check the different conditions for himself by running the auxiliary program SCAL. Sets of appropriate input values are indicated in the text as run numbers and summarized in tables.

In the following it is assumed that drawdown data of the pumped well and of piezometers or observation wells are available for the first 790 minutes of pumping and that piezometers or observation wells are drilled in the range of 10 to 300 m away from the pumped well.

6.2.1 Program JACOB

The analysis in the program JACOB is only based on the straight-line segment under a slope in a time-drawdown plot on semi-log paper. In general, it can be stated that the error in the estimate of the storativity will be greater than the error in the estimate of the transmissivity.

For the analysis of data from pumped wells in confined or unconfined aquifers the data plot will exhibit a straight-line segment under a slope irrespective of the KH/S ratio so that an analysis is usually possible and accurate (Table 6.1, Runs 1 to 3).
For the analysis of data from piezometers or observation wells this straight-line segment will only be present depending upon the relative order of magnitude of the KH/S ratio, the distance from the piezometer to the pumped well, and the total pumping time.

Table 6.1 Data sets of the program SCAL for analyses with JACOB

Run	Q	r	KH	H	S	KH/S
1	100	0.25	5	100	0.5	1×10^1
2	100	0.05	5	100	0.1	5×10^1
3	100	0.05	5000	100	0.0001	5×10^7
4	100	100	100	100	0.001	1×10^5
5	100	10	100	100	0.001	1×10^5
6	100	10	100	100	0.1	1×10^3

For relatively low ratios of KH/S the data plot will not exhibit a sufficient long part of the straight-line segment to make a reliable analysis (Table 6.1, Run 4). Selecting as time range 600 to 790 minutes (only the two last observed drawdowns), indicates that the pumping time should at least be some 3000 minutes in order to make an accurate analysis possible. The remedy is then either to pump longer or to place the piezometer closer to the well.

If the same set of data are used, but now for a piezometer 10 m away from the well (Table 6.1, Run 5), an accurate analysis is possible. If the KH/S ratio is taken even smaller (Table 6.1, Run 6), also an accurate analysis of the drawdown of a piezometer close to the pumped well is no longer possible. The only remedy is then to pump longer in time. This last situation can be expected to happen in unconfined aquifers with delayed yield.

6.2.2 Program HANTUSH

The analysis in the program HANTUSH is based on the location of the inflection point and its slope in a time-drawdown plot on semi-log paper. For the determination of the location of the inflection point the plot should reveal the steady-state drawdown or it should be possible to estimate this level from extrapolation. In general, it can be stated that the error in the estimate of the hydraulic resistance will be greater than the error in the estimate of the storativity which in its turn will be greater than the error in the estimate of the transmissivity.

For the analysis of data from pumped wells in leaky aquifers two typical situations will be discussed.

For relatively low KH/S values the data plot will not exhibit the horizontal straight-line segment indicating steady-state conditions. It depends upon the value of the hydraulic resistance whether the curved- line segment is present. For low hydraulic resistance values (Table 6.2, Run 1) the steady-state drawdown can still be estimated from the data; the location of the inflection point lies, however, outside the data range. An accurate analysis is still possible when for its slope the first two drawdown are taken. For higher hydraulic resistance values (Table 6.2, Run 2) the steady-state drawdown can be estimated from a trial and error procedure, being 2050 cm. The slope of the inflection point can now be determined from the data. For even higher values of the hydraulic resistance the plot will only exhibit a straight-line under a slope; even then the transmissivity value can be accurately determined. Because the steady-state

Table 6.2 Data sets of the program SCAL for analyses with HANTUSH

Run	Q	r	KH	H	S	c	KH/S
1	100	0.15	5	100	0.001	100	5×10^3
2	100	0.15	5	100	0.001	1500	5×10^3
3	100	0.15	100	10	0.00001	1500	1×10^7
4	100	0.15	100	10	0.00001	100	1×10^7
5	100	10	5	100	0.001	1500	5×10^3
6	100	100	100	10	0.00001	300	1×10^7

drawdown can no longer be estimated, the value of the hydraulic resistance cannot be determined.

For relatively high KH/S values the data plot will not exhibit the preceding straight-line segment under a slope, but only the curved-line segment ending in a horizontal straight-line segment. It depends upon the value of the hydraulic resistance whether from the first recorded drawdown data, the correct slope of the inflection point still can be determined and with that its location, even though it lies outside the plot. For high hydraulic resistance values (Table 6.2, Run 3) this estimate of the slope is still representing the correct slope. For low hydraulic resistance values (Table 6.2, Run 4), this estimate is not representing the true slope yielding an estimate of the transmissivity more than 100 per cent in error. So, applying the program HANTUSH to drawdown data of the pumped well will generally yield accurate estimates of the transmissivity unless the KH/S ratio is high combined with a low hydraulic resistance value.

For the analysis of data from piezometers or observation wells the same phenomena as discussed with the analysis of the pumped well will occur. For relatively low KH/S values combined with a high hydraulic resistance value the piezometer should be placed close to the pumped well to make a correct analysis possible (Table 6.2, Run 5). For relatively high KH/S values combined with a low hydraulic resistance value the piezometer should be placed not too close to the pumped well to make a correct analysis possible (Table 6.2, Run 6).

6.2.3 Program PARTIAL

The analysis in the program PARTIAL is based on the straight-line segment in a time-drawdown plot on semi-log paper.

For the analysis of pumped wells partially penetrating a confined or unconfined aquifers the data plot will usually exhibit a straight-line segment under a slope. Two typical situations will be discussed.

For relatively low KH/S values the data plot will exhibit a large part of the preceding curved line and only a short part of the straight-line segment under a slope. If this latter part is long enough, an accurate analysis is still possible (Table 6.3, Run 1). Taking a lower KH/S value or a greater aquifer thickness (Table 6.3, Run 2), makes an accurate analysis impossible. Selecting as time range 600 to 790 minutes and as thickness 88 m, indicates that the pumping time should at least be some 1000 minutes. The only remedy is then to pump longer in time.

Table 6.3 Data sets of the program SCAL for analyses with PARTIAL

Run	Q	r	KH	H	S	KH/S	b=1*
1	100	0.15	5	20	0.001	5×10^3	5
2	100	0.15	5	100	0.001	5×10^3	30
3	100	0.15	5000	20	0.001	5×10^6	5
4	100	0.15	5000	100	0.001	5×10^6	30
5	100	10	50	100	0.001	5×10^4	10
6	100	20	50	100	0.001	5×10^4	10
7	100	50	50	100	0.001	5×10^4	10

* fully screened

For high values of KH/S the data plot will only exhibit a straight-line under a slope. An analysis of the drawdown data of the pumped well will give an accurate estimate of the transmissivity (Table 6.3, Runs 3 and 4). Because the preceding curved-line segment is missing, the value of the thickness cannot be determined.

For the analysis of data from piezometers or observation wells the data plot will have one of the three following shapes. Relatively close to the pumped well the data plot will exhibit the second curved-line followed by a straight-line segment under a slope (Table 6.3, Run 5). When the piezometer is farther away from the pumped well, the first curved-line segment and the inflection point will also be present in the data plot (Table 6.3, Run 6). When the piezometer is even farther away, the data plot will become similar to that of a fully penetrated aquifer (Table 6.3, Run 7). In all three situations, the analysis will give accurate results, except for the thickness in the last situation. For lower ratios of KH/S the same phenomena will take place as depicted above, but at shorter distances from the pumped well, and vice versa. So, with low values of KH/S, the piezometer should be closely placed to the pumped well in order to make an accurate analysis possible. The opposite will occur with increasing thickness of the aquifer. So, for thick aquifers, the piezometer should be placed farther away from the pumped well to make a complete analysis possible.

6.2.4 Program RESIDUAL

The analysis in the program RESIDUAL is only based on the straight-line segment in a time-ratio residual-drawdown plot on semi-log paper. Whether such a plot exhibits a straight-line segment, depends upon the same factors as were mentioned for the program JACOB.

For the analysis of data from pumped wells in confined or unconfined aquifers the data plot will exhibit a preceding straight-line segment under a slope irrespective of the KH/S ratio so that the transmissivity value can be determined accurately (Table 6.4, Runs 1 to 3). Only for low values of KH/S the following curved-line segment will also be present.

For the analysis of data from piezometers or observation wells the preceding straight-line segment will only be present depending upon the relative order of magnitude of the KH/S ratio, the distance from the piezometer to the pumped well, and the total pumping time.

Table 6.4 Data sets of the program SCAL for analyses with RESIDUAL

Run	Q	r	KH	H	S	KH/S
1	100	0.25	5	100	0.5	1×10^1
2	100	0.05	5	100	0.1	5×10^1
3	100	0.05	5000	100	0.0001	5×10^7
4	100	100	100	100	0.001	1×10^5
5	100	10	100	100	0.001	1×10^5
6	100	10	50	100	0.1	5×10^2

For a relatively low value of KH/S combined with a relatively large distance from the piezometer to the pumped well the data plot will not exhibit a sufficiently long part of the straight-line segment to make a reliable analysis (Table 6.4, Run 4). Selecting as time-ratio range 2 to 2.5 (only the first two data), indicates that the upper range of the time-ratio should be less than 1. Although this condition is violated, the analysis still gives not too bad an estimate. In these cases the remedy is either to pump longer in time or to place the piezometer closer to the pumped well.

If the same set of data are used, but now for a piezometer 10 m away of the pumped well (Table 6.4, Run 5), an accurate analysis is possible.

If the KH/S ratio is taken even smaller (Table 6.4, Run 6), also an accurate analysis of the drawdown of a piezometer close to the pumped well is no longer possible. The only remedy is to pump longer in time.

6.3 Departures from theory under field conditions

So far, all the different analyses of drawdown or recovery data were based on sets of theoretical data. This was done to make the user familiar with the typical shapes of the drawdown curves from the different analytical solutions. In addition, the user could thus check the results of his analyses. With analyses which were made correctly and within the limits of applicability, it resulted automatically in almost perfect matches between the theoretical drawdown curves based on the analysis and the input data which were also based on theory.

Under field conditions an almost perfect match is more the exception than a rule. This implies that when the result of an analysis produces a match which is not perfect, it does not automatically mean that the analysis has not been made correctly. It should be remembered that all the presented methods are based on highly simplified representations of the natural aquifer. No real aquifers conform fully to these assumed geologic or hydrologic conditions. In itself it is really surprising that these methods often produce good results!

With this in mind, deviations between theoretical drawdown curves and field data could very well stem from the fact that one or more of the general assumptions and conditions mentioned in the beginning of Chapter 4 is not met in the field. To aid the user in distinguishing between these kinds of deviations and deviations which stem from the fact that the selected method is not the correct one for the test site, the most common departures from the theoretical curves are now discussed.

6.3.1 Early-time drawdown data

Delayed yield

The general assumption that water removed from storage is discharged instantaneously with decline of head, is not always met. In unconfined aquifers there will be often a time lag between the early elastic response of the aquifer and the subsequent downward movement of the watertable due to gravity drainage. This makes that in a time-drawdown plot the early-drawdowns are higher than those according to the theoretical curve based on the Theis equation. Figure 6.3 shows the results of an analysis based on field data of an observation well in an unconfined aquifer matched with the corresponding Theis curve. In this case the early-time drawdowns should not be taken into consideration when judging the goodness of fit between the field data and the theoretical curve.

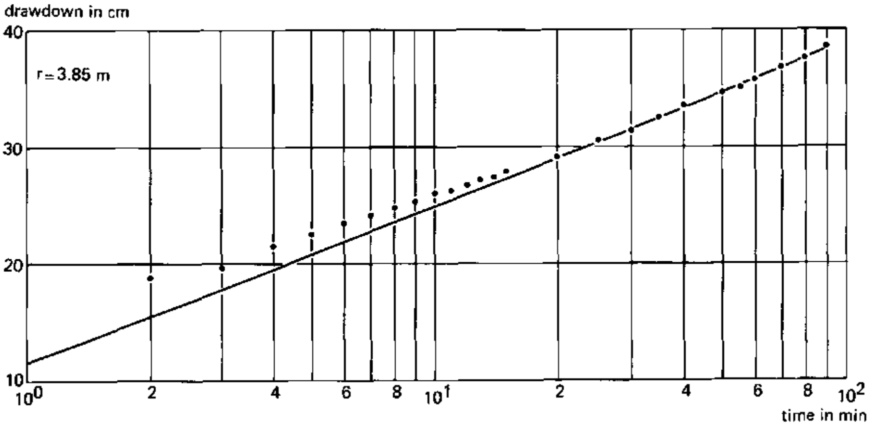


Figure 6.3 Effect of delayed yield on early-time drawdown data

Well storage

When the well bore storage cannot be neglected as is assumed in all presented methods, the opposite phenomenon takes place. Usually, this assumption is not violated when dealing with observation wells or piezometers. In analyzing drawdown data of the pumped well itself, its storage may, however, affect the early drawdowns. These early drawdowns reflect then also the withdrawal of water stored in the casing. With time, this phenomenon decreases as more and more water enters the well from the surrounding aquifer. Figure 6.4 shows the results of an analysis based on field data of the pumped well in an unconfined aquifer matched with the corresponding Theis curve. Also in this case the early-time drawdowns should be discarded when judging the goodness of fit between the field data and the theoretical curve.

In order to avoid misinterpretation of the data and take the first slope as being representative, use can be made of the equation of Schafer (1978) to calculate the critical time at which the well storage effect becomes negligible on the time-drawdown plot. This equation is based on that of Papadopulos and Cooper (1967); it reads

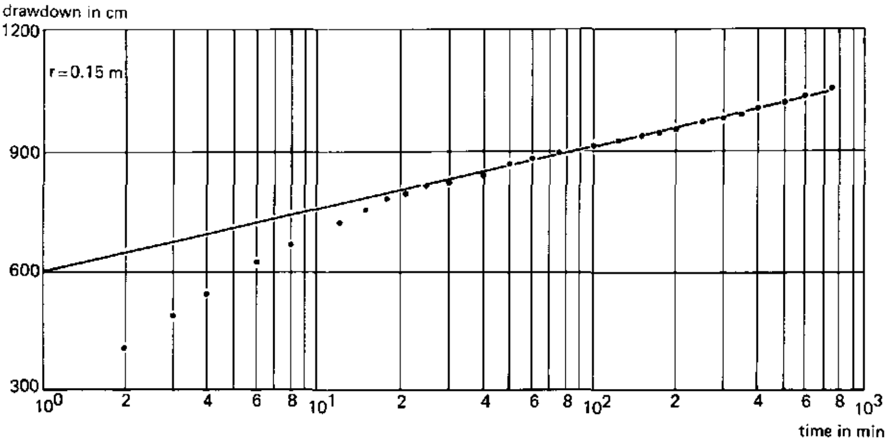


Figure 6.4 Effect of well storage on early-time drawdown data

$$t_c = \frac{1.7\, s_c(d_c^2 - d_p^2)}{Q}$$

where

t_c = time when well storage becomes negligible (min)
d_c = inside diameter of well casing (cm)
d_p = outside diameter of pump column pipe (cm)
Q = discharge rate of the pump (m^3/day)
s_c = drawdown in the well at time t_c(m)

By applying this equation, the early drawdown data prior to t_c should be discarded in a time-drawdown plot.

6.3.2 Late-time drawdown data

Steepening of late-time slope

All real aquifers are limited by geologic or hydrologic boundaries. However, when at the end of the pumping period no such boundaries have been met within the cone of depression, it is said that the aquifer has a seemingly infinite areal extent. When the cone of depression intersects an impervious boundary like a fault or an impermeable valley wall, it can expand no farther in that direction. The cone must expand and deepens more rapidly at the fault or valley wall to maintain the yield of the well.

All the presented methods also assume that the tested aquifer is homogeneous within the area influenced by the pumping. This condition is never fully met, but it depends on the variations in hydraulic conductivity whether these variations will cause deviations from the theoretical time-drawdown curves. When in one of the directions the hydraulic conductivity is decreasing, the slope of the time-drawdown curve will become steeper when the cone of depression is spreading into these finer sediments.

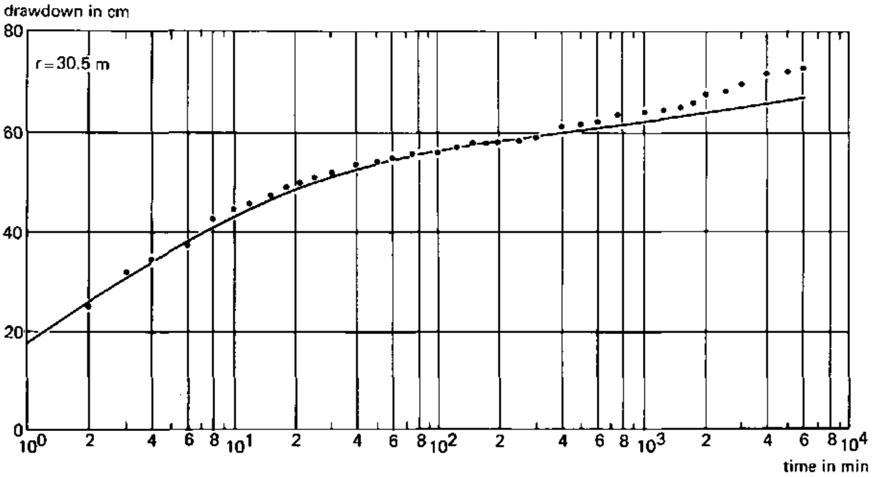


Figure 6.5 Steepening of the slope in late-time drawdown data

The typical shape resulting from this phenomenon is identical to that of an impervious boundary. Finally, it should be noted that well interference will also result in a similar phenomenon.

Figure 6.5 shows the results of an analysis based on field data of an observation well in an unconfined aquifer matched with the most appropriate Hantush curve for partially penetrating wells. In this case the late-time drawdowns should be discarded when judging the goodness of fit between the field data and the theoretical curve.

Flattening of late-time slope

An opposite phenomenon can be encountered when the cone of depression intersects an open water body. If the open water body is hydraulically connected with the aquifer, the aquifer is recharged at an increasing rate as the cone of depression spreads with time. This results in a flattening of the slope of the time-drawdown curve at later times. As phenomenon, it resembles the recharge which occurs in a leaky aquifer.

The same phenomenon takes place when in one of the directions the hydraulic conductivity or the aquifer thickness increases. Figure 6.6 shows the results of an analysis based on field data of an observation well in a confined aquifer matched with the corresponding Theis curve. In this case too the late-time drawdowns should be discarded when judging the goodness of fit between the field data and the theoretical curve.

6.3.3 Late-time residual-drawdown data

To detect whether some of the effects mentioned in the previous section took place, use can be made of the residual-drawdown data after the pump was shut down. Theoretically, the residual-drawdown data when plotted on semi-log paper versus t/t′ should pass through the lower left corner of Figure 6.7. When the curve intersects the zero residual-drawdown axis at t/t′ values larger than unity, it can be concluded that recharge took place during pumping. This is illustrated in Figure 6.7 where the results of an

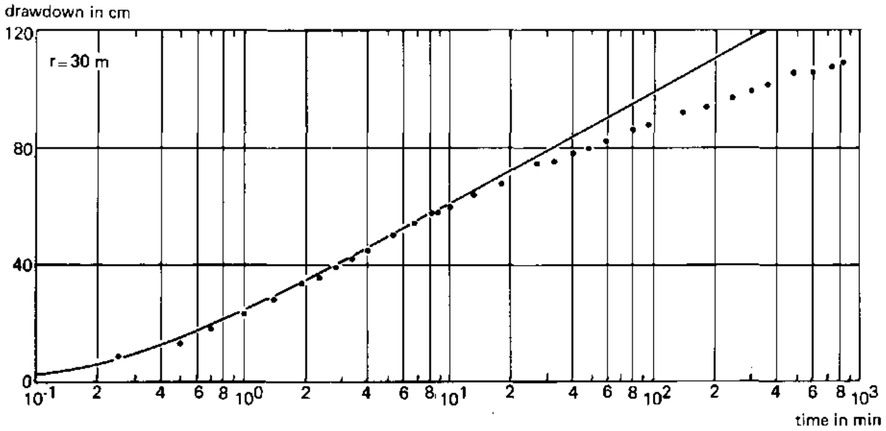


Figure 6.6 Effect of increased directional transmissivity on late-time drawdon data

analysis based on field data of an observation well in a leaky aquifer are shown.

It must be noted that small displacements in this direction can also indicate a variation of the storage coefficient. Quite often it is greater during the pumping period than during the recovery period.

When the residual-drawdown data lie on the other site of the theoretical curve, i.e. the residual drawdown is larger than zero at t/t′ value equal to unity, it can be concluded that the aquifer is limited.

Finally it should be noted that in all above cases no match between the field data and the theoretical Theis curve can be found, because of departures of the late-time drawdowns due to the phenomena described in the previous section.

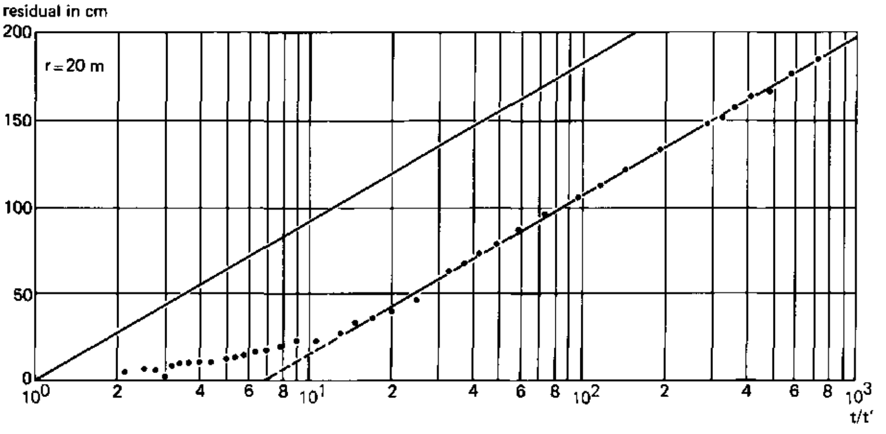


Figure 6.7 Effect of recharge by leakage on late-time drawdown data

6.3.4 Pumped well drawdown data

With all the presented methods it is assumed that the discharge rate of the pump is constant during the test. When the water level in the pumped well declines, many pumps show a decrease in discharge rate, which depends on the rate of decline with increasing pumping time. Especially shortly after the pump is started, minor changes in well discharge caused by variations in pump speed, may affect the early drawdowns.

A complete different category of test are the variable discharge tests. Here the discharge rate is purposely not constant. These tests like the step-drawdown test are primarily meant to determine the so-called well losses and the maximum yield of a well. These tests are not of direct interest for determining hydraulic characteristics. However, in the context of determining these parameters it is important to note that the water levels inside the pumped well itself, are generally lower than those directly outside the well screen. This implies that drawdown data of the pumped well cannot be used for analysis purposes unless corrected. Because the slope of the different straight-line segments in the time-drawdown data when plotted on semi-log paper, is not affected by this phenomenon, transmissivity values can still be determined accurately by using the uncorrected drawdown data. Storativity and hydraulic resistance values, however, are then not correct. This together with the fact that the effective radius of the pumped well is difficult to determine under field conditions and that the storativity and hydraulic resistance values are highly sensitive when it is not correctly determined, are the reasons why in the program package SATEM values of these parameters are not given.

6.4 Conclusions

A number of reasons why time-drawdown data may depart from theoretical curves, have been discussed. It will be clear that different phenomena can cause identical anomalies. Without proper knowledge of the geology of the test site a correct analysis is then impossible. But also in general it can be stated that knowledge of the geology of the test site is absolutely vital in analyzing single-well and aquifer test data. Because this knowledge is often fragmentary, determination of the hydraulic characteristics remains an art. This is the main reason why pure numerical computer codes with automatic matching procedures are dangerous to use.

Finally, it can be concluded that drawdown data from observation wells are usually more reliable and accurate than drawdown data from the pumped well itself. The latter data can be affected by minor changes in well discharge caused by variations in pump speed, by well storage, or by uncertain measurements of the true water level because of turbulence in the pumped well.

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APPENDIX A

Values of the Theis well function W(u) as function of 1/u

1/u	x10^{-1}	x10^{0}	x10^{1}	x10^{2}	x10^{3}	x10^{4}	x10^{5}	x10^{6}	x10^{7}	x10^{8}	x10^{9}
1.0	4.16(-6)	2.19(-1)	1.82	4.04	6.33	8.63	1.09(1)	1.32(1)	1.55(1)	1.78(1)	2.01(1)
1.2	2.60(-5)	2.93(-1)	1.99	4.22	6.51	8.82	1.11(1)	1.34(1)	1.57(1)	1.80(1)	2.03(1)
1.5	1.68(-4)	3.98(-1)	2.20	4.44	6.74	9.04	1.13(1)	1.36(1)	1.59(1)	1.82(1)	2.06(1)
2.0	1.15(-3)	5.60(-1)	2.47	4.73	7.02	9.33	1.16(1)	1.39(1)	1.62(1)	1.85(1)	2.08(1)
2.5	3.78(-3)	7.02(-1)	2.68	4.95	7.25	9.55	1.19(1)	1.42(1)	1.65(1)	1.88(1)	2.11(1)
3.0	8.57(-3)	8.29(-1)	2.86	5.13	7.43	9.73	1.20(1)	1.43(1)	1.66(1)	1.89(1)	2.12(1)
3.5	1.57(-2)	9.42(-1)	3.01	5.28	7.58	9.89	1.22(1)	1.45(1)	1.68(1)	1.91(1)	2.14(1)
4.0	2.49(-2)	1.04	3.14	5.42	7.72	1.00(1)	1.23(1)	1.46(1)	1.69(1)	1.92(1)	2.15(1)
4.5	3.61(-2)	1.14	3.25	5.53	7.83	1.01(1)	1.24(1)	1.47(1)	1.70(1)	1.93(1)	2.17(1)
5.0	4.89(-2)	1.22	3.35	5.64	7.94	1.02(1)	1.25(1)	1.48(1)	1.72(1)	1.95(1)	2.18(1)
6.0	7.83(-2)	1.37	3.53	5.82	8.12	1.04(1)	1.27(1)	1.50(1)	1.73(1)	1.96(1)	2.19(1)
7.0	1.11(-1)	1.51	3.69	5.98	8.28	1.06(1)	1.29(1)	1.52(1)	1.75(1)	1.98(1)	2.21(1)
8.0	1.46(-1)	1.62	3.82	6.11	8.41	1.07(1)	1.30(1)	1.53(1)	1.76(1)	1.99(1)	2.22(1)
9.0	1.83(-1)	1.73	3.93	6.23	8.53	1.08(1)	1.31(1)	1.54(1)	1.77(1)	2.00(1)	2.23(1)

APPENDIX B

Values of the Hantush well function W(u,B) as function of 1/u and B

1/u	B = .005	B = .01	B = .02	B = .03	B = .04	B = .05	B = .06	B = .07	B = .08	B = .09	B = .1
1.0											2.19(-1)
1.5										3.98(-1)	3.97(-1)
2.5		W(u,B) = W(u)					7.02(-1)	7.01(-1)	7.01(-1)	7.00(-1)	7.00(-1)
4.0							1.04	1.04	1.04	1.04	1.04
6.5							1.44	1.44	1.44	1.43	1.43
1.0(1)							1.82	1.81	1.81	1.81	1.80
1.5(1)			2.20	2.19	2.19	2.19	2.19	2.18	2.18	2.17	2.17
2.5(1)			2.68	2.68	2.67	2.67	2.66	2.66	2.65	2.64	2.63
4.0(1)		3.14	3.13	3.13	3.12	3.11	3.10	3.09	3.08	3.07	3.05
6.5(1)		3.61	3.61	3.60	3.59	3.58	3.56	3.54	3.52	3.49	3.47
1.0(2)		4.04	4.03	4.02	4.00	3.98	3.95	3.93	3.89	3.86	3.82
1.5(2)	4.44	4.44	4.43	4.41	4.38	4.35	4.31	4.27	4.22	4.17	4.11
2.5(2)	4.95	4.94	4.92	4.89	4.85	4.80	4.74	4.67	4.59	4.51	4.42
4.0(2)	5.41	5.41	5.38	5.33	5.27	5.19	5.09	4.99	4.88	4.76	4.64
6.5(2)	5.90	5.89	5.84	5.76	5.66	5.54	5.40	5.25	5.09	4.93	4.77
1.0(3)	6.33	6.31	6.23	6.12	5.97	5.80	5.61	5.41	5.21	5.01	4.83
1.5(3)	6.73	6.70	6.59	6.43	6.22	5.98	5.74	5.50	5.27	5.05	4.85
2.5(3)	7.23	7.19	7.01	6.76	6.45	6.14	5.83	5.55	5.29	5.06	
4.0(3)	7.69	7.62	7.35	6.99	6.59	6.20	5.86	5.56			
6.5(3)	8.16	8.05	7.65	7.14	6.65	6.22	5.87				
1.0(4)	8.57	8.40	7.84	7.21	6.67	6.23					
1.5(4)	8.95	8.70	7.96	7.24							
2.5(4)	9.40	9.01	8.03	7.25							
4.0(4)	9.78	9.22	8.05								
6.5(4)	1.01(1)	9.36	8.06								
1.0(5)	1.04(1)	9.42						W(u,B) = 2 K_o(B)			
1.5(5)	1.06(1)	9.44									
2.5(5)	1.07(1)										
4.0(5)	1.08(1)										
∞	1.08(1)	9.44	8.06	7.25	6.67	6.23	5.87	5.56	5.29	5.06	4.85

APPENDIX B (continued)

Values of the Hantush well function W(u,B) as function of 1/u and B

1/u	B = .2	B = .3	B = .4	B = .6	B = .8	B = 1	B = 2	B = 3	B = 4	B = 5	B = 6
1.0(-1)	4.15(-6)	4.15(-6)	4.14(-6)	4.12(-6)	4.10(-6)	4.06(-6)	3.79(-6)	3.36(-6)	2.84(-6)	2.29(-6)	1.80(-6)
1.5(-1)	1.68(-4)	1.68(-4)	1.67(-4)	1.66(-4)	1.65(-4)	1.63(-4)	1.47(-4)	1.25(-4)	9.86(-5)	7.30(-5)	5.03(-5)
2.5(-1)	3.77(-3)	3.76(-3)	3.75(-3)	3.71(-3)	3.65(-3)	3.58(-3)	3.06(-3)	2.35(-3)	1.63(-3)	1.02(-3)	5.79(-4)
4.0(-1)	2.48(-2)	2.47(-2)	2.46(-2)	2.42(-2)	2.37(-2)	2.30(-2)	1.82(-2)	1.23(-2)	7.22(-3)	3.66(-3)	1.69(-3)
6.5(-1)	9.40(-2)	9.35(-2)	9.27(-2)	9.05(-2)	8.75(-2)	8.39(-2)	5.90(-2)	3.35(-2)	1.57(-2)	6.42(-3)	2.38(-3)
1.0	2.18(-1)	2.16(-1)	2.14(-1)	2.06(-1)	1.97(-1)	1.85(-1)	1.14(-1)	5.34(-2)	2.07(-2)	7.27(-3)	2.48(-3)
1.5	3.95(-1)	3.90(-1)	3.84(-1)	3.66(-1)	3.44(-1)	3.17(-1)	1.66(-1)	6.48(-2)	2.21(-2)	7.38(-3)	2.49(-3)
2.5	6.93(-1)	6.81(-1)	6.65(-1)	6.21(-1)	5.65(-1)	5.02(-1)	2.10(-1)	6.91(-2)	2.23(-2)		
4.0	1.02	9.99(-1)	9.65(-1)	8.77(-1)	7.70(-1)	6.57(-1)	2.25(-1)	6.95(-2)			
6.5	1.40	1.35	1.29	1.13	9.46(-1)	7.68(-1)	2.28(-1)				
1.0(1)	1.75	1.67	1.56	1.31	1.05	8.19(-1)					
1.5(1)	2.08	1.95	1.79	1.44	1.10	8.37(-1)					
2.5(1)	2.48	2.27	2.02	1.52	1.13	8.42(-1)					
4.0(1)	2.81	2.49	2.14	1.55							
6.5(1)	3.10	2.64	2.21	1.55							
1.0(2)	3.29	2.71	2.23	1.56							
1.5(2)	3.41	2.74				$W(u,B) = 2K(B)$					
2.5(2)	3.48										
4.0(2)	3.50										
6.5(2)	3.51										
∞	3.51	2.74	2.23	1.56	1.13	8.42(-1)	2.28(-1)	6.95(-2)	2.23(-2)	7.38(-3)	2.49(-3)

APPENDIX C

Values of $K_o(x)$ and $e^x K_o(x)$ as function of x

x	$K_o(x)$	$e^x K_o(x)$	x	$K_o(x)$	$e^x K_o(x)$	x	$K_o(x)$	$e^x K_o(x)$	x	$K_o(x)$	$e^x K_o(x)$
1.0(-2)	4.72	4.77	3.8(-2)	3.39	3.52	6.6(-2)	2.84	3.03	9.4(-2)	2.49	2.73
1.1(-2)	4.63	4.68	3.9(-2)	3.36	3.50	6.7(-2)	2.82	3.02	9.5(-2)	2.48	2.72
1.2(-2)	4.54	4.59	4.0(-2)	3.34	3.47	6.8(-2)	2.81	3.01	9.6(-2)	2.47	2.72
1.3(-2)	4.46	4.52	4.1(-2)	3.31	3.45	6.9(-2)	2.79	2.99	9.7(-2)	2.46	2.71
1.4(-2)	4.38	4.45	4.2(-2)	3.29	3.43	7.0(-2)	2.78	2.98	9.8(-2)	2.45	2.70
1.5(-2)	4.32	4.38	4.3(-2)	3.26	3.41	7.1(-2)	2.77	2.97	9.9(-2)	2.44	2.69
1.6(-2)	4.25	4.32	4.4(-2)	3.24	3.39	7.2(-2)	2.75	2.96	1.0(-1)	2.43	2.68
1.7(-2)	4.19	4.26	4.5(-2)	3.22	3.37	7.3(-2)	2.74	2.95	1.1(-1)	2.33	2.60
1.8(-2)	4.13	4.21	4.6(-2)	3.20	3.35	7.4(-2)	2.72	2.93	1.2(-1)	2.25	2.53
1.9(-2)	4.08	4.16	4.7(-2)	3.18	3.33	7.5(-2)	2.71	2.92	1.3(-1)	2.17	2.47
2.0(-2)	4.03	4.11	4.8(-2)	3.15	3.31	7.6(-2)	2.70	2.91	1.4(-1)	2.10	2.41
2.1(-2)	3.98	4.06	4.9(-2)	3.13	3.29	7.7(-2)	2.69	2.90	1.5(-1)	2.03	2.36
2.2(-2)	3.93	4.02	5.0(-2)	3.11	3.27	7.8(-2)	2.67	2.89	1.6(-1)	1.97	2.31
2.3(-2)	3.89	3.98	5.1(-2)	3.09	3.26	7.9(-2)	2.66	2.88	1.7(-1)	1.91	2.26
2.4(-2)	3.85	3.94	5.2(-2)	3.08	3.24	8.0(-2)	2.65	2.87	1.8(-1)	1.85	2.22
2.5(-2)	3.81	3.90	5.3(-2)	3.06	3.22	8.1(-2)	2.64	2.86	1.9(-1)	1.80	2.18
2.6(-2)	3.77	3.87	5.4(-2)	3.04	3.21	8.2(-2)	2.62	2.85	2.0(-1)	1.75	2.14
2.7(-2)	3.73	3.83	5.5(-2)	3.02	3.19	8.3(-2)	2.61	2.84	2.1(-1)	1.71	2.10
2.8(-2)	3.69	3.80	5.6(-2)	3.00	3.17	8.4(-2)	2.60	2.83	2.2(-1)	1.66	2.07
2.9(-2)	3.66	3.76	5.7(-2)	2.98	3.16	8.5(-2)	2.59	2.82	2.3(-1)	1.62	2.04
3.0(-2)	3.62	3.73	5.8(-2)	2.97	3.14	8.6(-2)	2.58	2.81	2.4(-1)	1.58	2.01
3.1(-2)	3.59	3.70	5.9(-2)	2.95	3.13	8.7(-2)	2.56	2.80	2.5(-1)	1.54	1.98
3.2(-2)	3.56	3.67	6.0(-2)	2.93	3.11	8.8(-2)	2.55	2.79	2.6(-1)	1.50	1.95
3.3(-2)	3.53	3.65	6.1(-2)	2.92	3.10	8.9(-2)	2.54	2.78	2.7(-1)	1.47	1.93
3.4(-2)	3.50	3.62	6.2(-2)	2.90	3.09	9.0(-2)	2.53	2.77	2.8(-1)	1.44	1.90
3.5(-2)	3.47	3.59	6.3(-2)	2.88	3.07	9.1(-2)	2.52	2.76	2.9(-1)	1.40	1.88
3.6(-2)	3.44	3.57	6.4(-2)	2.87	3.06	9.2(-2)	2.51	2.75	3.0(-1)	1.37	1.85
3.7(-2)	3.41	3.54	6.5(-2)	2.85	3.04	9.3(-2)	2.50	2.74	3.1(-1)	1.34	1.83

APPENDIX C (continued)

Values of $K_o(x)$ and $e^x K_o(x)$ as function of x

x	$K_o(x)$	$e^x K_o(x)$	x	$K_o(x)$	$e^x K_o(x)$	x	$K_o(x)$	$e^x K_o(x)$	x	$K_o(x)$	$e^x K_o(x)$
3.2(-1)	1.31	1.81	6.0(-1)	7.78(-1)	1.42	8.8(-1)	5.01(-1)	1.21	2.6	5.54(-2)	7.46(-1)
3.3(-1)	1.29	1.79	6.1(-1)	7.65(-1)	1.41	8.9(-1)	4.94(-1)	1.20	2.7	4.93(-2)	7.33(-1)
3.4(-1)	1.26	1.77	6.2(-1)	7.52(-1)	1.40	9.0(-1)	4.87(-1)	1.20	2.8	4.38(-2)	7.21(-1)
3.5(-1)	1.23	1.75	6.3(-1)	7.40(-1)	1.39	9.1(-1)	4.80(-1)	1.19	2.9	3.90(-2)	7.09(-1)
3.6(-1)	1.21	1.73	6.4(-1)	7.28(-1)	1.38	9.2(-1)	4.73(-1)	1.19	3.0	3.47(-2)	6.98(-1)
3.7(-1)	1.18	1.71	6.5(-1)	7.16(-1)	1.37	9.3(-1)	4.66(-1)	1.18	3.1	3.10(-2)	6.87(-1)
3.8(-1)	1.16	1.70	6.6(-1)	7.04(-1)	1.36	9.4(-1)	4.59(-1)	1.18	3.2	2.76(-2)	6.77(-1)
3.9(-1)	1.14	1.68	6.7(-1)	6.93(-1)	1.35	9.5(-1)	4.52(-1)	1.17	3.3	2.46(-2)	6.67(-1)
4.0(-1)	1.11	1.66	6.8(-1)	6.82(-1)	1.35	9.6(-1)	4.46(-1)	1.16	3.4	2.20(-2)	6.58(-1)
4.1(-1)	1.09	1.65	6.9(-1)	6.71(-1)	1.34	9.7(-1)	4.40(-1)	1.16	3.5	1.96(-2)	6.49(-1)
4.2(-1)	1.07	1.63	7.0(-1)	6.61(-1)	1.33	9.8(-1)	4.33(-1)	1.15	3.6	1.75(-2)	6.40(-1)
4.3(-1)	1.05	1.62	7.1(-1)	6.50(-1)	1.32	9.9(-1)	4.27(-1)	1.15	3.7	1.56(-2)	6.32(-1)
4.4(-1)	1.03	1.60	7.2(-1)	6.40(-1)	1.31	1.0	4.21(-1)	1.14	3.8	1.40(-2)	6.24(-1)
4.5(-1)	1.01	1.59	7.3(-1)	6.30(-1)	1.31	1.1	3.66(-1)	1.10	3.9	1.25(-2)	6.17(-1)
4.6(-1)	9.94(-1)	1.57	7.4(-1)	6.20(-1)	1.30	1.2	3.19(-1)	1.06	4.0	1.12(-2)	6.09(-1)
4.7(-1)	9.76(-1)	1.56	7.5(-1)	6.11(-1)	1.29	1.3	2.78(-1)	1.02	4.1	9.98(-3)	6.02(-1)
4.8(-1)	9.58(-1)	1.55	7.6(-1)	6.01(-1)	1.29	1.4	2.44(-1)	9.88(-1)	4.2	8.93(-3)	5.95(-1)
4.9(-1)	9.41(-1)	1.54	7.7(-1)	5.92(-1)	1.28	1.5	2.14(-1)	9.58(-1)	4.3	7.99(-3)	5.89(-1)
5.0(-1)	9.24(-1)	1.52	7.8(-1)	5.83(-1)	1.27	1.6	1.88(-1)	9.31(-1)	4.4	7.15(-3)	5.82(-1)
5.1(-1)	9.08(-1)	1.51	7.9(-1)	5.74(-1)	1.26	1.7	1.65(-1)	9.06(-1)	4.5	6.40(-3)	5.76(-1)
5.2(-1)	8.92(-1)	1.50	8.0(-1)	5.65(-1)	1.26	1.8	1.46(-1)	8.83(-1)	4.6	5.73(-3)	5.70(-1)
5.3(-1)	8.77(-1)	1.49	8.1(-1)	5.57(-1)	1.25	1.9	1.29(-1)	8.61(-1)	4.7	5.13(-3)	5.64(-1)
5.4(-1)	8.61(-1)	1.48	8.2(-1)	5.48(-1)	1.25	2.0	1.14(-1)	8.42(-1)	4.8	4.60(-3)	5.59(-1)
5.5(-1)	8.47(-1)	1.47	8.3(-1)	5.40(-1)	1.24	2.1	1.01(-1)	8.25(-1)	4.9	4.12(-3)	5.53(-1)
5.6(-1)	8.32(-1)	1.46	8.4(-1)	5.32(-1)	1.23	2.2	8.93(-2)	8.06(-1)	5.0	3.69(-3)	5.48(-1)
5.7(-1)	8.18(-1)	1.45	8.5(-1)	5.24(-1)	1.23	2.3	7.91(-2)	7.89(-1)			
5.8(-1)	8.04(-1)	1.44	8.6(-1)	5.16(-1)	1.22	2.4	7.02(-2)	7.74(-1)			
5.9(-1)	7.91(-1)	1.43	8.7(-1)	5.09(-1)	1.21	2.5	6.23(-2)	7.60(-1)			

Appendix D

Description program INPUT

With the program INPUT the user can enter the water-level data measured in the piezometers as function of time, in another format than is required by the program SATEM.

After typing INPUT and pressing the ENTER key, the user is confronted with the following sequence of screen information.

Screen 1
This screen deals with the data to be used for the input. The user has basically two options: to enter the original data or to change original data stored in a file during a previous session. This file has the extension ORI.

Screen 2
This screen enables the user to enter the water-level data as depth to the watertable or as drawdown.

Screen 3
This screen deals with the dimension of the water-level data. It can be specified either as metres, centimetres, or as feet.

Screen 4
This screen deals with the dimension of time for which the water-level data were recorded. It can be specified either as time since pumping started in minutes or as clock time. When expressed in clock time, it should be specified as hours and minutes. For instance, ten minutes to eleven in the evening should be entered as 22.50.

Screen 5
This screen enables the user to enter the discharge of the pumped well in m^3/day, the total pumping time in min, and the total number of wells for which water level data are available.

If the user selected in Screen 4 the option 'clock time', the time at which pumping started, should also be prescribed.

Screen 6
This screen enables the user to enter for each well the distance to the pumped well in m, the total number of water level data, and the type of water level data. The user has the option to choose between 'pumping' or 'recovery'.

Screen 7
If the user selected in Screen 2 the option 'depth to the watertable', for each well the initial depth to the watertable prior to pumping should also be prescribed.

Screen 8
This screen enables the user to enter the water-level data as function of time according to the options selected in Screens 2, 3, and 4.

Screen 9
This screen allows the user to store the data. The user should specify a particular name. The program will automatically add the extension ORI to this name and store the original data. Subsequently, it will add the extension FTW to the same name and store the converted data to be used later with the programs JACOB, HANTUSH, and/or PARTIAL of the program package SATEM.

If water-level data were also recorded during recovery for one or more of the wells, the program will in addition add the extension REC to this name and store these converted data to be used later with the program RESIDUAL of the program package SATEM.

It must be noted that some of the specific data required for the various programs of SATEM still need to be prescribed when the user is actually running SATEM.

Appendix E

Description program SCAL

With the program SCAL the user can make theoretical single-well and aquifer test data. Sets of drawdown and/or residual-drawdown data can be created for the following situations:

- confined aquifer with a fully penetrating pumped well;
- leaky aquifer with a fully penetrating well;
- confined aquifer with a partially penetrating pumped well.

With above sets of theoretical data the user can gain more insight in the different analysis methods of the program package SATEM.

After typing SCAL and pressing the ENTER key, the user is confronted with the following sequence of questions.

The first three questions are related to select the appropriate condition. If the information displayed on the screen is correct, simply press the ENTER key. If not, type N (or n) and press the ENTER key.

It should be noted that when the user selects the option 'pumping test', a data set of drawdown and residual-drawdown values is created which can be analyzed with the programs JACOB, HANTUSH, or PARTIAL. When the user selects the option 'recovery test', a data set of residual-drawdown values is created which can be analyzed with the program RESIDUAL only.

The remaining questions are related to prescribe specific values to the required input parameters. SCAL only accepts values for these parameters within certain ranges (Table).

Overview of input parameters and ranges

Input parameters	Symbol	Range of accepted values
discharge of the pump	Q	0-10,000 m^3/day
distance from the pumped well	r	0.05-300 m
transmissivity of the aquifer	KH	5-3,000,000 m^2/day
thickness of the aquifer	H	5-3,000 m
storativity of the aquifer	S	5×10^{-6}-5×10^{-1}
hydraulic resistance aquitard	c	0-1,000,000 days
penetrating depth pumped well	b	5-H m
screen length pumped well	b-d	1-b m
penetrating depth observation well	b′	0-H m
screen length observation well	b′-d′	0-b′ m

Once the user has prescribed a value to the last required input parameter, the screen will display the message that the theoretical data are being made and that the name of the corresponding file is TEST.

Finally, it should be noted that for certain combinations of input parameters the theoretical residual-drawdown data will not be correct. In that case, a warning will also appear on the screen.