Harry Massop

SENSITIVITY ANALYSIS

OF THE

SURFACE WATER - GROUNDWATER INTERACTION

FOR THE

SANDY AREA OF THE NETHERLANDS

Enrique Gomez del Campo
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CHAPTER 1

INTRODUCTION

1.1 Purpose and Scope

The "Sensitivity Analysis of the Surface Water - Groundwater Interaction for the Sandy Area of the Netherlands" was carried out in the framework of a bilateral research project in support of the implementation of a nationwide geohydrological information system (REGIS) in the Netherlands.

This bilateral research project, conducted in cooperation between the TNO Institute for Applied Scientific Research (IGG-TNO) and the Winand Staring Centre for Integrated Land, Soil and Water Research (SC-DLO), is aimed at defining the information (variables and parameters) needed for efficient model use of the REGIS system, particularly with respect to the surface water - groundwater relation.

The objectives of the present sensitivity analysis are:

- To examine the response of the macroparameter *drainage resistance* to changes in several local parameters, typical for geohydrological situations in the Netherlands.
- To investigate the effect of these same local parameters on the distribution of flow to a ditch.

There have been several investigations similar to the one reported here, but either their purpose is different (van Drecht, 1983), they are mainly theoretical (de Lange, 1992), or the region of interest differs (IWACO, 1992).

1.2 Geohydrological Situations

The Netherlands can be divided into three major zones according to soil composition: the higher sandy areas inland, the relatively high areas of the most recent coastal and fluvial deposits, and a lower transition zone where extensive peat bogs exist.

At the surface in the south-western, western, northern, and central river districts of the Netherlands mainly loamy and clayey material of marine and fluvial origin dominates, together with some peat soils and fine sands. The soils in the southern, eastern, and north-eastern part of the Netherlands consists mainly of fine loamy sands, medium sand, and coarse sand. In the south, silt and silt loam soils occur.

The shallow groundwater levels in the sandy areas are largely controlled by the natural drainage system, strongly adapted to the needs of agriculture. In the coastal marine-clay areas the backbone of the drainage system is the former creek and gully system. In the peaty areas, both the landscape and the groundwater flow are almost all artificial. Peat bogs were drained by long parallel ditches; large peat deposits were excavated, leaving lakes, later to be pumped and reclaimed again.

This report concentrates on the characteristics of the sandy areas of the Netherlands.

Two main profiles are typical for the sandy areas: one with a layer of fine sand on top of a layer of coarse sand, and the other formed by two sand aquifers separated by an aquitard. The first profile is found in large parts of the Overijssel, Gelderland, Utrecht, and Noord Brabant provinces, the second is typical of the province of Drenthe and some parts of Noord-Brabant.

1.3 Limits of the Study

The profiles modeled do not represent a specific location, but a general area within the Netherlands. Therefore, there are no field measurements to calibrate the models used, and the quantitative results should be taken with caution. The range of the input parameters chosen is in agreement with the region of interest for this study. Although in order to limit the number of cases, the following parameters remain constant throughout the investigation: thickness of the lower aquifer, level of bottom of the ditch, level of water in the ditch, and specific recharge to the groundwater.

The symmetry of the cross-sections allows the model to have impermeable boundaries on the sides and bottom and since all simulations performed are steady state, the recharge intensity equals the discharge rate to the ditch and the water table does not change its position with time (ILRI, 1973). One last limitation of the present study is the inexistence of a seepage face in the modeling of the ditch.

CHAPTER 2

ANALYTICAL AND NUMERICAL METHODS

2.1 General

A mathematical model can simulate groundwater flow by means of one or several equations representing the physical processes that occur in the system, the heads or flows along the boundaries of the model, and the initial head distribution. Mathematical models can be solved analytically or numerically. Analytical methods are limited to flow problems in which the region of flow, boundary conditions, and geologic configuration are simple and regular. Numerical methods are much more versatile, but they are approximate and usually require the use of a computer. They are based on a discretization of the continuum that makes the region of flow.

2.2 Ernst Equation

The Ernst equation is one of the analytical formulas most frequently used to describe the flow of groundwater to drains under steady state conditions. It is applicable to two-layered soils, especially when the upper layer has a considerably lower hydraulic conductivity than the lower one. Also, the interface between the two layers can be either above or below the drain level.

Basically, Ernst divided the total hydraulic head into the sum of the hydraulic heads of the different flow components towards the drain, namely: vertical, horizontal, radial, and entrance flow.

The Ernst equation for an open drain or ditch can be written as:

$$h_{om}-h_{os}=q\frac{D_v}{k_v}+q\frac{L^2}{8k_hD}+q\frac{L}{\pi\, k_r}\ln\frac{\alpha\, D}{B}+qL\frac{c_{bs}}{B} \qquad (1)$$

0 + 1 + 3.4 + 100

then:

$$\gamma=\frac{(h_{om}-h_{os})}{q} \qquad (2)$$

where:

h_{om} = water table height midway between the ditches with respect to reference level.

h_{os} = level of water in the ditch with respect to reference level.

q = specific discharge to the ditch.

D_v = thickness of aquifer for vertical flow.

k_v = vertical hydraulic conductivity

~~c_{vf} = resistance to vertical flow~~

L = distance between the ditches.

B = width of the ditch.

k_h = horizontal hydraulic conductivity.

D = thickness of the aquifer for horizontal flow.

k_r = radial hydraulic conductivity.

α = geometry factor (usually set to 1).

c_{bs} = entrance resistance to the ditch.

γ = drainage resistance.

For a derivation of the Ernst equation see ILRI (1973).

2.3 Bruggeman Equation

The Bruggeman equation represents an improvement over the Ernst equation above in the sense that full two dimensional flow takes place in the upper layer and the lower boundary of the system is not impermeable, but has a constant head. The derivation of the Bruggeman equation has not yet been generally published, it will only be stated here:

$$q=\frac{[(c+\frac{D}{k_v})(1-\frac{B}{L})-BS]N-h_{os}}{(\frac{Lc_b}{B})+(c+\frac{D}{k_v})+SL} \tag{3}$$

$$S=\frac{AL^2}{\pi^3B^2k_v}\sum_{n=1}^{\infty}\frac{1}{n^3}\sin^2(\frac{n\pi B}{L})F(n,o) \tag{4}$$

$$F(n,o)=\frac{(n\alpha_1+1)e^{n\alpha_2}+(n\alpha_1-1)e^{-n\alpha_2}}{(n\alpha_1+1)e^{n\alpha_2}-(n\alpha_1-1)e^{-n\alpha_2}} \tag{5}$$

$$\alpha_1=\frac{2\pi k_v c}{AL} \tag{6}$$

$$\alpha_2=\frac{2\pi D}{AL} \tag{7}$$

$$A=\sqrt{\frac{k_v}{k_h}} \tag{8}$$

$$v_{zo}=(1-\frac{B}{L})N-q \tag{9}$$

$$\overline{h_o}=(c+\frac{D}{k_v})v_{zo} \tag{10}$$

$$\gamma=\frac{(\overline{h_o}-h_{os})}{q} \tag{11}$$

where:

- q = specific discharge to the ditch.
- c = resistance of the aquitard.
- D = thickness of the aquifer.
- k_v = vertical hydraulic conductivity.
- B = width of the ditch.
- L = distance between ditches.
- N = recharge to the phreatic layer
- h_{os} = level of water in the ditch with respect to a reference level.
- c_b = resistance of the bottom of the ditch.
- k_h = horizontal hydraulic conductivity.
- v_{zo} = flux through the separating layer.
- h_o = average head with respect to a reference level.

2.4 MODFLOW

MODFLOW is a widely used numerical groundwater model developed by the United States Geological Survey (USGS). It solves the general groundwater flow equation in three-dimensions under nonequilibrium conditions in a heterogeneous and anisotropic medium. Such equation can be written as:

$$\frac{\delta}{\delta x}(k_{xx}\frac{\delta h}{\delta x})+\frac{\delta}{\delta y}(k_{yy}\frac{\delta h}{\delta y})+\frac{\delta}{\delta z}(k_{zz}\frac{\delta h}{\delta z})-W=S_s\frac{\delta h}{\delta t} \tag{12}$$

where:

k_{xx}, k_{yy}, and k_{zz}	= hydraulic conductivity along the x,y, and z axes.
h	= potentiometric head.
W	= volumetric flux per unit volume (sinks and sources of water).
S_s	= specific storage of porous material.
t	= time.

Given equation 12 and the boundary and initial conditions of an aquifer system, MODFLOW solves for h(x,y,z,t) by replacing the continuous derivatives of equation 12 by finite-difference approximations at points called nodes. The nodes are located in the center of cells into which the region being modeled has been divided. Hydraulic properties are defined for each cell. The result is a set of N equations containing N values of unknown head, where N is the number of nodes. The time derivative on the right side of equation 12 is approximated by the backward difference method. Finally, the program solves the system of N linear equations for the unknown head at each node at the end of each time interval.

MODFLOW views a three dimensional system as a sequence of layers of porous material. The horizontal discretization of space is handled by reading the number of rows and columns, and their respective width. The thickness of each layer (vertical discretization) is specified indirectly, either as transmissivity, or by the input of hydraulic conductivity and top and bottom layer elevation. There are three types of layers in MODFLOW: always confined, always unconfined, and convertible (capable of being confined or unconfined). Only for the unconfined uppermost layer heads are calculated under the Dupuit assumptions. In the case when the model has more than one layer, a leakage term, to account for the flow of water between layers, has to be determined. This set up also allows to define an aquitard as a resistance term with no need to create a special layer in the model for it.

MODFLOW consists of a main routine and a series of highly independent subroutines. The subroutines are grouped into packages, each dealing with a specific feature of the hydrologic system to be simulated (drains, wells, etc.), or with a specific method for solving the linear equations describing the flow system.

For a complete description of MODFLOW and how to use it see McDonald and Harbaugh (1988).

CHAPTER 3

MODEL SET UP

3.1 General

Profile models are useful to study patterns in regional flow systems and when vertical flow is important. A profile model assumes that all flow occurs parallel to and in the plane of the profile, that is, no component of flow at an angle to the profile exists. In this investigation, MODFLOW (because it can deal with more complicated situations than the analytical formulas) is used to create cross-sectional models to represent the profiles mentioned at the end of Section 1.2.

3.2 Profile Description

Three different profiles were set up with MODFLOW to simulate the sandy areas; one to describe the sand aquifer system without aquitard, and two for systems with aquitard. For this last case, one profile characterizes the aquifer system when the aquitard is below the bottom of the ditch, the other when the aquitard is located above it. Figure 1 shows the three profiles modeled.

The surface water is represented by a ditch of depth h_b with water level h_w, width B, spacing L, and bottom and sides resistance c_{bs}. The groundwater by an aquifer system of thickness D_1 and hydraulic conductivity k_1 for the upper layer, thickness D_2 and hydraulic conductivity k_2 for the lower layer, an aquitard in between layers of resistance c_v and a specific recharge N.

In order to perform the sensitivity analysis a standard case was defined for each profile. In this manner, when one parameter is changed the rest are kept constant at the standard case value. The standard cases, shown in Table 1, represent the typical characteristics of each profile.

Table 1. Standard Case for Each Profile.

Profile	D_1	k_1	D_2	k_2	$\frac{k_{1v}}{k_{1h}}$	$\frac{k_{2v}}{k_{2h}}$	L	B	c_{bs}	$\frac{c_b}{c_s}$	h_b	h_w	N	c_v
	(m)	(m/d)	(m)	(m/d)			(m)	(m)	(d)		(m)	(m)	(m/d)	(d)
Open	3	3	50	30	1	1	100	2	2	1	1.5	1	.001	0
Aquitard below Ditch Bottom	3	3	50	30	1	1	100	2	2	1	1.5	1	.001	100
Aquitard above Ditch Bottom	1.5	3	50	30	1	1	100	2	2	1	1.5	1	.001	100

3.3 Model Discretization

Because of the symmetry of the profiles, heads are identical on both sides if cut in half, so only half profiles were modeled. Thus, for MODFLOW implementation purposes L becomes L/2 and B is now B/2, though the results shown and the values presented in the tables are for the full size profiles.

To create the cross-sectional models with MODFLOW the profiles were divided into cells. The width of each cell is given by the number and width of the columns into which the whole profile is divided. The depth of the cell depends on the number of layers used to represent the aquifer system and their respective depth. MODFLOW is a three-dimensional model, so the thickness of each cell is also needed, but since we are creating a cross-sectional model, the thickness of all the cells was set to 1 m. Figure 2, shows the discretization of the profiles, which is the same for all of them. Each cross-section has 16 layers, and 21, 26, or 28 columns depending on the size of L/2; 21 columns for L/2 equal to 15 m., 20 m., or 50 m., 26 for the 100 m. and 200 m. cases, and 28 colums when L/2 is equal to 300 m. or 500 m. Therefore, the total number of nodes in each model ranges from 336 to 448, with a higher concentration of nodes per cross-sectional area in the vicinity of the ditch.

With respect to the layer types, the uppermost layer in the model was defined as unconfined, the rest of the upper aquifer is made up of convertible type layers. The lower aquifer, since it is confined, consists only of confined type layers.

The ditch was defined by constant heads in the model cells representing it. This was done because the discretization needed for the sensitivity analysis created a ditch consisting of several model cells containing only water. The resistance of the ditch bottom was set through the use of the leakage term between layers, where the aquifer and the ditch meet, but only for the cells that make the width of this last one. The ditch side resistance necessitated the creation of a special column just for it, the width of which is 0.1 m. The hydraulic conductivity used for the part of the column that constitutes the ditch side was calculated by dividing the width of it by the resistance desired for the ditch side or wall.

Finally, the aquitard existing in two of the profiles was defined only as a resistance in the leakage term between the aquifer layers it separates.

3.4 Model Verification

In order to verify the suitability of MODFLOW for the required sensitivity analysis, and to select the proper module for the calculation of the surface water - groundwater interaction, the model was tested against the Bruggeman formula. For this purpose, a simple case that also satisfies the Bruggeman conditions was chosen. It was assumed that if the numerical solution would come close enough to the exact analytical solution, the model would also achieve sufficient accuracy for the sensitivity analysis of more complex cases. Therefore, the results of a simpler version of the MODFLOW models presented in this report were compared against those calculated using the BASIC program of van Drecht (1983) for solving the Bruggeman equation. The reason for using a simpler form was in order to comply with the Bruggeman equation assumptions (see Bruggeman, 1978). It should be stated that it is not the objective of this report to compare between methods of solving the flow of groundwater to ditches. It is enough to say that the differences found in the heads and drainage resistances between the two methods were in the order of two percent. The MODFLOW models of this investigation have a bottom and a side resistance for the ditch, therefore, in order to compared them correctly with models or analytical formulas that are defined with only a resistance for the bottom of the ditch, the width of the ditch in those formulas should be taken as the wetted perimeter.

3.5 External Calculations

The output from MODFLOW consists of the value of the head at the node of each cell. A short Fortran program, using these heads as input, was written to calculate the drainage resistance and the distribution of flow to the ditch. The drainage resistance is a simple groundwater head - discharge relation defined as the ratio of the difference between the highest head in the aquifer system and the head in the ditch to the specific discharge to the ditch. Since the simulations are steady state, all the water that comes in as groundwater recharge goes out through the ditch eventually. Therefore, the specific discharge to the ditch is equal to the specific recharge N for the area outside the ditch, and the only thing left to do is to calculate the difference in heads. The distribution of flow to the ditch is somewhat more complicated. Assuming that near to the ditch all significant head loss occurs across the ditch bottom resistance layer and that the layer just below it remains saturated, the part of the water flow between the aquifer and the ditch bottom can be defined as the difference between the head in the aquifer just below the ditch and the head in the ditch divided by the ditch bottom resistance (McDonald and Harbaugh, 1988). The above procedure is carried out for each of the cells located right below the ditch. Adding up the result of the computation for the cells previously mentioned gives the flow through the bottom of the ditch. The flow of water through the sides is simply obtained by substracting the flow through the bottom of the ditch from the total discharge to the ditch.

CHAPTER 4

CASES AND RESULTS

4.1 General

The different cases for each one of the profiles were generated by changing one parameter at a time within the ranges presented below. The parameters that are not changed stay at the standard case value (see Table 1). Fourteen parameters were used for this investigation (thirteen for the open profile case), four of which remained constant through out the study. Tables present the cases and results for each profile, and graphs show the variation of the drainage resistance with respect to a varying parameter for the three profiles together.

4.2 Open Profile

For the open profile (no aquitard) the parameters and their variation range are:

- thickness of fine sand cover -upper aquifer- (D_1) varying from 0 m to 10. m.
- fine sand hydraulic conductivity (k_1) varying from 1. m/day to 10. m/day.
- fixed thickness of coarse sand -lower aquifer- (D_2) equal to 50. m.
- coarse sand hydraulic conductivity (k_2) varying from 10. m/day to 50. m/day.
- ratio k_{1v}/k_{1h} varying from 0.1 to 1.0 . Holding steady k_{1h} at 3 m./day.
- ratio k_{2v}/k_{2h} varying from 0.1 to 1.0 . Holding steady k_{2h} at 3 m./day.
- distance between ditches (L) varying from 30. m to 1000. m.
- width of ditch (B) varying from 1. m to 6. m.
- resistance of ditch bottom and sides (c_{bs}) varying from 1. day to 10. days.
- ratio c_b/c_s -resistance of ditch bottom/resistance of ditch sides- varying from 1 to 10. Holding steady c_s at 2 days and increasing the value of c_b.
- fixed level of ditch bottom (h_b) of 1.5 m.
- fixed level of water in the ditch (h_w) of 1. m.
- fixed specific recharge to groundwater (N) of 0.001 m/day.

Table 2, shows the different cases generated for this profile together with the drainage resistance and the flow distribution computed for them. The drainge resistance graphs for the three profiles are presented in Section 4.5.

4.3 Profile with Aquitard Below Ditch Bottom

For the profile with aquitard below ditch bottom, the parameters used and their variation range are:

- thickness of fine sand cover -upper aquifer- (D_1) varying from 1.5 m to 10. m.
- fine sand hydraulic conductivity (k_1) varying from 1. m/day to 10. m/day.
- fixed thickness of coarse sand -lower aquifer- (D_2) equal to 50. m.
- coarse sand hydraulic conductivity (k_2) varying from 10. m/day to 50. m/day.
- ratio k_{1v}/k_{1h} varying from 0.1 to 1.0 . Holding steady k_{1h} at 3 m./day.
- ratio k_{2v}/k_{2h} varying from 0.1 to 1.0 . Holding steady k_{2h} at 3 m./day.
- distance between ditches (L) varying from 30. m to 1000. m.
- width of ditch (B) varying from 1. m to 6. m.
- resistance of ditch bottom and sides (c_{bs}) varying from 1. day to 10. days.
- ratio c_b/c_s -ditch bottom resistance/ditch sides resistance- varying from 1 to 10. Holding steady c_s at 2 days and increasing the value of c_b.
- fixed level of ditch bottom (h_b) of 1.5 m.
- fixed ditch water level (h_w) of 1. m.
- fixed specific recharge to groundwater (N) of 0.001 m/day
- resistance of aquitard (c_v) varying from 10. days to 1000. days.

Table 3, presents the different cases and the results for this profile. The drainage resistance plots are shown in Section 4.5

4.4 Profile with Aquitard Above Ditch Bottom

For the profile with aquitard above the ditch bottom the parameters and their ranges are:

- thickness of fine sand cover -upper aquifer- (D_1) varying from 0.5 m to 1.5 m.
- fine sand hydraulic conductivity (k_1) varying from 1. m/day to 10. m/day.
- fixed thickness of coarse sand -lower aquifer- (D_2) equal to 50. m.
- coarse sand hydraulic conductivity (k_2) varying from 10. m/day to 50. m/day.
- ratio k_{1v}/k_{1h} varying from 0.1 to 1.0 . Holding steady k_{1h} at 3 m./day.

- ratio k_{2v}/k_{2h} varying from 0.1 to 1.0 . Holding steady k_{2h} at 3 m./day.
- distance between ditches (L) varying from 30. m to 1000. m.
- width of ditch (B) varying from 1. m to 6. m.
- resistance of ditch bottom and sides (c_{bs}) varying from 1. day to 10. days.
- ratio c_b/c_s -ditch bottom resistance/ditch sides resistance- varying from 1 to 10. Holding steady c_s at 2 days and increasing the value of c_b.
- fixed level of ditch bottom (h_b) of 1.5 m.
- fixed level of water in the ditch (h_w) of 1. m.
- fixed specific recharge to groundwater (N) of 0.001 m/day
- resistance of aquitard (c_v) varying from 10. days to 1000. days.

Table 4, shows the different cases generated together with the results obtained using MODFLOW for the drainage resistance and the distribution of flow to a ditch. The drainage resistance graphs are presented in the next section.

4.5 Drainage Resistance Plots

Figures 3 to 12 show the calculated drainage resistance plotted against the changing parameters for the three profiles. A short description of each graph follows.

Figure 3. Drainage Resistance as a Function of the Thickness of the Upper Aquifer.

The effect of increasing the thickness of the upper aquifer on the drainage resistance is relatively small. A large part of the groundwater flows through the lower aquifer.

Open profile:

As long as the the thickness of the upper aquifer is small the drainage resistance is relatively low. An increase in the thickness of the upper aquifer induces a larger part of the groundwater to flow through it , causing the drainage resistance to increase slightly; also the thickness of fine material under the bottom of the ditch increases, creating a similar impact on the drainage resistance.

Profile with aquitard below the ditch bottom:

Due to the presence of the aquitard, a large part of the water is forced to flow through the upper aquifer causing a much higher drainage resistance as compared to the open profile case. As the graph shows, the drainage resistance is very sensitive to the thickness of the upper aquifer. For a thin upper aquifer the drainage resistance may reach values over 5 times higher than those for the open profile case.

Profile with aquitard above the ditch bottom:

As long as the upper aquifer is thin (less than 1meter) and the aquitard is located high in the profile, the freatic water table is found below this layer, making this profile behave like the open profile. When the aquitard is occurs at water level the drainage resistance jumps by a value of 100 days (the value of the aquitard) to about 169 days. This value decreases slightly as the aquitard reaches the depth of the ditch and a part of the water in the less permeable upper aquifer starts flowing through the sides of the ditch.

Figure 4. Drainage Resistance as a Function of the Hydraulic Conductivity of the Upper Aquifer.

With increasing hydraulic conductivity of the upper aquifer the drainage resistance clearly decreases for all profiles. The effect is strongest for the profile with an aquitard below the ditch, which blocks the flow of water down to the lower aquifer.

Open profile:

The drainage resistance is not very sensitive to the hydraulic conductivity for the upper aquifer, except for very low values. The main part of the discharge takes place through the lower aquifer with a relatively large transmissivity.

Profile with aquitard below the ditch bottom:

The drainage resistance is very dependent on the hydraulic conductivity of the upper aquifer, due to the presence of the aquitard that blocks the flow to the lower aquifer.

Profile with aquitard above the ditch bottom:

This is an intermediate situation between the other two. The curve is more or less parallel to the open profile curve, the drainage resistance being about 100 days higher than the one for the open profile. As most of the water flows through the lower aquifer the drainage resistance increases by the resistance of the aquitard. The intersection with the curve for the aquitard below the ditch profile is due to the difference in basic data (D1 = 1.5 meters instead of 3 meters for the latter case) and is, therefore, somewhat misleading.

Figure 5. Drainage Resistance as a Function of the Transmissivity of the Lower Aquifer.

The figure shows that for all profiles, the drainage resistance is not very sensitive to changes in the transmissivity of the lower aquifer in the range above 500 m^2/d. The drainage resistance is much lower for the open profile than for the profiles with the aquitard

Open profile:

The drainage resistance is low due to the full contribution of the lower aquifer.

Profile with aquitard below the ditch bottom:

The drainage resistance increases dramatically (more than 100 days) as compared to the open profile due to the fact that the groundwater flow through the lower aquifer is largely blocked by the aquitard.

Profile with aquitard above the ditch bottom:

The drainage resistance falls in between the other two profiles. This is due to the larger contribution of the lower aquifer, mainly as a result of easier discharge to the ditch, where the aquitard is interrupted.

Figure 6. Drainage Resistance as a Function of the Anisotropy (ratio k_v/k_h) of the Upper Aquifer.

The large differences in the drainage resistance for the three graphs correspond to differences in the contribution of the upper aquifer, as explained for figure 5. The values are the same as those of figure 5 for the standard case (equal values of k_v and k_h).

Open profile and Profile with aquitard below the ditch bottom:

The drainage resistance increases for a lower ratio between the vertical and horizontal hydraulic conductivities of the upper aquifer (moving left in the graph), the reason being that the vertical flow through the upper aquifer is gradually confronted with more resistance. The non-linear behaviour is caused by the changes in the contribution of the upper aquifer.

Profile with aquitard above the ditch bottom

In the case the aquitard is situated above the ditch bottom, the contribution of the upper aquifer in the discharge is almost negligible.. As the main part of the water has to move through the lower aquifer, there is a delay caused by the aquitard, but no influence on the distribution of flow, so a variation in the isotropy of the upper aquifer is of little influence on the resulting drainage resistance.

Figure 7. Drainage Resistance as a Function of the Anisotropy (ratio k_v/k_h) of the Lower Aquifer.

Figure 7 shows that the drainage resistance has low sensitivity to the changes in the anisotropy of the lower aquifer. The large differences in the positions of the graphs for different profiles have been explained in figure 5.

Open profile and Profile with aquitard above the ditch bottom:

These two profiles have in common that the participation of the upper aquifer in the groundwater discharge is relatively low for medium and high values of the transmissivity of the lower aquifer. There is a slight increase in the drainage resistance for low values of k_v.

Profile with aquitard below the ditch botom:

In this situation a relatively large part of the groundwater flow takes place through the upper aquifer, so that the influence of the anisotropy of the lower aquifer on the drainage resistance is negligible.

Figure 8. Drainage Resistance as a Function of the Distance between the Ditches.

The distance between the ditches is the parameter, among all the ones studied, that shows the greatest impact on the drainage resistance for each profile. The relation between these two parameters is not perfectly linear although it seems that way.

Open profile:

Comparing the behavior of this graph with the Ernst equation, we see that there is a linear relation between the drainage resistance and the radial and entrance resistance to the ditch, but quadratic for the horizontal resistance. As the distance between ditches increases most of the flow is through the lower aquifer, where the horizontal resistance is low, making the relation between the parameters almost a straight line.

Profile with aquitard below the ditch bottom:

The aquitard in this profile limits the movement of water through the lower aquifer, therefore, more flow occurs in the upper aquifer which has a higher resistance.

Profile with aquitard above the ditch bottom:

The behavior of the plot is almost identical to that of the open profile except that is shifted up by a factor equal to the resistance of the aquitard. This behavior is expected since flow for this profile occurs mostly in the lower aquifer for any drain spacing greater than 40 meters.

Figure 9. Drainage Resistance as a Function of the Width of the Ditch.

For this situation, the drainage resistance decreases with respect to the increase of the ditch width.

Open profile:

This behavior is expected since the area of the ditch is increasing with respect of that of the aquifer system.

Profile with aquitard below the ditch bottom:

The same pattern as above only shifted up

Profile with aquitard above the ditch bottom:

Figure 10. Drainage Resistance as a Function of the Resistance of the Bottom and the Sides of the Ditch.

This is a linear relation for all the profiles. The effect is just at the entrance to the ditch, so where the water flows in the aquifer system has no influence, only the total resistance to get to the ditch.

Open profile:

For the Ernst equation this relation is also linear.

Profile with aquitard below the ditch bottom:

The difference between the plot for this profile and the open profile is given only by the resistance of the aquitard and the flow resistance in the system.

Profile with aquitard above the ditch bottom:

In this case, the difference with the open profile is mostly given by the aquitard, since the upper layer take almost no part in the flow of the system.

Figure 11. Drainage Resistance as a Function of the Ratio between the Resistance of the Bottom of the Ditch and the Resistance of the Sides of the Ditch.

For all cases this relation shows a parabolic trend as the ratio of c_b/c_s increases.

Open profile:

As more water is forced to flow through the sides of the ditch instead of the bottom, the drainage resistance increases. The curve flattens as the amount of flow going through the bottom becomes smaller, showing only the resistance of the sides of the ditch.

Profile with aquitard below the ditch bottom:

This curve is the same as the one for the open profile, but shifted up an amount equal to the resistance of the aquifer system for this profile.

Profile with aquitard above the ditch bottom:

This profile starts with a value in between the two other profiles, since the resistance of this profile up to the ditch has that value. The greater slope of the curve for this profile is given by the fact that even when the bottom resistance is large there is still water flowing through it, as can be seen in table 4. It will eventually flatten out.

Figure 12. Drainage Resistance as a Function of the Resistance of the Aquitard.

Only two curves are shown here because only two profiles have an aquitard. For both profiles the drainage resistance shows a parabolic behavior as the aquitard resistance increases.

Profile with aquitard below the ditch bottom:

As the resistance of the aquitard increases, more water flows through the upper aquifer raising the value of the drainagee resistance. This occurs up to a value of 200 days for the aquitard, when most of the water flows above the aquitard and the curves flattens.

Profile with aquitard above the ditch bottom:

For this profile, the ditch drains the lower aquifer influencing the flow through the aquitard. So, because of the difference in heads over the aquitard, water still flows through it even when it has a high resistance value, causing a higher increase in the drainage resistance than in the other profile.

CHAPTER 5

CONCLUSIONS

5.1 Significance of Results

The responses of the drainage resistance and the distribution of flow to a dich to variations in several local parameters typical of the sandy areas of the Netherlands were investigated in this report. It was found that the parameter having the largest influence on the drainage resistance is the drain spacing (L) for all three profiles. The anisotropy of the lower aquifer, the one with the smallest influence on the drainage resistance, also for the three profiles. With respect to the distribution of flow, the width of the ditch, and the ratio between the resistance of the bottom and sides of the ditch are the parameters having the largest impact on the flow distribution. For the profile with an aquitard above the bottom of the ditch, the drain spacing and the aquitard resistance have a strong influence.

The results of this investigation could help in the calibration of models developed for the sandy areas. Furthermore, with the right analysis of the information contained here, it could be used to develope a plan for a better gathering of field-work information.

5.2 Further Work

It would be interesting to see how the parameters that were kept constant through out this investigation because of time limitations, affect the drainage resistance and the distribution of flow to the ditch.

This report focuses only on the characteristics of the sandy area of the Netherlands. In order to have a better understanding of the surface water - groundwater relation in the whole country, the other two general areas into which the Netherlands can be divided according to soil composition must be modeled.

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Table 2. Cases and Results for Open Profile.

D_1 (m)	k_1 (m/d)	k_2 (m/d)	k_{1v} / k_{1h}	k_{2v} / k_{2h}	L (m)	B (m)	c_{b*} (d)	c_b / c_s	c_v (d)	γ (d)	total flow to ditch (m^3/d)	flow thru bottom %	flow thru sides %
0,0	3	30	1	1	100	2	2	1	0	68.627	0.098	66	34
0.5	3	30	1	1	100	2	2	1	0	68.560	0.098	66	34
1.0	3	30	1	1	100	2	2	1	0	68.636	0.098	66	34
1.5	3	30	1	1	100	2	2	1	0	70.066	0.098	67	33
2.0	3	30	1	1	100	2	2	1	0	74.231	0.098	66	34
3.0	3	30	1	1	100	2	2	1	0	80.000	0.098	65	35
5.0	3	30	1	1	100	2	2	1	0	86.396	0.098	65	35
10.0	3	30	1	1	100	2	2	1	0	94.060	0.098	65	35
3	1	30	1	1	100	2	2	1	0	104.041	0.098	64	36
3	2	30	1	1	100	2	2	1	0	85.993	0.098	65	35
3	3	30	1	1	100	2	2	1	0	80.000	0.098	65	35
3	5	30	1	1	100	2	2	1	0	75.119	0.098	66	34
3	10	30	1	1	100	2	2	1	0	71.383	0.098	66	34
3	3	10	1	1	100	2	2	1	0	85.987	0.098	65	35
3	3	20	1	1	100	2	2	1	0	81.551	0.098	65	35
3	3	30	1	1	100	2	2	1	0	80.000	0.098	65	35
3	3	40	1	1	100	2	2	1	0	79.209	0.098	65	35
3	3	50	1	1	100	2	2	1	0	78.730	0.098	65	35
3	3	30	0.1	1	100	2	2	1	0	131.508	0.098	59	41
3	3	30	0.2	1	100	2	2	1	0	107.245	0.098	62	38
3	3	30	0.3	1	100	2	2	1	0	97.446	0.098	64	36
3	3	30	0.5	1	100	2	2	1	0	88.381	0.098	65	35
3	3	30	1.0	1	100	2	2	1	0	80.000	0.098	65	35
3	3	30	1	0.1	100	2	2	1	0	86.717	0.098	65	35
3	3	30	1	0.2	100	2	2	1	0	83.863	0.098	65	35
3	3	30	1	0.3	100	2	2	1	0	82.588	0.098	65	35
3	3	30	1	0.5	100	2	2	1	0	81.300	0.098	65	35
3	3	30	1	1.0	100	2	2	1	0	80.000	0.098	65	35
3	3	30	1	1	30	2	2	1	0	22.864	0.028	65	35
3	3	30	1	1	40	2	2	1	0	30.979	0.038	65	35
3	3	30	1	1	100	2	2	1	0	80.000	0.098	65	35
3	3	30	1	1	200	2	2	1	0	162.649	0.198	65	35
3	3	30	1	1	400	2	2	1	0	332.179	0.398	65	35
3	3	30	1	1	600	2	2	1	0	507.772	0.598	65	35
3	3	30	1	1	1000	2	2	1	0	877.796	0.998	65	35
3	3	30	1	1	100	1	2	1	0	116.302	0.099	49	51
3	3	30	1	1	100	2	2	1	0	80.000	0.098	65	35
3	3	30	1	1	100	3	2	1	0	61.251	0.097	74	26
3	3	30	1	1	100	4	2	1	0	49.705	0.096	79	21
3	3	30	1	1	100	6	2	1	0	36.118	0.094	84	16
3	3	30	1	1	100	2	1	1	0	47.708	0.098	65	35
3	3	30	1	1	100	2	2	1	0	80.000	0.098	65	35
3	3	30	1	1	100	2	5	1	0	176.752	0.098	66	34
3	3	30	1	1	100	2	10	1	0	338.823	0.098	66	34

Table 2 (continued). Cases and Results for Open Profile.

D_1 (m)	k_1 (m/d)	k_2 (m/d)	k_{1v} / k_{1h}	k_{2v} / k_{2h}	L (m)	B (m)	c_{bs} (d)	c_b / c_s	c_v (d)	γ (d)	total flow to ditch (m^3/d)	flow thru bottom %	flow thru sides %
3	3	30	1	1	100	2	2	1	0	80.000	0.098	65	35
3	3	30	1	1	100	2	2	2	0	111.915	0.098	50	50
3	3	30	1	1	100	2	2	5	0	154.736	0.098	29	71
3	3	30	1	1	100	2	2	10	0	179.127	0.098	17	83

Table 3. Cases and Results for Profile with Aquitard below the Ditch Bottom.

D_1 (m)	k_1 (m/d)	k_2 (m/d)	k_{1v} / k_{1h}	k_{2v} / k_{2h}	L (m)	B (m)	c_{bs} (d)	c_b / c_s	c_v (d)	γ (d)	total flow to ditch (m^3/d)	flow thru bottom %	flow thru sides %
1.5	3	30	1	1	100	2	2	1	100	449.318	0.098	8	92
2.0	3	30	1	1	100	2	2	1	100	290.574	0.098	61	39
3.0	3	30	1	1	100	2	2	1	100	211.784	0.098	64	36
5.0	3	30	1	1	100	2	2	1	100	156.550	0.098	65	35
10.0	3	30	1	1	100	2	2	1	100	120.701	0.098	65	35
3	1	30	1	1	100	2	2	1	100	374.585	0.098	61	39
3	2	30	1	1	100	2	2	1	100	262.440	0.098	63	37
3	3	30	1	1	100	2	2	1	100	211.784	0.098	64	36
3	5	30	1	1	100	2	2	1	100	162.611	0.098	65	35
3	10	30	1	1	100	2	2	1	100	118.342	0.098	65	35
3	3	10	1	1	100	2	2	1	100	212.116	0.098	64	36
3	3	20	1	1	100	2	2	1	100	211.861	0.098	64	36
3	3	30	1	1	100	2	2	1	100	211.784	0.098	64	36
3	3	40	1	1	100	2	2	1	100	211.742	0.098	64	36
3	3	50	1	1	100	2	2	1	100	211.715	0.098	64	36
3	3	30	0.1	1	100	2	2	1	100	237.269	0.098	58	42
3	3	30	0.2	1	100	2	2	1	100	224.459	0.098	61	39
3	3	30	0.3	1	100	2	2	1	100	219.668	0.098	62	38
3	3	30	0.5	1	100	2	2	1	100	215.395	0.098	63	37
3	3	30	1.0	1	100	2	2	1	100	211.784	0.098	64	36
3	3	30	1	0.1	100	2	2	1	100	212.129	0.098	64	36
3	3	30	1	0.2	100	2	2	1	100	212.002	0.098	64	36
3	3	30	1	0.3	100	2	2	1	100	211.910	0.098	64	36
3	3	30	1	0.5	100	2	2	1	100	211.848	0.098	64	36
3	3	30	1	1.0	100	2	2	1	100	211.784	0.098	64	36
3	3	30	1	1	30	2	2	1	100	35.699	0.028	64	36
3	3	30	1	1	40	2	2	1	100	55.067	0.038	64	36
3	3	30	1	1	100	2	2	1	100	211.784	0.098	64	36
3	3	30	1	1	200	2	2	1	100	495.360	0.198	64	36
3	3	30	1	1	400	2	2	1	100	998.585	0.398	64	36
3	3	30	1	1	600	2	2	1	100	1464.018	0.598	64	36
3	3	30	1	1	1000	2	2	1	100	2351.419	0.998	64	36
3	3	30	1	1	100	1	2	1	100	246.718	0.099	48	52
3	3	30	1	1	100	2	2	1	100	211.784	0.098	64	36
3	3	30	1	1	100	3	2	1	100	193.089	0.097	72	28
3	3	30	1	1	100	4	2	1	100	180.927	0.096	76	24
3	3	30	1	1	100	6	2	1	100	164.966	0.094	80	20
3	3	30	1	1	100	2	1	1	100	180.989	0.098	63	37
3	3	30	1	1	100	2	2	1	100	211.784	0.098	64	36
3	3	30	1	1	100	2	5	1	100	304.122	0.098	65	35
3	3	30	1	1	100	2	10	1	100	459.429	0.098	66	34
3	3	30	1	1	100	2	2	1	100	211.784	0.098	64	36
3	3	30	1	1	100	2	2	2	100	240.997	0.098	49	51

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Table 3 (continued). Cases and Results for Profile with Aquitard below the Ditch Bottom.

D_1	k_1	k_2	$\frac{k_{1v}}{k_{1h}}$	$\frac{k_{2v}}{k_{2h}}$	L	B	c_{b*}	$\frac{c_b}{c_s}$	c_v	γ	total flow to ditch	flow thru bottom	flow thru sides
(m)	(m/d)	(m/d)			(m)	(m)	(d)		(d)	(d)	(m^3/d)	%	%
3	3	30	1	1	100	2	2	5	100	280.337	0.098	29	71
3	3	30	1	1	100	2	2	10	100	302.821	0.098	17	83
3	3	30	1	1	100	2	2	1	10	128.410	0.098	64	36
3	3	30	1	1	100	2	2	1	20	151.388	0.098	64	36
3	3	30	1	1	100	2	2	1	50	187.157	0.098	64	36
3	3	30	1	1	100	2	2	1	100	211.784	0.098	64	36
3	3	30	1	1	100	2	2	1	200	229.881	0.098	64	36
3	3	30	1	1	100	2	2	1	500	243.745	0.098	64	36
3	3	30	1	1	100	2	2	1	1000	249.026	0.098	64	36

Table 4. Cases and Results for Profile with Aquitard above the Ditch Bottom.

D_1 (m)	k_1 (m/d)	k_2 (m/d)	$\frac{k_{1v}}{k_{1h}}$	$\frac{k_{2v}}{k_{2h}}$	L (m)	B (m)	c_{bs} (d)	$\frac{c_b}{c_s}$	c_v (d)	γ (d)	total flow to ditch (m^3/d)	flow thru bottom %	flow thru sides %
0.5	3	30	1	1	100	2	2	1	100	68.560	0.098	66	34
1.0	3	30	1	1	100	2	2	1	100	168.679	0.098	66	34
1.5	3	30	1	1	100	2	2	1	100	164.881	0.098	70	30
1.5	1	30	1	1	100	2	2	1	100	180.315	0.098	78	22
1.5	2	30	1	1	100	2	2	1	100	171.723	0.098	73	27
1.5	3	30	1	1	100	2	2	1	100	164.881	0.098	70	30
1.5	5	30	1	1	100	2	2	1	100	154.371	0.098	65	35
1.5	10	30	1	1	100	2	2	1	100	138.469	0.098	60	40
1.5	3	10	1	1	100	2	2	1	100	170.578	0.098	69	31
1.5	3	20	1	1	100	2	2	1	100	166.316	0.098	69	31
1.5	3	30	1	1	100	2	2	1	100	164.881	0.098	70	30
1.5	3	40	1	1	100	2	2	1	100	164.215	0.098	70	30
1.5	3	50	1	1	100	2	2	1	100	163.705	0.098	70	30
1.5	3	30	0.1	1	100	2	2	1	100	166.136	0.098	70	30
1.5	3	30	0.2	1	100	2	2	1	100	165.491	0.098	70	30
1.5	3	30	0.3	1	100	2	2	1	100	165.264	0.098	70	30
1.5	3	30	0.5	1	100	2	2	1	100	165.065	0.098	70	30
1.5	3	30	1.0	1	100	2	2	1	100	164.881	0.098	70	30
1.5	3	30	1	0.1	100	2	2	1	100	171.601	0.098	69	31
1.5	3	30	1	0.2	100	2	2	1	100	168.597	0.098	69	31
1.5	3	30	1	0.3	100	2	2	1	100	167.370	0.098	69	31
1.5	3	30	1	0.5	100	2	2	1	100	166.096	0.098	69	31
1.5	3	30	1	1.0	100	2	2	1	100	164.881	0.098	70	30
1.5	3	30	1	1	30	2	2	1	100	63.750	0.028	42	58
1.5	3	30	1	1	40	2	2	1	100	83.466	0.038	50	50
1.5	3	30	1	1	100	2	2	1	100	164.881	0.098	70	30
1.5	3	30	1	1	200	2	2	1	100	260.757	0.198	77	23
1.5	3	30	1	1	400	2	2	1	100	443.294	0.398	80	20
1.5	3	30	1	1	600	2	2	1	100	629.857	0.598	80	20
1.5	3	30	1	1	1000	2	2	1	100	1018.019	0.998	80	20
1.5	3	30	1	1	100	1	2	1	100	213.541	0.099	60	40
1.5	3	30	1	1	100	2	2	1	100	164.881	0.098	70	30
1.5	3	30	1	1	100	3	2	1	100	144.707	0.097	73	27
1.5	3	30	1	1	100	4	2	1	100	133.603	0.096	75	25
1.5	3	30	1	1	100	6	2	1	100	121.590	0.094	77	23
1.5	3	30	1	1	100	2	1	1	100	132.301	0.098	71	29
1.5	3	30	1	1	100	2	2	1	100	164.881	0.098	70	30
1.5	3	30	1	1	100	2	5	1	100	259.842	0.098	67	33
1.5	3	30	1	1	100	2	10	1	100	417.975	0.098	66	34
1.5	3	30	1	1	100	2	2	1	100	164.881	0.098	70	30
1.5	3	30	1	1	100	2	2	2	100	211.314	0.098	60	40
1.5	3	30	1	1	100	2	2	5	100	295.180	0.098	42	58
1.5	3	30	1	1	100	2	2	10	100	359.629	0.098	28	72

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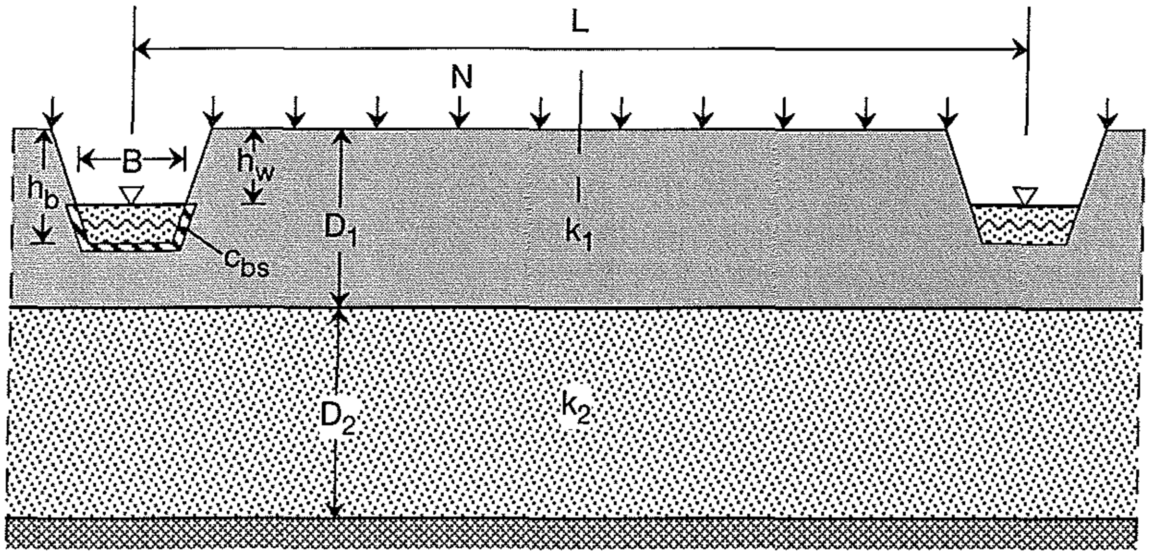
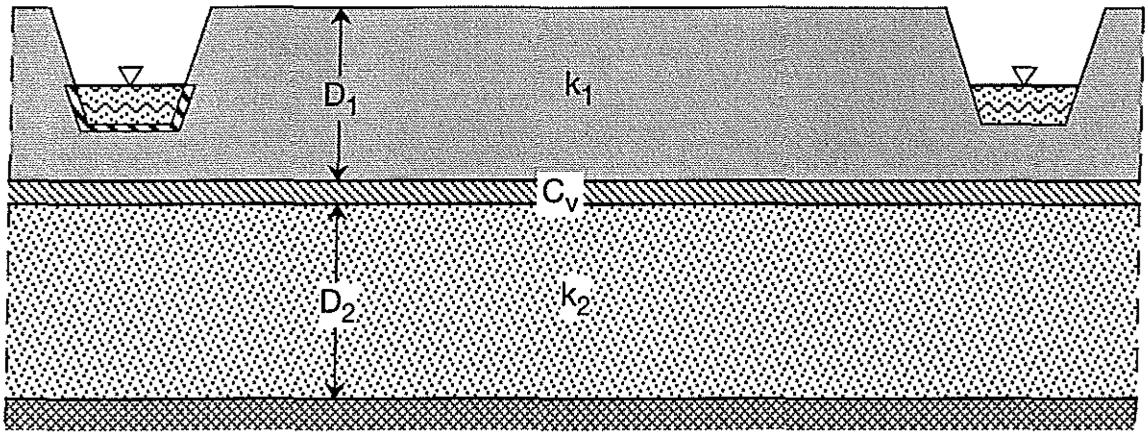
Table 4 (continued). Cases and Results for Profile with Aquitard above the Ditch Bottom.

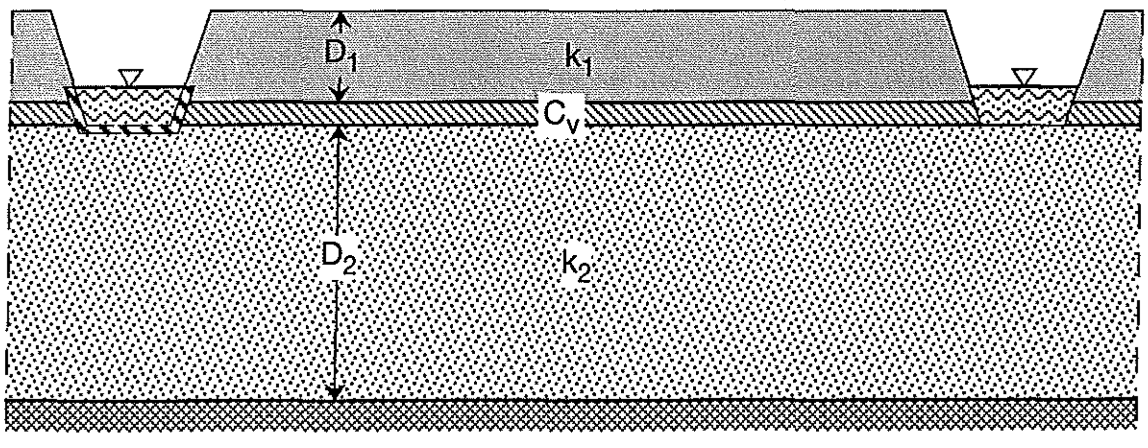
D_1 (m)	k_1 (m/d)	k_2 (m/d)	k_{1v} / k_{1h}	k_{2v} / k_{2h}	L (m)	B (m)	c_{bs} (d)	c_b / c_s	c_v (d)	γ (d)	total flow to ditch (m^3/d)	flow thru bottom %	flow thru sides %
1.5	3	30	1	1	100	2	2	1	10	85.766	0.098	73	27
1.5	3	30	1	1	100	2	2	1	20	96.319	0.098	74	26
1.5	3	30	1	1	100	2	2	1	50	124.211	0.098	73	27
1.5	3	30	1	1	100	2	2	1	100	164.881	0.098	70	30
1.5	3	30	1	1	100	2	2	1	200	230.618	0.098	63	37
1.5	3	30	1	1	100	2	2	1	500	353.380	0.098	47	53
1.5	3	30	1	1	100	2	2	1	1000	449.235	0.098	32	68



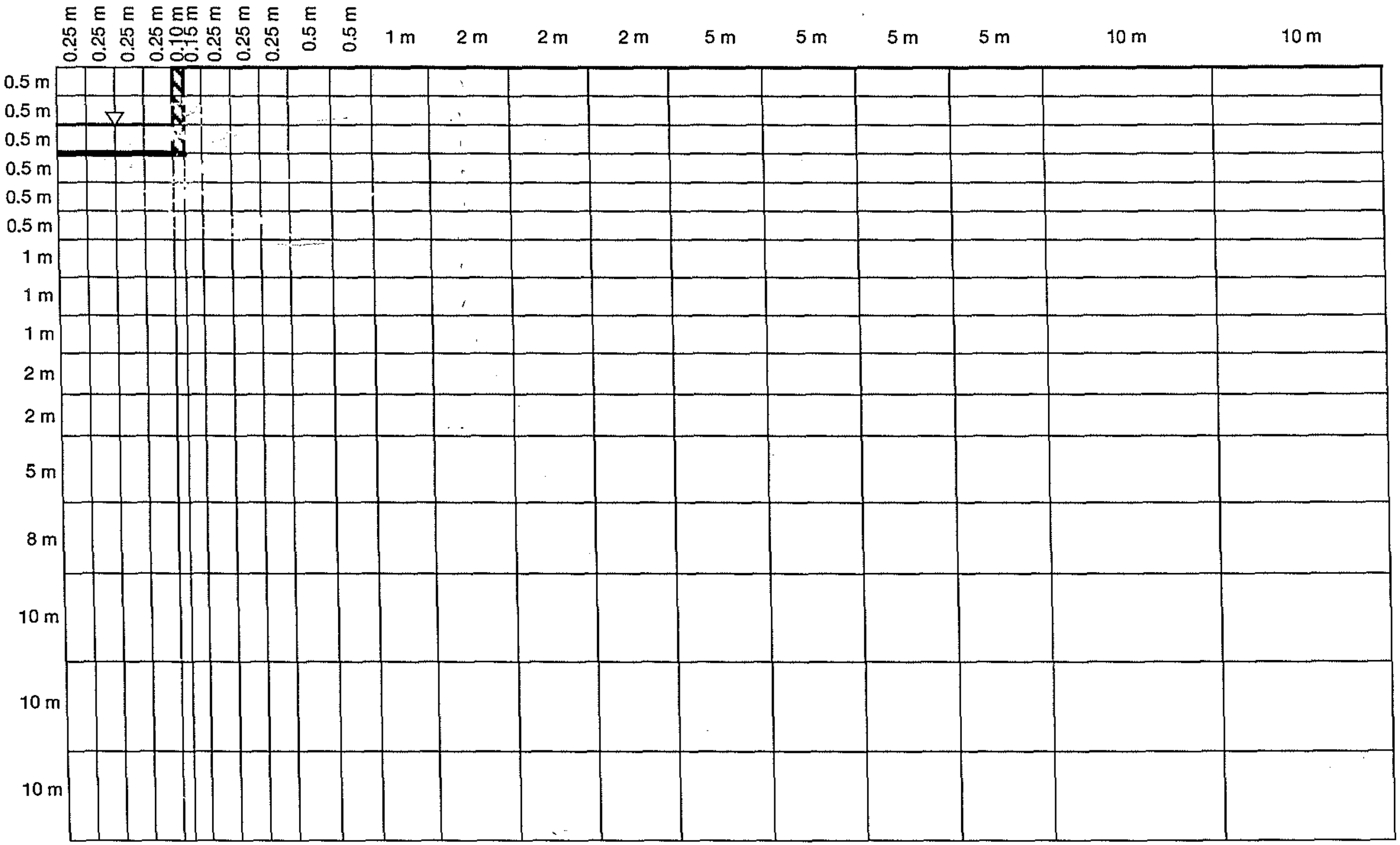
Open Profile



Profile with Aquitard below Ditch Bottom



Profile with Aquitard above Ditch Bottom


0.25 m
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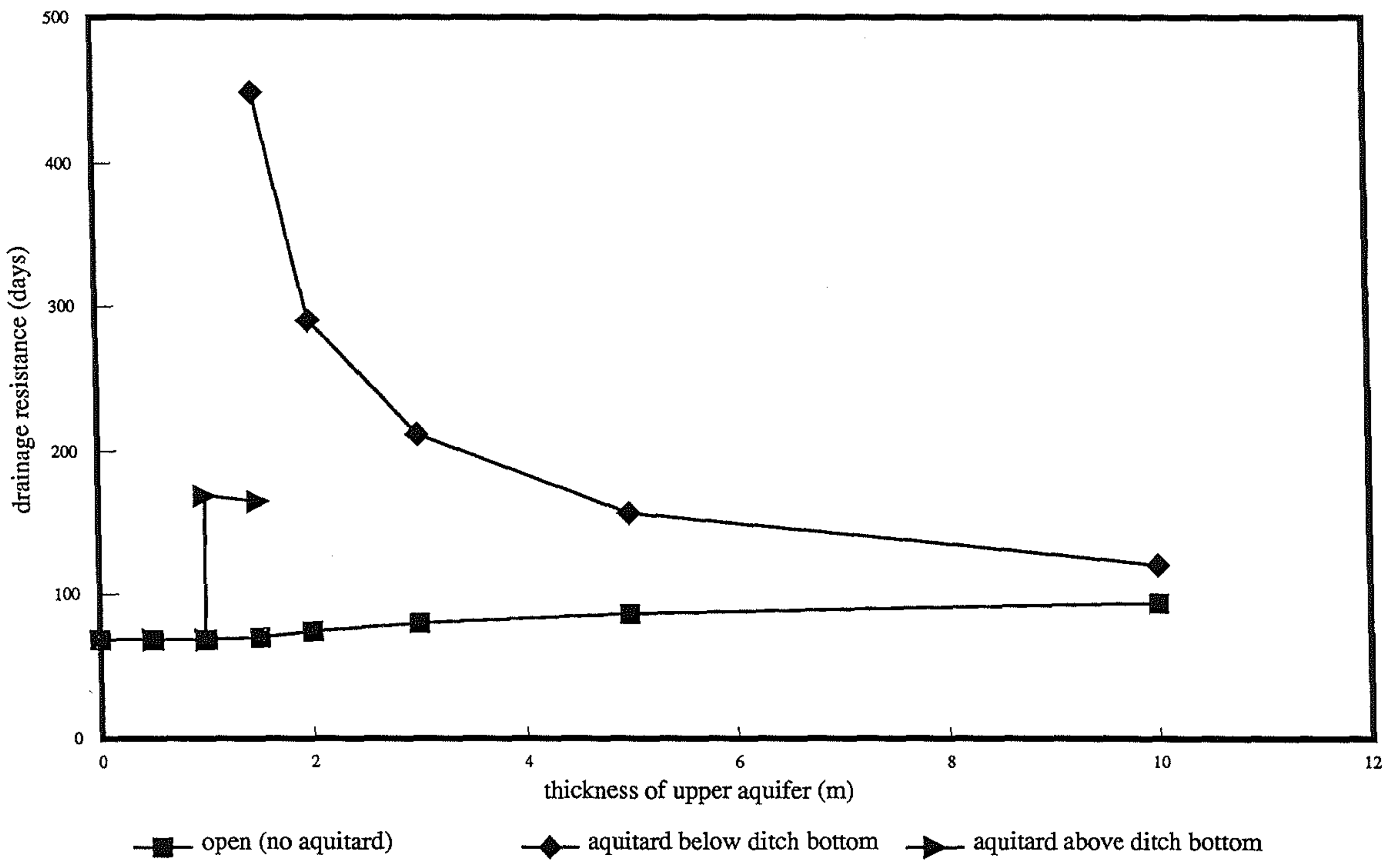
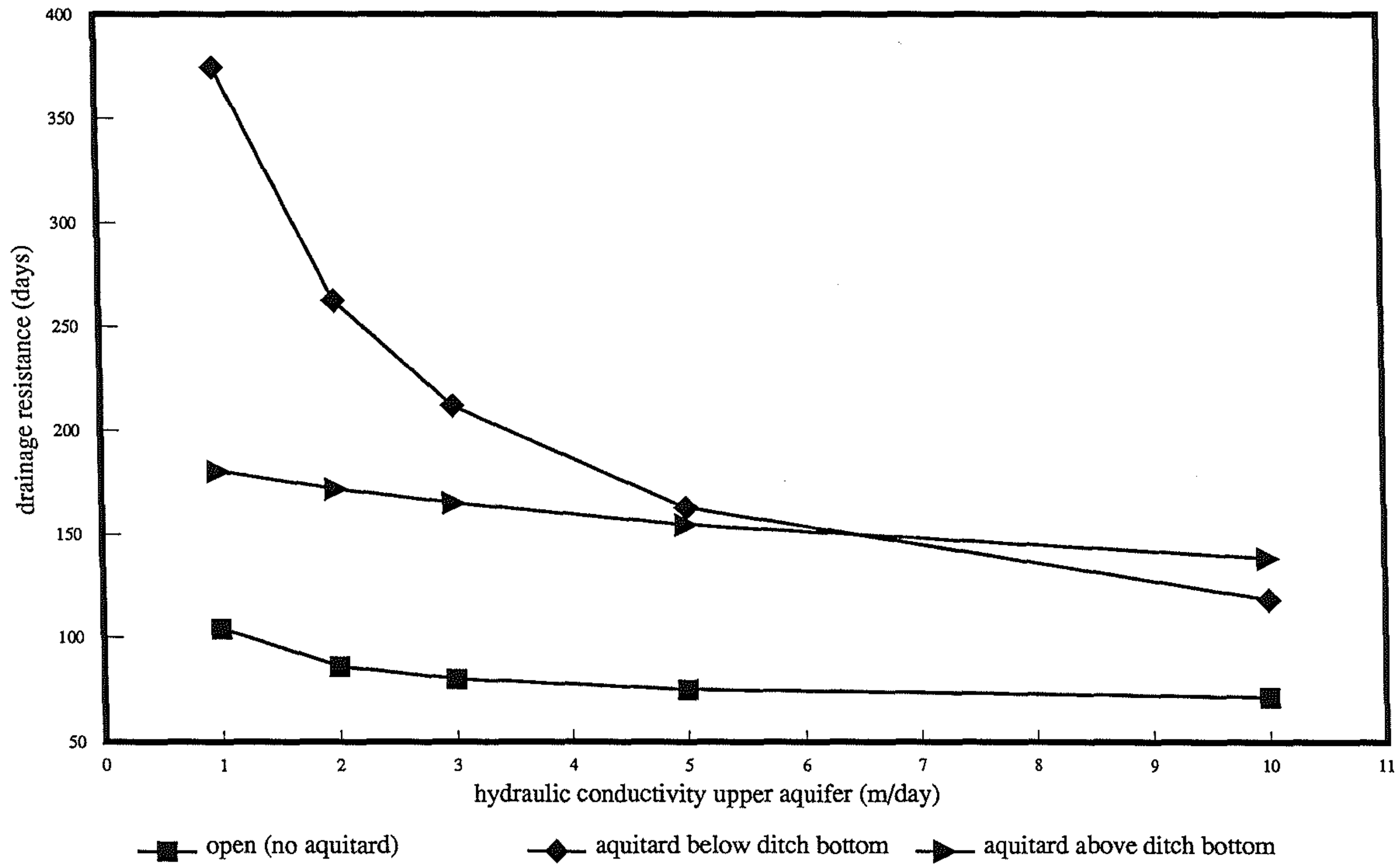
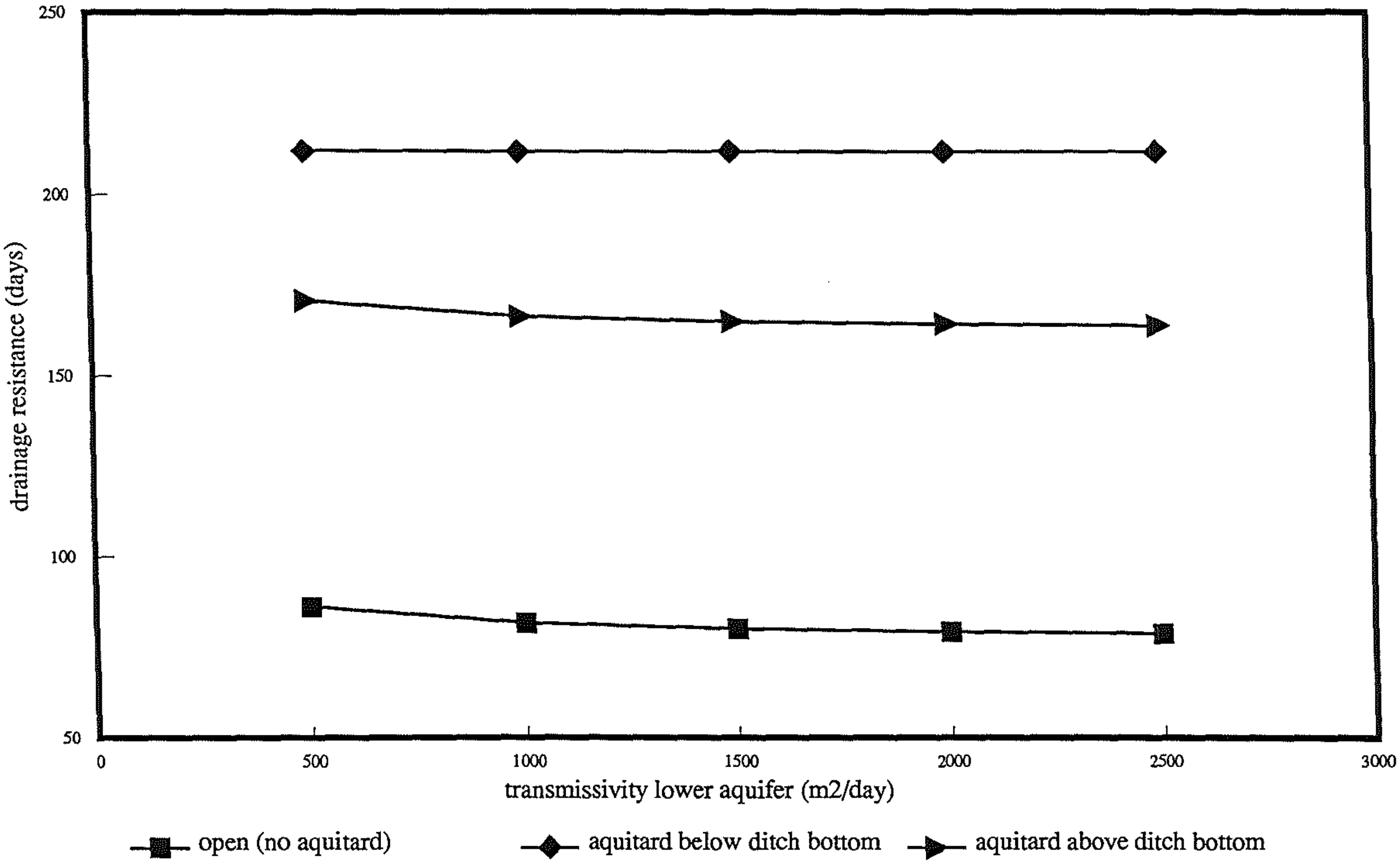
2 m
5 m
8 m
10 m
10 m
10 m



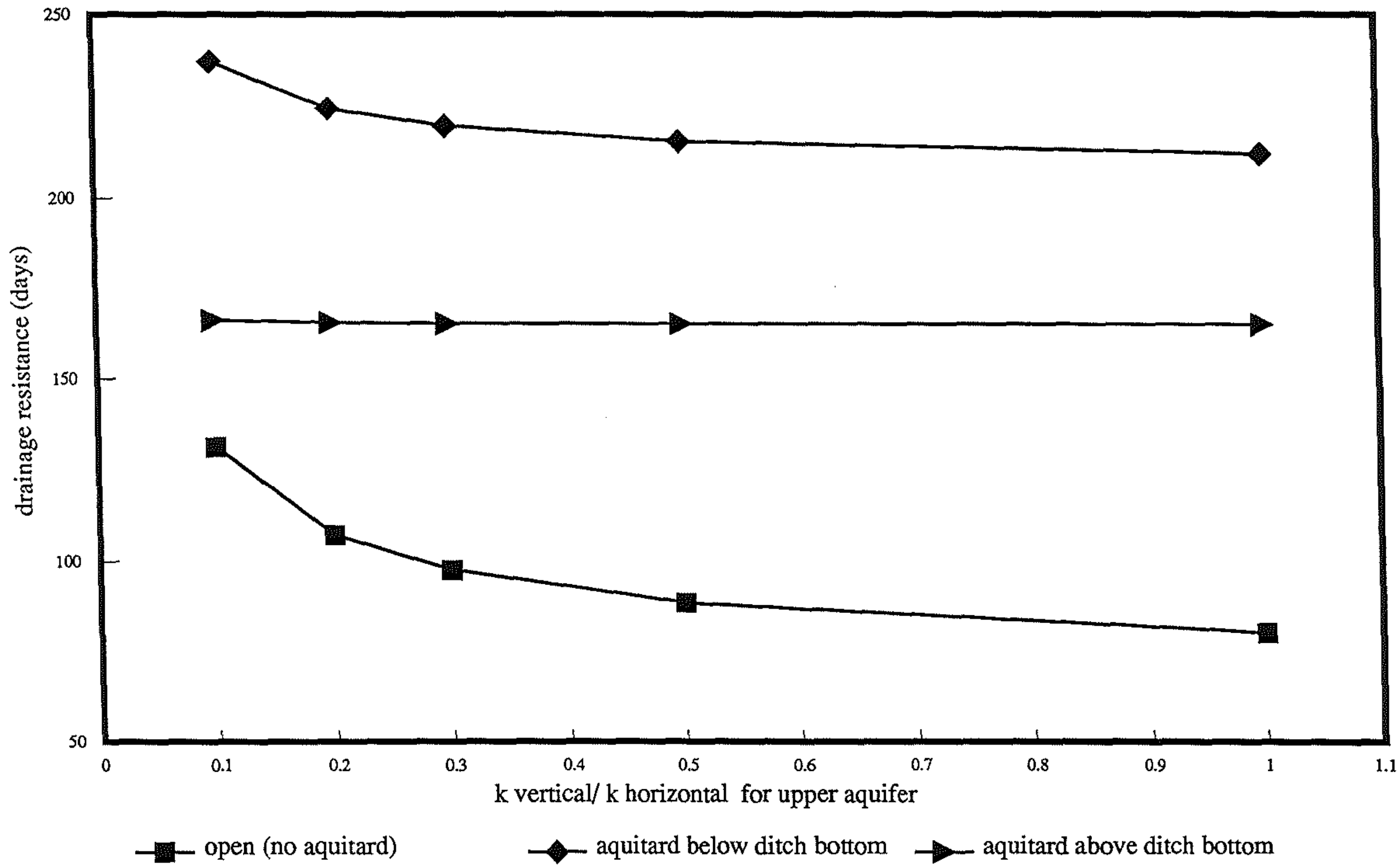
drainage resistance (days)
500
400
300
200
100
0
0
2
4
6
8
10
12
thickness of upper aquifer (m)
open (no aquitard)
aquitard below ditch bottom
aquitard above ditch bottom

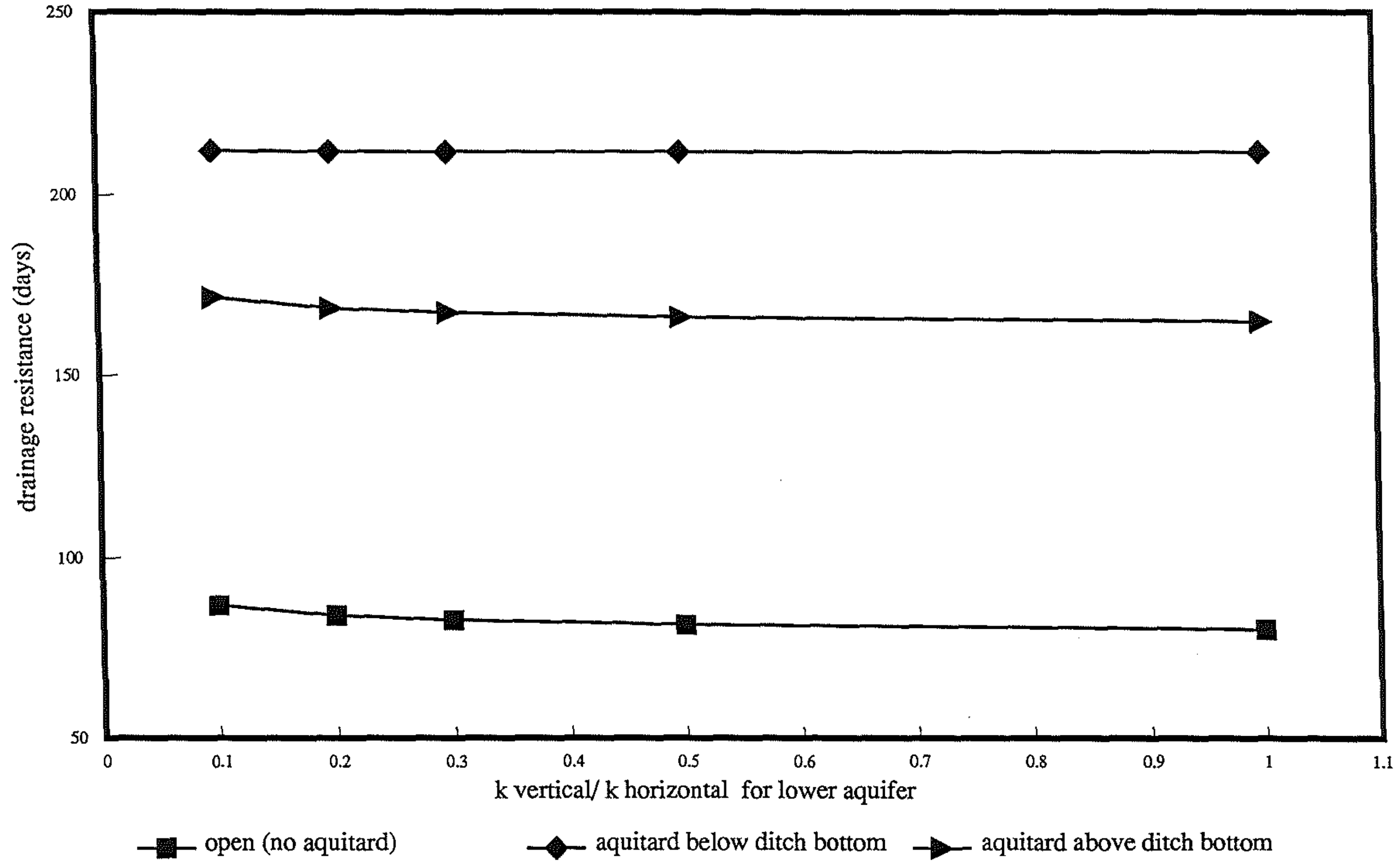


drainage resistance (days)
400
350
300
250
200
150
100
50
0
1
2
3
4
5
6
7
8
9
10
11
hydraulic conductivity upper aquifer (m/day)
open (no aquitard)
aquitard below ditch bottom
aquitard above ditch bottom

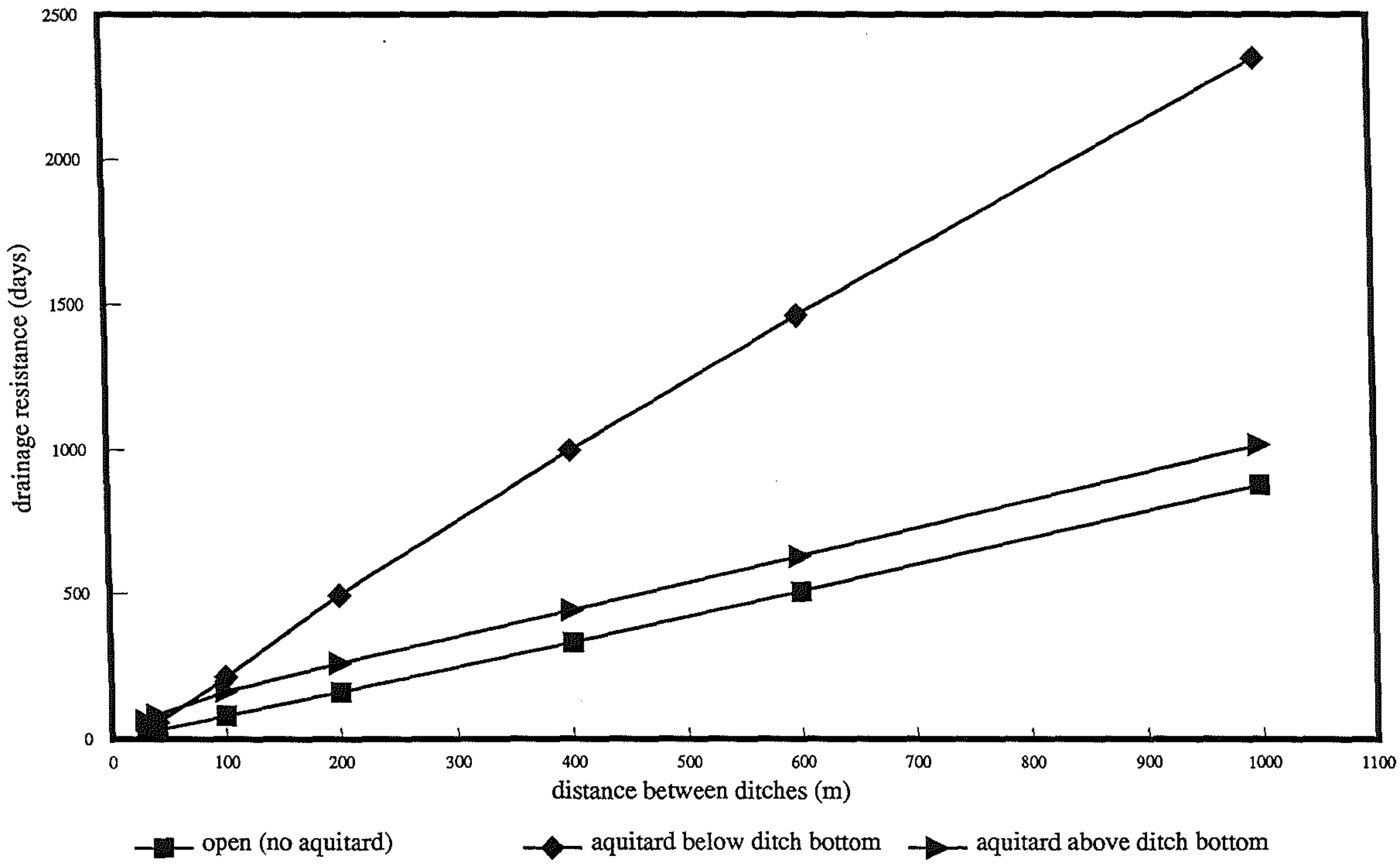


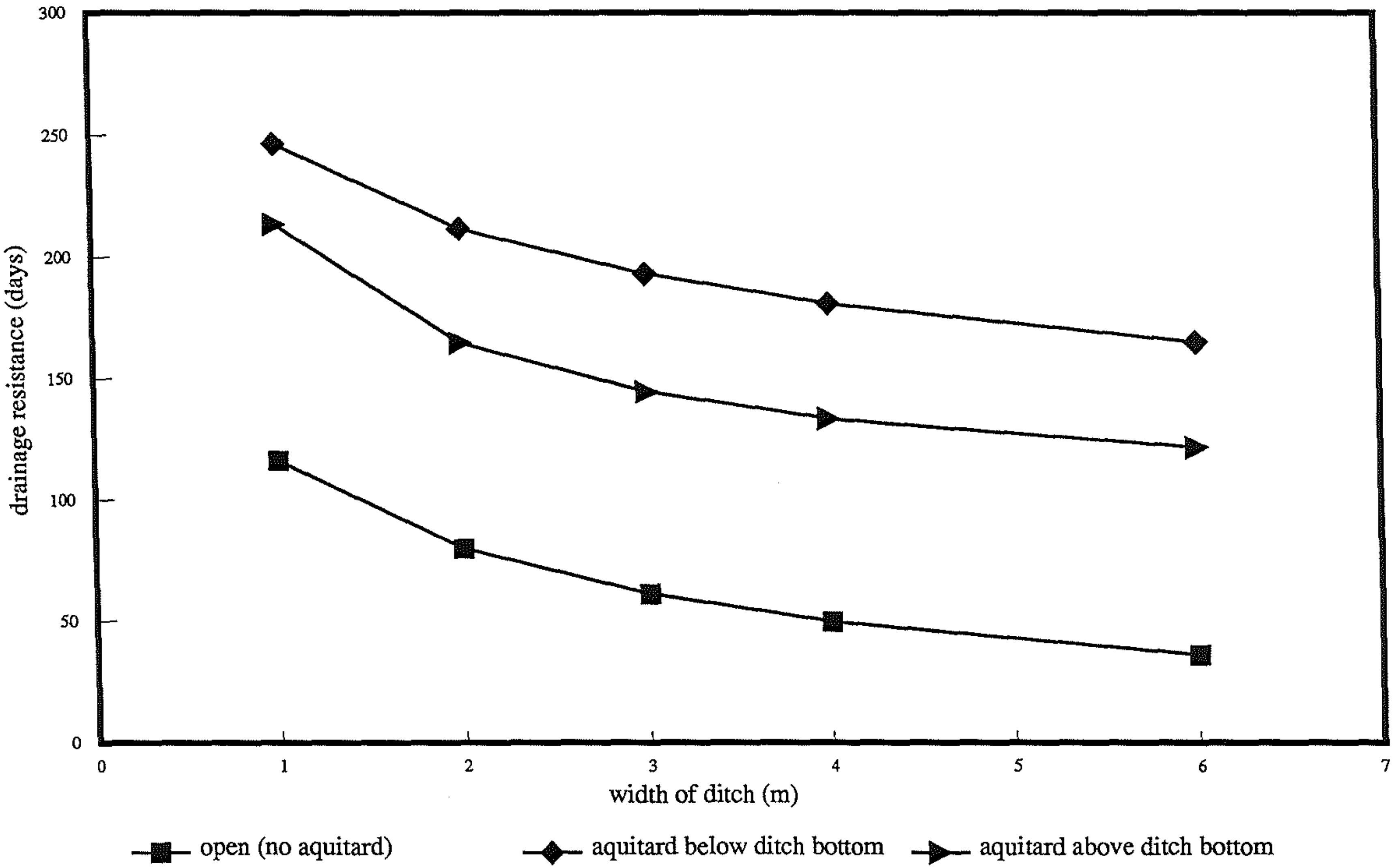
250
200
150
100
50
drainage resistance (days)
0
500
1000
1500
2000
2500
3000
transmissivity lower aquifer (m2/day)
open (no aquitard)
aquitard below ditch bottom
aquitard above ditch bottom


250
200
150
100
50
drainage resistance (days)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
k vertical/ k horizontal for upper aquifer
open (no aquitard)
aquitard below ditch bottom
aquitard above ditch bottom

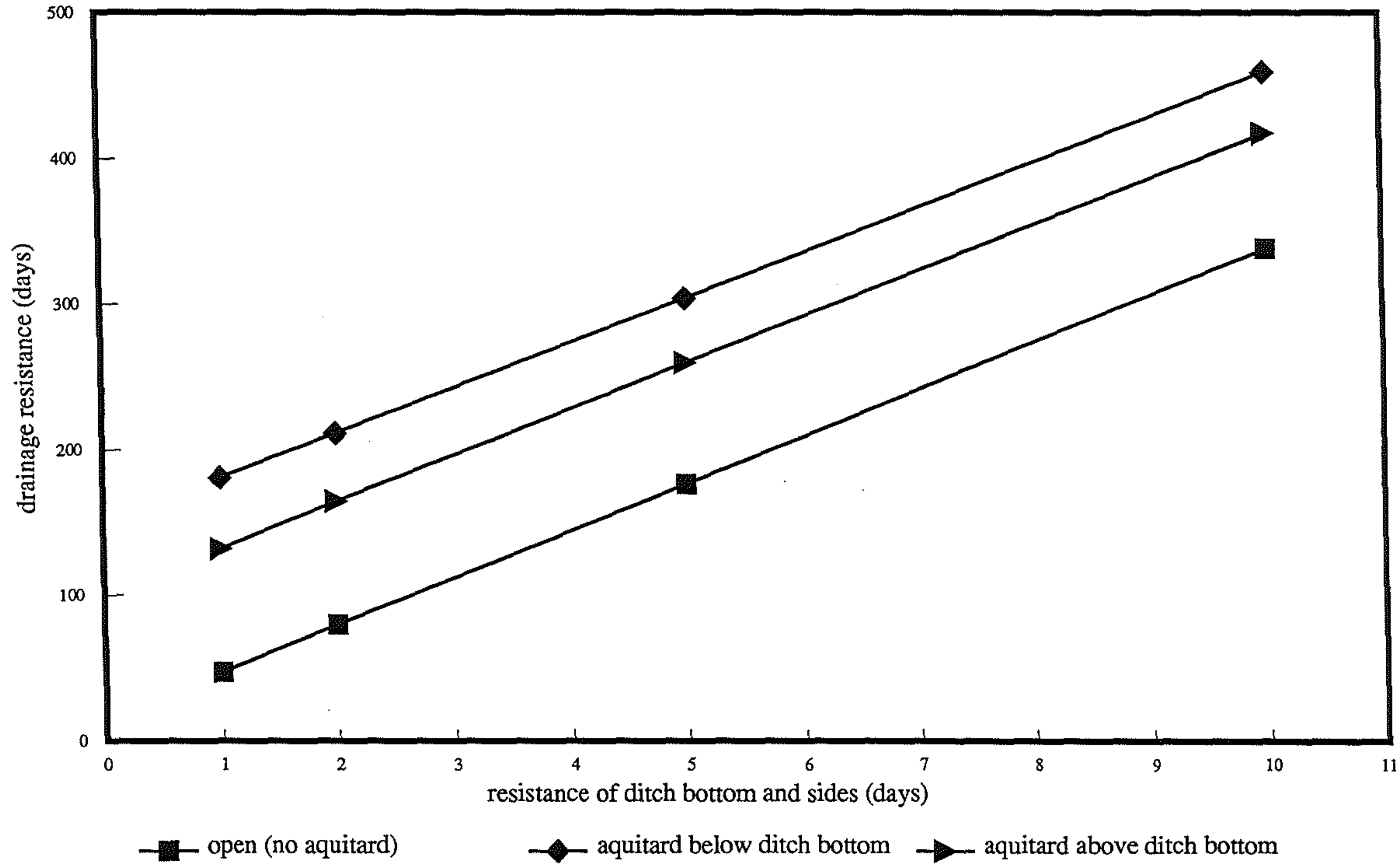


250
200
150
100
50
drainage resistance (days)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
k vertical/ k horizontal for lower aquifer
open (no aquitard)
aquitard below ditch bottom
aquitard above ditch bottom

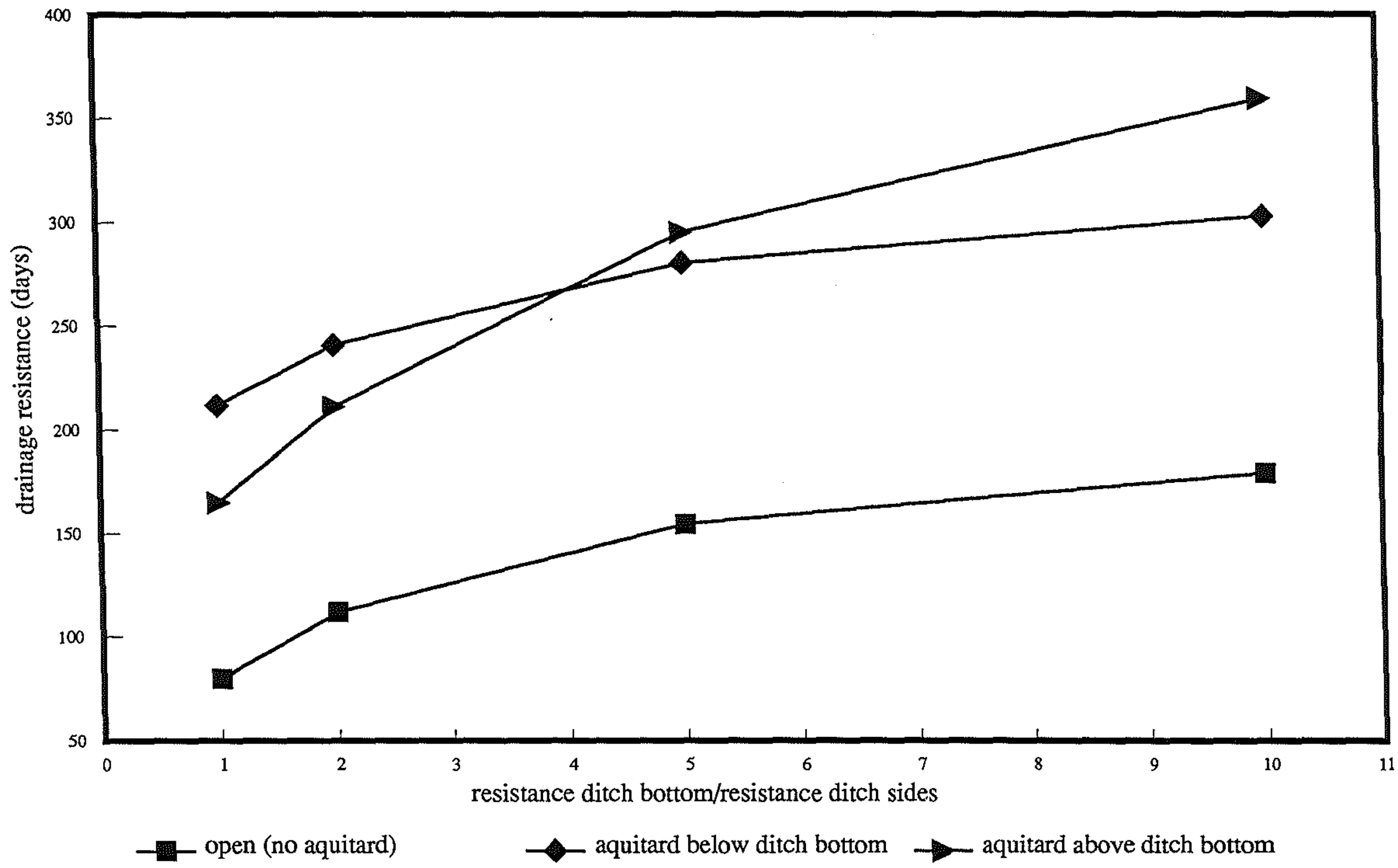

2500
2000
1500
1000
500
0
drainage resistance (days)
0
100
200
300
400
500
600
700
800
900
1000
1100
distance between ditches (m)
open (no aquitard)
aquitard below ditch bottom
aquitard above ditch bottom



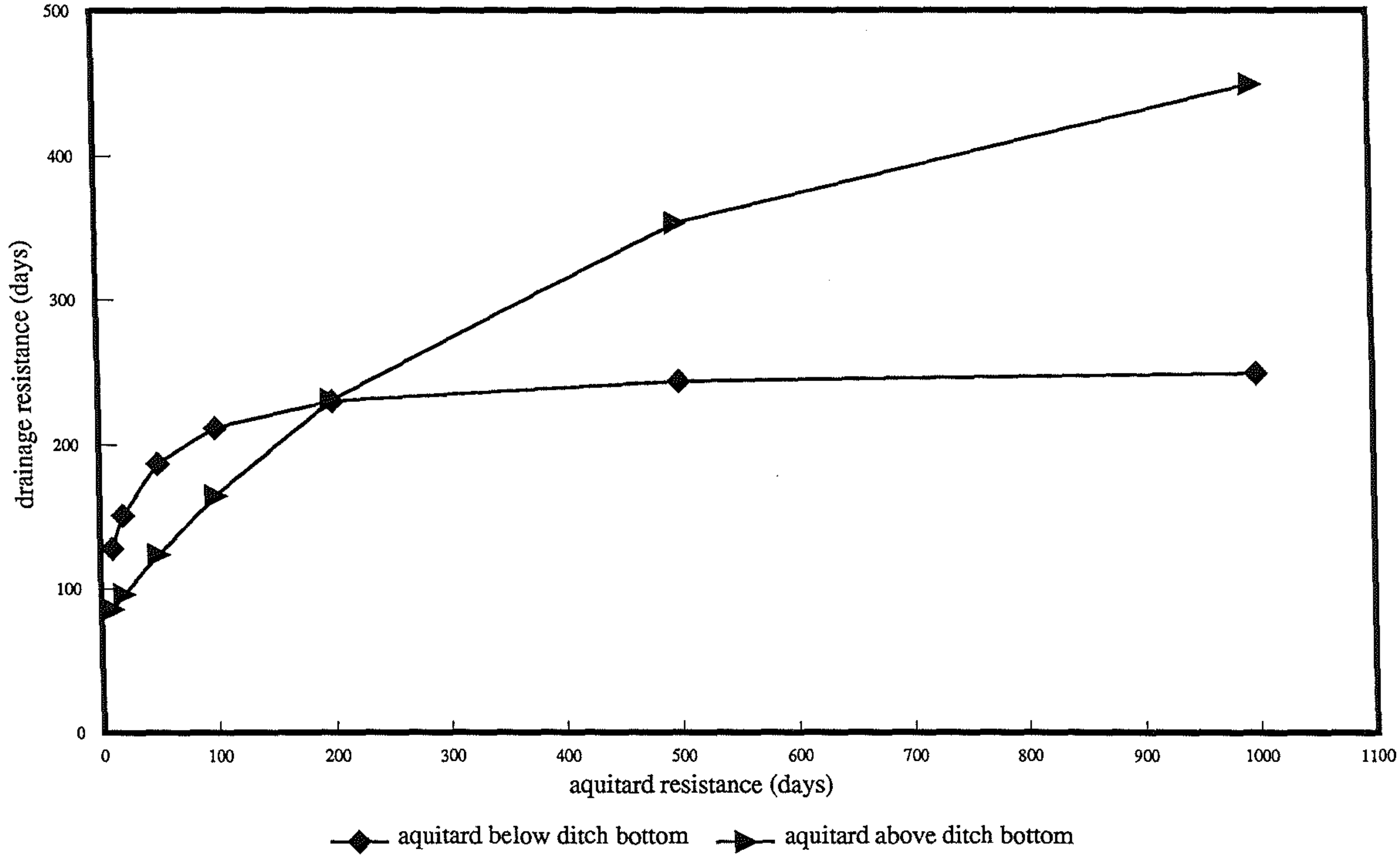
300
250
200
150
100
50
0
drainage resistance (days)
0
1
2
3
4
5
6
7
width of ditch (m)
open (no aquitard)
aquitard below ditch bottom
aquitard above ditch bottom



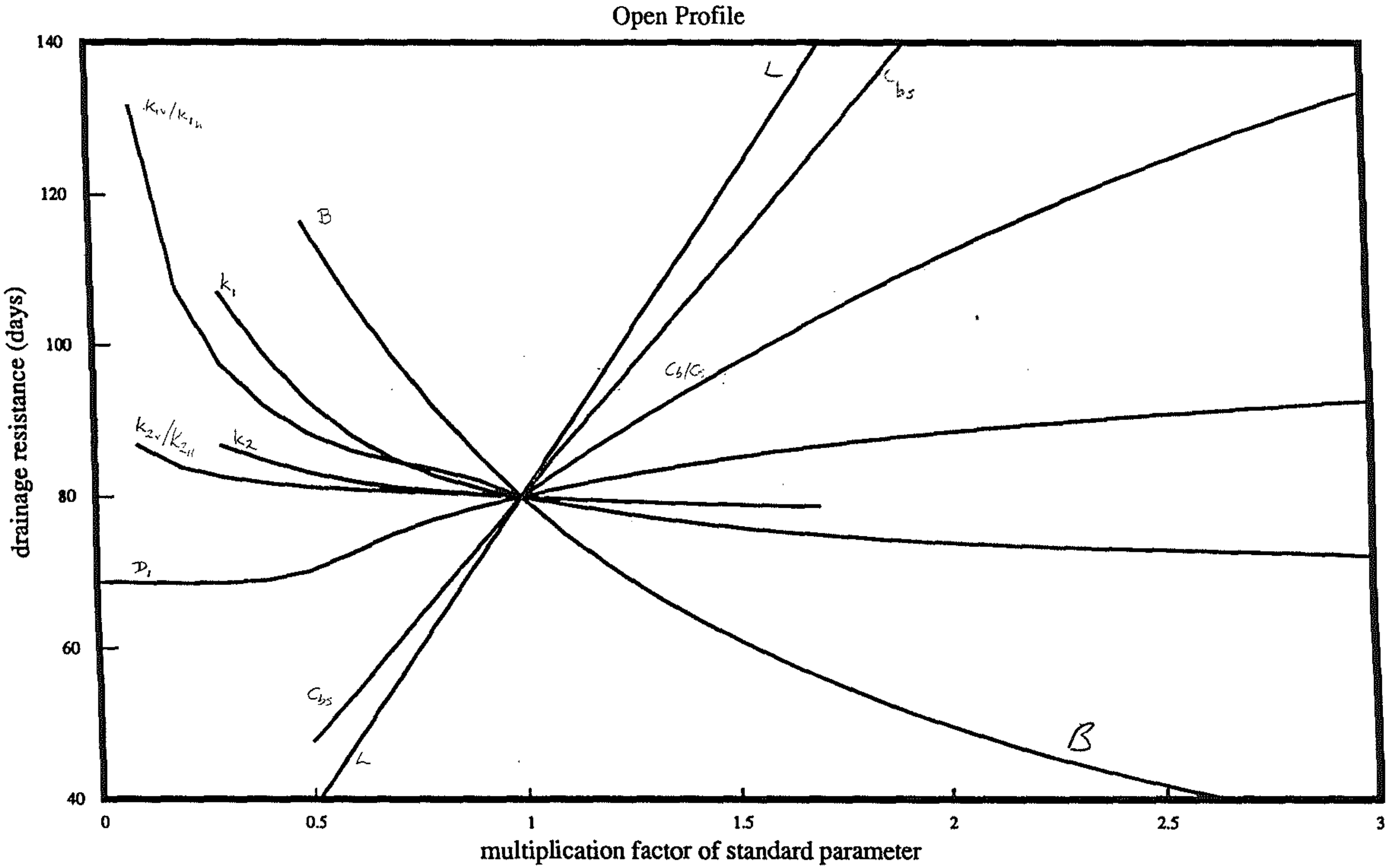
500
400
300
200
100
0
drainage resistance (days)
0
1
2
3
4
5
6
7
8
9
10
11
resistance of ditch bottom and sides (days)
open (no aquitard)
aquitard below ditch bottom
aquitard above ditch bottom



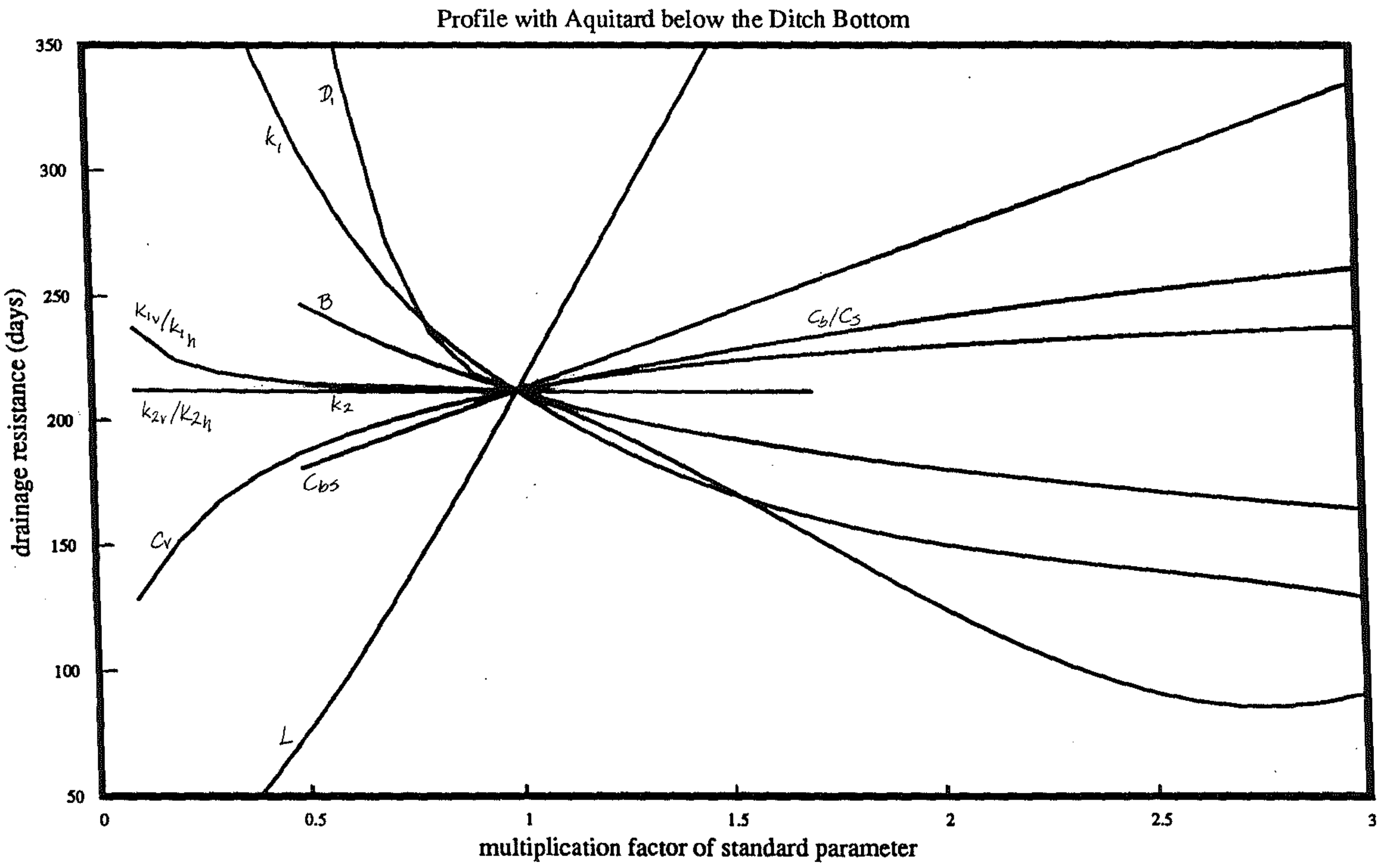
400
350
300
250
200
150
100
50
drainage resistance (days)
0
1
2
3
4
5
6
7
8
9
10
11
resistance ditch bottom/resistance ditch sides
open (no aquitard)
aquitard below ditch bottom
aquitard above ditch bottom



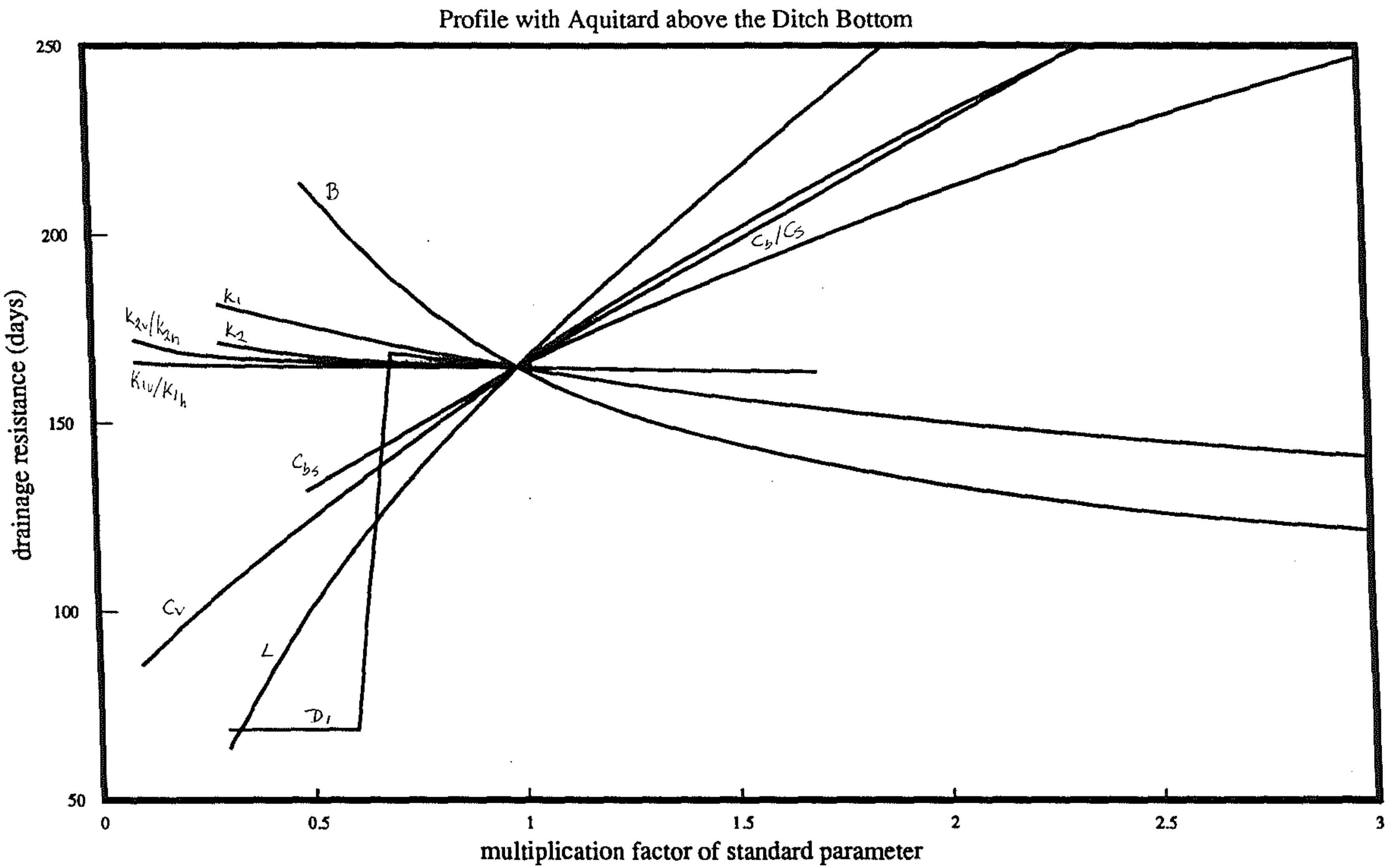
500
400
300
200
100
0
drainage resistance (days)
0
100
200
300
400
500
600
700
800
900
1000
1100
aquitard resistance (days)
aquitard below ditch bottom
aquitard above ditch bottom



Open Profile
drainage resistance (days)
multiplication factor of standard parameter
140
120
100
80
60
40
0
0.5
1
1.5
2
2.5
3
L
C_{bs}
B
k_1
k_2
C_b/C_s
D_1



Profile with Aquitard below the Ditch Bottom
drainage resistance (days)
multiplication factor of standard parameter
350
300
250
200
150
100
50
0
0.5
1
1.5
2
2.5
3
D_1
k_1
B
k_{1v}/k_{1h}
k_2
k_{2v}/k_{2h}
C_b/C_s
C_{bs}
C_v
L



Profile with Aquitard above the Ditch Bottom
250
200
150
100
50
0
0.5
1
1.5
2
2.5
3
drainage resistance (days)
multiplication factor of standard parameter
B
c_b/c_s
k_1
k_{2v}/k_{2h}
k_2
k_{1v}/k_{1h}
c_{bs}
c_v
L
D_1