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Workbook:
1.1. DRAINAGE FOR AGRICULTURE
drainage and hydrology

DRAINAGE

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Workbook
1.1. DRAINAGE FOR AGRICULTURE
drainage and hydrology

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DRAINAGE AND HYDROLOGY/SALINITY

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1 DRAINAGE AND HYDROLOGY

1.1 Water balances of agricultural land

In Figure 1.1 the soil profile is divided into four different reservoirs.

s: Reservoir above the soil surface (surface reservoir)

r: Reservoir below the soil surface from which evapotranspiration takes place. Normally, this reservoir is taken equal to the rootzone.

x: Reservoir of the transition zone between rootzone and aquifer. Its lower limit can be fixed in different ways according to local conditions:

1 - at the interface between a clay layer on top of a sandy layer, provided that the watertable remains above the interface
2 - at the annually deepest depth of the watertable
3 - at the deepest depth to which the influence of a subsurface drainage system extends
4 - at the depth where horizontal groundwater flow is converted into vertical flow of groundwater or vice versa.

q: Reservoir of the aquifer resting on an impermeable layer.

Each reservoir has incoming and outgoing groundwater factors as shown in the figure. The water balance is based on the principle of the conservation of mass for boundaries defined in space and time and can be written as:

$$\text{Inflow} = \text{Outflow} + \Delta W \qquad (1.1)$$

where:

ΔW = change in water storage

When the change in storage is positive, the water content increases and, when negative (i.e. there is depletion instead of storage), it decreases.

The ΔW values of the different reservoirs can be indicated by ΔW_s, ΔW_r, ΔW_x and ΔW_q respectively.

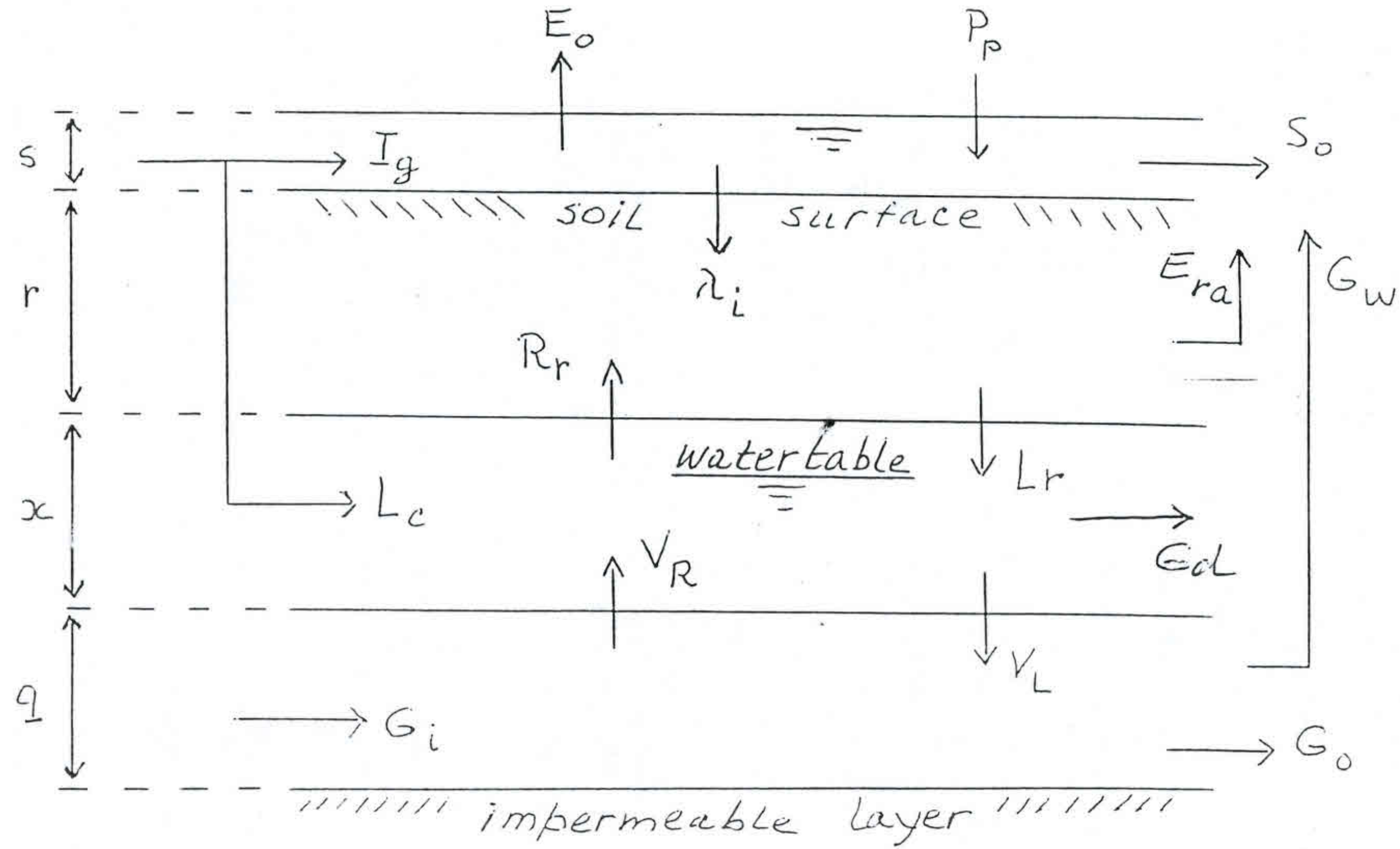


Figure 1.1 The concept of 4 reservoirs with hydrological inflow and outflow components

LIST OF SYMBOLS

Waterbalance Factors in figure 1.1

E_o	Evaporation from open water on the soil surface.
E_{ra}	Actual evapotranspiration from the rootzone. When the rootzone is moist, it equals the potential evapotranspiration E_p, otherwise it will be less.
G_d	Subsurface drainage, natural (G_{dn}) or artificial (G_{da}), to channels, ditches or pipe systems. The suffixes "dn" and "da" are not used in the given waterbalances, but can be introduced.
G_i	Horizontally incoming groundwater into the aquifer.
G_o	Horizontally outgoing groundwater from the aquifer.
G_w	Pumping from wells placed in the aquifer.
I_g	Horizontally incoming surface water. This can consist of natural inundation and/or gross surface irrigation.
L_c	Infiltration, from river or canal systems into the transition zone, often referred to as seepage losses from canals.
L_r	Percolation of water from the unsaturated rootzone into the transition zone.
λ_i	Infiltration of water through the soil surface into the rootzone.
P_p	Downwardly incoming water to the surface: precipitaion (incl.snow), rainfall, sprinkler irrigation.
R_r	Capillary rise of water from the transition zone into the unsaturated rootzone, i.e. the watertable is below the rootzone.
S_o	Surface runoff (natural, S_{on}) or surface drainage (artificial, S_{oa}). The suffices "on" and "oa" are not used in the given waterbalances, but can be introduced.
V_R	Vertically upward seepage of water from the saturated aquifer into the transition zone.
V_L	Vertically downward drainage of water from the saturated transition zone into the aquifer.

Assuming the watertable to be in the transition zone, the following waterbalances can be made for each reservoir using the symbols shown in the figure and explained in the list of symbols.

1.2 The surface reservoir

The surface reservoir is located on top of the soil. The water balance of the surface reservoir for a certain period reads:

$$\ldots\ldots + \ldots\ldots = \ldots\ldots + \ldots\ldots + \ldots\ldots + \ldots\ldots \qquad (1.2)$$

where: P_p is the amount of water vertically reaching the soil surface, such as precipitation and sprinkler irrigation, I_g is the gross irrigation inflow including the natural surface inflow and the drain and well water used for irrigation, but excluding the percolation losses from the canal system, E_o is the amount of evaporation from open water, λ_i is the amount of water infiltrated through the soil surface into the root zone, S_o is the amount of surface runoff or surface drainage leaving the area, and ΔW_s is the change in amount of water stored in the surface reservoir.

1.3 The rootzone

The rootzone (r) corresponds to the depth of soil from which evapotranspiration takes place. Its water balance reads:

$$\ldots\ldots + \ldots\ldots = \ldots\ldots + \ldots\ldots + \ldots\ldots \qquad (1.3)$$

where: R_r is the amount of capillary rise into the rootzone, E_{ra} is the amount of actual evapotranspiration from the rootzone, L_r is the amount of percolation losses from the rootzone, and ΔW_r is the storage of water in the rootzone.

The factor R_r is the opposite of L_r and these components cannot occur simultaneously, i.e. when $R_r > 0$ then $L_r = 0$ and vice versa.

When water balances are made for fairly long periods of time, for instance a season or a year, the storage ΔW_r is often negligibly small compared to the other hydrological components. Therefore, this storage is set equal to zero and the water balance changes to:

$$..... + ... = ... + ... \qquad (1.4)$$

1.4 The transition zone

The transition zone (x) is the zone between rootzone and aquifer. Its lower limit can be fixed in different ways according to local conditions: (a) at the interface between a clay layer on top of a sandy layer, (b) at the annually greatest depth to watertable, (c) at the greatest depth to which the influence of a subsurface drainage system extends, (d) at the depth where horizontal groundwater flow is converted into vertical flow of groundwater or vice versa. The water balance of the transition zone, reads:

$$.... + ... + ... = ... + ... + ... + ... \qquad (1.5)$$

where: L_c is the percolation loss from the irrigation canal system, V_R is the amount of vertical upward seepage from the aquifer into the transition zone, V_L is the amount of vertical downward drainage from the saturated transition zone to the aquifer, G_d is the total amount of natural or artificial drainage of groundwater to ditches or pipe drains, and ΔW_x is the water storage in the transition zone.

The component V_R is the opposite of V_L and these cannot occur simultaneously, i.e. when $V_R > 0$ then $V_L = 0$ and vice versa.

1.5 The aquifer

The water balance of the aquifer (q) can be written as:

$$ \ldots\ldots + \ldots\ldots = \ldots\ldots + \ldots\ldots + \ldots\ldots + \ldots\ldots \qquad (1.6) $$

where: G_i is the amount horizontal groundwater inflow through the aquifer, G_o is the amount of horizontal groundwater outflow through the aquifer, G_w is the amount groundwater pumped from the aquifer through wells, and ΔW_q is the groundwater storage in the aquifer.

When the aquifer is not elastic (compressible or decompressible) and the aquifer is saturated, the value of ΔW_q is zero.

1.6 Combined balances (water table in transition zone)

When the watertable is in the transition zone, the balances of the surface reservoir and the rootzone may be combined in to the topsoil waterbalance, by adding balances 1.2 and 1.3 and using

$$ E_a = E_o + E_{ra} \qquad (1.7) $$

where E_a is the total actual evapotranspiration. This gives:

$$ \ldots\ldots + \ldots\ldots + \ldots\ldots = \ldots\ldots + \ldots\ldots + \ldots\ldots + \ldots\ldots + \ldots\ldots \qquad (1.8) $$

In the topsoil waterbalance, the infiltration component λ_i is not present. This component is a vertical flow linking the two reservoirs. It is called a linkage component. Using:

$$ I_f = I_g - S_o \qquad (1.9) $$

$$ V_s = P_p + I_g \qquad (1.10) $$

where I_f is the net field irrigation and V_s represents the net surface water resource, balance 1.8 can be reduced to:

$$ \ldots\ldots + \ldots\ldots + = \ldots\ldots + \ldots\ldots + \ldots\ldots + \ldots\ldots \qquad (1.11) $$

With a watertable in the transition zone, the balances of the transition zone and aquifer can be combined into the <u>geo-hydrologic water balance</u>, in which the storage ΔW_q may be considered zero as the aquifer is fully saturated:

.... + ... + ... = ... + ... + ... + ... + ... (1.12)

Here, the linkage components V_R and V_L have vanished.

It is also possible to combine three reservoirs. For example, joining the water balances of the surface reservoir (1.2), the root zone (1.3), and the transition zone (1.5), gives the <u>agronomic water-balance</u>.

..... + ... + ... = ... + ... + ...

+ ..... + ... + ... + ... + ... (1.13)

Here the linkage factors ..... and ..... have disappeared.

When the watertable is not in the transition zone, it may be above the soil surface, in the rootzone or in the aquifer. The water balances can be adjusted accordingly, as discussed below.

1.7 Watertable above the soil surface

When the water table remains above the soil surface, the values of ΔW_r, ΔW_x and ΔW_q are zero, as the soil is fully saturated. When, in addition, the water flows from the subsoil into the surface reservoir, the infiltration λ_i becomes negative. Thus, it is preferable to combine the water balances of all the reservoirs (1.2, 1.3, 1.5, and 1.6):

..... + ... + ... + ... =

..... + ... + ... + ... + ... + ... (1.14)

In this <u>overall water balance</u>, all linkage components have disappeared.

1.8 Watertable in the rootzone

When the watertable is in the rootzone, the capillary rise R_r and percolation L_r do not exist, because the transition zone is saturated. Also, the values of ΔW_x and ΔW_q are zero. Thus it is preferable to combine the water balances of rootzone (1.3), transition zone (1.5) and aquifer (1.6), giving the <u>subsoil waterbalance</u>:

.... + ... + ... = ... + ... + ... + ... + ... (1.15)

1.9 Watertable in the aquifer

When the watertable is in the aquifer, the saturated, vertical, flows into or from the transition zone (V_R and V_L) do not exist. In this case one can use either the geo-hydrologic (1.11) or the subsoil (1.15) water balances.

1.10 Reduced number of reservoirs

When one of the four reservoirs is not present, the balances become simpler. For example, when there is no aquifer, the geohydrologic waterbalance (1.11) no longer exists as it will be reduced to the transition zone balance (1.5) with $V_L = 0$ and $V_R = 0$. Also, the subsoil waterbalance (1.15) will be reduced to:

(1.15r) $\quad \lambda_i + L_c = E_{ra} + G_d + G_w + \Delta W_r$

and the overall waterbalance (1.14) to:

(1.14r) $\quad P_p + I_g + L_c = E_a + S_o + G_d + G_w + \Delta W_s$

When two or more reservoirs are absent, the waterbalance equations become still more simple. Examples will not be given.

1.11 Steady state

When the waterbalances are made for fairly long periods (e.g. per season or per year), in many cases the ΔW values (changes in storage) are small compared to the values of the other factors (components) of the waterbalance. Then, the ΔW values can be ignored, so that the waterbalances can be simplified. When Δ is taken zero, i.e. the amounts of all incoming and all outgoing water are equal, one obtains a steady state.

Therefore, over fairly long periods of time, the waterbalance can often be considered in steady state. For example, the water balance of the transition zone (1.5) in steady state is:

(1.5s) $$L_r + L_c + V_r = R_r + V_L + G_d$$

The geohydrologic waterbalance (1.12) in steady state is:

(1.12s) $$L_r + L_c + G_i = R_r + G_o + G_d + G_w$$

while the agronomic waterbalance (1.13) in steady state is:

(1.13s) $$P_p + I_g + L_c + V_R = I_o + S_o + E_a + G_d + V_L$$

The overall waterbalance (1.14) in steady state will be

(1.14s) $$P_p + I_g + L_c + G_i = E_a + S_o + G_o + G_d + G_w$$

and the subsoil waterbalance (1.15) in steady state is:

(1.15s) $$\lambda_i + L_c + G_i = E_{ra} + G_o + G_d + G_w$$

All the above examples of steady state balances contain the subsurface drainage component (G_d) so there are different expressions available to calculate this component depending on the availability of data.

1.12 Net and excess values

Linkage factors along the same reservoir boundary having arrows pointing in <u>opposite</u> direction, especially percolation L_r versus capillary rise R_r and upward seepage V_R versus downward drainage V_L, cannot occur at the same time but they an occur alternately in different periods of time. Over a longer period of time, one factor will be greater than the other and they can be combined into <u>net values</u>. For example:

(1.16c) $R_{rN} = R_r - L_r \quad > 0$ Net capillary rise

(1.16p) $L_{rN} = L_r - R_r \quad > 0$ Net percolation

Note that $R_{rN}>0$ when $L_{rN}=0$ and $L_{rN}>0$ when $R_{rN}=0$.

(1.17u) $V_{Rn} = V_R - V_L \quad > 0$ Net upward seepage

(1.17d) $V_{Ln} = V_L - V_R \quad > 0$ Net downward drainage

Note that $V_{Rn}>0$ when $V_{Ln}=0$ and $V_{Ln}>0$ when $V_{Rn}=0$.

The horizontal inflow (G_i) and outflow (G_o) of groundwater, which have arrows pointing in the <u>same</u> direction can be combined into <u>excess values</u>:

(1.18i) $G_{in} = G_i - G_o \quad > 0$ Excess inflow over outflow

(1.18o) $G_{on} = G_o - G_i \quad > 0$ Excess outflow over inflow

Note that $G_{in}>0$ when $G_{on}=0$ and $G_{on}>0$ when $G_{in}=0$.

With the net and excess values, the previous balances can be simplified further. The steady state balance of the aquifer (see 1.6, with $\Delta W_q=0$), for example, can now be written as:

$$G_{in} = V_{Rn} + G_w \qquad (1.16inR)$$

or:

$$G_{in} = G_w - V_{Ln} \qquad (1.16inL)$$

or:

$$G_{on} = V_{Ln} - G_w \qquad (1.19on)$$

2 EXAMPLES OF WATER BALANCES

Example 2.1

An example of the surface water balance is given in Figure 2.1, giving the relation between surface runoff and rainfall. The principle illustrated in the figure is used in the Curve Number Method (Chapter 4.4, Publ. 16, ILRI, 1994).

Example 2.2

Another example, based on climatic data in The Netherlands, is presented in Figure 2.2. It concerns a simplified topsoil waterbalance (1.8) in which I_g, E_o, S_o, R_r and ΔW_s are taken equal to zero:

$$P_p = E_{ra} + L_r + \Delta W_r$$

The drainable surplus of Figure 2.2 is taken equal to the percolation (L_r). The factors are shown in the following table:

	Summer Apr-Aug	Winter Sep-Mar	Whole year
Rain P_p (mm)	360	360	720
Evaporation E_{ra} (mm)	480	60	540
Storage ΔW_r (mm)	-120	+120	0
Percolaton L_r (mm)	0	180	180

Fixing the drainage season from November up to March (120 days), the average drainable surplus equals L_r = 180/120 = 1.5 mm/day.

Figure 2.1 Illustration of a surface water balance during periods of high rainfall: $S_o = P_p - \lambda_i - \Delta W_s$, with $\Delta W_s = E_o$ after rain has ceased

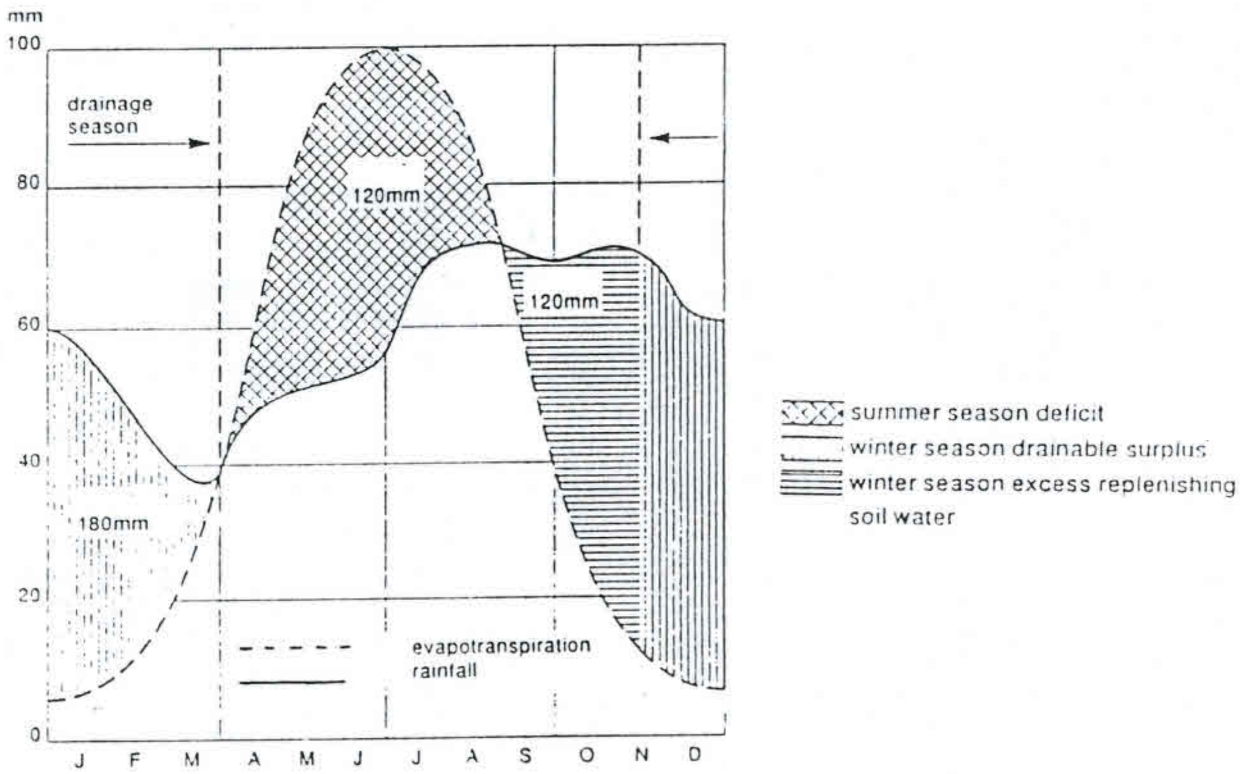


Figure 2.2 Average monthly precipitation and evaporation in The Netherlands

Example 2.3
As a third example, a drainage problem is shown in Figure 2.3, which is caused by groundwater flow from a higher irrigated area. The amount of incoming water through the sandy layer can be calculated as:

$$G_{i1} = K_s s_w D_s$$

where:

- G_{i1}= discharge in the sandy layer (m³/day per m width in a direction perpendicular to the plane of the drawing -> m^2/day)
- K_s= hydraulic conductivity of the sandy soil (m/day)
- s_w= slope of the watertable (m/m)
- D_s= depth of flow in the sandy soil (m)

In the example G_{i1} equals ..... x ..... x ..... = ... m²/d.

The evapotranspiration and capillary rise from a watertable at 0.3 - 0.5 m depth will be a considerable fraction of the potential evapotranspiration (E_o = 6 to 8 mm/d). Estimating the actual evapotranspiration E_{ra} = 3.5 mm/d, the total evapotranspiration over a length L = 1000 m will be

$$E_a = E_{ra}L = ... \times .... = ... \text{ m}^2/\text{d}$$

Since E_a is almost 100 times larger than G_{i1}, it must be concluded that existing drainage problems cannot be caused by the inflow G_{i1}.

There must be an underground flow G_{i2} (see the figure) breaking through the compact clay layer and resulting into a vertical upward seepage (V_R = 3.5 mm/d) otherwise the watertable cannot be maintained at shallow depth.

The clay layer is not impermeable but its hydraulic conductivity is enough to permit the passage of the vertical upward flow.

It is seen that the watertable crosses the clay layer at its downstream part. This is also an indication that the clay layer is not impermeable.

A subsurface interceptor drain, reaching the compact clay layer, would have little influence on the drainage problem.

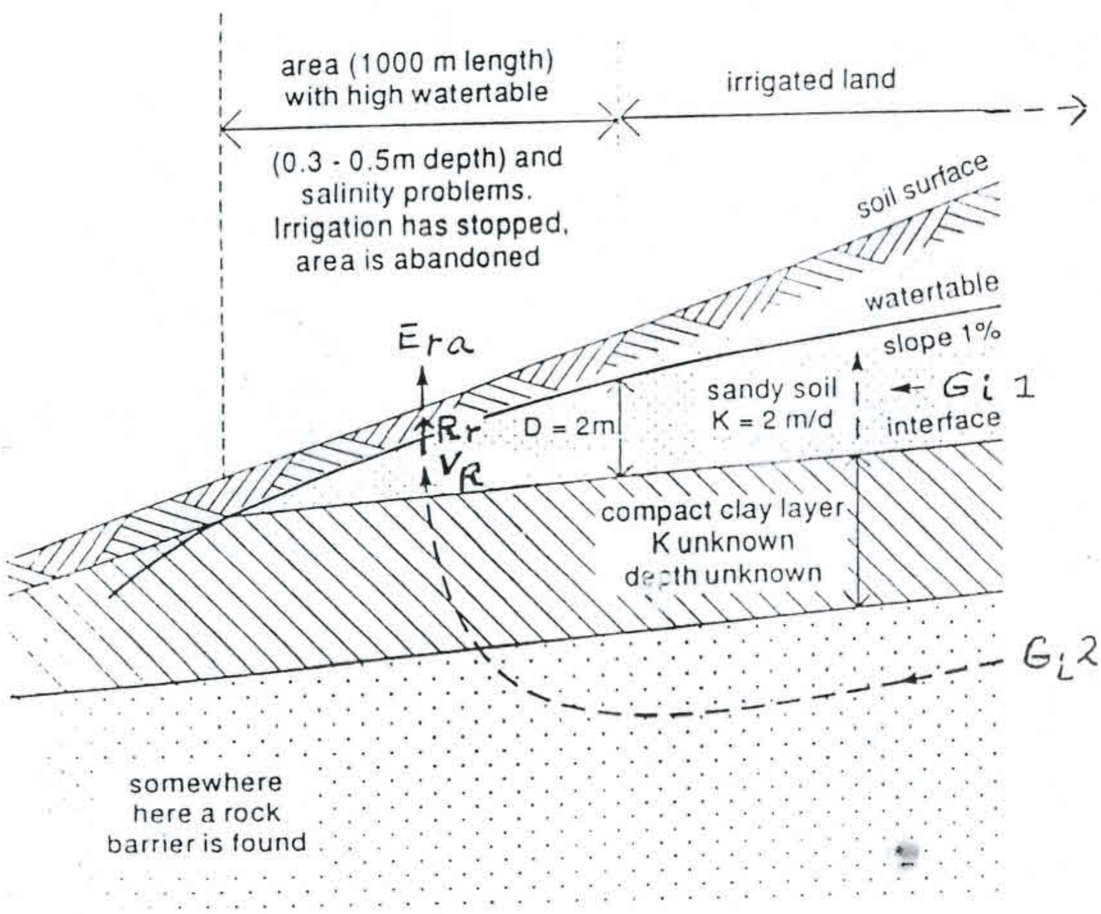


Figure 2.3 Water balance factors in an arid region with subsurface interception drainage problems

Example 2.4

If groundwater breaks through a slowly permeable soil layer, as in Figure 2.4, it may occur, that the vertical upward seepage increases after drainage, at the same time reducing the outflow of groundwater and alleviating the drainage problem downstream of the area drained. This can be explained as follows.

The upward seepage (V_L) can be calculated as:

$$V_L = K_v H_p / D_s \qquad \text{m/day}$$

where:

K_v = vertical hydraulic conductivity of the slowly permeable layer (m/day)

H_p = piezometric overpressure in the highly permeable layer (m)

D_s = thickness of the saturated part of the slowly permeable layer (m)

Using suffix 1 and 2 for the situation before and after drainage respectively, it is found that $H_{p2} > H_{p1}$, and $D_{s2} < D_{s1}$, hence: $V_{L2} > V_{L1}$.

If the groundwater flow comes from a far away source, the inflow G_{i1} will be equal to G_{i2}, so that $G_{o2} < G_{o1}$: groundwater is intercepted by the drainage system, and downstream of it the watertable is also lowered.

If, on the other hand, the source is nearby, (e.g. a canal) it may happen that $G_{i2} > G_{i1}$: the drains attract additional water from the source.

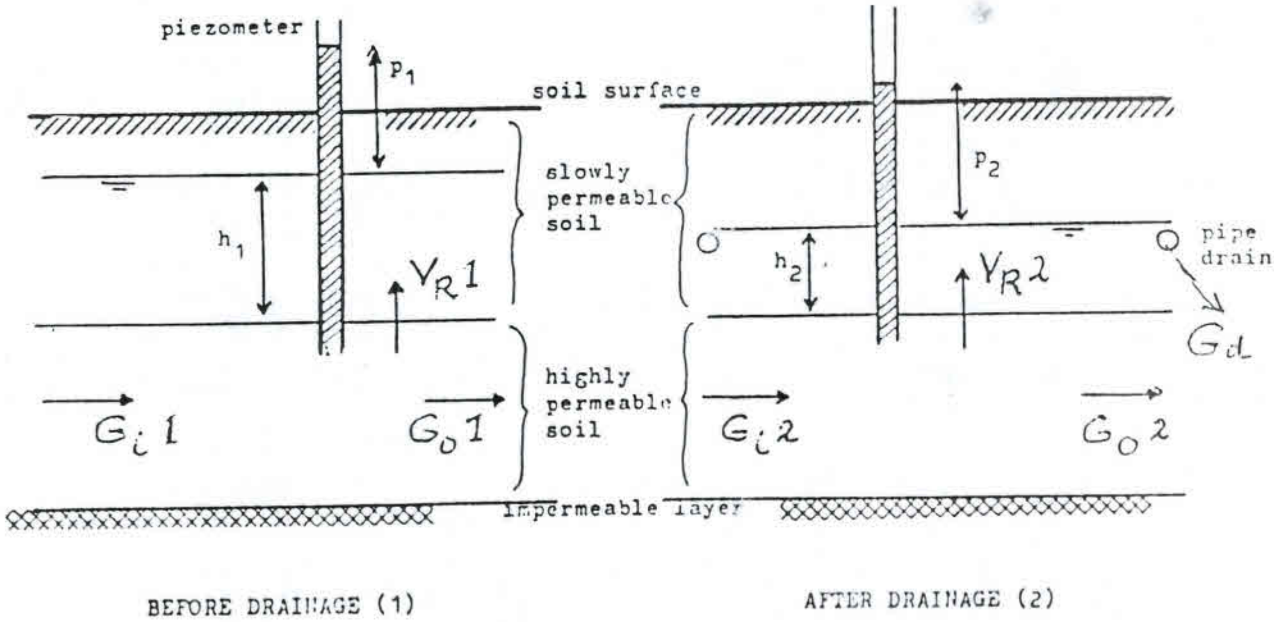


Figure 2.4 Illustrating a semi confined aquifer where lowering the watertable by drainage increases V_R, and reduces G_o

Example 2.5

Drainage by pumping from wells is often applied in irrigated land with the aim to reuse the drainage water for irrigation. However, at low irrigation efficiencies, the pumping and the subsequent energy losses can be considerable. This can be illustrated by means of a water balance. Let us assume a closed system (Figure 2.5) where surface water is applied (I_f m³/year) for field irrigation. The gross irrigation (I_g m³/year) consists of the surface water brought in by the irrigation canal system mixed with pumped well water (G_w m³/year): $I_g = I_f + G_w$.

Suppose that the consumptive use of the crop equals E_{ra} (m³/year) and the total field irrigation efficiency equals $F_{ft} = E_{ra}/I_g$.

Then, all water not used by the crop becomes deep percolation: $L_r = I_f + G_w - E_{ra}$ or $L_r = (1 - F_{ft})\ (I_f + G_w)$.

Since this percolation is pumped up again for irrigation use we have: $G_w = L_r$ and $G_w = (1 - F_{ft})\ (I_f + G_w)$, or:

$$\frac{G_w}{I_f} = \frac{1 - F_{ft}}{F_{ft}}$$

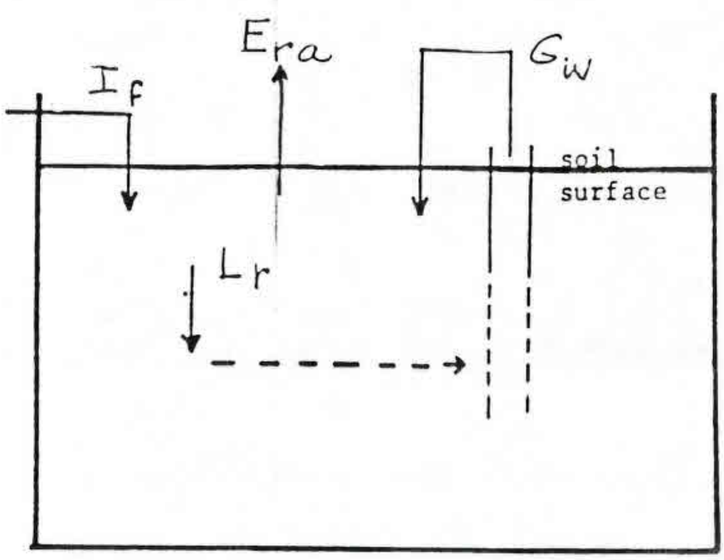


Figure 2.5 Reuse of pumped drainage water for irrigation

Now, the following table can be made

F_{ft}	= 0.20	0.25	0.33	0.50
$\frac{G_w}{I_f}$	=	....	....	....

It is seen that at low irrigation efficiencies the pumping is several times greater than the surface irrigation. This is due to the fact that a drop of water must, on the average, be pumped around several times before it is used by the plants.

Example 2.6

Infiltration and percolation are often not regularly distributed in the field. Figure 2.6 and 2.7 show some of the irregularities due to variations in soil properties at short distances.

Example 2.7

This example concerns the collectors for surface drainage systems in sugarcane plantations in the rainy, tropical, coastal region of Guyana (South America). Reference is made to ILRI Publ. 16, page 683 - 685. As the symbols used here are slightly different, the procedure is repeated with adjusted symbols. The surface water balance (1.2) can be rewritten as:

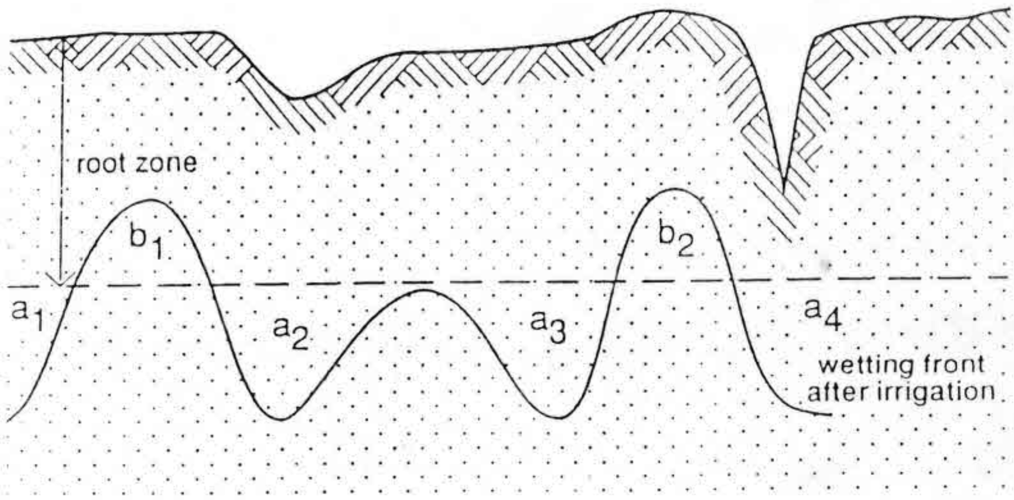
$$S_o = P_p - \lambda_i - E_o + I_g - \Delta W_s$$

In this example, the term I_g can be set equal to zero.

Because we consider a short period with intensive rainfall, the term E_o can also be neglected. Thus the balance can be reduced to:

..... = ... - ..... - .....

The Curve Number Method (Chap. 4.4, Publ. 16, ILRI 1994) uses this balance to calculate the runoff. This will be used here.



a_1 excess due to high infiltration capacity
b_1 shortage due to low infiltration capacity
a_2 excess due to depression in soil surface
a_3 excess due to low moisture holding capacity
b_2 shortage due to elevation of soil surface
a_4 excess due to cracking

Figure 2.6 Random variation of deep percolation in an irrigated field

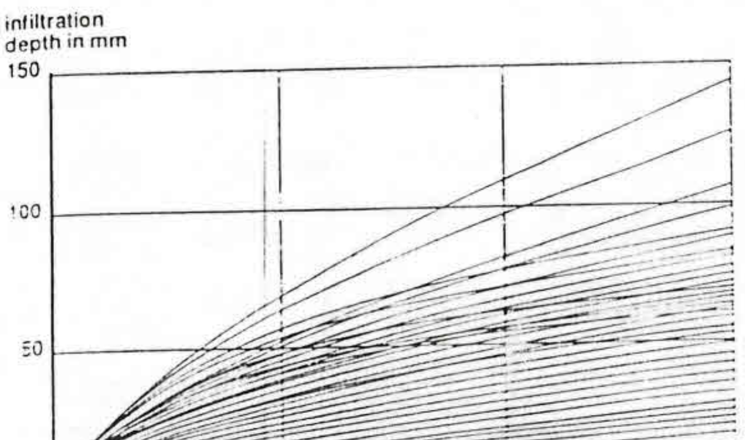


Figure 2.7 Accumulated infiltration versus time measured with 63 infiltrometers set at 1 m spacing on a 7 by 9 m grid in a sandy loam soil (Jaynes et al. 1988)

Table 2.1 shows data on the cumulative 1 to 5-day rainfall with a 10-year return period and the resulting cumulative surface runoff S_{oc} calculated with the Curve Number method, using a Curve Number value of 40.

This empirical method takes into account the storage ΔW_s and infiltration λ_i in the sugarcane fields, but not the temporary, dynamic (live), storage ΔW_d in the fields that is needed to induce the discharge, as will be explained below.

Table 2.1 also shows the daily surface runoff S_{od} and the surface runoff rate S_{oa} as a time average of the cumulative surface runoff: $S_{oa} = S_{oc}/t$, where t is the time or duration in days.

Note that at each time duration: $S_{oc} = \Sigma S_{od}$, where the summation (Σ) is taken over the time periods up to and including the duration considered, and $S_{oa} = \Sigma S_{od}/t$.

The daily dynamic storage ΔW_{dd} can be found from: $\Delta W_{dd} = S_{od} - S_{oa}$.

Table 2.2 shows the development of daily (ΔW_{dd}) and cumulative (ΔW_{dc}) dynamic storage with time ($\Delta W_{dc} = \Sigma\Delta W_{dd}$).

Further, it shows the cumulative surface discharge (Q_{sc}) passing through the drains can be calculated from:

$Q_{sc} = S_{oc} - \Delta W_{dc}$ and the daily discharge from:

$Q_{sd} = S_{od} - \Delta W_{dd}$. Note that $Q_{sc} = \Sigma Q_{sd}$.

It can be seen from Table 2.2 that the daily storage ΔW_{dd} is positive up to the critical time t = 3 days, after which it becomes negative. The cumulative storage $\Delta W_{dc} = \Sigma\Delta W_{dd}$ therefore increases up to t = 3 days, and afterwards it decreases.

The table also shows that the maximum daily discharge Q_{sd}(max) equals 35 mm/d and occurs during the 3rd day and it also equals the maximum average runoff S_{oa}(max) in Table 2.1.

The design discharge capacity of the main drainage system (.. mm/day or ... m^3/day per ha or ...... l/s per ha) can be therefore chosen as the maximum value of the average surface runoff rate. It occurs after 3 days, which is the <u>critical period</u> because with shorter or longer durations the S_{oa} values are less than 35 mm/d.

The cumulative surface runoff (S_{oc}, Column 3 in Table 2.1) is plotted in Figure 2.8 against the time. It shows a curve with an S-shape. The slope of the tangent line from the origin to this curve also indicates the required discharge capacity of the collectors, with a return period of 10 years (tan a = 35 mm/d).

The S-shape of the runoff curve, which is initially quite flat, shows that the drainage system cannot immediately function at its maximum capacity: there is a delay in the functioning and a necessary dynamic (live) storage.

Table 2.1 Example of a rainfall-runoff relationship with a return period of 10 years in example 1.7, using the Curve Number method with a value CN = 40

		Surface runoff		
Duration t (days)	Cumulative rain (mm)	Cumulative S_{oc} (mm)	Daily S_{od} (mm)	Average rate S_{oa} (mm/day)
1	150	14	14 - 0 = ...	....
2	250	59	59 - 14 = ...	....
3	325	104	104 - 59 = ...	....
4	360	128	... - .. = ...	....
5	375	138	... - .. = ...	....

Table 2.2 Daily and cumulative dynamic storage and discharge derived from Table 2.1

Time	Storage		Discharge	
(d)	Daily ΔW_{dd} (mm)	Cumulative ΔW_{dc} (mm)	Cumulative Q_{sc} (mm)	Daily Q_{sd} (mm)
1	..0	..0	..14	..14
2	...	...	....	....
3	...	...	....	....
4	- ...	...	....	....
5	- ...	...	....	....

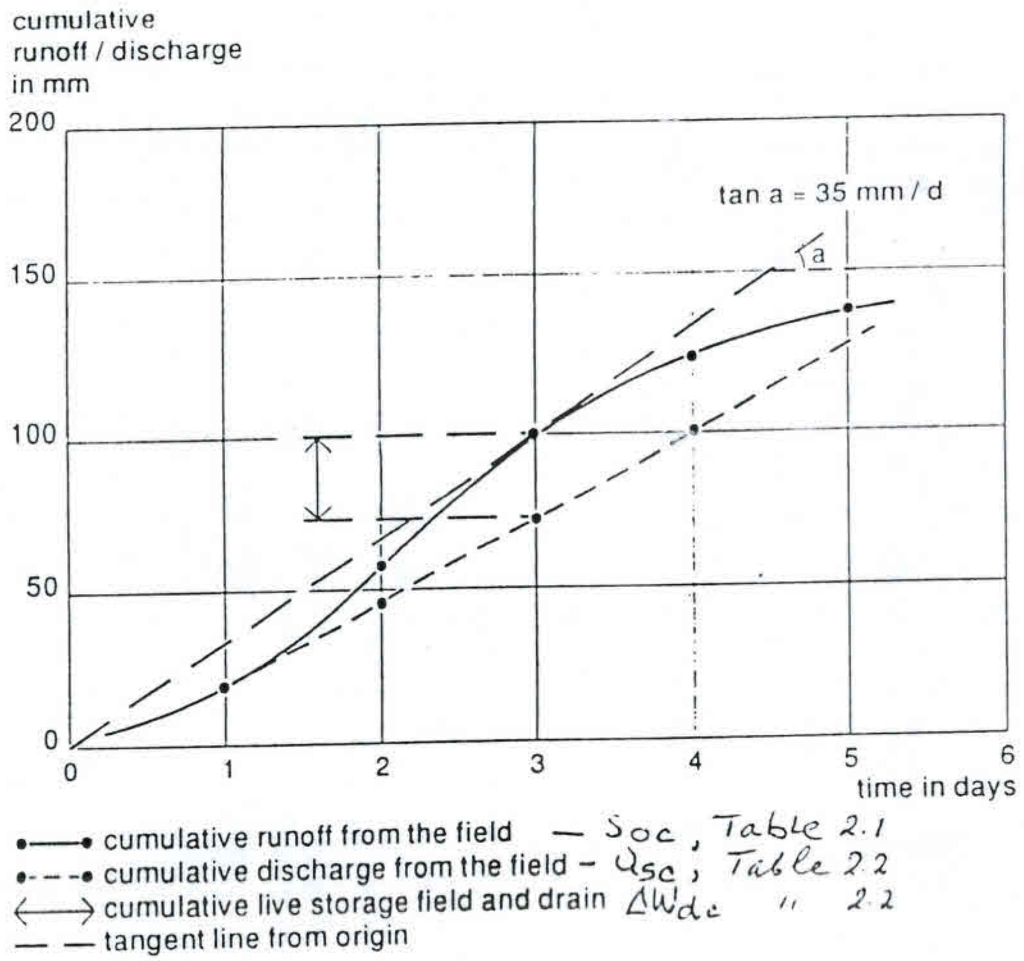


Figure 2.8 Runoff and discharge in time in example 2.7.

3 SALT BALANCES

On the basis of water balances it is possible to make salt balances. Using the steady-state agronomic water balance (1.13s), and assuming $E_o = L_c = V_L = S_o = 0$, we obtain the simplified agronomic balance as:

$$\ldots\ldots + \ldots\ldots + \ldots\ldots = \ldots\ldots + \ldots\ldots \tag{3.1}$$

The simplifying assumptions are often justified when it concerns an irrigated area in a (semi)arid region without natural drainage to the aquifer.

The salt balance is obtained by multiplying the waterbalance factors with their respective salt concentrations:

$$I_g C_{ir} + V_R C_q = G_d C_d + \Delta Z_{rt} \tag{3.2}$$

where:

- C_{ir} = salt concentration of irrigation water, including the use of drain and/or well water for irrigation
- C_q = salt concentration of groundwater in the aquifer
- C_d = salt concentration of drainage water
- ΔZ_{rt} = increase in salt content of rootzone and transition zone

In the above salt balance it has been assumed that the rain P_p contains no salts (i.e. the area is not nearby the sea) and that the uptake of salts by the plants through the evapotranspiration E_{ra} is negligible.

Stating that $\Delta Z_{rt} = 0$ (i.e. allowing no increase in salt content) one finds:

$$I_g = \frac{\ldots\ldots \times \ldots\ldots - \ldots\ldots \times \ldots\ldots}{\ldots\ldots} \tag{3.3}$$

Using the same simplifying assumptions, the steady-state water balance (1.5s) of the transition zone can be written as:

$$G_d = L_r - R_r + V_R \tag{3.4}$$

The corresponding salt balance is:

$$G_d C_d = L_{rn} C_L + V_R C_q \tag{3.5}$$

where: $L_{rn} = L_r - R_r$ (net percolation, balance 1.16p) and C_L is the salt concentration of the percolating water. Combining salt balances 3.3 and 3.5 yields:

$$I_g = \;.....\; x \;.....\; / \;..... \tag{3.6}$$

The salt concentration (C_L) of the percolation or leaching water is a function of the salt concentration of the soil moisture in the rootzone:

$$C_L = f(C_r) \tag{3.7}$$

This is the <u>leaching efficiency</u> function (Chapter 15.3, Publ. 16, ILRI, 1994). The function represents the effects of the heterogeneity of the soil in vertical and horizontal direction, and the subsequent irregular passage of water and salt through the soil (Figure 3.1). Therefore balance 3.6 becomes:

$$I_g = L_{rn} f(C_r)/C_{ir} \tag{3.8}$$

Further, using the simplifying assumptions mentioned before, the topsoil water balance in steady state yields:

$$L_{rn} = \;.....\; + \;.....\; - \;..... \tag{3.9}$$

The last two equations combined give:

$$I_g = \frac{(\;.....\; + \;.....\; - \;.....\;)\;.....}{.....} \tag{3.10}$$

After rearrangement, to make the previous equation explicit in I_g, it can be changed into:

$$I_g = \frac{(E_{ra} - P_p)\ f(C_r)}{f(C_r) - C_{ir}} \tag{3.11}$$

This is the irrigation requirement for salinity control.

From the above formula it is seen that, to maintain a certain permissible salt concentration of the rootzone ($C_r = C_{rp}$), the irrigation I_g should be more than $E_{ra} - P_p$ (i.e. there should be excess irrigation) and that more excess irrigation is required as its salt concentration (C_{ir}) increases.

Drainage for salinity control, therefore, can only be helpful if the irrigation is appropriate.

The corresponding drainage discharge can be determined from the agronomic water balance in steady state (1.13s) as:

$$G_d = \ldots\ldots + \ldots\ldots + \ldots\ldots - \ldots\ldots \tag{3.12}$$

or, after substitution of Equation 3.11:

$$G_d = (E_{ra} - P_p)\ \frac{f(C_r)}{f(C_r) - C_{ir}} + P_p + V_R - E_{ra} \tag{3.13}$$

From this formula it is seen that the discharge effect of drainage, rather than its waterlevel effect, governs the salinity control. Hence, for salinity control, the depth of the watertable is only of secondary importance.

An exception exists in the situation with upward seepage of salty ground water and subsequent capillary rise during long periods without sufficient irrigation (e.g. fallow land) and rain. Deep drainage is then required to intercept the groundwater before it reaches the rootzone, if this is economically feasible, keeping in mind that the land is not productive during fallow periods.

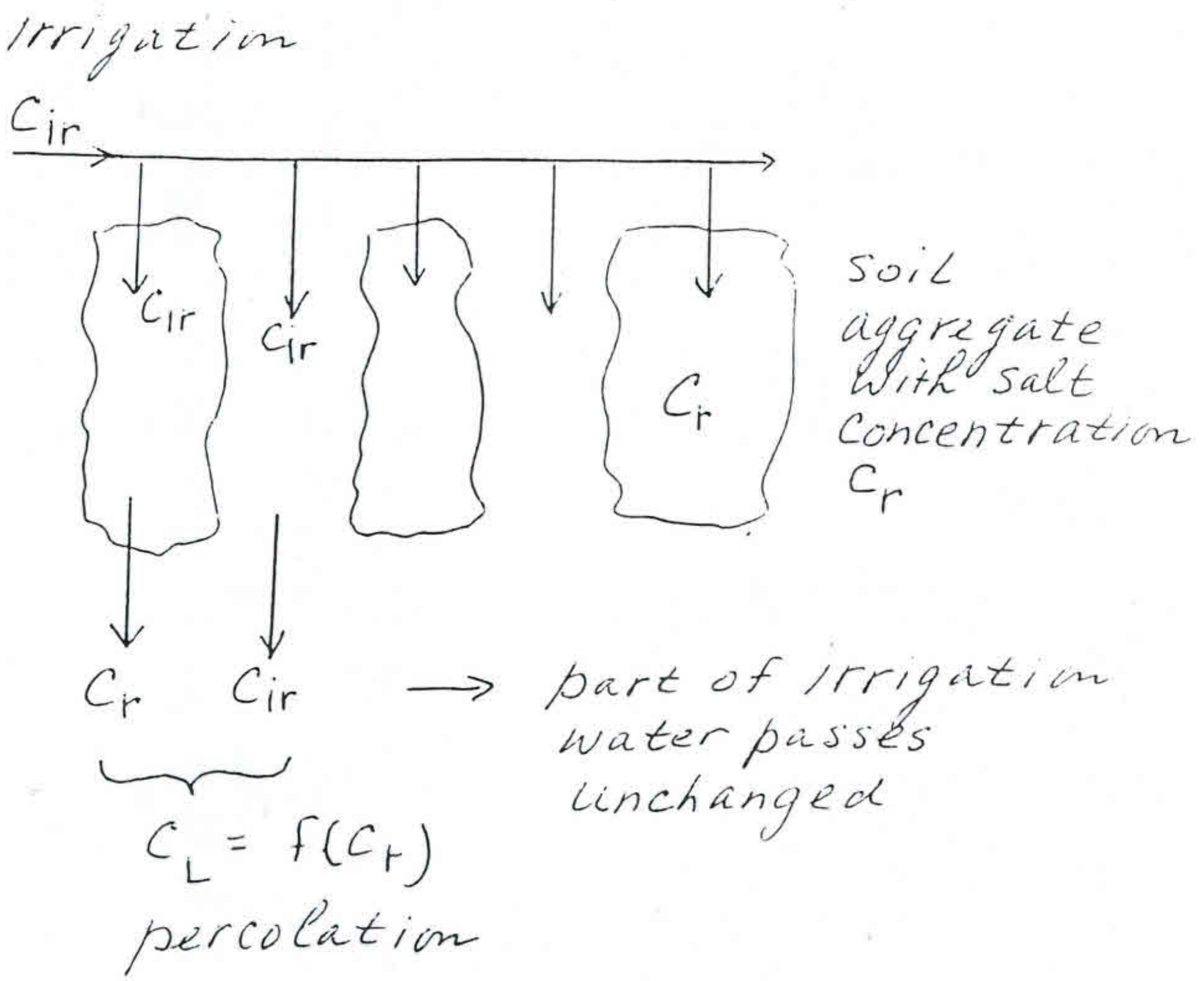


Figure 3.1 The salt concentration of the percolation water depends on the degree of mixing of infiltration water with the soil aggregates

4 EXAMPLES OF SALT BALANCES

Example 4.1

An example of salt balances is given in Figure 4.1, from which it is seen that salinization (salt accumulation) can take place both at relatively shallow and deep watertables. This explains why it is difficult to detect a clear relation between depth of watertable and soil salinity (Figure 4.2). Further it illustrates why in arid regions with flat land and scarcity of water it is advantageous for a farmer to apply as much irrigation water as possible; the fallow land of his neighbour then serves as an evaporation pan favouring the salt balance of the irrigated land.

In dry regions with scarcity of irrigation water, the distribution of this water over the area will probably be very irregular, both in time and in space, as follows:

a) A part of the area will be irrigated with excess water; there will be sufficient leaching; salinity problems are absent; the deep percolation losses will disappear through seepage, capillary rise and evaporation in neighbouring fallow land;
b) A part of the area will be irrigated with an insufficient amount of water; no leaching will take place and salinity problems will develop, even when there is no upward seepage of groundwater.
c) A part of the area is not irrigated (fallow); salinity problems may or may not develop dependent on the presence or absence of upward seepage;
d) Some parts of the area are permanently irrigated, other parts are only seasonally irrigated, the remaining parts are either irrigated once in a number of years or hardly ever.

Efficient salinity control in areas with scarce irrigation water, therefore, is primarily a matter of efficient management of irrigation water. Drainage is only a complementary activity. It would make little sense to drain fields that are not irrigated yearly or that have no drainable surplus even when irrigated. Sometimes it is advisable not to install a drainage system at all, but to use the permanently fallow land as "evaporation pan" for the drainage water from irrigated fields (see a.), if this is socially acceptable.

In the irrigation management, not only the application of the correct amount of irrigation is important but also the land levelling.

This is illustrated in Figure 4.3 showing poorly levelled land.

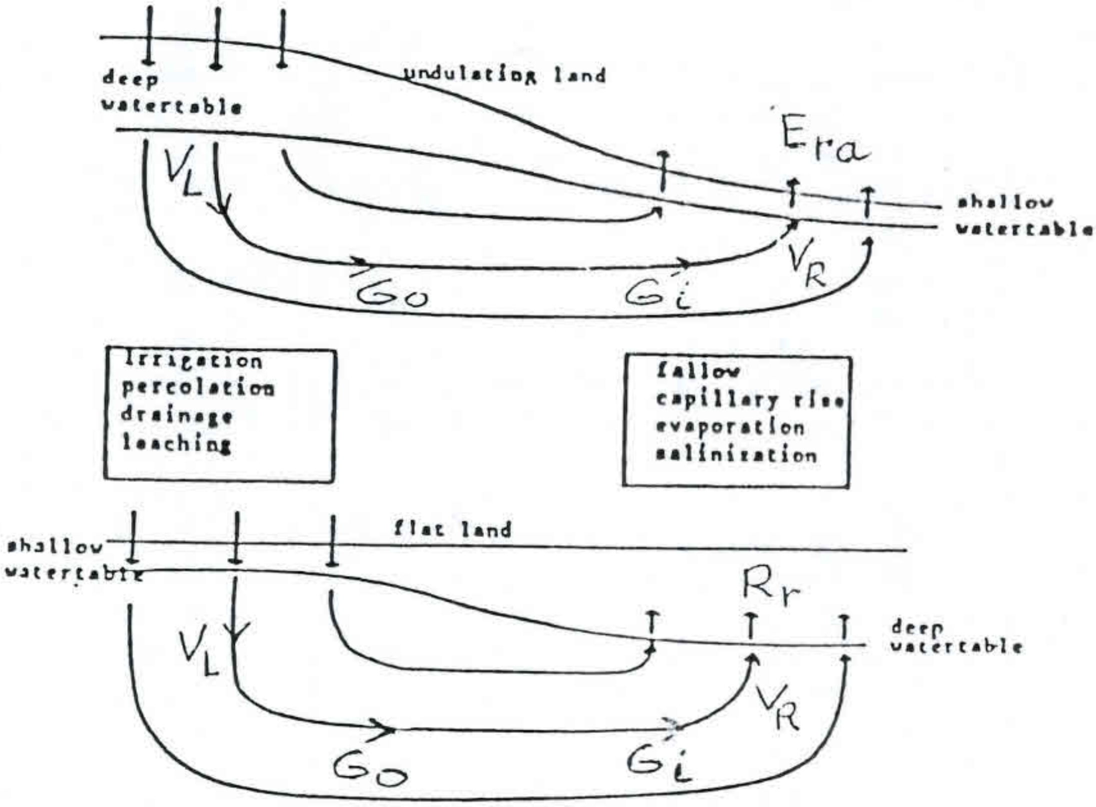


Figure 4.1 Examples of the relation between hydrology and salinization

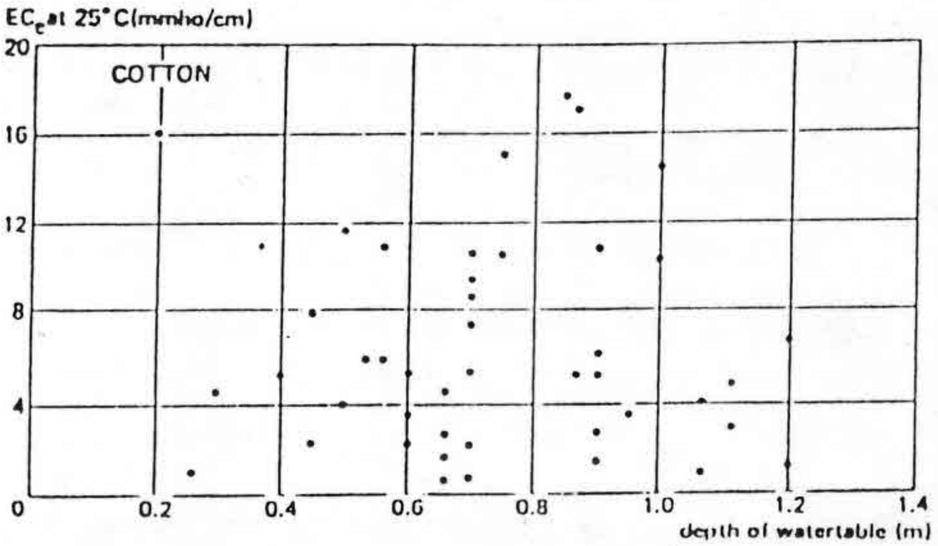


Figure 4.2 Relation between soil salinity (expressed in electric conductivity of saturation extract of topsoil) and depth of watertable at harvest date (Lenselink et al. 1978)

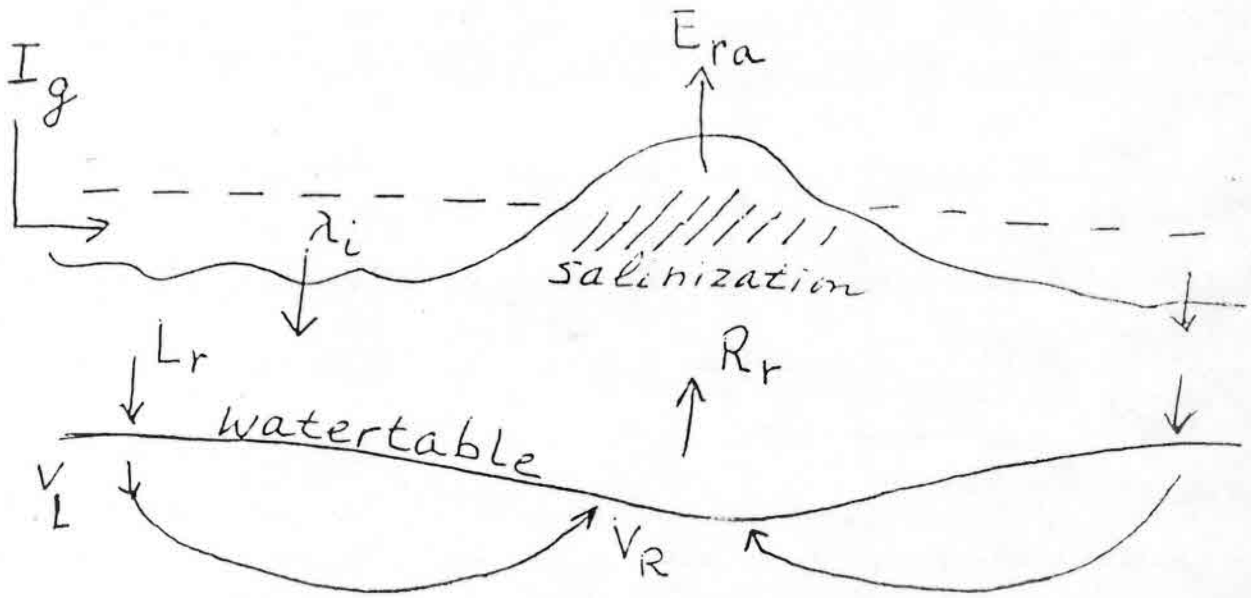


Figure 4.3 Example of salinization in uneven land.

Example 4.2
In Figure 4.3 it is seen that little irrigation water infiltrates in the higher part of the irrigated field. Here, the watertable is relatively deep. In the lower part of the field the infiltration is much more, and the watertable is relatively high. As a result, groundwater moves from the lower part of the field to the higher part. The lower part has sufficient percolation and natural drainage to maintain a favourable salt balance. In the higher part, however, no leaching occurs. On the contrary, it receives seepage water from the adjacent lower parts and, since the soil in the higher part is dry, the seepage water enters the rootzone by capillary rise which is followed by evaporation.

Hence, salt accumulation and salinization occurs in the higher part. This also indicates that, if the land is irrigated by furrow systems, it is necessary to reshape the furrow system from time to time, otherwise salt keeps accumulating in the furrows.

Not only differences in topography, but also spatial differences in infiltration capacity or waterholding capacity of the soil, as shown in Figures 2.6 and 2.7, lead to a patchy development of the salinity in an irrigated field. Therefore, a little over-irrigation is necessary from time to time, to secure proper leaching of the parts having high waterholding capacity or low infiltration (Fig. 4.4).

Example 4.3
Salt balances can be calculated for a series of years, assuming different water management practices. An example of salinity calculations for 30 years is given in Figure 4.5, in which the irrigation and the pumping of groundwater is made variable, but the drainage system remains as it was in the first year.

Note that the symbols used in the figure deviate from those used previously.

The figure shows that 20% more irrigation water during the dry winter season would accelerate the desalinization of the root zone (line SR/RU/AI). Conversely 20% less irrigation water reduces the speed of desalinization considerably (upper line SR/RU/RI). The salinity of the root zone is higher at

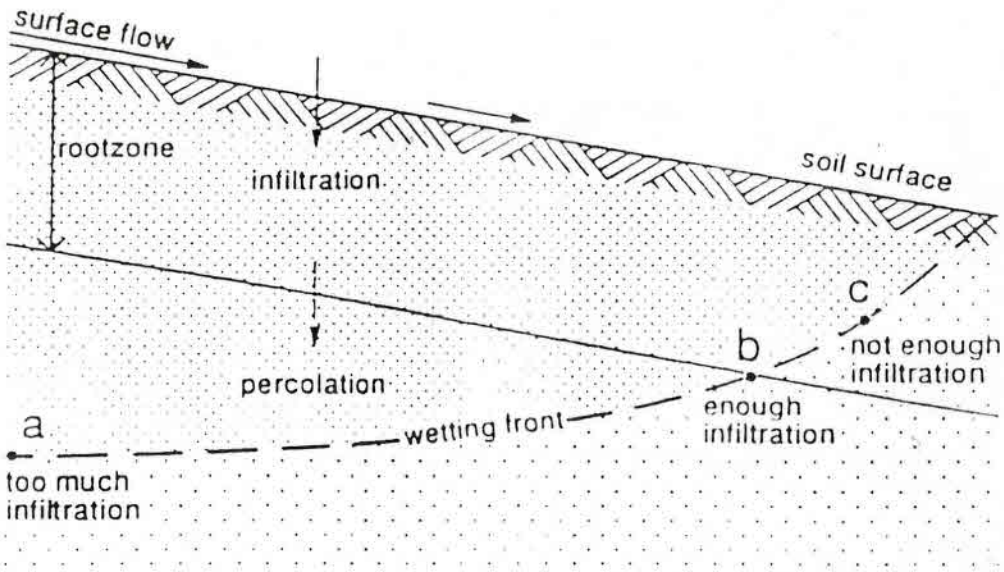


Figure 4.4 Systematic irregularity in spatial distribution of percolation in an irrigated field.

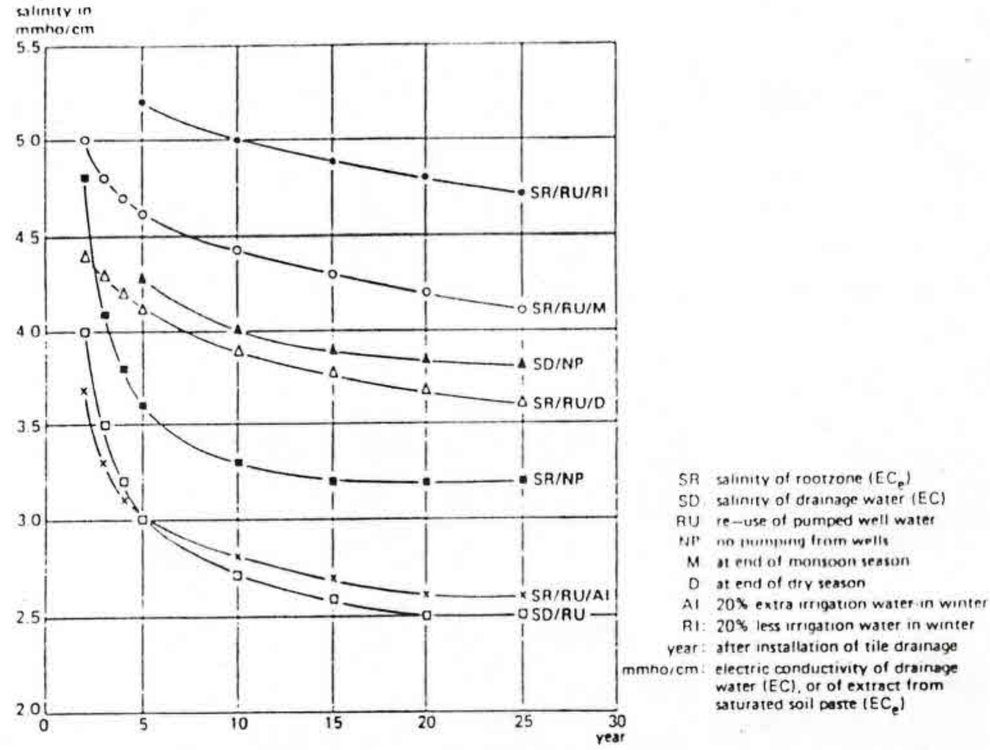


Figure 4.5 Example of the prediction of water and soil salinity under different water management options using water and salt balances in the Mundlana Pilot Area, Haryana, India (from the work of O.P. Singh, see ILRI Annual Report 1987)

the end of the hot monsoon season than at the end of the winter season (compare lines SR/RU/M and SR/RU/D). Apparently the amount of rainfall during the monsoon season is not sufficient to prevent a slight resalinization. Further the figure shows that the use of pumped groundwater retards the desalinization (compare lines SR/RU/M and SR/NP), but it speeds up the reduction of the salt concentration in the drainage water (compare lines SD/RU and SD/NP).

Example 4.4

An example of the application of Equation 3.11 is given below and illustrated in Figure 4.6.

In an area there is an irrigation season of 100 days followed by a rainfed cropping season (265 days). The water balance factors during these periods are shown in Figure 4.6 and in the following table.

Table 3.1 Waterbalance factors of Figure 4.6

Irrigation season			Rainfed season (unirrigated)		
P_p	=	100 mm	P_p	=	500 mm
E_{ra}	=	500 mm	E_{ra}	=	800 mm
V_R	=	100 mm	V_R	=	200 mm
I_g	=	... mm	I_g	=	0 mm
ΔW_r	=	... mm	ΔW_r	=	... mm
L_r	=	... mm	L_r	=	... mm
R_r	=	... mm	R_r	=	100 mm
G_d	=	... mm	G_d	=	... mm
C_{ir}	=	1 mmho/cm			

The leaching efficiency function $f(C_r)$ is taken simply equal to C_{rp} (i.e. the salt concentration of the percolation water equals the permissible salt concentration C_{rp} of the soil moisture in the rootzone, the leaching efficiency is 100%), and the permissible salt concentration of the soil moisture in the rootzone is fixed in EC as $C_r = C_{rp} = 8$ mmho/cm or dS/m.

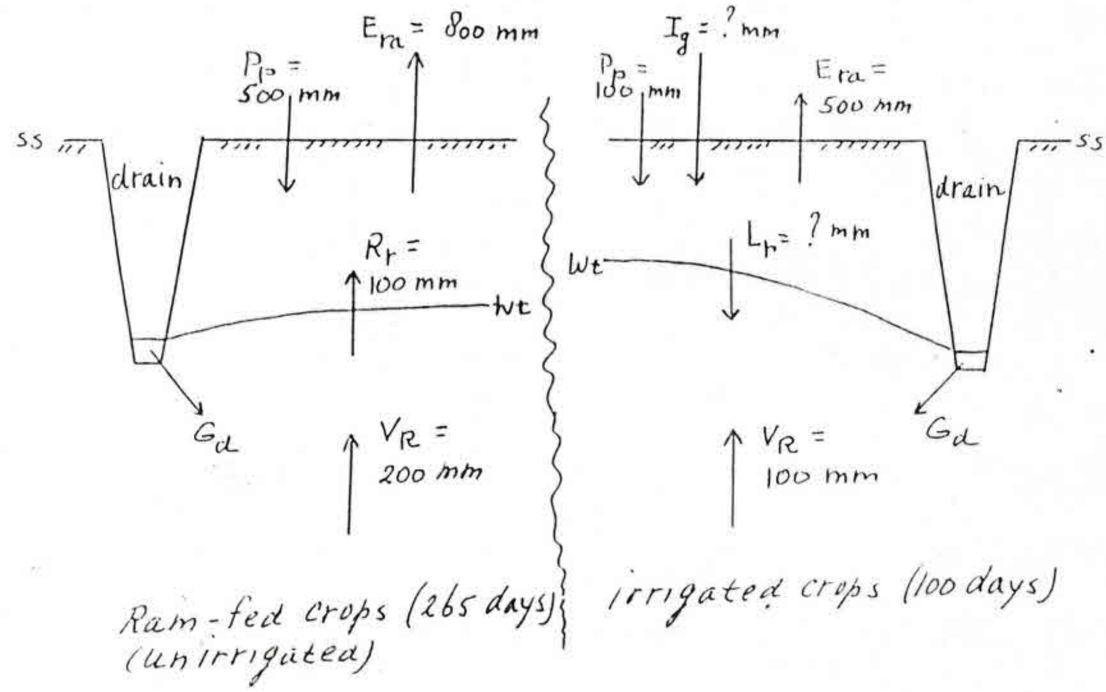


Figure 4.6 Illustration of water balance factors in an area with an irrigation and non-irrigation season as used in the example of application of Equation 3.11 (ss = soil surface; wt = watertable)

Applying equation 3.11 using the data of the whole year we obtain the irrigation requirement for salinity control as:

I_g = (.... + ... - .... - ....) .... /(... - ...) = ... mm

This amount of irrigation water is required to:

- cover the consumptive use of the crop in the irrigation season:
  $E_{ra} - P_p$ = ... - ..... = ... mm;
- replenish the soil moisture that has been used by the crops in the non-irrigation season:
  $\Delta W_r = E_{ra} - P_p - R_r$ = ... - ... - ... = ... mm;
- leach the salts that have been brought in by the capillary rise in the non-irrigation season;
- leach the salts that have been brought in with the irrigation water.

Since EC=1 mmho/cm or dS/m (the salt concentration of the irrigation water) corresponds to rougly 0.6 g salt/l water - 0.6 kg salt per m³ water, and since per ha annually 0.800 m x 10000 m² = 8000 m³ of irrigation water is applied per ha, this means that actually ..... kg/m³ x ..... m³ = ... kg of salt per ha is introduced to the land by irrigation, and these salts need also to be leached annually if no salt accumulation is to take place ($\Delta Z_{rt} = 0$).

The yearly net percolation can be found from $L_{rn} = L_r - R_r$ or from:

$$L_{rn} = I_g - (E_{ra} - P_p) = \ldots - (\ldots + \ldots - \ldots - \ldots) = \ldots \text{ mm}$$

which is about .... % of the irrigation.

The yearly total amount of drainage water is:

$$G_d = L_{rn} + V_R = \ldots\ldots + \ldots\ldots = \ldots\ldots \text{ mm}$$

The required seasonal drainage discharge rates per day rate are:

- Irrigation season (with positive storage):

$$I_g + P_p + V_R - E_{ra} - \Delta W_r)/100 \text{ days} =$$

$$(\ldots + \ldots + \ldots - \ldots - \ldots)/\ldots = \ldots\ldots \text{ mm/day;}$$

- Rainfed season (with negative storage):

$$P_p + V_R - E_{ra} - \Delta W_r)/265 \text{ days} =$$

$$(\ldots + \ldots - \ldots + \ldots)/\ldots = \ldots\ldots \text{ mm/day;}$$

so that the irrigation season is the critical period for drain design.

NOTE 1

The permissible soil salinity in the balance refers to field saturation or soil moisture content at field capacity. The EC value of a saturated paste in the laboratory contains about twice as much water. So the ECe of the extract of the paste would be about 8/2 = 4 dS/m.

NOTE 2

If the irrigation requirement for salinity control is calculated only with the data of the irrigation season, one obtains:

I_g = 457 mm, instead of 800 mm.

Using I_g = 457 mm, and taking the water balance of the non-irrigation season into account, this would result in a salt concentration C_r greater than the permissible salt concentration C_{rp} assumed at EC = 8 mmho/cm or dS/m. In fact, when I_g < 700 mm, (the total evaporation minus the rainfall) there can be no equilibrium value of C_r, but it will increase continuously.

It is concluded, therefore, that salt balance calculations should be made for long periods of time, instead of for seasons only, especially when the upward seepage of ground water and the seaonal storage plays an important role.

5 SOIL SALINITY AND PLANT GROWTH

Soil salinity refers to the presence of high concentrations of soluble salts in the soil moisture of the root zone. These concentrations of soluble salts, through their high osmotic pressures, affect plant growth by restricting the uptake of water by the roots. All plants are subject to this influence, but sensitivity to high osmotic pressures varies widely among plants species. Salinity can also affect plant growth because the high concentration of salts in the soil solution interferes with a balanced absorption of essential nutritional ions by the plants.

The main effects of salinity on plant growth and crop production are:

- Slow and insufficient germination of seeds, a patchy stand of the crop;
- Physiologic drought, wilting, and desiccation of plants;
- Stunted growth, small leaves, short stems and branches;
- Blueish-green leaf colour;
- Retarded flowering, fewer flowers, sterility, and smaller seeds;
- Growth of salt-tolerant or halophilous weed plants;
- As a result of all these unfavourable factors, low yields of seeds and other plant parts.

Soil salinity can be expressed as the salt concentration of an extract of a saturated paste of the soil expressed in:

- g salt per 100 g water (%, percent or parts per hundred), g salt per l water (i.e. parts per mil or per thousand) or: mg salt per l water (parts per million, 1 ppm = 0.001 per mil and 1 ppm = 0.0001 %);
- eq. (equivalent) or milli eq. (meq) salt per l water;
- electric conductivity (ECe) at 25 degrees C in milli mho/cm (mmho/cm) or, with the same value, dS/m (deci Siemens per m).

The relation between the above magnitudes is roughly:

- 1 g/l	~	1.7 m mho/cm	~	17 m eq/l
- 1 m mho/cm	~	0.6 g/l	~	10 m eq/l
- 1 m eq/l	~	0.1 m mho/cm	~	0.06 g/l

The relation between the salt concentration of the extract of a saturated paste (ECe) and the salt concentration of the soil moisture at field capacity is about 1:2.

The relation between the ECe and the soil salinity expressed in g salt per 100 g soil is about 20:1.

The relation between ECe and the EC value of a 1:2 mixture of soil and water on weight basis is shown in Figure 5.1. The extract of a saturated paste needs centrifuging, whereas the measurement in the 1:2 supension can be done directly. In general one finds: ECe = 4 to 5 $EC_{1:2}$.

The term 'salt tolerance' indicates the degree of salinity a plant can withstand without being appreciably affected in its growth or development. In field experiments with some principal crops Bernstein (1974) determined the salinity levels causing yield reduction of 10%, 25% and 50%. For comparison, rice showed a reduction in yield of 10%, 25% and 50% at an ECe of 5, 6 and 8 respectively, whereas the same yield reductions for barley were found at higher ECe values of 12, 16 and 18 respectively.

It appeared that most field crops (e.g. wheat, oats, rice and rye) have a salt tolerance of ECe of 4 to 8 mmho/cm.

Some field crops (barley, sugar beet, cotton), vegetables (garden beets, kale, spinach, asparagus), and fruit crops (date palm, mulberry, olive, pomegranate, jujube) have a higher salt tolerance of ECe is 8 to 16 mmho/cm. Some grasses such as Sporobolus, Pucinellia, Cynodon dactylon (Bermuda grasses), Chloris gayana (Rhodes grass) and Agropyron elongatum (tall wheatgrass) also have a high salt tolerance (ECe is 8 to 16 mmho/cm).

Beans are salt-sensitive, having a salt tolerance of ECe = 2 to 4 mmho/cm.

Examples of crop production as a function of salinity under field conditions are given in Table 5.1 and Figures 5.2 to 5.13.

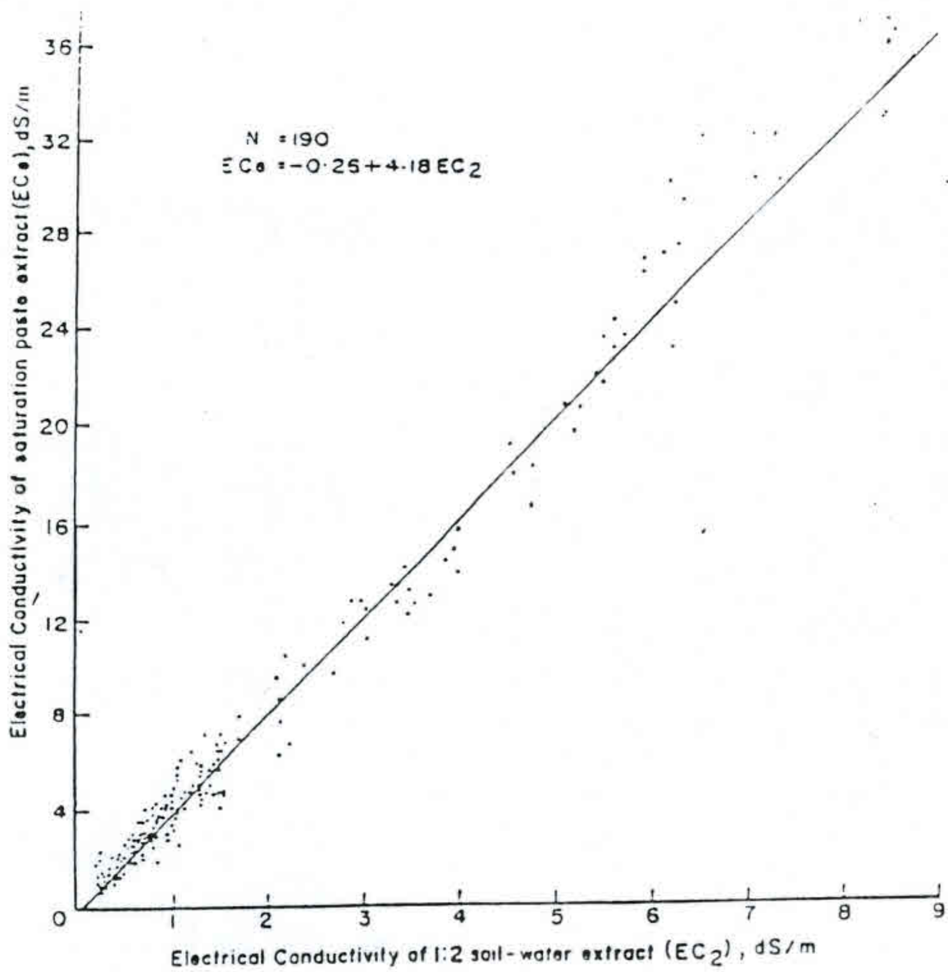


Figure 5.1 Relation between EC values of a saturated paste and a 1:2 soil water suspension. Data from Dr. D.P.Sharma, Central Soil Salinity Research Institute, Karnal, India.

Figure 5.2 shows that sorghum yields are not affected by soil salinity values up to ECe = ... mmho/cm. The many low yields in the range of ECe = ... - .... mmho/cm must be due to a limiting factor other than salinity.

Table 5.1 shows the rice production (Y in kg/ha) as a function of soil salinity (ECe in mmho/cm of topsoil 0-20 cm) in a pilot area (Chiclayo, Peru). Data from Alva et al. 1976:

Table 5.1

Year	1970/1971	1971/1972	1972/1973
Y	580	4,850	5,820 *)
ECe	40	19	16

*) average of timely transplanted rice 6,400 kg/ha and late transplanted rice 3,520 kg/ha.

Figure 5.3 indicates that cotton tolerates soil salinity values up to ECe = ... to ... mmho/cm. Perhaps the tolerance of cotton is even higher, but there are insufficient data with ECe more than ... draw a firm conclusion about the break point. Since the figure represents a random sample, it is possible to conclude that only a small percentage of the cotton fields (roughly ... %) may have a salinity problem.

Figure 5.4 shows the same trend as Figure 5.3. There are apparently no cotton fields with salinity problems.

Figures 5.5 and 5.6 make it clear that wheat yields are not affected by salinity values up to ECe = ... mmho/cm. In Figure 5.5 only a small percentage of wheat fields (about .... %) shows salinity problems, so that contrary to Figure 5.6 there is no great salinity problem.

Figure 5.7 shows that maize is more sensitive than sorghum, cotton and wheat. The critical value is probably somewhere between ECe = ... to ... mmho/cm.

Figure 5.8 shows that the yield of berseem (Egyptian clover) is negatively affected by soil salinity values of ECe > ... mmho/cm. The percentage of berseem fields with salinity problems is higher than for the other crops, which is due to the higher sensitivity of berseem to soil salinity.

From Figure 5.9 it is seen that barley yields are affected negatively at ECe values above ... to ... mmho/cm. A large part of the experimental field has salinty problems for barley.

The tolerance of mustard to soil salinity (Figure 5.10) is similar to that of wheat: about ... mmho/cm.

Figure 5.11 shows that rice is only slightly more tolerant to soil salinity than berseem, the critical value being at ECe = ... to ... mmho/cm. The percentage of rice fields affected by salinity problems is considerable (about ... %). Some ... % of the rice fields have strong salinity problems (ECe > 6 mmho/cm). For these fields a salinity control programme might result in a yield increase of about ..... kg/acre, namely from .... kg/acre to .... kg/acre. In the other ... % of the fields, a salinity control program would have little effect.

The differences between Figure 5.11 and Table 5.1 can probably be attributed to the salinity of the standing water layer in the rice fields. This water layer was regularly refreshed in the area represented in Table 5.1, so that its salt concentration was kept at a low level.

From Figure 5.11 it is also seen that apparently the salinity problems were higher in 1982 than in 1981 (please explain ....). For the evaluation of seasonal effects, however, one would require more years of observation.

The relation between the grain yield of rice and salt concentration of the surface water layer (Sw) is given in Figure 5.12. It is seen that Sw values of more than ..... mmho/cm are harmful for the crop. Nijland and El Guindy (1986) have shown that the Sw value exerts a greater influence on the yield than the soil salinity. The lower parts of the fields have apparently higher salinities than the higher parts. Please explain ....

The influence of soil salinity on yield is determined by many factors, for example seedling emergence (Figure 5.13). The figure shows that seedling emergence reduces at values of $X = 5 \times EC_{1:2}$ greater than 6 dS/m, but at the safe values below 6 there are also instances of poor emergence due to other factors than salinity.

Data from Mexico, Carrizo irrigation district, on wheat yield (Y) and soil salinity (ECe, dS/m) measured at 0-30 cm (EC1) and 30-60 cm (EC2) depth yielded the following multiple regression equation (data from IMTA, Cuernavaca, Mexico):

$$Y = 7.8 - 0.49 \times EC1 + 0.02 \times EC2.$$

The standard error of the regression coefficient of EC1 is 0.09, hence it is highly significant. The regression coefficient of EC2 is relatively small and insignificant. Does this mean that meaurement of EC1 is sufficient to characterize the soil salinity? .... YES/NO
Please explain ....

If the land is liable to become saline, adequate irrigation, if necessary together with drainage (when natural drainage is insufficient), will remove or reduce these dangers, thus ensuring a better crop production.

If the land is already saline it can be reclaimed with a good combination of drainage and irrigation. Often the introduction of a reclamation crop will accelerate the process of reclamation.

For example, lowland rice is often used during reclamation in subtropical and tropical climates. The flooded conditions of the fields promote a continuous leaching of salt from the soil, and also a dilution of the salt in the soil water. Moreover the fact that rice seedlings may be grown in nurseries, under less saline conditions, makes it possible to grow transplanted rice during the early phase of reclamation. Please explain ....

Grasses (Bermuda grass or tall wheat grass) and barley may be chosen as reclamation crops in climates less favourable for rice production.

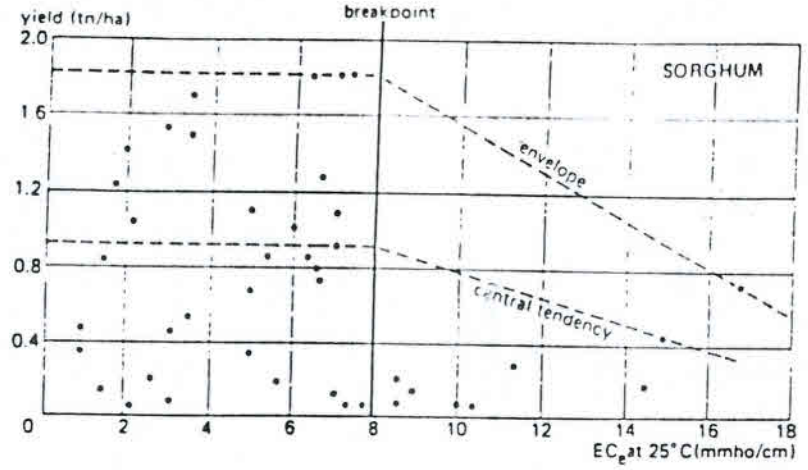


Figure 5.2 Relation between grain yield of sorghum in farmers' fields and soil salinity (ECe) at harvest date in Khairpur, Pakistan (Lenselink et al. 1978)

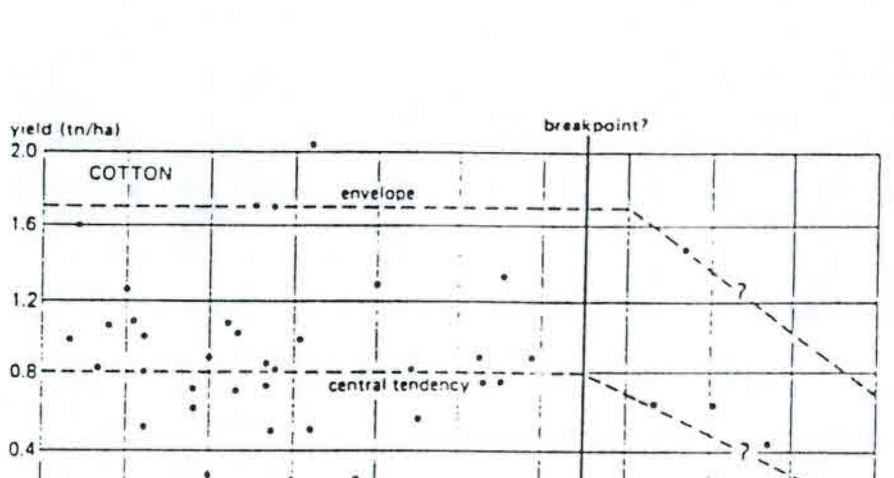


Figure 5.3 Relation beteen yield of cotton in farmers' fields and soil salinity (ECe) at harvest date in Khairpur, Pakistan (Lenselink et al. 1978)

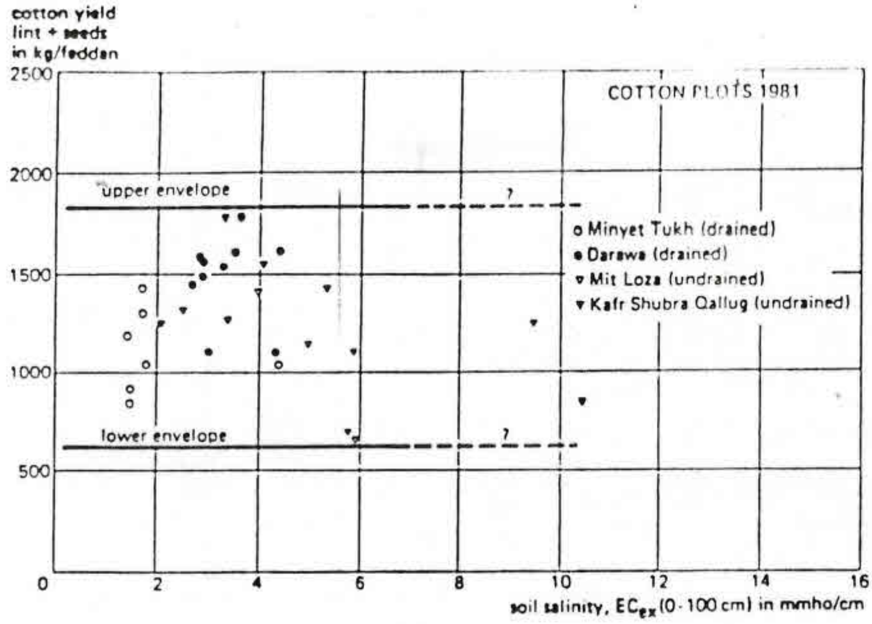


Figure 5.4 Relation between cotton yield in farmers' field and soil salinity (ECe) in the Nile delta, Egypt (Advisory Panel 1982)

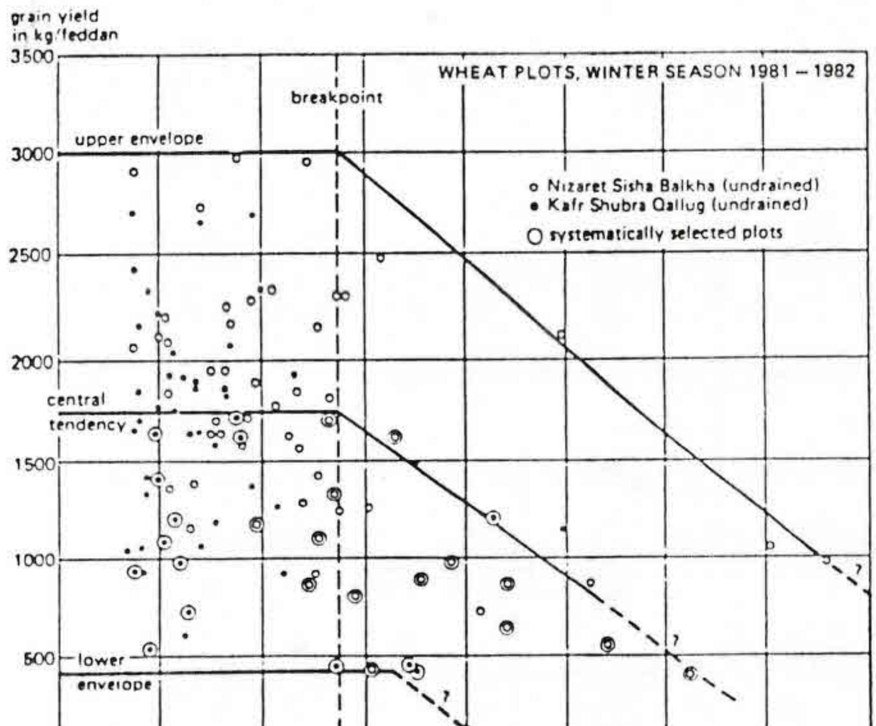


Figure 5.5 Relation between wheat yield in farmers' fields and soil salinity at harvest in the Nile delta, Egypt (Nijland and El Guindy 1984)

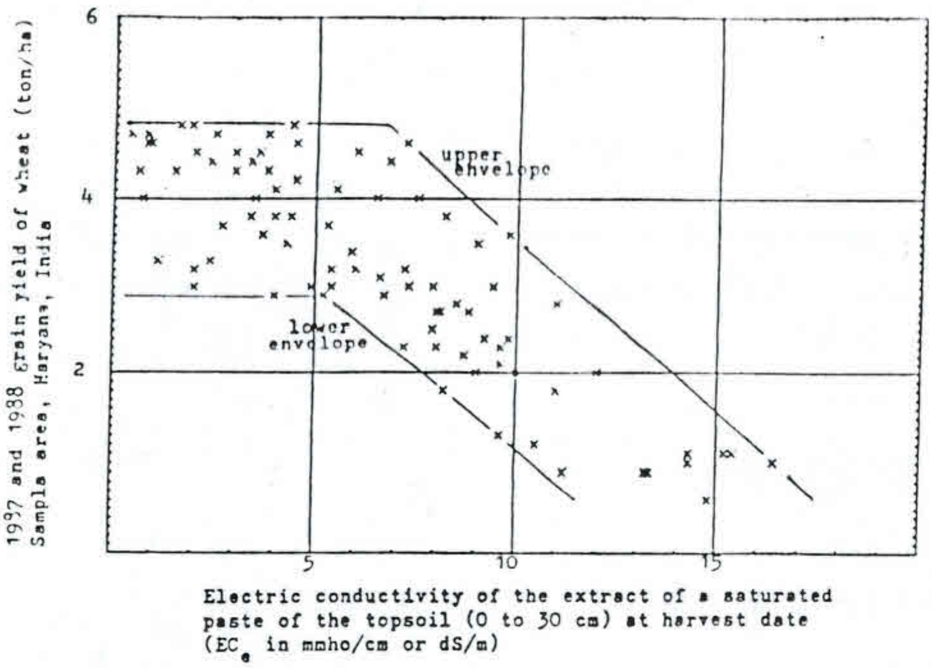


Figure 5.6 Relation between yield and soil salinity (expressed in ECe). Data from D.P. Sharma and K.N. Singh, Central Soil Salinity Research Institute, Karnal, India (Oosterbaan et al. 1990)

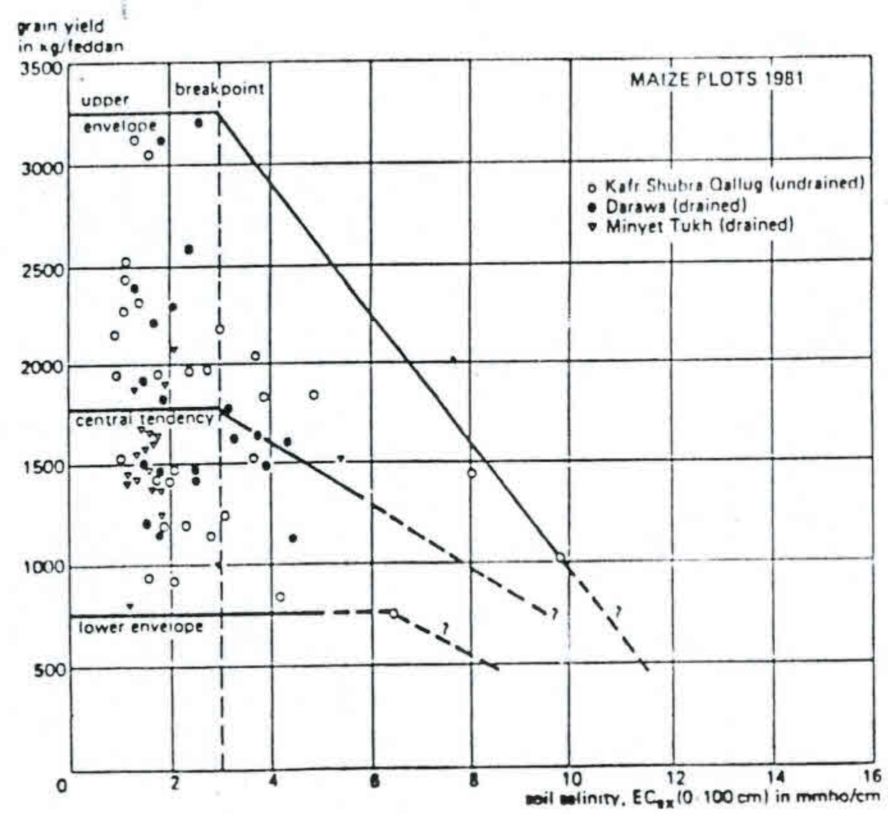


Figure 5.7 Relation between maize yield and soil salinity in farmers' fields at harvest date in the Nile delta, Egypt (Nijland and El Guindy 1984)

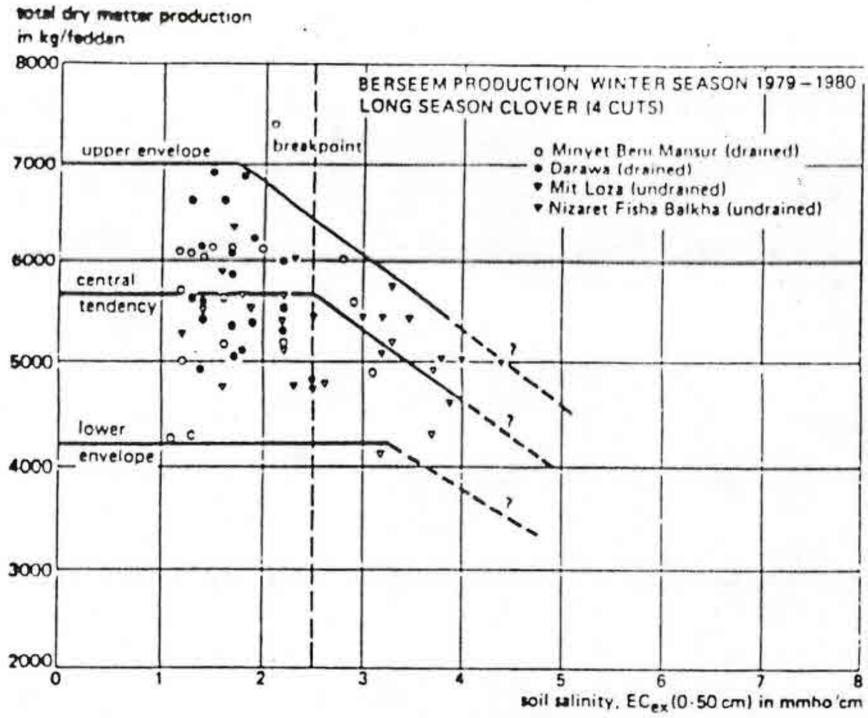


Figure 5.8 Relation between berseem yield in farmers' fields and soil salinity during the growing season in various villages in the Nile Delta in Egypt (Nijland and El Guindy 1984)

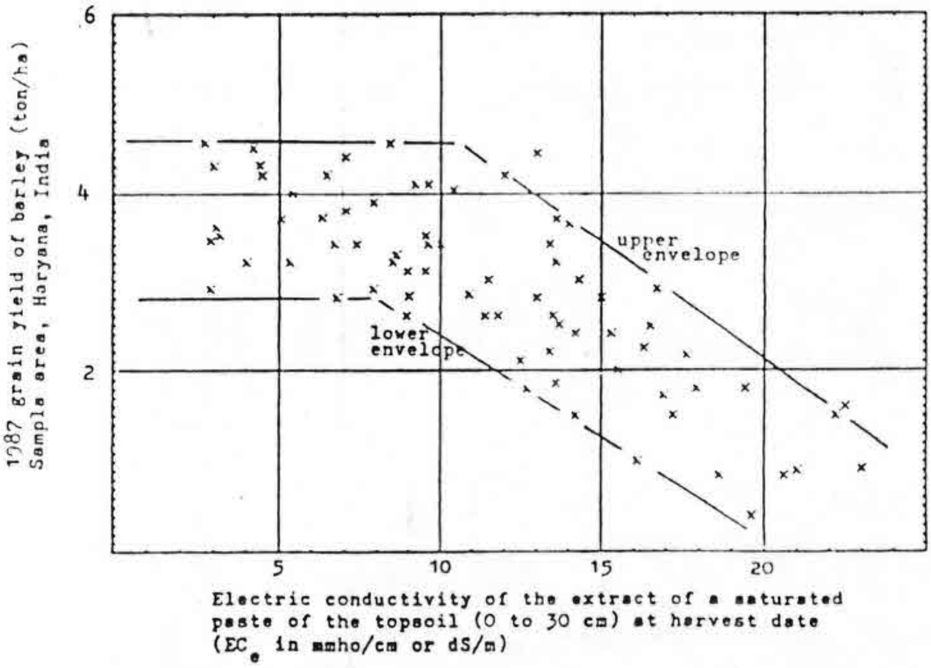


Figure 5.9 Relation between barley yield and soil salinity (expressed in ECe). Data from D.P. Sharma and K.N. Singh, Central Soil Salinity Institute, Karnal, India (Oosterbaan et al. 1990)

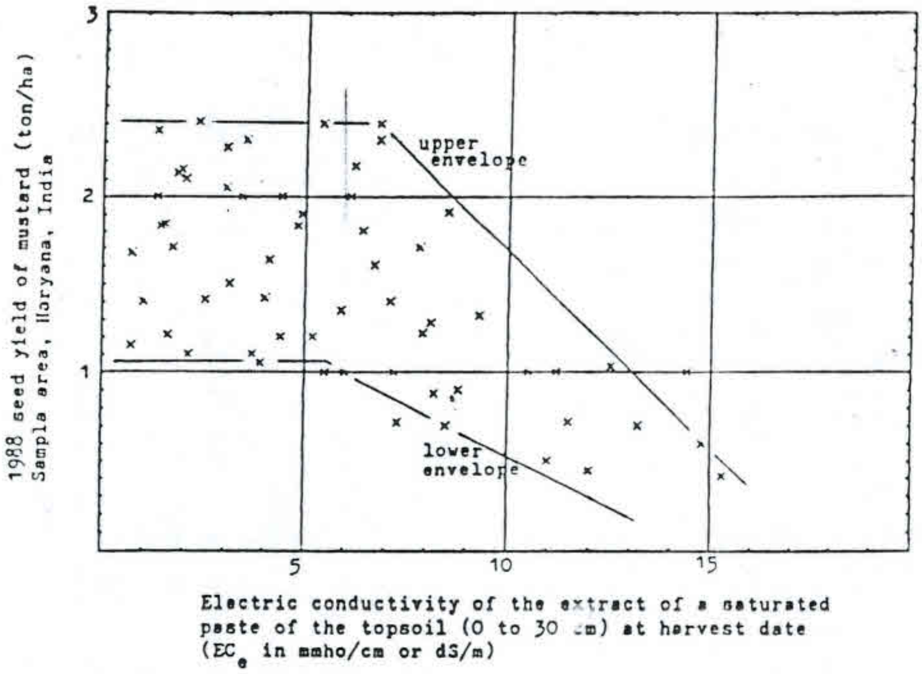


Figure 5.10 Relation between mustard yield and soil salinity (expressed in ECe). Data from D.P. Sharma and K.N. Singh, Central Soil Salinity Research Institute, Karnal, India (Oosterbaan et al. 1990)

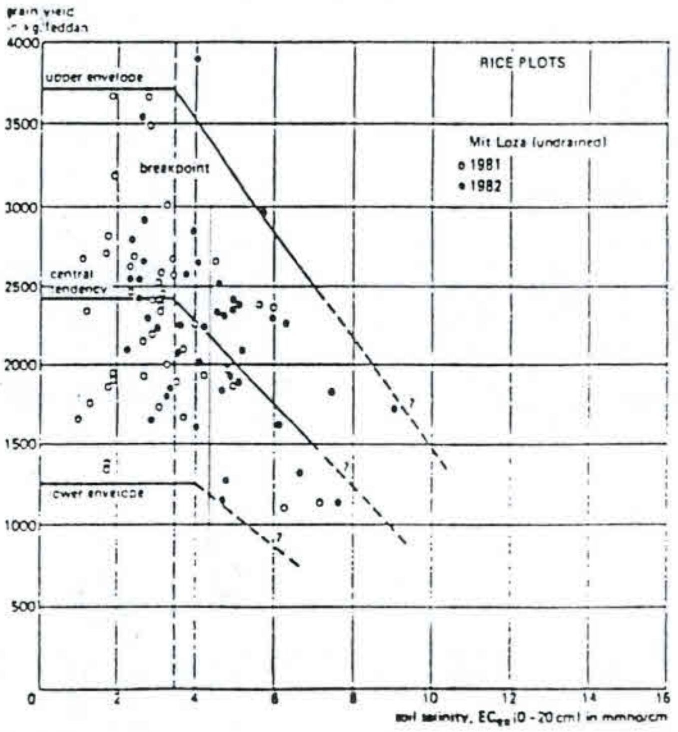


Figure 5.11 Relation between rice yield and soil salinity at harvest date in the Nile Delta, Egypt (Nijland and El Guindy 1984)

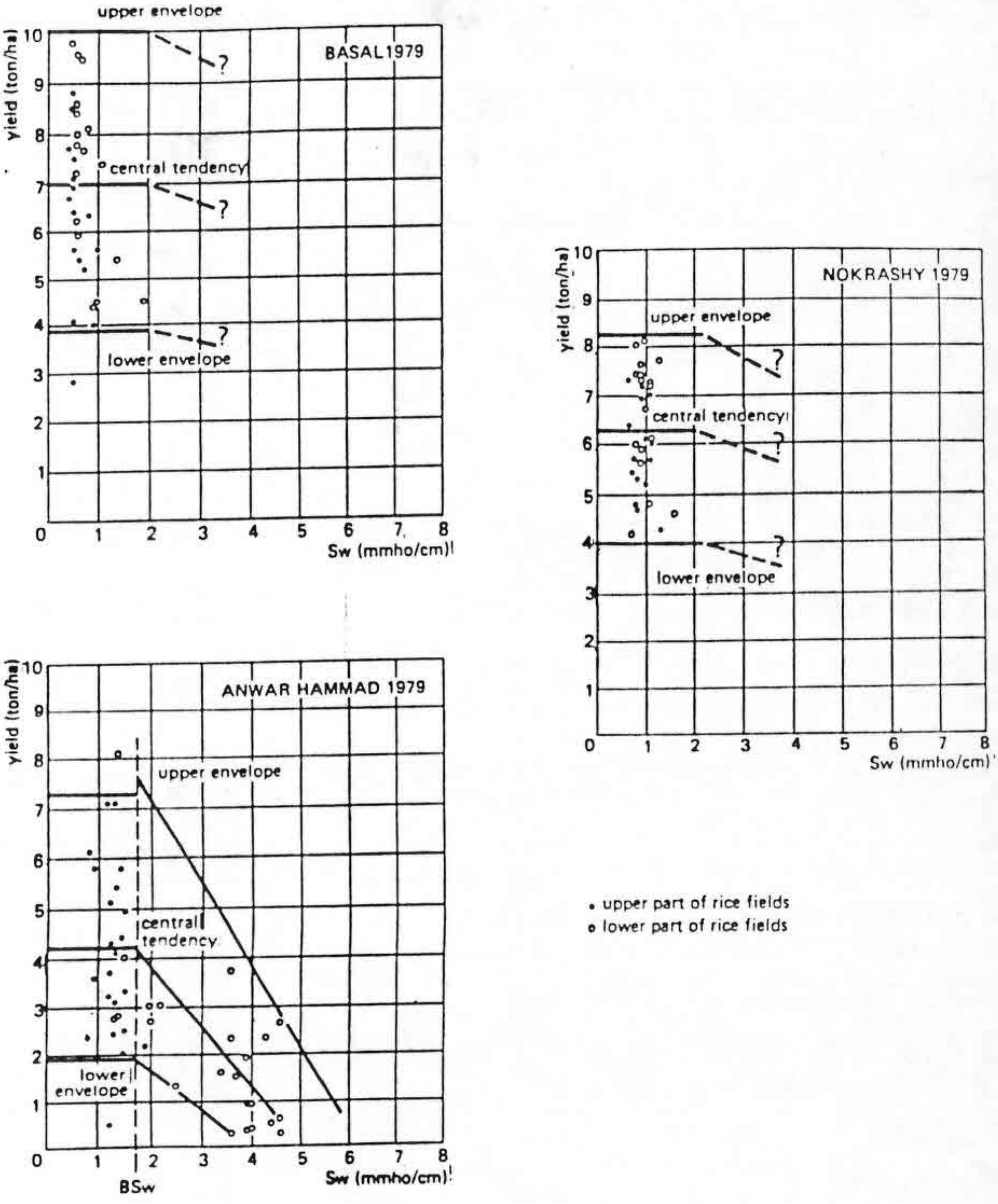


Figure 5.12 Relation between rice yield and salt concentration of the surface water (Sw) in farmers' fields in the Nile Delta, Egypt (Nijland and El Guindy 1986)

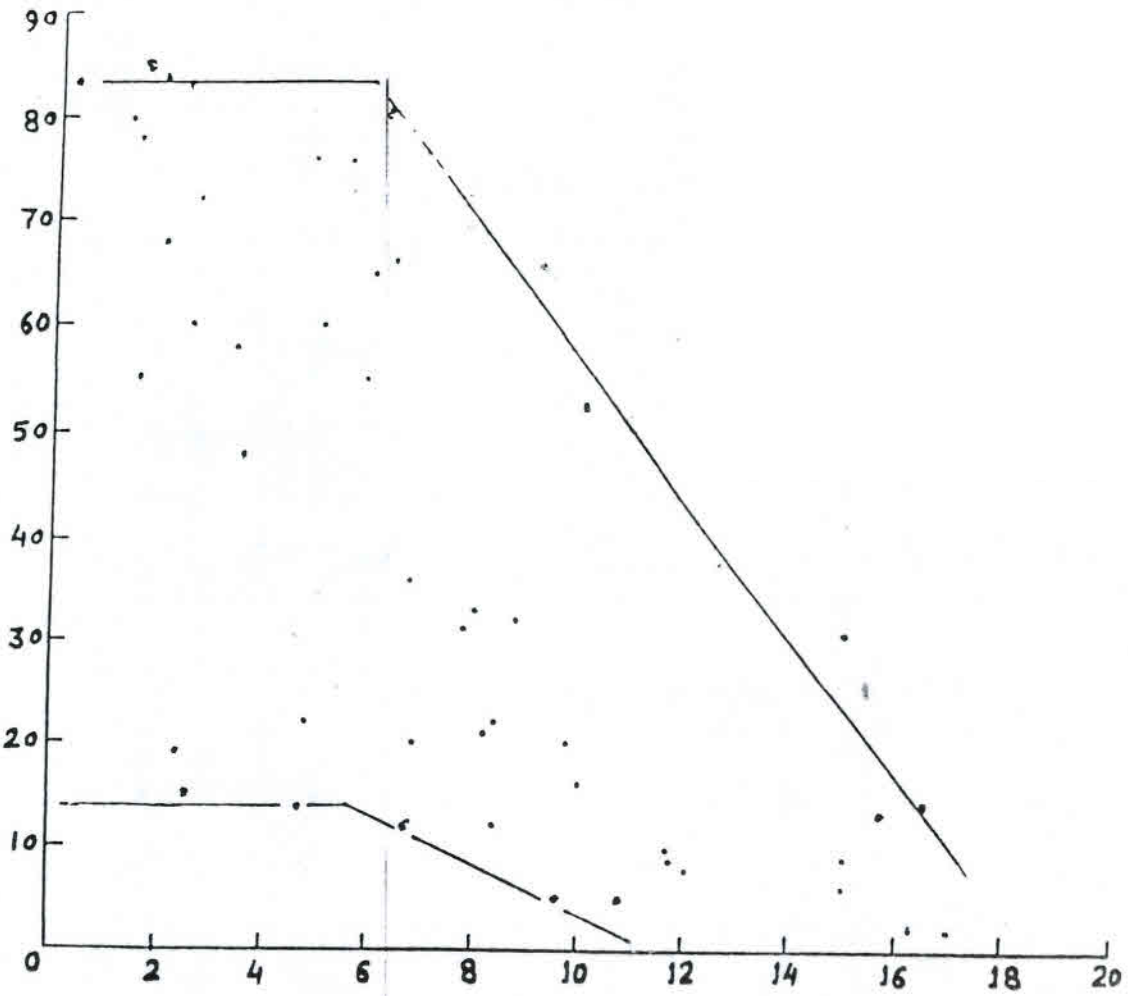


Figure 5.13 Seedling emergence of sorghum versus soil salinity. Data from D.P.Sharma, CSSRI, Karnal, India

6 SOIL ALKALINITY

Soil alkalinity is associated with the presence of sodium-carbonates (Na_2CO_3) in the soil, either as a result of natural mineralization of the soil particles or brought in by irrigation and/or flood water. The sodium carbonate, when dissolved in water, dissociates into $2Na^+$ (two sodium cations, i.e. ions with a positive electric charge) and CO_3^{--} (a carbonate an-ion, i.e. an ion with a double negative electric charge).

The sodium-carbonate can react with water to produce carbon-dioxyde (CO_2), escaping as a gas, and sodium-hydroxide (Na^+OH^-), which is alkaline and gives high pH values (pH>10).

To understand this reaction, we may consider the water (H_2O) as being partly dissociated into H^+ (hydrogen) and OH^- (hydroxy) ions. In pure, neutral water, the concentration of H^+ and OH^- ions equals 10^{-7} eq/l each (respectively 10^{-7} g/l and 17×10^{-7} g/l), a very small concentration.

The pH, being the negative log value of the H^+ concentration, is 7. Similarly, the pOH is also 7.

Please note that one unit decrease in pH indicates a tenfold increase of the H^+ concentration. Similarly, each unit increase in pH indicates a tenfold increase of the OH^- concentration.

In water with dissolved salts, the concentrations of the H^+ and OH^- ions may change, but the sum of pH and pOH remains equal to 14.

Water with excess H^+ ions is called acid (pH < 6), and water with excess OH^- ions is called alkaline (pH > 8). Soil moisture with pH < 4 is called very acid and with pH > 10 very alkaline.

The reaction between Na_2CO_3 and H_2O can represented as follows:

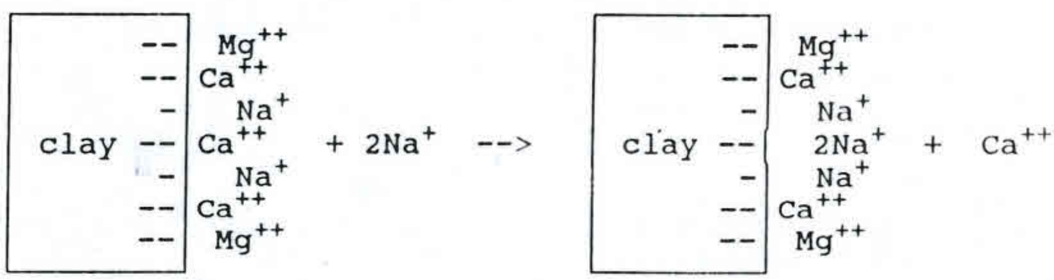
$$2Na^+ + CO_3^{--} + 2H^+ + 2OH^- \rightarrow 2Na^+ + 2OH^- + H_2CO_3$$

The acid H_2CO_3 is unstable and produces H_2O and CO_2 (carbon dioxide gas, escaping into the atmosphere). This explains the remaining alkalinity in the form of soluble sodium hydroxide.

Not all sodium carbonate follows the above chemical reaction. The remaining sodium carbonate, and hence the presence of CO_3^{--} ions, causes $CaCO_3$ (which is only slightly soluble) to precipitate as solid calciumcarbonate (limestone). Hence, the calcium ions Ca^{++} are immobilized:

$$2Na^+ + CO_3^{--} + Ca^{++} \;\text{-->}\; 2Na^+ + CaCO_3 \text{ (solid)}$$

The presence of abundant Na^+ ions and the precipitation of Ca^{++} ions causes the clay particles, which have negative electric charges along their surfaces, to adsorb more Na^+ and, in exchange, release Ca^{++}, increasing their exchangeable sodium percentage (ESP) as follows:



Clay particles with considerable ESP (> 16) and in contact with water occupy a larger volume than otherwise, because the Na^+ ions are quite mobile and have smaller electric charges than Ca^{++} ions, hence they are adsorbed less coherently to the surface of the clay particle and they float farther away: the soil swells.

The phenomenon is called <u>sodicity</u> and results in deterioration of the soil structure, and especially crust formation and compaction of the top layer.

Hence the infiltration capacity of the soil and the water availability in the soil is reduced, whereas the surface waterlogging or runoff is increased. Seedling emergence and crop production are badly affected. However, this effect is suppressed when the soil moisture is saline. Please explain ....

Certain clay minerals with 100% ESP (i.e. fully sodium saturated) are called bentonite which is used in civil engineering to place impermeable curtains in the soil, e.g. below dams, to prevent seepage of water.

The problems of alkalinity and sodicity go hand in hand. Alkaline/sodic soils are not necessarily saline, and the alkalinity problem is worse as the salinity is less. Alkalinity problems are more pronounced in clay soils than in loamy, silty or sandy soils. The clay soils containing montmorrillonitic or smectitic minerals (swelling clays) are more subject to alkalinity problems than illitic or kaolinitic clay soils. The reason is that the former types of clay have larger specific surface areas (i.e. the surface area of the soil particles divided by their volume). Please give an example ....

Alkaline/sodic soils with solid $CaCO_3$ can be reclaimed with grass cultures, ensuring the incorporation of much acidifying organic material into the soil, and the leaching of the excess sodium. This reverses the above processes.

Similarly, it is also possible to reclaim alkaline soils by adding acidifying minerals like pyrite (see next section on acid sulphate soils).

If necessary, the amendment gypsum (calcium sulphate, $CaSO_4$) can also be applied. Please explain ....
....

The quality of the irrigation water in relation to the alkalinity hazard is expressed by the following two indices:

1) The sodium adsorption ratio (SAR)

$$SAR = \frac{[Na^+]}{\sqrt{[Ca^{++}/2 + Mg^{++}/2]}} = \frac{\{Na^+/23\}}{\sqrt{\{Ca^{++}/40 + Mg^{++}/24\}}}$$

where: [] stands for concentration in meq/l, and
{} stands for concentration in mg/l.

It is seen that Mg (Magnesium) is thought to play a similar role as the Calcium

The SAR should not be much higher than 20 and preferably less than 10;

When the soil has been exposed to water with a certain SAR value for some time, the ESP value tends to become about equal to the SAR value.

2) The residual sodium carbonate content (RSC, meq/l):

$$RSC = [HCO_3^- + CO_3^{--}] - [Ca^{++} + Mg^{++}]$$

$$= \{HCO_3^- /61 + CO_3^{--}/30\} - \{Ca^{++}/20 + Mg^{++}/12\}$$

which must not be much higher than 1 and preferably less than 0.5.

Note that the above expression recognises the presence of bicarbotes (HCO_3^-), the form in which most carbonates are dissolved. For simplicity reasons, this was not considered in the foregoing explanations.

Comment
Saline soils are mostly also sodic but not very alkaline, but upon leaching they are usually converted into non-sodic soils as the Na^+ ions are easily removed. Therefore, the problem of sodicity is more acute in non-saline sodic soils than in saline sodic soils.

7 SOIL ACIDITY

When draining pyrite (FeS_2) containing soils (also called cat-clays), the soil may become extremely acid (pH < 4) due to oxidation (reaction with oxygen, O_2, gas) of pyrite into into sulphuric acid (H_2SO_4), giving acid sulphate soils. In its simplest form, the chemical reaction is:

$$2FeS_2 + 9O_2 + 4H_2O \dashrightarrow 8H^+ + 4SO_4^{--} + 2Fe(OH)_3 \text{ (solid)}$$

The product $Fe(OH)_3$, iron (III) hydroxide (orange), precipitates as a solid, insoluble mineral, by which the alkalinity is immobilized and the acidity remains. In alkaline soils, in contrast, it is the escape of CO_2 gas and the precipitation of $CaCO_3$ that causes the removal of acidity from the system whereby the alkalinity remains.

The process of acidification is accompanied by the formation of high amounts of aluminium (Al^{+++} ions, released from clay minerals under influence of the acidity), which are harmful to the crop.

Other products of the chemical reactions are:

H_2S	hydrogen sulphide, a smelly gas;
S	sulphur (yellow)
FeS	iron (II) sulphide (black/grey/blue)
Fe_2O_3	(haematite, iron (III) oxide, red coloured)
FeO.OH	goethite (brown)
Fe Compounds (e.g. jarosite, yellow)	
H-Clay	(hydrogen clay with a large fraction of adsorbed H^+ ions, a stable mineral, but poor in nutrients).

It can be seen that the iron can be present in bi-valent (II) and tri-valent (III) forms (Fe^{++}, the ferro ion, and Fe^{+++}, the ferri ion respectively). The ferro form is soluble, whereas the ferri form is not. The more oxidised the soil becomes, the more the ferri forms will dominate.

Acid suphate soils exhibit an array of colours ranging from black, to brown, blue-grey, red, orange and yellow.

The hydrogen clay can be improved by admitting sea water: the hydrogen adsorbed will be replaced by the Mg and Na present in the sea water.

Cat-clays occur mainly in coastal lowland (Beek et al. 1980) and are often not cultivated or, if they are, planted under rice, so that the soil can be kept wet preventing oxidation. Subsurface drainage of these soils is normally not advisable. However, cultivated acid sulphate soils can often not be kept wet continuously because of climatic dry spells and shortages of irrigation water. In such a situation, surface drainage may help to remove the acidic and toxic chemicals (formed in the dry spells) during rainy periods. On the long run surface drainage can help to reclaim acid sulphate soils (Oosterbaan 1982). For additional information reference is made to Dent (1986). See also the following table.

Table 7.1 Drainage and yield of Malaysian oil palm on acid sulphate soils (after Toh Peng Yin and Poon Yew Chin 1982)

	yield in tons of fresh fruit per ha											
year :	60	61	62a)	63	64	65	66b)	67	68	69	70	71
yield:	17	14	15	12	8	2	4	8	14	19	18	19

a) drainage depth and intensity increased
b) watertable raised again to counter negative effects of a)

Note that subsurface drainage can be harmful. Can the soils recover after reducing drainage again? .... YES/NO
Please explain ....

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INTERNATIONAL COURSE ON LAND DRAINAGE ICLD

Workbook
1.2. SOILS AND DRAINAGE

DRAINAGE

From 19 August to 6 December 2002, Wageningen, The Netherlands

FORTYFIRST INTERNATIONAL COURSE ON LAND DRAINAGE
Wageningen – The Netherlands, 2002

Workbook

1.2. SOILS AND DRAINAGE

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SOILS and DRAINAGE

SUMMARY

The role of the soils in drainage is explained. Where possible only aspects relevant for drainage purposes are considered. The following will be discussed.

Soil formation
Kinds of Soil (Soil Classification)
Vertical differentiation
  Soil horizons and field observations
  Chemical and physical soil properties
Horizontal differentiation
Soil Inventory
Soils and Agricultural Productivity

The text below describes the contents of the lectures by statements, while in brackets [..] reference is made to explanatory text in ILRI publication 16: Drainage Principles and Applications. H.P Ritzema (ed)

1. SOIL FORMATION [16:77-81]

Soil is a part of a system in which physical, chemical and biological processes act [16:80-81].

Therefore soils are formed through the impact of so-called soil-forming factors [16:78-80]

- climate
- vegetation & fauna (exl. Man)
- human influences
- parent material
- topography (incl hydrology)
- time

Rock (defined by composition and formation) undergoes weathering and will result in different kinds of soil parent material.
Soil parent material (non-consolidated material) is subject to soil formation, and at the same time to erosional processes.
Consequently a wide variety soils are found in nature.
Because time is required to form a certain kind of soil, change of climates over time will even amplify the variety of soils.
Most of the differences are visible, they can be easily discriminated. The rules for discrimination differ all over the world. Thus different classification system are in use.

2. KINDS OF SOIL (acc. to the FAO-Unesco Legend of Soil Map of the World)

Most classification systems use as a main entrance the soil forming factors. This led to the classification on the basis of the zonality concept (the russian classical classification of Docuchaev), i.e.

- zonal soils (climate)
- intrazonal soils (local dominance of topography, parent material)
- azonal soils (recently formed soils (river deposits), with limited effect of soil formation)

Presently the FAO-Unesco soil classification system is often used. It serves as the legend for the Soil Map of the World of 1 : 5 000 000 (FAO-Unesco, 1988).

Classification systems have a hierarchical structure. To categorize criterions are used [16:104-107]

At the highest level the key of the FAO-Unesco classification [16:105] shows consecutively the soil forming factors to distinguish. The underlined Major Soil Groupings are the most relevant ones to drainage.

1. Distinction of organic and mineral soils (main soil forming factor: parent material) [peat soils are distinguished (FAO-Unesco calls them Histosol, histos=tissue]

2. Soils with a clear human signature (soil forming factor: human influences) [man-made soils are singled out: Anthrosols]

3. Mineral soils are classified on their composition and particle size (parent material) [soils of volcanic origin and extreme textural composition: heavy* clay (Andosol, Arenosol, Vertisol) and sandy soils]

4. Mineral soil different in position in the landscape (soil forming factor: topography) [lowland (wetland*, Gleysol, Fluvisol) soils and soils of elevated regions (Leptosol, Regosol)]

5. Mineral soils as determined by their age (soil forming factor is time) [Cambisols are azonal soils, not confined to a certain (climatic) region]

6. Mineral soils ordained by the climate (soil forming factor: climate); four (4) climatic regions determine the remaining Major Soil groupings

6a. Tropical and Subtropical regions
[Plinthosol, Ferralsol, Nitisol, Acrisol, Alisol, Lixisol]

6b. Arid and semi-arid regions
[Solonchak, Solonetz, Gypsisol, Calcisol]

6c. Steppes and steppic regions
   [Kastanozem, Chernozom, Phaeozem, Greyzem]

6d. Sub-humid Forest and Grassland regions
   [Luvisol, Podzoluvisol, Planosol, Podzol]

Below the level of Major Soil Groupings reside the Soil Types. Major Soil Groupings like the Chernozem may have developed gleyic properties (they are called Gleyic Chernozem). Thus aspects concerning drainage may become relevant at a lower hierarchical level in a different Major Soil Grouping. This might be the consequence of a rather specific location in the landscape, e.g. an area relatively low with groundwater close to the surface in a rather dry climate.

Note that

1) most of the soil names are derived from Latin or Greek
2) often doubtful distinctions are made. The main reason is that soil forming processes create a dynamic environment, moreover the status of knowledge in this field is still incomplete. For example, the groundwater regime may change over time. Sometimes certain features are conditioned and such fossile characteristics cannot always be recognized.

3. VERTICAL DIFFERENTIATION IN SOILS [16:81-84]

Vertical differentiation can be caused by two processes:

1. by sedimentation, this results in so-called geogenetic layers (soil layers)

2. by pedo-genesis, forming pedogene layers (soil horizons)

The configuration of the layers determines the soil profile.

3.1 IDENTIFICATION IN THE FIELD

To identify the different soil layers, horizons the following soil characteristics are used.

3.1.1 SOIL HORIZONS

Organic horizons:	H, O
Mineral horizons:	A (accumulation of organic matter)
	E (eluviation of organic or mineral components)
	B (illuviation of components of overlying horizons)
	C (unconsolidated, parent material)
	R (rotten, parent rock)

Specific features such as salinity, calcium carbonate content, gleyic properties etc. are indicated by a suffix or prefix

3.1.2 SOIL PROPERTIES DETECTABLE IN THE FIELD

texture [16:85-87]

- a triangle is used to visualize the different soil textures [16:85-87]
- estimation based on comparison with measured texture as a rule of thumb
- heavy clay important for drainage conditions
- accessibility, workability are very much depending on the drainage conditions

structure [16:90-91]

- soil particles can be bound together in aggregates
- structure is related to texture, consistency and porosity
- soil can be structure-less or have blocky, prismatic, columnar or platy structure-elements [16:90]
- depending on for example the biological activity in the soil the elements can be angular or sub-angular

porosity [16:92-93]

- different sizes, continuous of dis-continuous
- important for air and water flow and water retention (qualities: water and oxygen availability)

consistency [16:90]

- consistency changes with texture and composition
- consistency depends to a large extent on the moisture status of the soil; therefore a distinction is made between stickiness/plasticity (wet), friability (moist) and coherency (dry)
- consistency is important to qualities such as workability and accessibility

cementation

- different cementating agent move in the soil $CaCO_3$, iron-oxides, silicium
- depending on the circumstances they may fill up pores between particles and create a hard pan (duripan)
- cementation affects rooting if created sufficiently close to the surface

nodules

- the appearance of nodules in the profile tells about the drainage conditions

color (wet and dry) [16:91]

- three characteristics of light determine the color: hue, value and chroma
- indicator for gleyic, acid sulphate properties
- indicator for organic matter content

stoniness

- stones on the surface and in the profile affect the land use
- at the surface stones interfere with tillage
- in the soil the availability of water is affected
- the description of the soil indicates the degree of stoniness

artifacts

- artifacts indicate the degree to which the soil is still natural

soil depth

- the soil depth affects soil rooting
- parent rock, cementation, heavy clay layers determine the soil depth

chemical properties

- in the field only a limited number of properties is measured
- often measured pH (sodicity), EC (salinity), H_2O_2 (acid sulphate)

The examples show the different kinds of soil horizons and soil layers together with soil profile descriptions [16:82] (more: excursion ISRIC):

3.2 MEASURED SOIL PROPERTIES

Soil properties to characterize the soil are called Soil Characteristics [16:85-99]

Chemical characteristics; [16:97-99]; Klute et al (1986a)

Salinity; [16:99]

- affects plant growth; the osmotic pressure causes toxic and water stress effects on plants
- certain plants (halophytes) withstand high salt concentrations better than other plants
- it is measured as electrical conductivity (EC) or total salt content (weight %)
- Saline soils are typical for arid regions and coastal regions
- the source can be irrigation water, ground water or in case of coastal areas sea-water

Sodicity; [16:98]

- refers to the presence of sodium (Na^+)
- if dominantly present in the soil water the diffuse double layer will become relative extensive causing the dispersion of soil particles
- high sodium concentrations mean usually high pH (>8)
- High pH will affect nutrient availability
- low soil permeability and lack of oxygen for plant roots

Cation Exchange Capacity and Base Saturation; [16:97-98]

- the fine fraction of the soil (clay minerals) has a negative charge; the result is the cation exchange capacity (CEC, cmol/kg)
- CEC withholds cations from leaching; thus affects soil fertility
- the degree of neutralization of CEC by cations is called Base Saturation (BS) and is expressed as a percentage
- when BS < 100% H-AL-complexes are responsable for neutralizing the negative charge of the fine earth

Available nutrients

- nutrients are essential to plant growth
- they are present as organic and anorganic compounds
- with laboratory measurements the availability of nutrients (in particular N, P, K) is detected
- plant nutrient requirements determine whether we speak of primary (N, P, K), secondary (S, Ca etc) and micro-nutrients (Mo, Zn, Fe etc)

Physical characteristics; [16:46-47]; Klute et al (1986b)

Soil texture; [16:88-89]; [16:97]

- soil texture is best measured with the pipette method

- two kinds of clay mineral crystalline structures
  a) kaolinitic clays (1:1 type: Si+Al layers); non-expanding clays
  b) illitic clays (2:1 type: Si+Al+Si layers); expanding clays; montmorrillonite (vertisol) belong to this group

- clay has a so-called cation exchange capacity (C.E.C), i.e. they have a negative charge that is neutralized by cations in the surrounding soil water

- the kind of clay affects these physico-chemical properties; swelling/shrinking occurs, particularly with montmorillonite (in Vertisols)

- If the neutralization of the negative charge is not balanced in an appropriate way, the soil structure is affected very negatively. For example if sodium (Na^+) dominates, soil structure is in danger. Compared to Ca^{++} the soil requires more monovalent cations to neutralize the negative charge, this results in the dispersion of clay particles

Consistency; [16:90]

- in the laboratory characteristics such as Liquid Limit, Plastic limit are measured; they are the so-called Atterberg's limits
- they express in soil moisture content the soil's response to workability and traficability

Bulk density; [16:91-92]

- expresses the part of the soil's volume that is solid material
- soil bulk density is usually expressed in gm per cubic cm (gm/cm^3)

Infiltration rate; [16:96]

- the infiltration rate changes with the soil water content
- infiltration curve change with the kind of soil
- infiltration rate determines to a large extent the overland flow (rainfall-runoff relation) [16:125-128]

Soil water retention curves; [16:93-95]

- a retention curve tells about the water content at different levels of soil water tension

Soil water retention curves (continued)

- retention curves reflect pore-size distribution [16:92-93]
- water is expressed in volume fraction or volume percentage
- knowing the soil's bulk density the soil weight can be calculated
- [16:95] & [16:411] show retention curves
- indirectly retention curves describe the amount of air in the soil

Hydraulic conductivity; [16:46]; [16:96]; [16:234]; [16:410-415]

- pore-size distribution determines to a large extent the unsaturated hydraulic conductivity
- [16:411] presents the relation soil water tension - unsaturated hydraulic conductivity for some different sandy soil textures

Soil temperature; [16:97]

- soil temperature regimes are above all a function of the solar radiation, the soil heat conductivity and soil heat capacity of the soil
- heat conductivity and heat capacity depend on the soil density and the soil water content
- water have a considerable effect on the soil heat capacity
- the course of soil temperature follows which a lag the solar radiation

Biological characteristics

Organic matter

- is a source of energy for soil living organisms
- the organic matter shows usually different degrees of decay
- its accumulation depends mainly on plant growth, temperature and rainfall (histosols)
- in extensive agriculture organic matter is an important producer of nutrients, in particular for nitrogen (N)
- the mineralization of organic matter is a function of temperature, water content, pH and the quality of org. matter

4. HORIZONTAL DIFFERENTIATION [16:83-84]

Variation in soil properties in horizontal direction are common at each scale, provided the legend is well constructed.
It is difficult to distinguish variations in properties from measurement errors.
The change in soil types can be of different nature, i.e. more or less abrupt or gradual.
Though most soil properties are rather robust, others changes in time. Soil texture is for example rather robust, but the salt content of the soil can change from year to year.
Annual changes in organic matter content are also measurable.

To map the vertical and horizontal differentiation soil survey techniques are used.
Most of the inventories is based on knowledge of the development of different kinds of landscape. Where determinism ends statistical techniques are used. In soil survey geo-statistics is used.

5. SOIL INVENTORY [16:99-104]

In Soil Survey an attempt is made to delineate areas that contain similar soil types

Remote images (including Aerial photography) are analyzed;

Because only surface features are shown on the remote images, a provisional map is produced.

The provisional mapping is usually based on a physiographic interpretation of the land.

Elements that play a role in the analysis of the remote images are landscape, relief, drainage conditions, drainage pattern, land use, parceling, etc. these elements indirectly indicate differences between soils.
[not all remote images allow for the analysis of all possible elements, e.g. if no stereoscopic view can be developed it will be impossible to analysis the relief]

This results in a so-called photo-interpretation; the mapping is accompanied by a legend

The legend is not necessarily similar to the classification of the soil. The legend is based on natural boundaries, which do not always coincide with criteria used in soil classification.

Next comes the check in the field; at that stage adjustments in the boundaries may have to be made.

The distinguished units are described (soil profile descriptions), certain chemical and physical in situ measurement are carried out; samples are taken and sent to the laboratory

At the end the mapping is finalized, accompanied by a report.

Nowadays, the different steps in Soil Survey are automated as much as possible.

6. SOILS AND SOIL PRODUCTIVITY

Soil qualities have a direct bearing on the productivity of the soil.

The Soil Inventory (Soil Survey) is the basis for the evaluation of the soil qualities.

Soil qualities are derived from the information of the soil survey report, in particular the physical and chemical analysis will play a role.

Qualities are not independent, however they help to identity the kind of constraint the soil puts or may put on the productivity of the land (FAO's Framework for Land Evaluation, ILRI publication no 17)

For the assessment of the agricultural productivity soils are to be considered a part of a larger system

Soil is not identical to land; the land comprises soil, atmosphere, hydrology etc

A hierarchical system developed by crop modelers gives a structured overview of the qualities that affect agricultural productivity; they are limited to the production of the land:

1. Potential Biomass production (only the radiation regime and temperature regime are limiting)

2. Water limited production (besides radiation and temperature, water has become limited)

3. Nutrient limited production (now soil fertility has become limited too)

4. Effect of weed control (the degree of weed control may lead to further reduction in production)

5. Pests and diseases (control of pests and disease may be insufficient and result in further decline of the productivity)

Except for step 1, the soil plays a role in the productivity of the land

The water limited production is based on the water balance (soil has a buffering function as long as there is rain and/or irrigation)

Under 3. the soil's fertility play a role.

In case of 4. the soil may affect :

a) the competition between weed and the crop,
b) workability and trafficability

The control of pests and diseases is for example affected by the workability of the soil.

More details on the evaluation of the land's productivity (techniques) in e.g. FAO's Framework for Land Evaluation.

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Soils and Drainage

Otto Spaargaren

ISRIC - International Soil Reference and Information Centre

Subjects of Lecture

- Soil forming factors
- Kinds of soil
- Soils influenced by water and evaporation
- Soil horizons and soil characteristics
- Problem soils for drainage
- Soil resource inventories for drainage
- Effects of drainage on soil fertility

What is Soil ?

Soil is the dirt that covers the rock.

A geologist's point-of-view

What is Soil ?

Soil is a natural body comprised of solids, liquid and gases that occurs on the land surface, occupies space, and is characterized by one or both of the following:

- Horizons or layers that are distinguishable from the initial material as a result of additions, losses, transfers, and transformations of energy and matter; *or*
- The ability to support rooted plants in a natural environment.

Soil Taxonomy, 1999

What is Soil ?

Soil is a tri-dimensional body with properties that reflect the impact of ***climate***, of ***vegetation***, ***fauna*** and ***Man***, of ***topography*** on the soil's ***parent material*** over a variable ***time*** span.

FAO World Soil Resources Report **94**, *2001*

Soil Forming Factors

- Vegetation and Fauna (excl. of man)
- Human Influences
- Parent material
- Topography (incl. of hydrology and drainage)
- Time
- Climate

Kinds of Soil (1)

- Organic soils (*Histosols*)
- Soils conditioned by man (*Anthrosols*)
- Soils conditioned by parent material (*Andosols, Arenosols, Vertisols*)
- Soils conditioned by topography (*Fluvisols, Gleysols, Leptosols, Regosols*)
- Soils conditioned by time (*Cambisols*)

Kinds of Soil (2)

- Soils conditioned by climate:
  - Tropical and subtropical (*Ferralsols, Nitisols, Acrisols, Alisols, Lixisols, Plinthosols*)
  - Arid and semi-arid (*Solonchaks, Solonetz, Gypsisols, Durisols, Calcisols*)
  - Steppe (*Kastanozems, Chernozems, Phaeozems*)
  - Temperate (*Luvisols, Albeluvisols, Podzols, Planosols, Umbrisols*)
  - Cold (*Cryosols*)

Soils influenced by water (1)

- **Histosols**

  Accumulation of organic materials

Soils influenced by water (2)

- **Gleysols**

  Influenced by groundwater

Soils influenced by water (3)

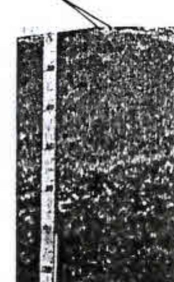
- **Fluvisols**

  Alluvial deposits

Soils influenced by water (4)

- **Plinthosols**

  Iron accumulation ('plinthite')



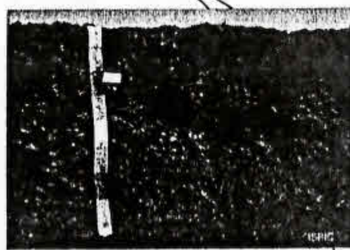
Soils influenced by water (5)

- **Albeluvisols**
  (Podzoluvisols)

  Surface wetness and limited hydraulic conductivity

Soils influenced by water (6)

- **Vertisols**
  Shrink - swell clays



Soils influenced by water (7)

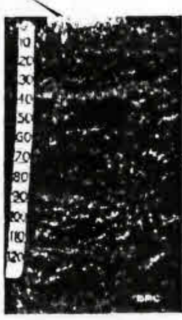
- **Solonchaks**
  Accumulation of soluble salts

Soils influenced by water (8)

- **Solonetz**
  Accumulation of sodium

Soils influenced by water (9)

- **Planosols**
  Surface wetness and abrupt textural change



Soils influenced by evaporation (1)

- **Gypsisols**
  Accumulation of gypsum

Soils influenced by evaporation (2)

- **Durisols**

  Accumulation of silica

Soils influenced by evaporation (3)

- **Calcisols**

  Accumulation of calcium carbonate

Soil Identification

- Soil horizons
- Soil properties
- Horizontal and vertical extent

Soil Horizons (1)

Organic horizons:

H or O

H = wet
O = dry

Soil Horizons (2)

Mineral horizons:

A (organic matter)
E (eluviation)
B (illuviation)
C (unconsolidated, parent material)

Soil Horizons (3)

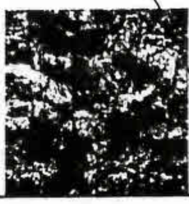
Mineral horizons:

R (rotten, parent rock)

Mottles and Nodules

Mottles and nodules, concentric or irregularly shaped concentrations of translocated substances, are indicative of water movements and drainage conditions.

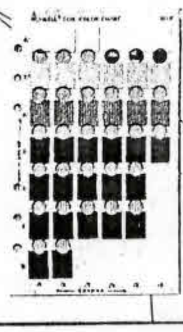
E.g. iron and manganese concentrations indicate periodic wetness.



Colour

Colour of the soil is expressed in **hue**, **value**, and **chroma**, using the Munsell Soil Color Charts.

Colour is used, for example, as indicator for wetness and presence of organic matter.



Stoniness

Stoniness is described as it affects, amongst others, tillage operations and water availability.

Biological Activity

Biological activity by larger soil animals and bacteria/fungi contributes to:

- Release of nutrients
- Production of humus
- Homogenisation of soils
- Creation of porosity

Soil Depth

Soil depth is determined by parent rock, cemented horizons, or strongly contrasting layers (e.g. heavy clay).

Such horizons or layers affect the rooting depth of plants.

Chemical Characteristics

- Salinity (Electrical Conductivity (EC) and Soluble Salts)
- Sodicity/Alkalinity (pH)
- Cation Exchange Capacity (CEC) and Base Saturation
- Available Nutrients (N, P, K, S, Ca, Mg, micro-nutrients)
- Organic Matter

Soil Properties

- Detectable in the field
- Measurable in the laboratory
- Visible under the microscope

Field Characteristics

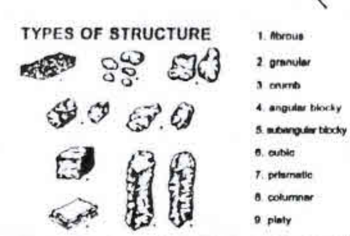
- Texture
- Structure
- Porosity
- Consistency
- Cementation
- Mottles and nodules
- Colour
- Stoniness
- Biological activity
- Soil depth

Texture

Soil texture describes the proportion of the sand (2-0.05 mm), silt (0.05-0.002 mm), and clay-sized (<0.002 mm) particles

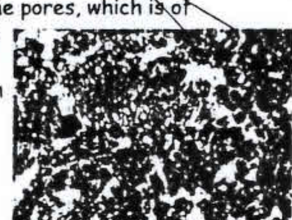
Structure

Soil structure describes the arrangement of the particles into different forms of aggregates



Porosity

Porosity describes the size, form, orientation, and continuity of the pores, which is of importance for the air and water flow and water retention in the soil



Consistency

Consistency describes the state of **stickiness/plasticity** of the soil **when wet**, the state of **friability when moist**, and the **state of coherency when dry**.

Consistency determines to a large extent the workability of the soil and the accessibility of the land.

Salinity

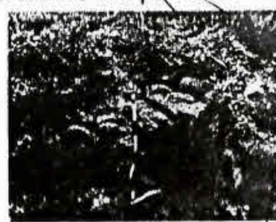
Salinity is measured as EC (mS cm^{-1}) or total salt content (weight %). It affects plant growth as osmotic pressure causes toxic and water stress effects.

Salinity can often be recognized by a *Halophyte* vegetation.

Sodicity/Alkalinity

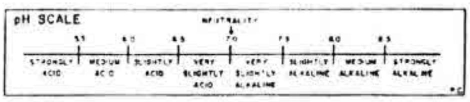
Sodicity refers to the presence of sodium (Na^{+}), causing dispersion of soil particles and high pH.

It is usually associated with low subsoil permeability and lack of oxygen for plants.



pH Ranges

The soil acidity or pH can range from near to **2** (in acid sulphate soils) to over **10** (in saline soils). The ranges are described as follows:



Cation Exchange Capacity

Clay minerals and organic compounds in the soil have a negative charge; they will bind positively charged cations and withhold them from leaching.

The total negative charge is called **Cation Exchange Capacity (CEC)**, expressed in $cmol_c\ kg^{-1}$ soil, and is an important measure for soil fertility assessment.

Base Saturation (BS)

Base saturation in soils expresses the degree of neutralization of the Cation Exchange Capacity by calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na).

If BS is less than 100%, hydrogen (H) and aluminium (Al) are responsible for neutralizing the remaining negative charge, and is expressed as **exchangeable acidity**.

Available Nutrients

Nutrients are bound by the soil's exchange complex, or released by decaying organic matter.

Distinguished are **macro**-nutrients (N, P, K), **meso**-nutrients (S, Ca, Mg, etc), and **micro**-nutrients (Mo, Zn, Fe, Cu, Mn, B, etc).

Their availability is a function of the soil pH.

Physical Characteristics

- Soil Texture
- Consistency
- Bulk Density
- Infiltration Rate
- Soil Water Retention
- Hydraulic Conductivity
- Soil Temperature

Soil Texture

Soil texture measurement involves the separation of the individual soil particles and determination of the **sand** (2-0.05 mm), **silt** (0.05 - 0.002 mm), and **clay** (<0.002 mm) fractions.

Most common methods used are the pipette and the hydrometer methods.

Consistency

Consistency measurements determine the **liquid** and **plastic** limits of the soil, also known as **Atterberg's** limits.

They express in soil moisture content (in weight %) the soil's response to **workability** and **trafficability**.

Bulk Density

Bulk density (BD) expresses in kg m^{-3} the part of the soil volume that is solid, and is related to the soil's porosity.

Porosity can be calculated from the bulk density and particle density as follows:

$$\text{Porosity (\%)} = (1 - D_b/D_p) \times 100$$

Infiltration Rate

Infiltration rate is measured in the field using the double ring method.

Infiltration rates depend on the moisture status of the soil (dry, moist, wet), and the kind of soil (clayey, sandy).

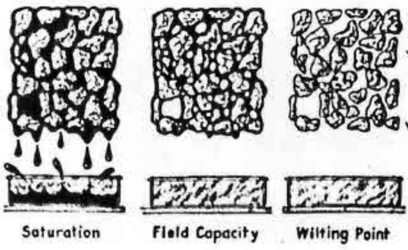
It determines to a large extent the rainfall - runoff relation.

Soil Water Retention (1)

Soil water retention is studied by analyzing the release of moisture from soil sample completely saturated with water to a state of dryness.

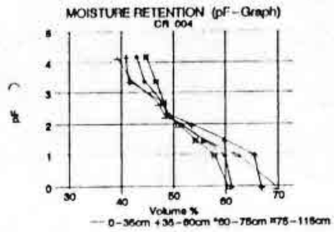
The measurements give indications about the **field capacity** (optimal condition for plant growth) and the **wilting point** (no more plant-available water), and thus about the total amount of water for plant growth.

Soil Water Retention (2)



Soil Water Retention (3)

Example of soil water retention curves



Hydraulic Conductivity

Saturated hydraulic conductivity is for each soil type different but constant (see Darcy's Law).

Unsaturated hydraulic conductivity is largely determined by the pore-size distribution and varies with the moisture content of the soil.

Soil Temperature

Soil temperature is a function of the **solar radiation**, and the **heat conductivity** and **capacity** of the soil.

Heat conductivity and capacity depend on the soil density, the soil moisture content and the soil material.

Soil temperature variations follow with a lag the solar radiation.

Problem Soils for Drainage

Six soil types pose specific problems in relation to drainage, viz.

- Potentially Acid Sulphate Soils *(Protothionic Fluvisols* and *Gleysols)*
- Shrink-swell Clays *(Vertisols)*
- Soils with Plinthite *(Plinthosols)*
- Saline Soils *(Solonchaks)*
- Organic Soils *(Histosols)*
- Unripe Sediments *(specific Fluvisols)*

Potentially Acid Sulphate Soils (1)

Characteristics:

- Low-lying level areas
- Associated with brackish or salt water
- Prone to flooding
- Contain pyrite (FeS_2)

Potentially Acid Sulphate Soils (2)

Potentially Acid Sulphate Soils (3)

Potentially Acid Sulphate Soils (4)

Main chemical reactions:

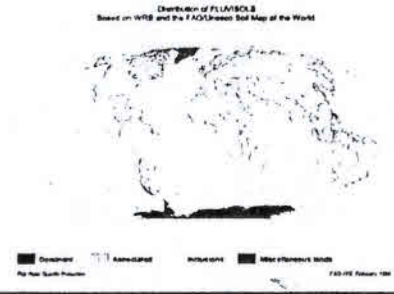
$4FeS_2 + 15O_2 + 10H_2O \leftrightarrow 4FeOOH + 8H_2SO_4$

$2KAlSi_3O_8 + 6Fe(OH)_3 + 4H_2SO_4 \leftrightarrow$
$2KFe_3(SO_4)_2(OH)_6 + Al_2Si_2O_5(OH)_4 + 4SiO_2 + 5H_2O$

$KFe_3(SO_4)_2(OH)_6 + H_2O \leftrightarrow FeOOH + 2H_2SO_4 + KOH$

$2FeOOH - H_2O \leftrightarrow Fe_2O_3$

Potentially Acid Sulphate Soils (5)



Potentially Acid Sulphate Soils (6)

Two (opposite) strategies for reclaiming potentially acid sulphate soils:

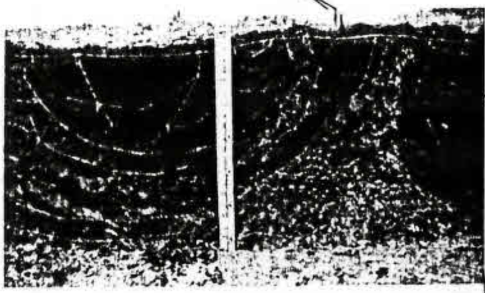
- To drain and completely oxidize the soil, then leaching of the acidity.
- To maintain a high groundwater table to prevent oxidation.

Shrink – Swell Soils (1)

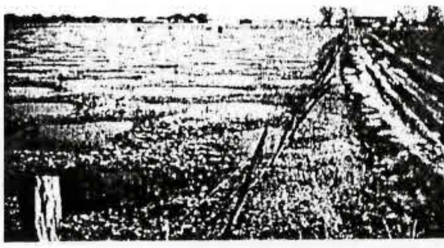
Characteristics:

- Level areas
- Associated with alternating wet and dry seasons
- Prone to flooding
- High clay content with dominantly montmorillonite, a clay mineral that swells taking up water and shrinks releasing water
- Self-mulching

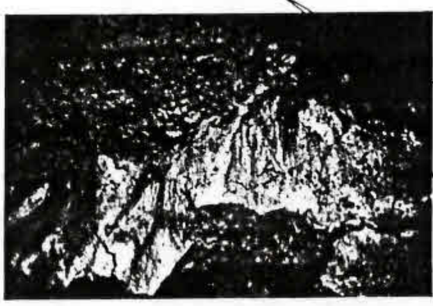
Shrink - Swell Soils (2)



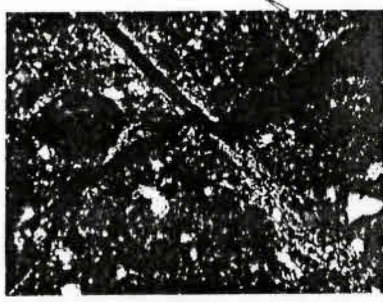
Shrink - Swell Soils (3)



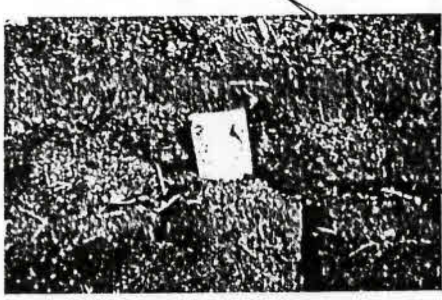
Shrink - Swell Soils (4)



Shrink - Swell Soils (5)



Shrink - Swell Soils (6)



Shrink - Swell Soils (7)

Shrink - Swell Soils (8)

Shrink - Swell Soils (9)

Management options:

- Surface drainage only.
- Maintaining moist condition to limit soil movement by irrigation during the dry period.

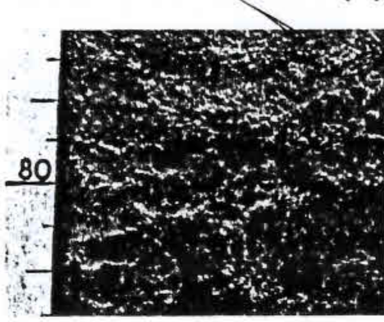
Soils with Plinthite (1)

Characteristics:

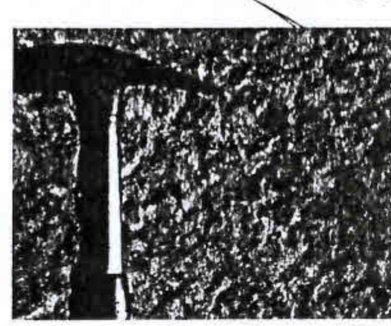
- Low-lying areas (e.g. valleys) in moist tropical regions
- Formed under the influence of groundwater and lateral water flows from adjacent uplands
- Contains an iron-rich, humus-poor layer, which hardens irreversibly under the influence of repeated drying and wetting

Soils with Plinthite (2)

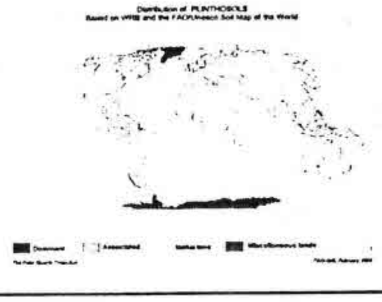
Soils with Plinthite (3)



Soils with Plinthite (4)



Soils with Plinthite (5)



Soils with Plinthite (6)

Management options:

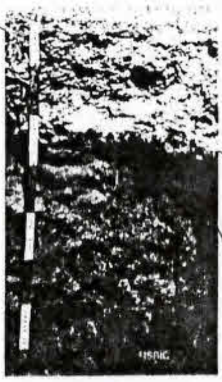
- Not to be drained below the plinthic layer.
- If hardened, erosion control measures are needed to prevent the hardened layer to come to the surface.

Saline Soils (1)

Characteristics:

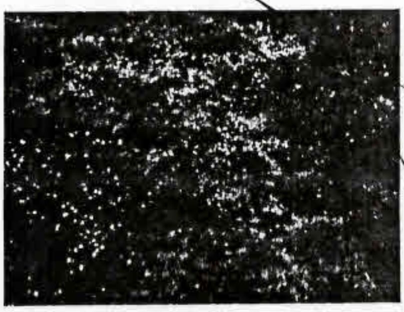
- High groundwater table
- High salt content
- Often saline parent material
- Prone to crusting
- Prone to erosion

Saline Soils (2)



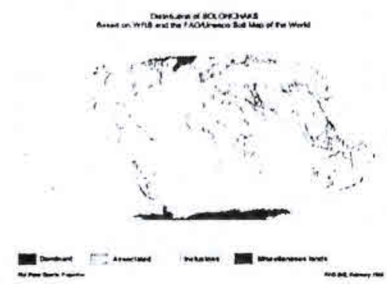
Saline Soils (3)

Saline Soils (4)



Saline Soils (5)

Saline Soils (6)



Saline Soils (7)

Management options:

- Drainage possible but a flushing regime has to be maintained to prevent resalinization by capillary rise.

Organic Soils (1)

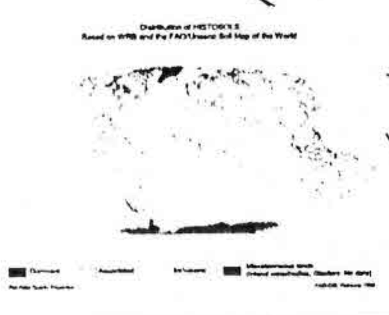
Characteristics:

- High water content
- High organic matter content
- Low bulk density
- High groundwater table
- Low bearing capacity
- Subject to subsidence upon drainage

Organic Soils (2)

Organic Soils (3)

Organic Soils (4)



Organic Soils (5)

Management options:

- Drainage is a must but rate of subsidence has to be taken into account
- Require close monitoring of the groundwater table

Unripe Sediments (1)

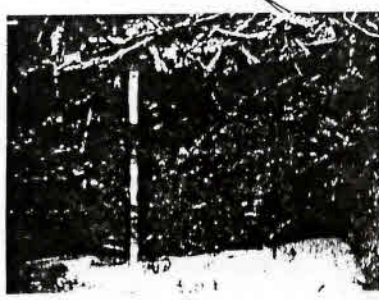
Characteristics:

- Occur on tidal marshes, swamps, shallow lakes and newly empoldered areas
- Fine textured
- High water content
- High n-value:

$$n = (A-0.2R)/(L+3H)$$

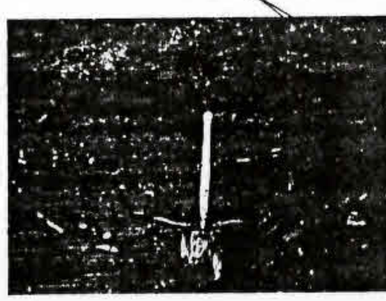
A: % water; R: % silt+sand; L: % clay; H: % organic matter

Unripe Sediments (2)



Unripe Sediments (3)

Unripe Sediments (4)



Unripe Sediments (5)

Unripe Sediments (6)

Management options:

- Pre-drainage treatment with reed or other plants that extract large amounts of water from the soil
- Surface and subsurface drainage has to be installed

Soil Resource Inventories for Drainage (1)

Soil resource inventories aim to delineate areas that contain similar soil types.

Most soil resource inventories are multi-purpose, to be used more than once to reduce costs.

Consequently, for specific purposes the soil information needs to be interpreted.

Soil Resource Inventories for Drainage (2)

Soil resource inventories are made at a variety of scales:

5 000 000	General inventory	World, continent
500 000	Exploratory	Country
100 000	Reconnaissance	Province, state
50 000	Semi-detailed	District, town
10 000	Detailed	Farm planning
2 000	Very detailed	Farm management

Soil Resource Inventories for Drainage (3)

For drainage purposes scales of 1 : 5 000 and larger are the most suitable.

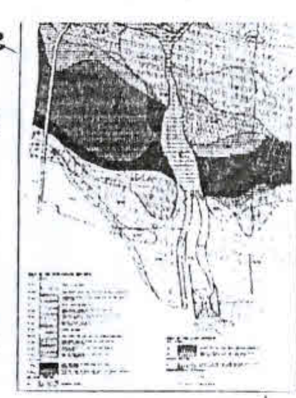
Soil survey for drainage requires specific components not recorded during 'normal' surveys, i.e.:

- Hydraulic conductivity data
- Infiltration rate data

Soil Resource Inventories for Drainage (4)

Amla Area Soil Map (Pakistan)

1 : 3 960 (16 inch = 1 mile)



Effects of Drainage on Soil Fertility

Drainage will change the soil in several respects:

- Change in micro-flora, soil fauna and microbial activity
- Increased mineralization of organic matter
- Oxidation of reduced substances
- Creation of a leaching regime
- Modification in soil structure
- Compaction of the surface layer
- Change in soil temperature variations

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41th INTERNATIONAL COURSE ON LAND DRAINAGE ICLD

Lecture Notes
1.3. WATER IN UNSATURATED ZONE

DRAINAGE

From 19 August to 6 December 2002, Wageningen, The Netherlands

FORTYFIRST INTERNATIONAL COURSE ON LAND DRAINAGE
Wageningen – The Netherlands, 2002

Lecture Notes
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Lecturer ICLD 2002

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Lecture notes for the International Course on Land Drainage are not official publications. They may be altered from year to year. Lecture notes have been published as: Drainage Principles and Applications, ILRI Publication 16, Wageningen 1974, and as a revised version in 1994.

CONTENTS

1 INTRODUCTION and OBJECTIVES

The lectures will give you some basic understanding of the physical behaviour of soil water in the unsaturated zone. After the lectures, you can define and explain the following concepts:

- water content,
- water potential,
- water retention characteristic,
- storage coefficient,
- hydraulic conductivity and
- the water balance.

You will be able to:

- explain the meaning of the water retention characteristic and apply some aspects of it for drainage practice;
- calculate the matric head distribution in the unsaturated zone of a soil profile in hydraulic equilibrium and during steady state flow;
- calculate the flux density of steady state flow through the unsaturated zone, if the potentials and hydraulic characteristic are given.

These lecture notes contain several questions for self study. At page 27 and 28 the answers can be found. Four computer programs are part of the lecture notes. These programs can be used to illustrate the soil hydraulic characteristics, to calculate the storage coefficient and to calculate capillary rise and infiltration. The *computer exercises* are helpful to test whether or not you can apply the theory in calculations.

The movie "How water moves in the soil" will be shown at the end of the lectures . This movie made by Walter Gardner illustrates the basic conceptions needed to understand water movement for irrigation practice.

These lecture notes are supplementary to ILRI publication 16: Drainage Principles and Applications (revised version 1994); pages 91 to 97 and 383 to 410.

2 SYMBOLS

The symbols used in this workbook are listed below. The description with their basic SI units are given. In practice and in this workbook, other SI units are used, e.g. cm d^{-1} for the conductivity in stead of m s^{-1}. The symbols and terminology used are in accordance with the directives of ISO Technical Committee 190 'Soil Quality'.

a	distance, m
h_a	pneumatic head, m
h_g	gravitational head, m
h_m	matric head, m
h_h	hydraulic head, m
h_o	osmotic head, m
h_p	pressure or tensiometer head, m
h_t	total head, m
H	hydraulic head, m
K	hydraulic conductivity, m s^{-1}
m	mass, kg
m_a	mass of air, kg
m_s	mass of solids, kg
m_w	mass of water, kg
p	pressure (see h for subscripts), Pa
r	radius, m
v	flux density, m s^{-1}
V	volume, m^3
V_a	volume of air, m^3
V_s	volume of solids, m^3
V_w	volume of water, m^3
w	water content mass ratio, kg kg^{-1} = 1
z	vertical coordinate (upwards positive), m
z_0	reference level, m
ϵ	porosity, 1
θ	water content volume fraction, 1
μ	storage coefficient, 1
${}^b\rho$	dry bulk density, kg m^{-3}
ρ_s	density of solids, kg m^{-3}
ρ_w	density of water ($\approx$ 1000 kg m^{-3}), kg m^{-3}
Ψ	potential (see h for subscripts), J kg^{-1}

3 SOIL WATER CONTENT

The main constituents of soil in the unsaturated zone are solid particles, water and air. In the saturated zone there is no air present. Taking a certain volume of soil V, containing a volume $V_{s(olids)}$, a volume $V_{w(ater)}$ and a volume $V_{a(ir)}$, then one can write:

$$V = V_s + V_w + V_a \tag{3.1}$$

in which $V_w + V_a$ is defined as the volume of the pore space. This pore space can be expressed as a fraction ϵ, according to:

$$\epsilon = \frac{V_w + V_a}{V} \tag{3.2}$$

and is called porosity.
The soil water content can be expressed as a volume fraction or as a mass ratio. The water content volume fraction or volumetric water content θ is defined as:

$$\theta = \frac{V_w}{V} \tag{3.3}$$

Denoting the mass of dry solids as m_s and of soil water as m_w, the water content on a mass basis expressed as a ratio reads as

$$w = \frac{m_w}{m_s} \tag{3.4}$$

To convert w into θ one needs to know the dry bulk density ${}^b\rho$, which is defined as the mass of dry soil divided by its volume:

$${}^b\rho = \frac{m_s}{V} \tag{3.5}$$

Since $V_w = \dfrac{m_w}{\rho_w}$ one can write:

$$\theta = \frac{V_w}{V} = \frac{\dfrac{m_w}{\rho_w}}{V} = \frac{\dfrac{m_w}{\rho_w}}{\dfrac{m_s}{{}^b\rho}} = \frac{{}^b\rho}{\rho_w} \cdot \frac{m_w}{m_s} = \frac{{}^b\rho}{\rho_w} \cdot w \tag{3.6}$$

In practice one often expresses the water content over a depth of soil directly in mm of water. So, $\theta = 0.01$ means 1 mm of water per 100 mm soil layer.

The dry bulk density, ${}^{b}\rho$, should not be confused with the density of the solid particles, ρ_s, which is for mineral soils in the range of 2650 to 2700 kg m^{-3}. Knowing ${}^{b}\rho$ and ρ_s one can compute the porosity ϵ as:

$$\epsilon = \frac{V_w + V_a}{V} = \frac{V - V_s}{V} = 1 - \frac{V_s}{V} = 1 - \frac{\frac{m_s}{\rho_s}}{\frac{m_s}{{}^{b}\rho}} = 1 - \frac{{}^{b}\rho}{\rho_s} \tag{3.7}$$

Question 3.1:

A soil sample of 100 cm^3 is dried. It requires 40 g of water to saturate. Find the porosity for this soil.

Question 3.2:

Assume that the soil of question 3.1 is located on an irrigated farm. The farmer wants to saturate down to 25 cm depth.

a) Calculate the volume of water he has to apply per cm^2 of soil surface.

b) If this were to be applied as a single application, what would be the depth of flooding?

4 SOIL WATER POTENTIALS, PRESSURES and HEADS

Water rises in glass tubes. This is due to the attraction of water molecules and the solid material at the air/water interface. The water rises higher in small diameter tubes than in larger diameter tubes, see figure 4.1. You can say that a column of water is hanging on a ring of water molecules attached to wall of the tube. In equilibrium, the weight of the column of water equals this attraction.

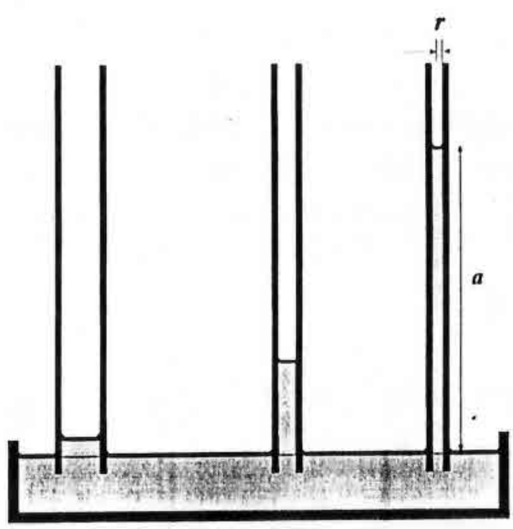

Figure 4.1. Capillary rise of water in tubes with different diameters

One can derive that:

$$a = \frac{1.5\,10^{-5}}{r} \quad \text{(m)} \qquad (4.1)$$

Where a is the height of the water column, in m, and r is the inner radius of the tube, in m.

You can see a soil as a very complex structure of tubes. The water in small tubes is very tightly bound, or in other words, you have to work hard to remove the water. The water in the larger tubes can be removed easily. You can say also that the energy status of the water in the small pores is much lower than in the larger pores. The total energy of the water is the sum of the energy due to the interaction of the water with the soil matric and the energy due to gravitation and the energy due to other factors like external gas pressure and osmotic forces. Working with energies is not very convenient since the energy of the water depends on the amount of water considered. Therefore one uses potential, i.e. the energy of the water divided by its mass.

The total soil water potential, ψ_t, is the sum of several components, just like the total energy:

$$\psi_t = \psi_m + \psi_g + \psi_o + \psi_a + ... \quad (J\ kg^{-1}) \tag{4.2}$$

where

ψ_t = total potential
ψ_m = matric potential, arising from interactions between the soil matric and water
ψ_g = gravitational potential, arising from the gravitational force
ψ_o = osmotic potential, arising from the presence of salts in the soil water
ψ_a = pneumatic potential, arising from an external gas pressure

In soil physics one works often with pressures and heads. The pressure, or pressure equivalent of the soil water potential, is the energy of the soil water divided by its volume. The total soil water pressure can be written as a sum of several components, just like potentials:

$$p_t = p_m + p_g + p_o + p_a + ... \quad (J\ m^{-3} = N m^{-2} = Pa) \tag{4.3}$$

The head, or head equivalent of the soil water potential, is the energy of the soil water divided by its weight. The total soil water pressure can be written as a sum of several components, just like potentials and pressures:

$$h_t = h_m + h_g + h_o + h_a + ... \quad (J\ N^{-1} = m) \tag{4.4}$$

The relationship between potentials and pressures and the head equivalent of the potential is given by:

$$\psi_t = \frac{p_t}{\rho_w} = g h_t \tag{4.5}$$

where ρ_w is the density of the soil water and g is the acceleration due to gravity.

All potentials and equivalents are relative measures, or in other words one has to define the reference or zero level of all components. The surface of free and pure water at atmospheric pressure is taken as a reference for all components, except for the gravitational potential, pressure and head. The gravitational potential or equivalent is taken zero at a convenient level, often the soil surface or the ground water level.

In soil physics and hydrology, one prefers to use heads for its simplicity. It has the dimension of length, expressed in the basic unit m, but also the unit of cm is often used.

The pneumatic head, h_a, is zero in most natural situations. The air in all pores is at atmospheric pressure. The osmotic head, h_o, can be neglected in those cases where the chemical composition of the soil water is the same everywhere in the profile. In many natural situations equation 4.4 reduces to:

$$h_t = h_m + h_g \tag{4.6}$$

The matric head, h_m, is negative in the unsaturated zone. One has to apply work to remove the water from the pores. In the saturated zone, h_m is positive. The water flows out a saturated soil by itself.

The pressure head, h_p, is the sum of matric and pneumatic head and can be measured with a tensiometer:

$$h_p = h_m + h_a \tag{4.7a}$$

The pressure heads is also called tensiometer head. In those cases where $h_a = 0$, the pressure head equals the matric head:

$$h_p = h_m \tag{4.7b}$$

The gravitational head, h_g, is the distance from the reference level to the point of interest. h_g is positive above the reference plane and negative under that plane. One can write:

$$h_g = z - z_0 \tag{4.8}$$

where z is the vertical coordinate and z_0 the position of the reference plane. Only in the case that the origin of the coordinate system is in the reference plane $h_g = z$. Note that we always take the vertical coordinate positive in the upward direction.

The sum of h_p and h_g is called the hydraulic head:

$$h_h = h_p + h_g = h_p + z - z_0 \tag{4.9a}$$

or

hydraulic head = *pressure head* + *gravitational head* (4.9b)

If we take the reference plane of h_g at the origin we can write:

$$h_h = h_p + z \tag{4.9c}$$

Often one writes H for h_h and h for h_p :

$$H = h + z \tag{4.9d}$$

Note that equation 4.9d is only valid if the reference plane of h_g is chosen at the origin of the vertical coordinate.

The differences in hydraulic heads determine the direction of the flow of soil water. Water flows from high to low heads. No water flows if the hydraulic head is the same everywhere, or:

$$\frac{\partial h_h}{\partial z} = 0 \qquad (4.10)$$

Such a situation is illustrated in Figure 4.2. The watertable is at 100 cm depth, and both the reference level of the gravitational head and the vertical origin is arbitrarily taken at this watertable depth. We assume atmospheric pressure of the soil air in the whole column. One tensiometer is installed at 50 cm depth, another tensiometer (which in this case may also be an open tube, i.e. a piezometer) at 140 cm depth. With Figure 4.2 one can illustrate the heads that are involved. At the watertable the matric head $h_m = 0$, because the water is at atmospheric pressure. Above the watertable $h_m < 0$, below it $h_m > 0$. For tensiometer 1 the matric head is represented by the height of the open end of the water column, $h_m = -50$ cm, and gravitational head by the height above reference level, $h_g = 50$ cm. Thus $h_h = h_m + h_g = -50 + 50 = 0$ cm. In the same way, one can derive for tensiometer 2 that: $h_m = +40$ cm and $h_g = -40$ cm, thus $h_h = +40 - 40 = 0$. Hence, everywhere in the soil column $h_h = 0$ cm.

Question 4.1:
Derive h_m, h_g and h_h for tensiometer 1 and 2 when both the reference level of h_g and the origin of the vertical coordinate are chosen at the bottom of the soil column.

Thus, everywhere in the soil column $h_h = 50$ cm. It appears that by choosing the reference level of h_g at another place the absolute magnitude of hydraulic head changes due to changes in h_g.

Question 4.2:
Derive h_m, h_g and h_h for tensiometer 1 and 2 when the reference level of h_g is chosen at the soil surface and the origin of z is chosen at the bottom of the soil column.

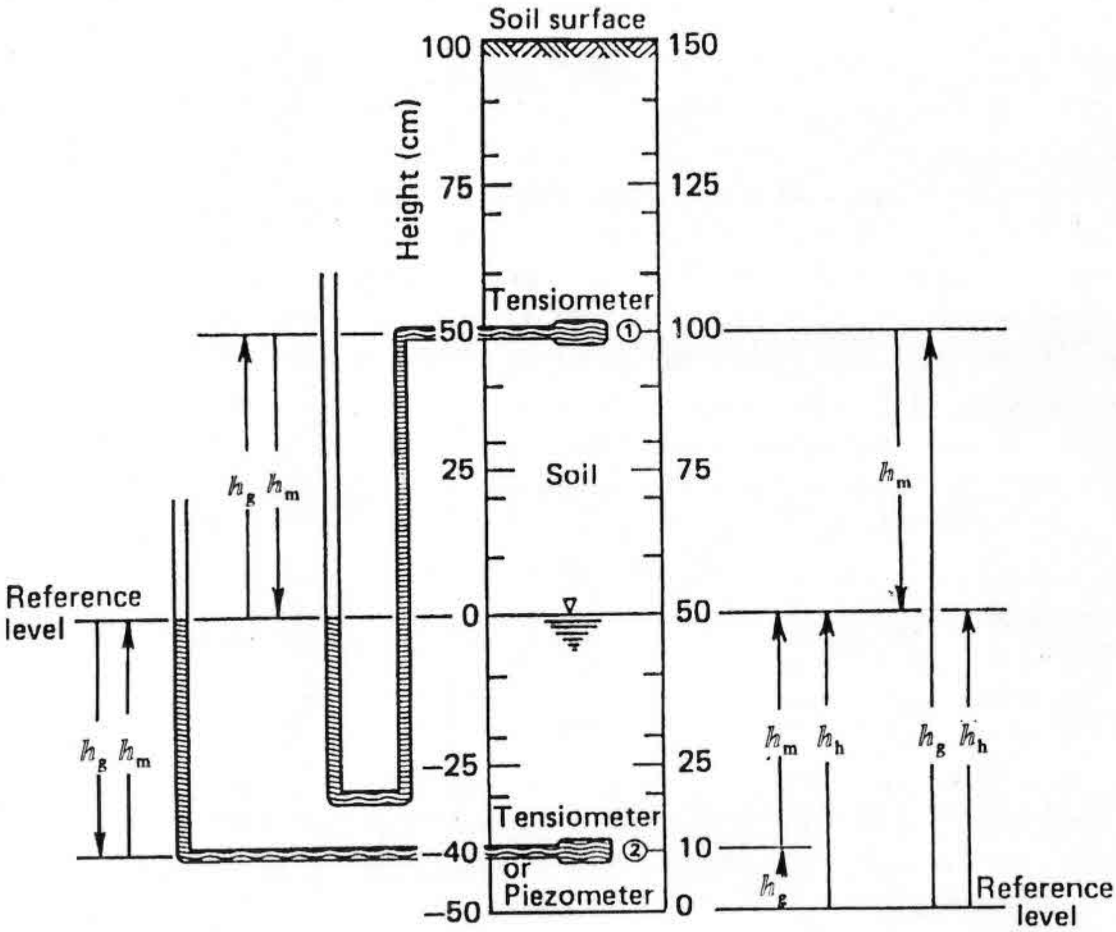

Figure 4.2. Soil at equilibrium conditions (= no flow) with a watertable at a depth of 100 cm, a tensiometer at 50 cm depth and a tensiometer/piezometer at 140 cm depth

5 SOIL WATER RETENTION CHARACTERISTIC

5.1 Theory

We have seen in section 4 that the matric head of water in the unsaturated soil arises from interactions between soil particles and water. In wet, coarse-textured media capillary forces are dominant while in dry soils adsorption is most important. In fine-textured media, exhibiting colloidal properties, double-layer effects may become significant. If the matric head of the soil changes, the water content of the soil will also change. At high matric heads only the larges pores are filled with air, at low matric heads also the small pores are filled with air. The graph representing the relationship between matric head and water content is generally called the soil water retention characteristic or the retention curve. The range of matric heads varies from 0 cm for saturation down to -10^7 cm for oven-dry conditions. Usually the logarithm of the matric head is plotted to see both the details at high matric heads and the whole range. In some countries the term *pF* is used. In analogy with *pH*, *pF* is defined as the logarithm of the absolute value of h_m in cm of water divided by 1 cm:

$$pF = \log_{10}\frac{|h_m|}{1\,\mathrm{cm}} \tag{5.1}$$

Figure 5.1 shows the water retention characteristic of a loam soil. The water retention characteristic is sometimes referred to as pF-curve. The following points can be distinguished in this graph:

Saturation

The intersection point of the curve with the water content axis ($h_m = -1$ cm; $pF = 0$) gives the water content of the soil under nearly saturated conditions, which means that this point almost indicates the fraction of all water filled pores or the porosity ε.

Field capacity

There exists several definitions of field capacity. It indicates the soil water status in equilibrium (see section 4). It depends on the distance to the ground water table. We will use a matric head of -100 cm ($pF = 2$) for the field capacity in theses lecture notes. The air content at field capacity is called aeration porosity. It is important for the diffusion of oxygen to the plant roots. Usually an aeration porosity of 0.10 to 0.15 (= 10 to 15 vol.%) is satisfactory for plant growth. In drainage practice aeration porosity is often called drainable pore space or effective porosity.

Wilting point

The wilting point or permanent wilting point is the point where the roots cannot take any water from the soil any more. The plant will die when it is too long in this condition. The wilting point is not the same for all plants. We will use a value of -15,800 cm or -16,000 cm ($pF = 4.2$).

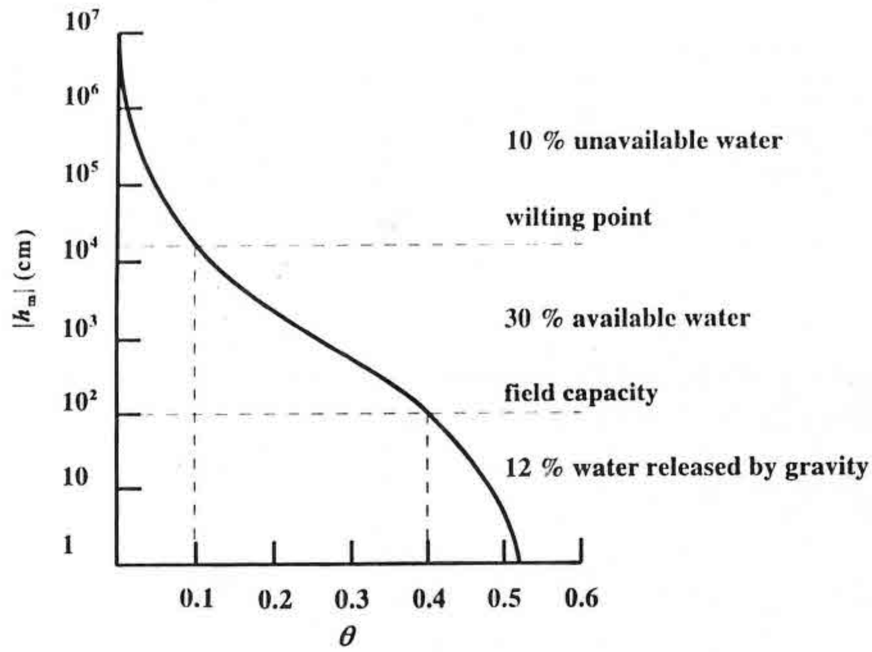

Figure 5.1. The water retention characteristic of a loam soil.

Oven-dry point

By definition, the oven-dry point is the point where the water content of the soil is zero. It is reached after drying a soil to constant mass in an oven at 105 °C. It corresponds with $h_m = -10^7$ cm ($pF = 7$).

Available water

The amount of water held by a soil between field capacity and wilting point is defined as the amount of water available for plants. The lower h_m, the more difficult it is for the roots to extract the soil water. Therefore, to get optimum plant production, it is better not to allow the soil to dry out to the wilting point. The matric head at which soil water begins to limit plant growth is roughly about -400 to -1000 cm. In practice this implies that the drought limit is reached when 0.40 to 0.60 of the available water is used. This amount of water is often referred to as readily available water.

Question 5.1.1:

For a homogeneous silt loam soil the following data are obtained:

h_m (cm)	-1	-100	-16,000
pF	0	2	4.2
θ	0.509	0.461	0.092

Calculate:
a) Total porosity ε;
b) Air content at field capacity;
c) Amount of water available for plants;
d) Amount of water available when the rooting depth is 50 cm;
e) How much water may be lost by transpiration before crop growth gets limited;
f) What is the characterization of these conditions for agricultural use.

Computer exercise
Use program SOILS to plot different water retention characteristics.
1) Select from the Staring Series the following soils:
   coarse sand
   sandy loam
   clay
   peat
2) Get the saturated water content (h_m = 0 cm) for these soils;
3) Get the water content at h_m = -100 cm for these soils;
4) Get the water content at h_m = -16000 cm for these soils;
5) Which aspects of the characteristics of these soils do strike you most?

5.2 Storage coefficient

If a field is in hydraulic equilibrium and if there is no drainage, the water table will rise after a period with rain. After the field is in hydraulic equilibrium again, the rise of the water table will be more than the amount of rain, since only the empty pores can be filled with water. Just above the water table almost all pores are filled with water. The higher above the water table, the more pores can be filled with water. In a fine textured soil there are less pores that can be filled with water than in a coarse textured soil at the same level above the water table. The water table rise after a certain amount of rain gives the buffering capacity of the soil or the storage capacity μ:

$$\mu = \frac{\text{ammount of rainfall} \quad (\text{mm})}{\text{change in watertable depth} \quad (\text{mm})} \qquad (5.2)$$

In stead of considering the amount of rainfall, we can also look at the amount of water drained out of the profile after lowering the water table. That amount of water equals also the difference in water storage in the profile before and after the change of the water table or:

$$\mu = \frac{\text{change in soil water storage of the profile (mm)}}{\text{change in watertable depth (mm)}} \qquad (5.3)$$

We can illustrate the above equation with Figure 5.2. We have a profile in hydraulic equilibrium with a water table at -75 cm. The distribution of h_m is given by the distance to the water table (see section 4) and is drawn in Figure 5.2B. To calculate the water storage in the profile, we have to know the water content distribution in the profile. We can derive that from the distribution of h_m and the water retention characteristic drawn in Figure 5.2A. The resulting θ distribution is drawn in Figure 5.2C. The water storage ($\theta \cdot z$) is given as the area under curve 1 in Figure 5.2C. If the water table is lowered to -100 cm, we will get in a similar way the distribution of h_m and θ in the profile. The water storage is now given as the area under curve 2 in Figure 5.2C. The difference between the water storage in situation 1 and 2 is given by the hatched area in Figure 5.2C.

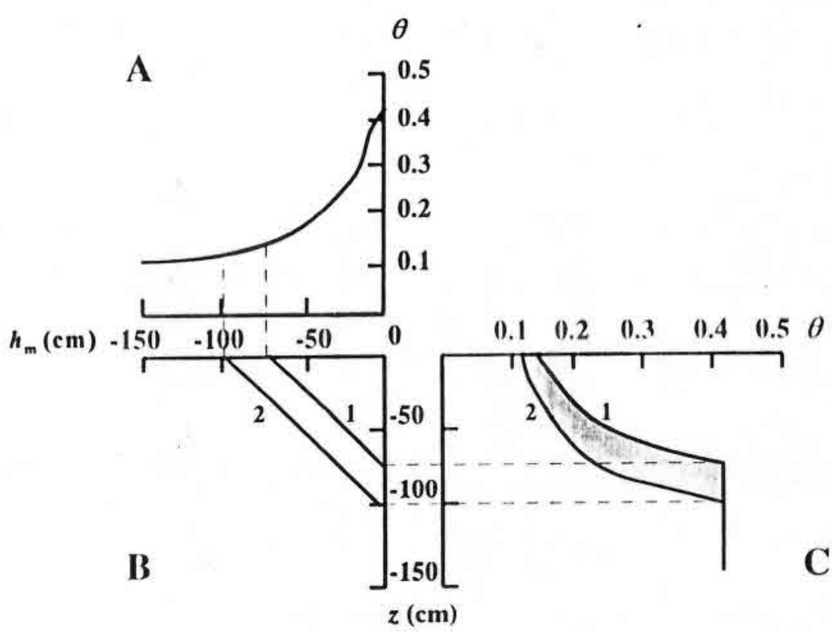

Figure 5.2. Graphical evaluation of the storage coefficient μ for a sandy loam. The matric head distribution with depth (B) and the water retention characteristic (A) gives the water content distribution (C) in the profile. The situation for a water table at -75 and at -100 cm is shown. μ is the hatched area of figure C (7 cm) divided by the change in water table (25 cm), $\mu = 0.28$.

Computer exercise

Use the program STORAGE to calculate the storage coefficient for different soils.

1) Select the soil **sandy loam** from the Staring Series.
2) Choose -50 cm for the old table and -100 cm for the new water table. What is the storage coefficient?
3) Choose -100 cm for the old table and -150 cm for the new water table. What is the storage coefficient now?
4) Choose -150 cm for the old table and -200 cm for the new water table. What is the storage coefficient now?
5) Is the storage coefficient a constant?
6) Select the soil **coarse sand** from the Staring Series and repeat steps 2 to 5.
7) Can you explain the differences between sandy loam and coarse sand?

6 FLOW OF WATER

6.1 Basics

We have seen earlier that flow is caused by differences in hydraulic head h_h. For the one dimensional flow of water in both saturated as unsaturated soil, Darcy's law applies

$$v = - K \frac{\partial h_h}{\partial z} \tag{6.1}$$

where

- v = flux density or apparent flow velocity , cm d^{-1};
- K = hydraulic conductivity, cm d^{-1};
- h_h = hydraulic head, cm;
- z = vertical coordinate, cm.

In the case of saturated (ground water) flow the total soil pore space is available for flow. However, with unsaturated flow part of the pores are filled with air and this part does not participate in the flow. Therefore, the hydraulic conductivity must be smaller than in case of saturated flow. Thus, with decreasing soil water content the available flow area will decrease and also the hydraulic conductivity. For unsaturated soil, K is not a constant any more. K is dependent on the soil water content θ or, because $\theta = f\{h_m\}$, on the matric head

$$K = f\{\theta\} \text{ or } K = f\{h_m\}$$

as an example for a clay soil see Figure 6.1.
For unsaturated soils one uses for K sometimes the term *capillary conductivity*.
In contrast to saturated ground water flow which is mainly in a horizontal direction, flow of water in the unsaturated zone is mainly in the vertical direction. Vertical flow of soil water occurs either as *capillary rise* ($v > 0$) or as *infiltration* ($v < 0$).

Computer exercise
Use program SOILS to plot different conductivity curves.

1) Select from the Staring Series the following soils:
   - coarse sand
   - sandy loam
   - clay
   - peat
2) Get hydraulic conductivity at a water content of 0.30 for these soils;
3) Which aspects of the conductivity of these soils do strike you most?

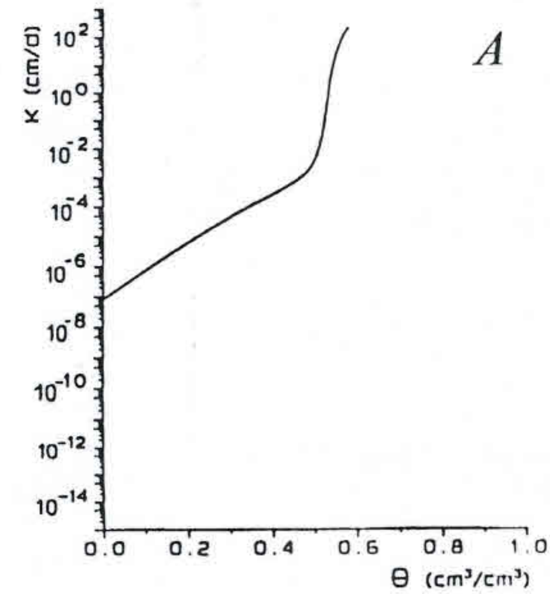

Figure 6.1a Relation between hydraulic conductivity K and soil water content θ for clay

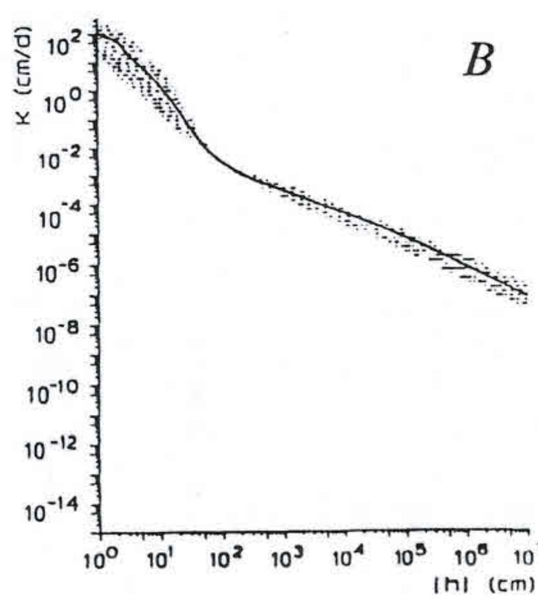

Figure 6.1b Hydraulic conductivity K versus soil water matric head h_m for the clay soil of Figure 6.1a.

Substitution of $h_h = h_p + h_g$ (Equation 4.8a) and $h_g = z - z_0$ (Equation 4.7) into Equation 6.1 yields

$$v = -K \frac{\partial h_h}{\partial z} = -K \left(\frac{\partial h_p}{\partial z} + \frac{\partial (z - z_0)}{\partial z}\right) = -K \left(\frac{\partial h_p}{\partial z} + 1\right) \qquad (6.2)$$

In order to get a complete mathematical description for unsaturated flow, we apply the continuity principle (Law of Conservation of Matter)

$$\frac{\partial \theta}{\partial t} = -\frac{\partial v}{\partial z} \quad (\mathrm{d}^{-1}) \qquad (6.3)$$

where t is time (d).
Substitution of 6.2 in 6.3 yields the pressure head form of the flow equation in unsaturated soils

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left(K\left(\frac{\partial h_p}{\partial z} + 1\right)\right) \qquad (6.4)$$

Equation 6.4 is nonlinear because of the dependency of K and h_p on θ. To avoid the problem of the two dependent variables θ and h_p, the derivative of θ with respect to h_p can be introduced, which is known as the differential water capacity C

$$C = \frac{\partial \theta}{\partial h_p} \quad (\mathrm{cm}^{-1}) \qquad (6.5)$$

Writing

$$\frac{\partial \theta}{\partial t} = \frac{\partial \theta}{\partial h_p} \cdot \frac{\partial h_p}{\partial t} \qquad (6.6)$$

and substituting Equations 6.5 and 6.6 into Equation 6.4 yields

$$\frac{\partial h_p}{\partial t} = \frac{1}{C\{h_p\}} \frac{\partial}{\partial z} K\{h_p\}\left(\frac{\partial h_p}{\partial z} + 1\right) \qquad (6.7)$$

Written in this form, Equation 6.7 provides the basis for predicting transient soil water movement in layered soils of which each layer may have different physical properties.

This equation is a nonlinear partial differential equation. The non-linearity causes problems in its solution. Analytical solutions are known for special cases only. Most problems can be solved with numerical models that run on computers.

Question 6.1.1:

Two tensiometers are installed in a field. At a particular time, the position of tensiometer 1 is 60 cm above the water table and the measured pressure head h_{p1} equals -130 cm. The position of tensiometer 2 is 50 cm above the water table and h_{p2} = -100 cm.

a) Is there any vertical water movement in the profile? Why?
b) If there is water movement, will it be in downward (drainage) direction or in upward (capillary rise) direction?
c) Calculate the relative magnitude of the flux density. Use a value k for the hydraulic conductivity *K*.
d) Calculate the flux density for the case that the tensiometers are installed in a clay soil. Use program SOILS to obtain a value for *K*. Alternatively you can read a value from Figure 6.1b.

6.2 Steady state flow

The most simple flow case is the steady state vertical flow situation. In that case $\partial\theta/\partial t$ = 0 and Equation 6.4 reduces to

$$\frac{\partial}{\partial z} K(\frac{\partial h_p}{\partial z} + 1) = 0 \quad \text{or} \quad \partial K(\frac{\partial h_p}{\partial z} + 1) = 0 \qquad (6.8)$$

Integration yields

$$K(\frac{\partial h_p}{\partial z} + 1) = c \qquad (6.9)$$

where c is the integration constant. Comparison with Equation 6.2 shows that we are back at Darcy's equation, with v = -c. Rewriting 6.2 yields

$$\frac{\partial z}{\partial h_p} = \frac{1}{-1 - \frac{v}{K}} \qquad (6.10)$$

As the right hand term of 6.10 is a function of h_p, integration is possible when we assume that *K* is constant within the interval h_{p1} - h_{p2}, hence

$$\int_{z_1}^{z_2} dz = \int_{h_{p1}}^{h_{p2}} \frac{1}{1 - \frac{v}{K\{h_p\}}} dh_p \qquad (6.11)$$

or

$$z_2 = z_1 + \frac{h_{p2} - h_{p1}}{-1 - \frac{v}{K\{\bar{h}_p\}}} \qquad (6.12)$$

where $\bar{h}_p = (h_{p1} + h_{p2})/2$ or $\bar{h}_p = -\sqrt{h_{p1}.h_{p2}}$

One is now able to calculate by means of Equation 6.12 for various values of flux v (positive or negative!) the pressure head profiles with depth. Remember that $h_p = h_m$ if $h_a = 0$.

In Figure 6.2 the matric or pressure head profile above the watertable for $v = 0.10$ cm.d^{-1} is shown. Thus the maximal height to which a capillary flux of 0.1 cm.d^{-1} can rise is 56 cm. Also the pressure head profiles for other capillary fluxes v are shown. It can be seen that for example for $v = 0.02$ cm.d^{-1} the maximal height of capillary rise is about 150 cm above the watertable. In principle for each type of homogeneous soil z - h_m - v relationships similar to Figure 6.2 can be computed when the $K\{h_m\}$ relationship is known. Note that for steady state infiltration rates, the calculation procedure goes along the same lines, but then negative values for the flux density v are used in Equation 6.12.

Computer exercise

Use program CAPRISE to plot matric head profiles for a capillary rise at different flux densities.

1) Select the soil **silty clay** from the Staring Series.
2) Get the maximal height of the capillary rise for flux densities of 0.001, 0.01, 0.02, 0.05, 0.1 and 0.2 cm d^{-1}
3) Select also from the Staring Series the following soils:
   - coarse sand
   - sandy loam
   - clay
   - peat
4) Which differences between these soils do strike you most?

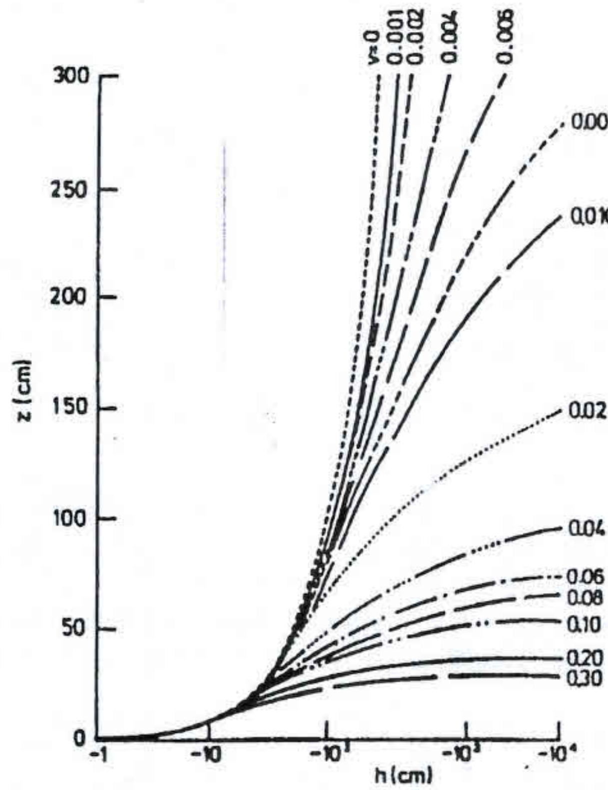

Figure 6.2 Relation between height of capillary rise above the watertable z and pressure head h_p at different fluxes of upward flow v (cm.d^{-1}) for the clay soil of Figure 6.1

Computer exercise

Use program INFILTR to plot pressure head profiles for different infiltration rates.

1) Select the soil **silty clay** from the Staring Series and choose an infiltration rate of -0.001 cm d^{-1} and a water table depth of 200 cm.
2) Plot also the pressure head profiles for infiltration rates of -0.01, -0.1 and -1.0 cm d^{-1}
3) Select from the Staring Series also the following soils:
   - coarse sand
   - sandy loam
   - clay
   - peat
4) Which differences between these soils do strike you most?

6.3 Water Balance

We have seen in the preceding paragraphs that water is stored in the soil profile. We can calculate the amount of water stored by integrating the water content over the profile of interest. Usually, the profile is taken from the bottom of the root zone to the soil surface. This knowledge is needed to know how much water is available for the crop and how much water has to be irrigated. The changes in the storage of soil water are calculated with the *water balance* or water budget:

$$\Delta W = P + I + C - (A + D + E) \qquad (6.14)$$

where:

ΔW	=	change in the amount of water storage, mm
P	=	precipitation, mm
I	=	irrigation, mm
C	=	capillary rise, mm
A	=	net surface run-off, mm
D	=	drainage, mm
E	=	evapotranspiration (sum of transpiration from plants and evaporation from the soil), mm

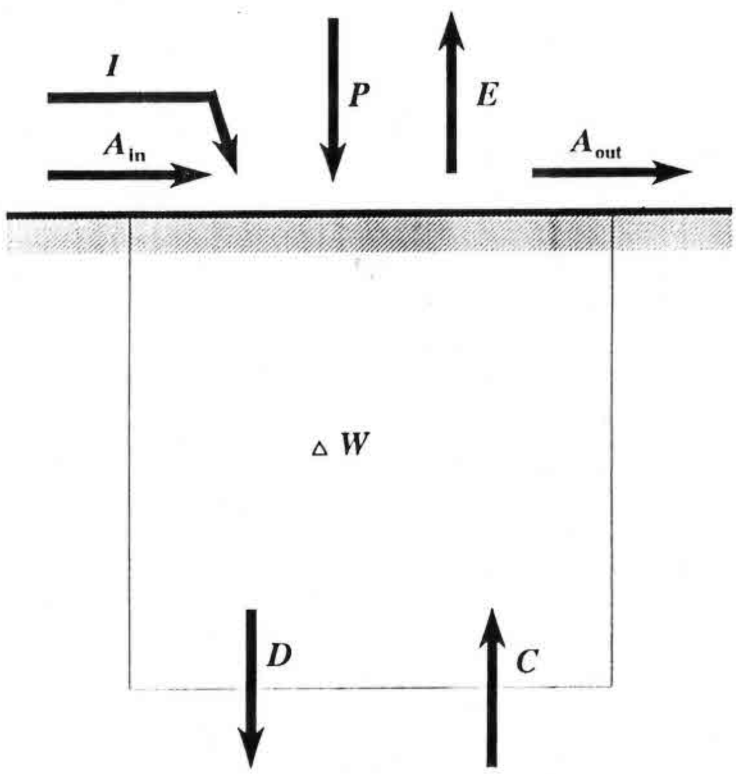

Figure 6.3 Scematic drawing of a water balance

The water balance is calculated over a certain period, e.g. a week or growing season. The amount of water entering the profile, $P + I + C$, is balanced against the amount of water leaving the profile, $A + D + E$.

Question 6.3.1:

At an experimental field with maize the daily evapotranspiration and precipitation are measured. The field is not irrigated. The root zone is 50 cm deep. The water storage in this profile at 2-7-1985 is 105 mm and 80 mm at 8-7-1985. The daily evapotranspiration during this period is: 2.6, 4.0, 4.0, 3.1, 2.8, 2.8 and 1.8 mm. There is no precipitation except 0.6 mm on 8-7-'85.

a) Calculate the change in water storage during the week from 2 to 8-7-'85.
b) Calculate the drainage or capillary rise during this week.
c) Is there drainage or capillary rise during this week? Why?
d) A total capillary rise of 0.08 mm was calculated during this week. This figure was calculated from pressure head measurements and the hydraulic conductivity at the lower boundary of the profile. Does this measurement of the capillary rise agree with the data obtained from the water balance? Why?

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TABLE 1

Volumetric water content, θ ($m^3\,m^{-3}$), as a function of the matric head, h_m (cm), (after Wösten et al. 1994)

	h_m (cm)													
Soil type	0	-1	-2	-5	-10	-20	-50	-100	-200	-500	-1000	-2000	-16,000	-10^6
coarse sand	.320	.320	.318	.308	.276	.206	.102	.056	.032	.018	.014	.012	.010	.010
fine sand	.360	.360	.360	.358	.353	.331	.235	.135	.070	.031	.019	.014	.010	.010
loamy fine sand	.340	.340	.339	.337	.330	.314	.263	.206	.151	.097	.069	.050	.022	.011
sandy loam	.470	.470	.469	.467	.462	.451	.417	.372	.315	.239	.191	.151	.075	.018
fine sandy loam	.360	.360	.359	.356	.349	.331	.276	.216	.158	.099	.068	.047	.015	.002
loam	.490	.490	.489	.488	.484	.476	.452	.417	.369	.299	.250	.207	.116	.036
silt	.410	.410	.410	.409	.407	.403	.389	.367	.332	.273	.229	.190	.108	.038
silty loam	.380	.380	.380	.380	.380	.379	.375	.366	.340	.264	.187	.123	.030	.002
clay loam	.420	.419	.419	.416	.412	.404	.385	.362	.334	.295	.267	.241	.176	.094
silty clay	.560	.560	.559	.558	.555	.550	.534	.511	.479	.428	.388	.349	.252	.131
clay	.570	.569	.569	.566	.563	.555	.537	.514	.487	.446	.415	.386	.307	.195
peat	.860	.859	.858	.855	.847	.831	.781	.715	.629	.508	.425	.353	.200	.065

TABLE 2

Hydraulic conductivity, K (cm d^{-1}), as a function of the matric head, h_m (cm), (after Wösten et al. 1994)

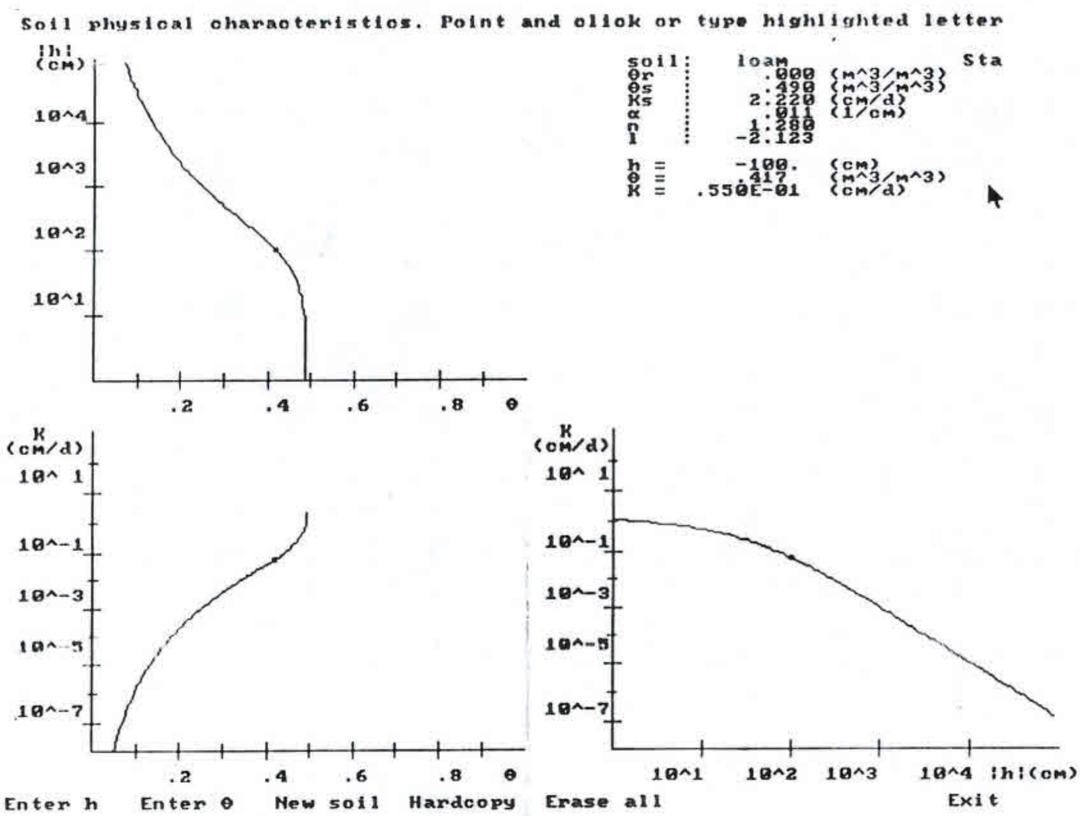
	h_m (cm)												
Soil type	0	-1	-2	-5	-10	-20	-50	-100	-200	-500	-1000	-2000	-16,000
coarse sand	43.55	39.24	34.83	23.09	10.45	2.099	.072	.004	.17 10^{-3}	.28 10^{-5}	.13 10^{-6}	.57 10^{-8}	.51 10^{-12}
fine sand	13.21	12.90	12.52	11.25	9.08	5.426	.945	.091	.54 10^{-2}	.11 10^{-3}	.54 10^{-5}	.27 10^{-6}	.33 10^{-10}
loamy fine sand	18.30	14.39	12.70	9.58	6.62	3.606	.923	.208	.36 10^{-1}	.29 10^{-2}	.42 10^{-3}	.59 10^{-4}	.16 10^{-6}
sandy loam	9.08	5.39	4.57	3.33	2.33	1.391	.492	.162	.41 10^{-1}	.54 10^{-2}	.11 10^{-2}	.20 10^{-3}	.14 10^{-5}
fine sandy loam	53.10	40.59	35.51	26.37	17.94	9.617	2.432	.551	.97 10^{-1}	.81 10^{-2}	.12 10^{-2}	.17 10^{-3}	.51 10^{-6}
loam	2.22	1.15	.97	.71	.51	.321	.135	.055	.19 10^{-1}	.36 10^{-2}	.97 10^{-3}	.25 10^{-3}	.43 10^{-5}
silt	3.70	2.20	1.91	1.47	1.11	.740	.325	.126	.35 10^{-1}	.40 10^{-2}	.63 10^{-3}	.92 10^{-4}	.25 10^{-6}
silty loam	.36	.35	.34	.33	.30	.274	.209	.142	.70 10^{-1}	.13 10^{-1}	.20 10^{-2}	.22 10^{-3}	.20 10^{-6}
clay loam	13.79	2.83	2.14	1.31	.79	.410	.128	.042	.12 10^{-1}	.20 10^{-2}	.48 10^{-3}	.12 10^{-3}	.15 10^{-5}
silty clay	1.14	.31	.25	.17	.12	.075	.033	.015	.59 10^{-2}	.15 10^{-2}	.50 10^{-3}	.16 10^{-3}	.53 10^{-5}
clay	3.32	.44	.33	.20	.12	.068	.025	.010	.34 10^{-2}	.79 10^{-3}	.25 10^{-3}	.77 10^{-4}	.22 10^{-5}
peat	2.75	1.34	1.11	.79	.55	.332	.128	.048	.15 10^{-1}	.27 10^{-2}	.68 10^{-3}	.17 10^{-3}	.24 10^{-5}

COMPUTER PROGRAMS

Several computer programs have been developed to calculate and to plot soil characteristics and processes. All programs run under the DOS operating system on a IBM (compatible) personal computer. A VGA graphics adapter is needed and a mouse is recommended to run the programs. All programs work in an interactive way. You just have to click on the menus or to type the highlighted letter. You will get a short help by typing the program name followed by a ? on the DOS command line (e.g. c:\>soils ?).

SOILS

A program to plot the water retention characteristic and the hydraulic conductivity. You can choose from several soils from the USA or the Netherlands. You can also enter your own parameters to describe the physical properties of a soil.



SOILS, an example of the main screen showing the water retention characteristic and the hydraulic conductivity.

CAPRISE

A program to calculate and plot the matric head and water content distribution for stationary capillary rise in a homogeneous soil. You can choose from the same soils as program SOILS.

INFILTR

A program to calculate and plot the matric head and water content distribution for stationary infiltration or capillary rise in a homogeneous soil. You can choose from the same soils as program SOILS.

STORAGE

A program to calculate and plot the matric head and water content distribution for a homogeneous soil to enable the calculation of the storage coefficient. You can choose from the same soils as program SOILS.

ANSWERS

Answer 3.1:

From (3.2): $\epsilon = \frac{V_w + V_a}{V}$. At satruation $V_a = 0$:

$$\epsilon = \frac{V_w}{V} = \frac{\frac{m_w}{\rho_w}}{V} = \frac{\frac{40}{1}}{100} = 0.4$$

Answer 3.2.a:
Volume of soil to saturate under every cm^2 = 25 x 1 x 1 = 25 cm^3. Pore space to fill in this volume = ϵV = 0.4 x 25 = 10 cm^3. Therefore, the farmer has to apply 10 cm^3 per cm^2 surface area.
Answer 3.2.b:
The depth would be 10 cm^3/1 cm^2 = 10 cm.

Answer 4.1:
For tensiometer 1 the matric head (= pressure head) h_m is -50 cm; the gravitational head h_g is +100 cm. The hydraulic head h_h = -50 + 100 = 50 cm.
For tensiometer 2 the matric head h_m is +40 cm; the gravitational head h_g is +10 cm. The hydraulic head h_h = 40 + 10 = 50 cm.

Answer 5.1.1:

a) From (3.2): $\epsilon = \frac{V_w + V_a}{V}$

at saturation $V_a = 0$ and $\epsilon = \frac{V_w}{V} \approx \theta\,\{\text{at } h_m = -1 \text{ cm or } pF = 0\} = 0.509$.

b) The air content is the total pore space minus the water content at field capacity:
air content = $\epsilon - \theta\,\{h_m = -100 \text{ cm}\} \approx 0.509 - 0.461 = 0.048$.

c) The amount of water available for plants is the water content at field capacity minus the water content at the wilting point:
available water = $\theta\,\{h_m = -100 \text{ cm}\} - \theta\,\{h_m = -15{,}800 \text{ cm}\} = 0.461 - 0.092 = 0.369$.

d) The amount of available water with a rooting depth d of 50 cm:
available water is = $\theta \cdot d = 50 \cdot 0.369 = 18.45$ cm.

e) Crop growth gets limited if $h_m < -400$ to -1000 cm or if approximately 0.40 to 0.60 of the available water is used:

available water = 18.45 · 0.40 = 7.38 to 18.45 · 0.60 = 11.07 cm.

f) This soil has a large amount of water, but poor aeration conditions.

Answer 6.1.1:

a) We calculate the hydraulic head h_h for the two tensiometers. We use the water table as reference level:

$h_{h1} = h_{p1} + h_{g1} = -130 + 60 = -70$ cm

$h_{h2} = h_{p2} + h_{g2} = -100 + 50 = -50$ cm

There is no equilibrium, since $h_{h1} \neq h_{h2}$. So, there is a vertical flow.

b) The flow is in upward direction, since $h_{h1} < h_{h2}$. The water flows to the lowest potential.

c) We calculate the flux density v with formula (6.1).

$$v = -K\frac{\partial h_h}{\partial h_g} \approx -K\frac{\Delta h_h}{\Delta h_g} = -K\frac{h_{h1} - h_{h2}}{z_1 - z_2} =$$
$$= -K\frac{-70 - -50}{60 - 50} = -K\frac{-20}{10} = 2K$$

with K = k: v = 2k

d) We have to obtain a value for $K\{h_m\}$ for a certain h_m. We use the geometric mean of h_{p1} and h_{p2}:

$$\bar{h}_m = \bar{h}_p = -\sqrt{h_{p1} \,.\, h_{p2}} = -\sqrt{-130 \,.\, -100} \approx -114 \text{ cm}$$

Program SOILS gives a value of 0.008 cm/d for K if we select a clay soil from the Staring series. The flux density becomes:

$v = 2K = 0.016$ cm/d $= 1.6 10^{-2}$ cm/d

We can read from figure 6.1b a value of approximately 2.10^{-3} cm/d for K. The flux density becomes:

$v = 2K = 4.10^{-3}$ cm/d

Answer 6.3.1:

a) During the week of 2 to 8-7-'85 the water storage of the profile decreases from 105 to 80 mm. therefore ΔW = 80 - 105 = -25 mm.

b) We calculate the drainage + the capillary rise from the water balance. The total evapo-transpiration during this week is: E = 21.1 mm; the precipitation is: P = 0.6 mm; the irrigation I and surface run-off A are zero. The water balance gives:

$\Delta W = -25 = 0.6 + 0 + C - (0 + D + 21.1) = -20.5 + C - D$

The total drainage - capillary rise during the week becomes:

$D - C = -20.5 + 25 = 4.5$ mm

c) The drainage - capillary rise term is positive. Therefore there is drainage and no capillary rise.

d) The drainage and capillary rise are calculated from measurements. All measurements contain errors. If we have an error of 5% in the measurements of the water storage in the profile, the error in ΔW can add up to 5% of 105 mm + 5% of 80 mm = 9.25 mm. Therefore the differences between the calculations of b) and d) are understandable.

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ALTERRA

41th
INTERNATIONAL COURSE ON LAND DRAINAGE ICLD

Workbook
2.0 DRAIN SPACING EQUATIONS

DRAINAGE

From 19 August to 6 December 2002, Wageningen, The Netherlands

FORTYFIRST INTERNATIONAL COURSE ON LAND DRAINAGE
Wageningen – The Netherlands, 2002

Workbook
2.0. DRAIN SPACING EQUATIONS

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ILRI

Lecturer ICLD 2002

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Contents

EXECUTIVE SUMMARY

Course:	International course on land drainage/ICLD
Subject:	Drain spacing
Lecturer:	P.W. Vehmeyer, ILRI
Time allocation:	Lectures : 10 hours Exercises : 16 hours Test : 2 hours Study time : 7 hours
Lecture notes:	Portions of ILRI Publication 16 (second completely revised edition 1994) and this workbook.
Teaching method:	Lectures, exercises, a video presentation, and computer use and demonstration.
Objective:	To introduce the basics of groundwater flow, and the principles and the application of the most common equations for calculating the drain spacing under various soil and hydrological conditions.
Related lectures:	Drainage for Agriculture Soils and Drainage Water in the Unsaturated Zone Auger-Hole Measurements Sub-Surface Drainage Design Environment Design Exercise Sub-Surface Drainage

1 INTRODUCTION

Sub-surface drainage

Sub-surface drainage systems are used in agricultural lands (i) to control the *water table* or (ii) to control the amount of *salts* in the root zone. A sub-surface drainage system induces the *excess* of water and salts to flow through the soil towards wells, mole drains, pipe drains, and/or open drains, from where it can be evacuated.

Theory

Reference

In this series of lectures we shall discuss the basics of sub-surface flow to drains under saturated soil conditions. The lectures follow the theory presented in the completely revised 2nd edition of ILRI Publication 16 *"Drainage Principles and Applications*" 1994. For a definition of the technical terms used in this workbook, please see the *Glossary* of Publication 16, on pages 1095-1106.

This work book

The *purpose* of this workbook is to guide you, the course participant, through the relevant theory of Publication 16. Chapter 2 of this workbook states the *objectives* of this series of lectures, Chapter 3 indicates the *links* with other lectures in the course, and Chapter 4 discusses the *teaching methods*. Fundamental *physical concepts* governing the flow of groundwater to drains and wells are treated in Chapter 5. These physical principles underlie the *equations* that are used to describe (i) the flow of groundwater to parallel drains or wells and (ii) a number of seepage problems. Such *drainage equations* relate drain properties, like depth and spacing, to hydrological soil parameters, like the depth of the water table, the soil's hydraulic conductivity, and the corresponding drain discharge. The most common *steady-* and *unsteady-state* equations are discussed in Chapters 6 and 7. Their *application* under different soil and hydrological conditions will be shown in a special exercise (Chapter 8). Some test questions are given in Chapter 9.

2 TEACHING OBJECTIVES

Goals

After this series of lectures and exercises you, as a participant, can:

- explain the flow of water through saturated soil, using common physical properties and basic laws;

- solve simple groundwater flow problems based on Darcy -, Laplace -, and Dupuit-Forchheimer theory;
- quote and apply steady-state drainage equations of Hooghoudt and Ernst;.
- make and use a Hooghoudt spreadsheet;
- reproduce and apply non-steady drainage equations of Glover-Dumm and De Zeeuw-Hellinga;
- explain the advantages, limitations, and interconnections of the above drainage equations.

Approach

In studying this subject, it is important to realise that your main aim should be to understand the analytic approach of a drainage problem, and not to learn facts and figures by heart.

3 RELATED COURSE SUBJECTS

Computations

Horizontal systems

Agriculture

Hydr. conductivity

Unsaturated flow

During the design stage of a sub-surface drainage system, you must interact with many related subjects, and not only apply equations. Of course, drainage equations are needed when you want to *design* a sub-surface drainage system (*Lecture* Sub-surface Drainage Design and Publication 16, *Chapter 21*). Their application is based on the agricultural needs (*Lecture* Drainage for Agriculture and Publication 16, *Chapter 17*) and the prevailing soil and hydrological conditions, of which the hydraulic conductivity is the most important one (*Lecture* Drainage Research and Publication 16, *Chapter 12*). These soil hydrological constants are difficult to measure (*Workshop* Auger-Hole Method). The elevation of the water table is also influenced by the flow of water in the unsaturated zone (*Lecture* Water in the Unsaturated Zone and Publication 16, *Chapter 11*).

Environment

With the introduction of a sub-surface drainage system you are manipulating the water table and the water and salt balance in your project area in order to increase or to sustain agricultural production. However, these manipulations trigger side-effects in the surrounding environment (*Lecture* Environment and Publication 16, *Chapter 25*). You should also consider these effects when you design a sub-surface drainage system.

4 TEACHING METHODS

Blocks

The course material of our subject is divided into five blocks. It will be presented as a combination of the following elements: lectures, short problems to solve, self-study, a video presentation, computer use and demonstration, a test, and a larger exercise.

Video

Lectures

After the first introductory classroom lecture, the second block on groundwater flow is a combination of lectures, short problems and self-study, while also the video "A viscous fluid model for demonstration of groundwater flow to parallel drains" will be shown. Block 3 has an identical structure (except for the video). The classroom sessions will be used to introduce the subject, to explain the theory, and to highlight the most important aspects.

Problems

Working sessions

Individual study

Short problems, contained in this workbook, will also be introduced in Blocks 2 and 3 during classroom sessions, after which you, as a participant, can start working on them (working session). These sessions will include the use of spreadsheets on the computer. Questions during these working sessions will give rise to comments and explanations from the lecturer. You are supposed to finalise the exercise as a home assignment, so as to be ready by the next classroom session (individual study). In this classroom session, the completed exercise will be discussed, and a short summary of what was learnt and how it relates to the next topic will be given.

Final exercise

Test

Block 3 is followed by block 4, which is a special Exercise Sub-Surface Drainage, in which the practical use and limitations of the drainage equations are illustrated. The subject is concluded by a written test (block 5), so that you yourself and the course management can assess your level of understanding (marking is done for this purpose only!). Table 1 presents an overview of the approximate time per block and per teaching element.

Materials

During lecturing, overhead sheets will be used, as well as the whiteboard. For the short problems and the Exercise you need a pocket calculator. For part of the exercises you will need a personal computer. For the explanation of the Exercise (Block 4), the lecturer will use a spreadsheet program on the personal computer (and a beamer).

Table 1 Approximate study load in hours

Block	Topic	Lect-ures	Exer-cises	Indiv. study
1	Introduction	1	-	-
2	Basics of groundwater flow	2	2	1
3	Drain spacing	7	8	2
4	Exercise sub-surface drainage	-	6	3
5	Test	-	2	1
Total		10	18	7

5 BASICS OF GROUNDWATER FLOW

☞ *Study the theory presented in Chapter 7 of Publication 16*

Water properties

Basic laws

First, a number of *physical properties* of water are defined, and some *fundamental laws* are illustrated, with emphasis on the *conservation of mass*, the *continuity* equation, and the types of *energy* (Publication 16, Sections 7.1 - 7.3).

Darcy's Law

Water conductivity

The fundamental equation describing *one-dimensional* flow of groundwater is Darcy's Law (Publication 16, Chapter 7.4). The *proportionality factor* in this equation is known as the hydraulic conductivity, which is the reciprocal of the *resistance to flow*. The hydraulic conductivity depends on properties like the temperature of the water, the grain-size distribution and the porosity of the soil, and the size and shape of its grains. It is difficult to measure accurately and it can *vary* at short distances (Lecture Soil Hydrological Constants and Practical Auger-Hole Method).

Darcy's Law can be used to solve simple one-dimensional groundwater flow problems, as illustrated in Problems 1 & 2.

Problem 1 Calculation of lateral seepage flow

In a sloping area, a sandy layer lies on top of an impervious clay layer. Two piezometers have been installed to monitor the piezometric pressures in the sandy layer (Figure 1).

- *Indicate the direction of groundwater flow in Figure 1.*
- *Assuming the groundwater flow takes place only through the sand layer, calculate the rate of flow through an area 500 m wide perpendicular to the shown section.*

Note: The water table runs parallel to the impervious layer.

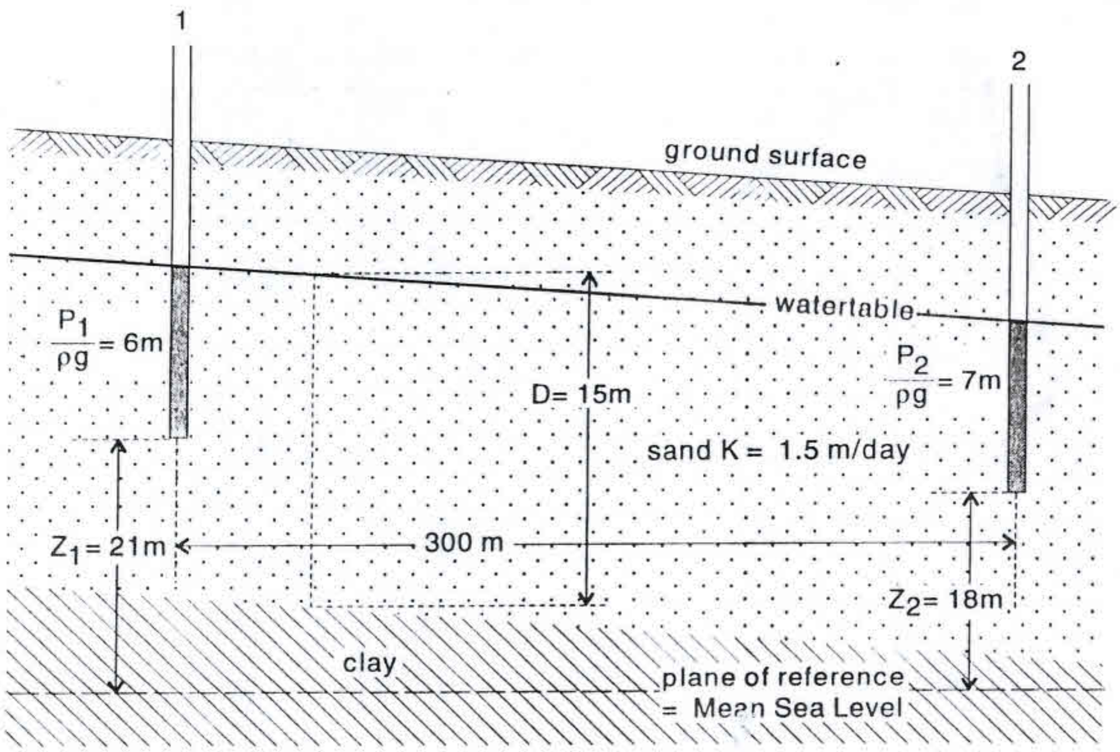

Figure 1 Groundwater flow in a sloping sandy area

Problem 2 Calculation of upward seepage

In an agricultural area, a thick clay layer with a low permeability (i.e. an aquitard) overlies a permeable aquifer. The piezometric level in the aquifer exceeds the phreatic level in the clay layer as shown in Figure 2.

- *Calculate the upward seepage rate.*
- *How high is the vertical resistance of the clay layer?*

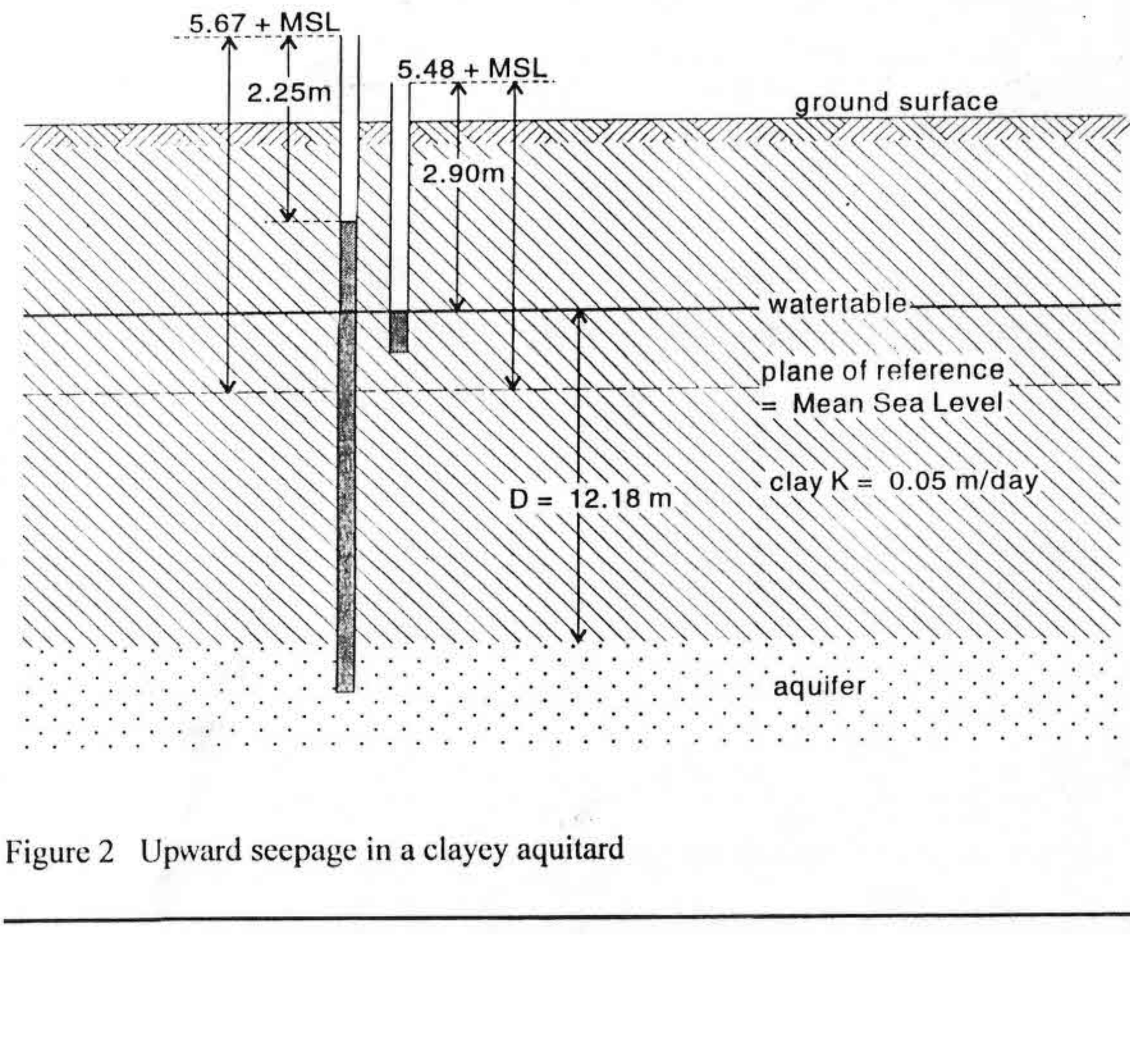

Figure 2 Upward seepage in a clayey aquitard

Until now we have only treated one-dimensional flow problems, however most groundwater flow is two or three dimensional. Two-dimensional flow can be described by a set of partial differential equations: streamlines and equipotential lines (Publication 16, Chapter 17.6). Streamlines describe the flow path of water particles, whereas equipotential lines connect points with equal energy levels.

Streamlines

Equipotential lines

Streamlines and equipotential lines intersect each other at right angles, thus forming a flow net which divides the flow region in "approximate squares", so-called flow nets. By definition, each square represents an equal amount of flow and an equal decrease in energy level, so that small squares indicate areas of high flow intensity and large squares of low flow intensity.

Flow nets

It is hard to visualise the flow of groundwater, but with the viscous fluid model groundwater flow towards parallel drains can be simulated. In the soil, the water flowing towards the drains meets (1) external resistance from friction with the walls of the pores and (2) internal resistance due to viscosity.

Flow model

In the model this resistance is simulated by:

- replacing the flow through the pores by flow between two narrow-placed parallel plates; and
- replacing the water by an oil with a higher viscosity.

The use of the model is demonstrated in a video showing the groundwater flow to parallel drains using an oily fluid. For more information see: *Homma, F. 1968. A viscous fluid model for demonstration of groundwater flow to parallel drains. ILRI Bulletin 10, 31 p.*

Video

Reference

Problem 3 Groundwater flow to parallel drains

The video illustrated how the viscous fluid model was used to simulate the flow of groundwater to parallel drains. Streamlines were made visible by using a blue tracer.

- *Can you draw the streamlines for the two situations presented in Figure 3?*
- *In which situation will the influence of the impervious layer be more pronounced?*

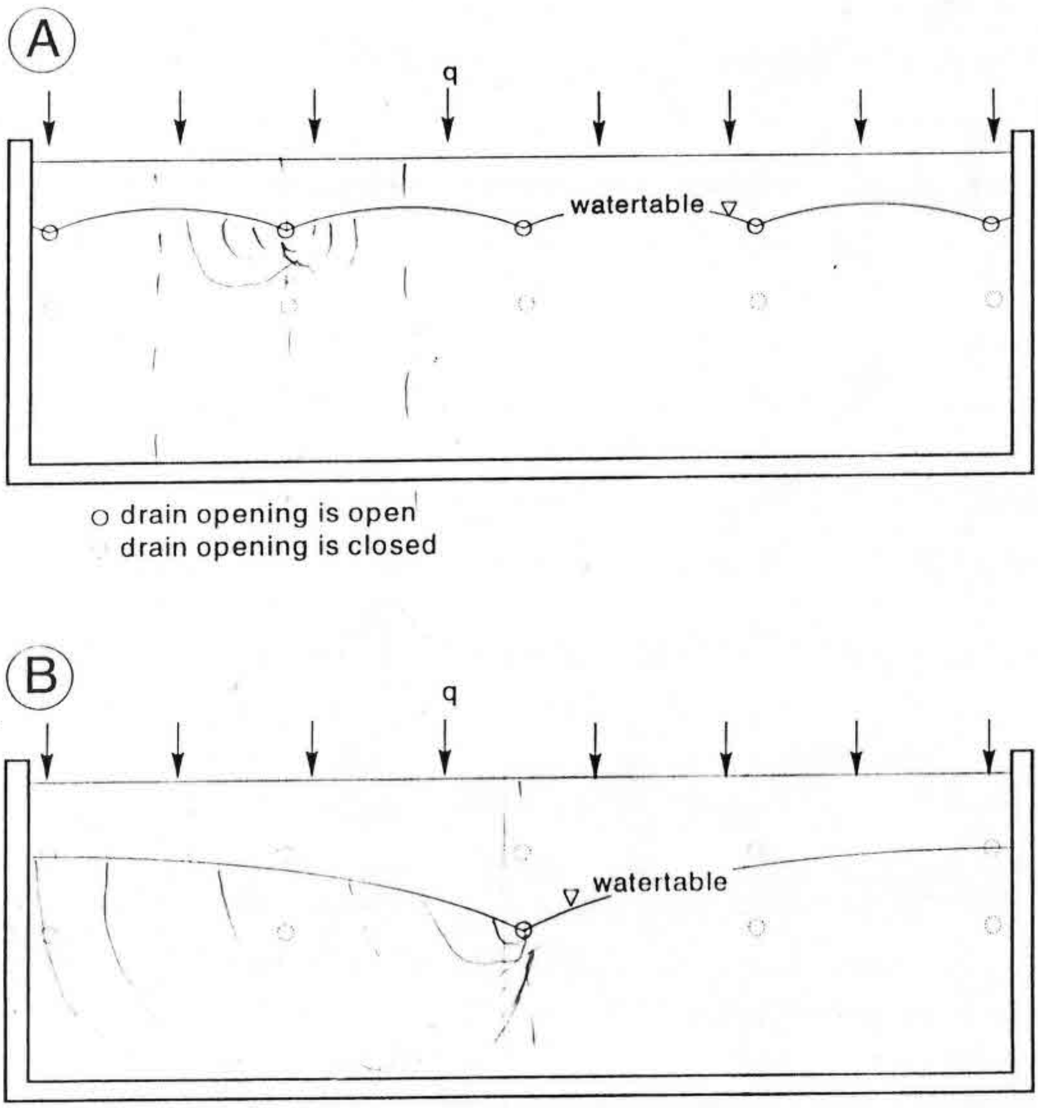

Figure 3 Simulation of groundwater flow using the viscous fluid model

Laplace equation

Two-dimensional flow can be calculated using the Laplace equation. However, a solution to a particular groundwater flow problem can only be obtained if the conditions at the boundaries are known (Publication 16, Section 7.7).

Boundary conditions

Mathematically exact solutions to two-dimensional flow problems are rather complex. Furthermore, the boundary conditions are often not known exactly, the soil is - in general - heterogeneous, or the recharge to the groundwater is not uniform distributed. Under these circumstances, results of the same accuracy can be obtained from simplified methods based on a number of assumptions. Several examples, based on the Dupuit-Forchheimer theory, are presented in Section 7.8 of Publication 16. In Problem 4, the Laplace Equation is used to solve a two-dimensional groundwater flow problem.

Dupuit-Forchheimer

Problem 4 Calculation of a curved water table

Figure 4 shows a strip of land drained by two parallel ditches, with constant, but different water levels. A constant flow, R, recharges the water table.

When $R = 0.008$ *m/d* $h_1 = 8.0$ *m* $L = 50$ *m*

$K = 0.2$ *m/d* $h_2 = 5.0$ *m*

and knowing that the equation of the curved water table reads as below, answer:

$$h^2 = -\frac{R}{K}x^2 + \left(\frac{h_2^2 - h_1^2}{L} + \frac{RL}{K}\right)x + h_1^2$$

- *At which distance x from the left-hand ditch reaches the water table its highest point?*
- *What is the maximum value of h?*
- *What is the discharge into the right-hand ditch, per 100 metre length along the ditch?*
- *What happens after the recharge ceases?*

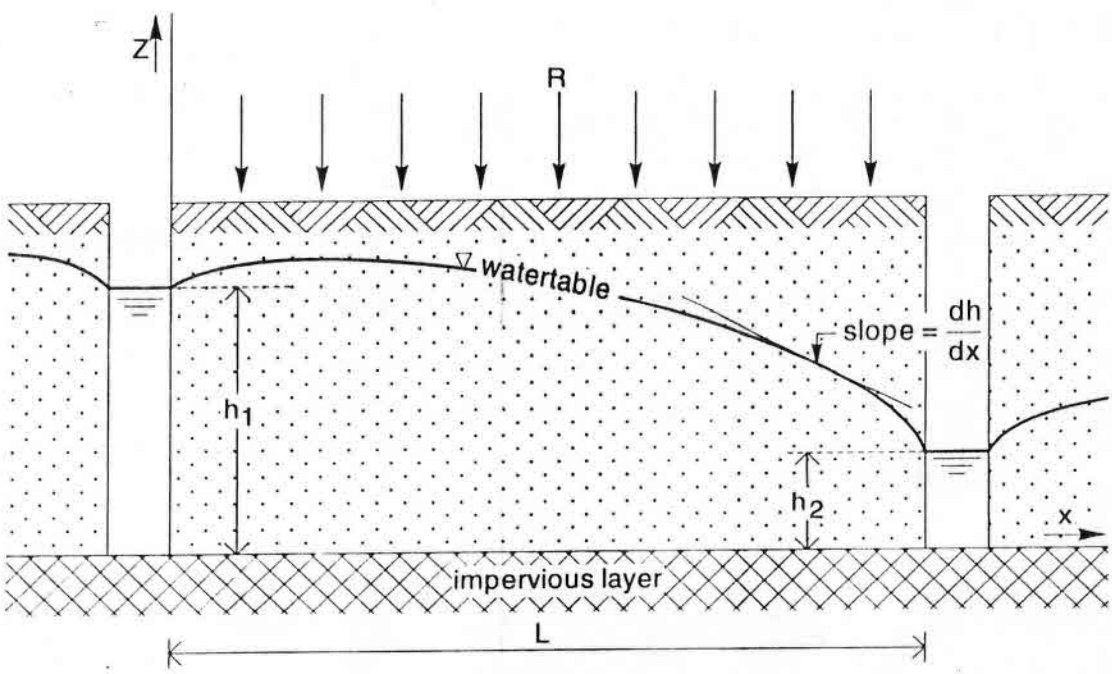

Figure 4 A strip of land drained by two parallel drains

Hydraulic conductivity

Groundwater flow problems can only be solved with the Darcy or Laplace Equation if the hydraulic conductivity is known. It has already been mentioned that the hydraulic conductivity is not a constant and that it is difficult to measure (see also Lecture 14 Soil Hydrological Constants or Publication 16, Chapter 12). An example of measuring the hydraulic conductivity in the laboratory using the Darcy equation is given in Problem 5.

Problem 5 Calculation of the hydraulic conductivity

Figure 5 (overleaf) shows the vertical section of a container filled with three different soil layers. A constant flow of water is maintained through the container. The rate of flow is measured by collecting the discharge at the outflow in a cylinder of known volume over a certain time period: $Q = 80\ cm^3$ in 5 min. The cross-sectional area of the container is 1520 cm^2. The hydraulic head is observed at various levels by means of eight piezometers:

$h_1 = 2.365\ m$	$h_5 = 1.587\ m$
$h_2 = 2.345\ m$	$h_6 = 1.364\ m$
$h_3 = 2.338\ m$	$h_7 = 1.362\ m$
$h_4 = 2.034\ m$	$h_8 = 1.360\ m$

☞ *Calculate the hydraulic conductivity of each soil layer.*

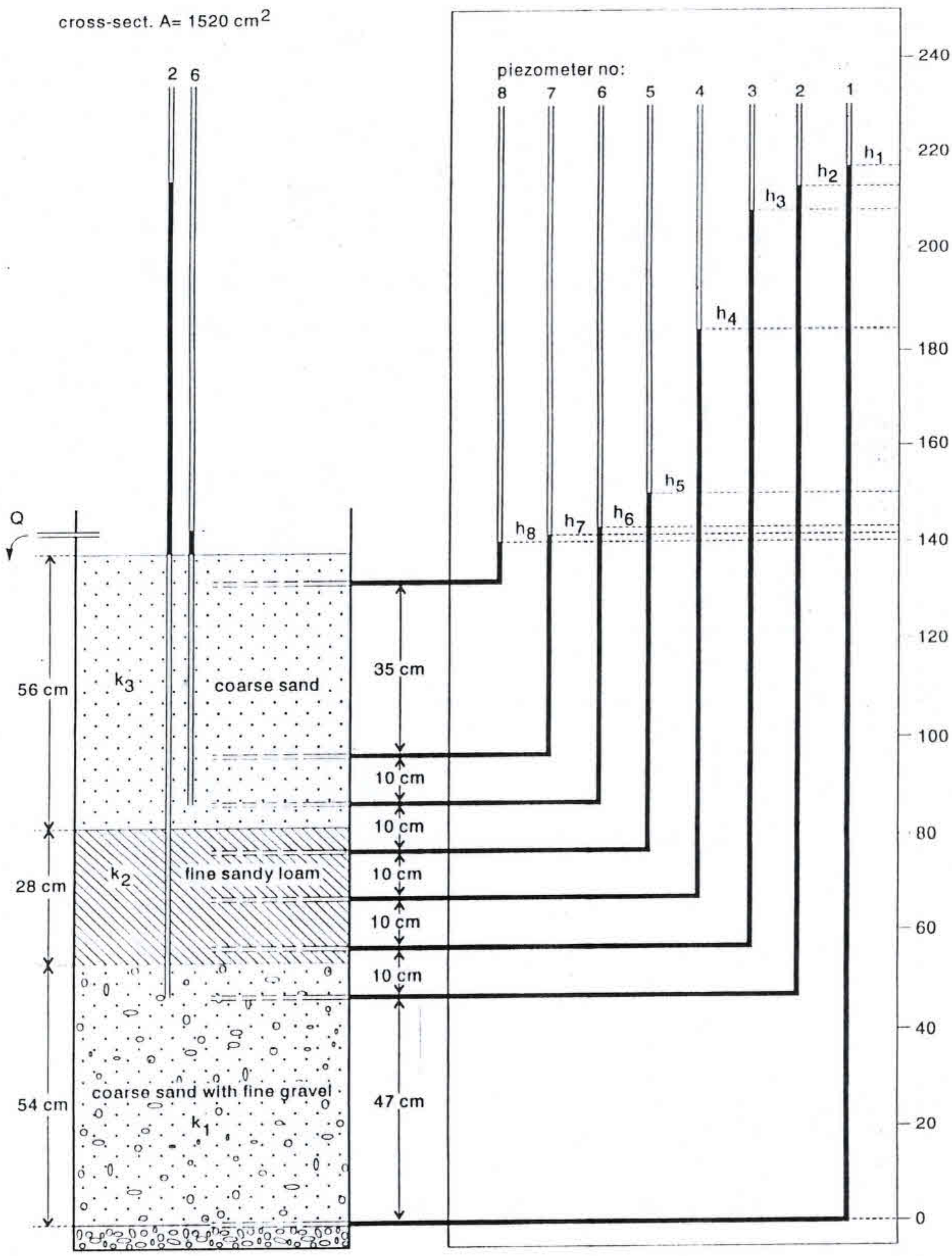

Figure 5 Laboratory set-up to measure the hydraulic conductivity of a three-layer soil profile

6 SPACING OF HORIZONTAL SUB-SURFACE DRAINS

☞ *Study the theory presented in Chapter 8 of Publication 16*

Drainage equations

Technical criteria

Soil properties

Agricultural criteria

Drainage equations relate *technical criteria* to *soil characteristics* and to *agricultural design criteria* (Publication 16, Section 8.2.4). Technical criteria or *drain properties* are the *depth*, *size* and *spacing* of drains or wells. Soil characteristics are the *hydraulic conductivity*, the *drainable porosity* and the *depth of the impervious layer*. And agricultural criteria are the required *depth of the water table* and the corresponding *design discharge*. For more information on drainage design criteria see Chapter 17 of Publication 16.

All equations discussed in the following lectures are based on the theory and assumptions presented in Chapter 5 of this workbook (Basics of Groundwater Flow). There are two types of drainage equations: *steady-state* equations and *unsteady-state* equations. Both types are derived using the Dupuit-Forchheimer theory (Publication 16, Section 8.2). In addition to this, they are based on the following assumptions:

Assumptions

- the pattern of flow to the drains is one- or two-dimensional;
- recharge to the groundwater is uniform over the field;
- there is no spatial variability within a soil layer, and;
- the entrance resistance of the drains can be neglected.

Steady-state equations

Steady-state equations are based on the assumption that the recharge to the groundwater, stemming either from precipitation or irrigation, equals the drain discharge. We shall discuss only the three most common steady-state equations, i.e. the Donnan equation, the Hooghoudt equation and the Ernst equation.

Donnan equation

The Donnan equation is based on a flow pattern of parallel, horizontal streamlines (Publication 16, Section 8.2.1). In addition, a *homogeneous* soil profile is assumed and the drains are placed on top of the impervious subsoil. There is only flow *above the drain level.* These assumptions limit the use of the Donnan equation.

Hooghoudt equation

The Hooghoudt equation (Publication 16, Section 8.2.1) is also based on the Dupuit-Forchheimer assumptions, but can be used for drains installed at any depth in a *homogeneous* soil or in a *two-layered* soil profile, provided that the interface between the layers is at drain level. This means that flow to the drains takes place *above* and *below* drain level, and that the flow lines will converge towards the drains. Hooghoudt accounted for this additional radial head loss by replacing the actual depth of flow by a smaller, *equivalent depth.*

Ernst equation

The Ernst equation uses a two-dimensional flow pattern (Publication 16, Section 8.2.2). The flow path and the corresponding head losses are divided into a *vertical*, a *horizontal* and a *radial* component.

Application of steady-state equations

The question *which equation to use* in a particular situation depends mainly on the soil profile and the relative position of the drains in this profile (Publication 16, Section 8.2.3). The Ernst equation is generally applicable for two-layered soil profiles, although the Hooghoudt Equation gives better results when the calculated drain spacing exceeds the depth of the permeable layer four times or more.

Problem 6 Drain spacing calculation using Hooghoudt

A farmer in the north-eastern part of The Netherlands wants to drain his pasture fields. The following data are available:

Soil profile:

0 - 0.20 m below soil surface	*K = 10.0 m/d*
0.20 - 1.20 m below soil surface	*K = 0.35 m/d*
1.20 - 6.20 m below soil surface	*K = 0.70 m/d*

Below 6.20 m, the soil is considered impervious.

The rainfall surplus, being the rate of recharge to the groundwater, is 8 mm/d, and the required depth of the water table is 0.40 m below soil surface. Drainage will be by means of pipe drains with a radius of 0.10 m and a depth of 1.20 m below soil surface.

- *Make a drawing of the situation, and;*
- *Calculate the drain spacing using the Hooghoudt equation.*

Problem 7 Drain spacing calculation using Ernst

As an alternative to the situation in Problem 6, we lower the drain depth to 1.50 m below soil surface. The values of q, r_0, and the required water-table depth remain the same.

- *Make again a drawing of the situation and calculate the drain spacing using the appropriate form of the Ernst equation.*
- *What is the contribution of the vertical, horizontal and radial flow to the total head loss (in %)?*

Unsteady-state equations	The assumption that the recharge to the groundwater equals the drain discharge is not always justified. Common examples are *irrigated* fields, or humid areas with *high-intensity rainfall*. Under these conditions, the unsteady-state equations are sometimes more appropriate (Publication 16, Section 8.3).
Glover-Dumm equation	The Glover-Dumm equation describes the fall of the water table after an instantaneous rise above drain level.
De Zeeuw-Hellinga equation	The De Zeeuw-Hellinga equation describes a fluctuating water table, i.e. when the recharge to the groundwater varies with time.
Drainable porosity	The use of the unsteady state equations is restricted because it is even more difficult to measure the *drainable porosity* in the field than to measure the hydraulic conductivity. For more information see Section 11.3.5 of Publication 16.

Problem 8 Drain spacing calculation using Glover-Dumm

In an irrigated area the hydraulic conductivity of the soil is 0.25 m/d. The depth of the impervious layer is assumed to be at 11.80 m below soil surface. The drainable porosity of the soil is 8% (μ = 0.08). The fields are irrigated every 10 days. The field application depth is 100 mm of which 25% is assumed to become percolation loss. The water table is not permitted to rise within 1.0 m depth from the soil surface.

Drains with a radius of 0.1 m will be installed at a depth of 1.80 m below the soil surface.

☞ *Calculate the drain spacing with the Glover-Dumm equation.*

Between two irrigations, the water table drops from 1.0 m to 1.3 m.

☞ *What is the total discharge during this period in mm and what is the average discharge per day if one does not take the shape of the water table into account?*

☞ *What is the actual discharge rate q (mm/d) as a function of time?*

7 USING EXCEL FOR DRAIN-SPACING CALCULATIONS

You have learnt that we compute the drain spacing with steady-state equations (Donnan, Hooghoudt, Ernst) or with unsteady-state equations (Glover-Dumm, De Zeeuw-Hellinga). In problems 6 (Hooghoudt), 7 (Ernst), and 8 (Glover-Dumm) you have exercised with the most important ones. There are quite some computations involved, which become tedious especially if the spacing needs to be calculated frequently. Therefore, it is useful to automate these computations, which can conveniently be done with a spreadsheet program like Excel. Below, we start with making a calculation template for Hooghoudt's equation, as an example of what is possible. It can be considered as a simple alternative for Van der Molen and Wesseling's Fortran program (1991), mentioned in Publ. 16, page 268.

The exercise: Use Excel for making a simple Hooghoudt calculation program
See also: Publication 16, Chapter 8, Section 8.2.1: The Hooghoudt Equation

Your task is to complete a worksheet for a simple Excel program, which allows you:

(i) to input data for the different variables; and then

(ii) to perform an iteration to find the drain spacing according to Hooghoudt's equation: $q*L^2 = 8*K_b*d*h + 4*K_t*h^2$.

<u>Procedure:</u>

1. Making a specific calculation program can be done in one of the programming languages. An example of a **Fortran program** can be found on your floppy disk as A:\HOOG\HOOG.EXE. Run this program and enter the following data:

Maximum hydraulic head (h)	1.50 m
Drain radius (r_o)	0.05 m
Hydraulic cond. above drain (K_t)	0.10 m/d
Hydraulic cond. below drain (K_b)	1.0 m/d
Depth of impervious layer (D)	3.0 m
Drain discharge (q)	0.005 m/d
Initial value of drain spacing (L)	20 m

and find the final calculated **drain spacing,** L, as 76 m.

2. Such a small calculation program can also be made in **Excel**, and we are going to make it in this small exercise. Start Excel 97 and **Open** file A:\HOOG\HOOG_1.XLS.

3 Note that we already prepared a template with seven variables, a column where you must enter INPUT DATA, and a section for the iteration to save time. If necessary, make a **situation drawing** on paper and note that:

   h = drain depth - allowed water table;
   D = aquiclude depth - drain depth;
   K_t = upper conductivity (t for top)
   K_b = lower conductivity (b for bottom);
   q = steady recharge = drain discharge;
   r_o = drain radius (calculate equivalent for open drains from $r_o = u/\pi$);
   L = drain spacing.

   The entered values for the variables relate to the same situation as under 1) above.

4. Now press the [→] key a number of times to show the screen to the right (addresses K1, etcetera). This screen holds the **Calculation procedure**, which is the basis for the small program. Remember that the calculation of L is not straightforward, since the equivalent depth d must be calculated first and d is a function of the wanted L. Chapter 8 mentions a **direct solution** procedure for d, based on Van der Molen & Wesseling (1991). Let us start entering the missing equations (in cells N11-N15, N17, N18, N20, and E20).

5. For the calculation procedure we need values for D (aquiclude depth minus drain depth), for the drain radius, r_o, and an initial value for L. Both D and r_o are found from the input data, while the initial value for L must be specified under Assume in the first template. This assumed value is then copied to the Calculation procedure screen. So: **Make** the contents of cell D20 appear in **cell N11**. Then calculate depth D as =E11-E9 in **cell N12**. Then calculate x in **cell N13** by entering the appropriate formula.

6. Calculating **F(x)** requires a bit of work. Press [→] again a number of times and see columns V and W, which can assist us in calculating F(x) as a series. In column V we have entered a number of n-values (numbers 1,2,3,..., 39), in column W we have entered =ln(1/tanh(n*x)), because the hyperbolic cotangent is not present in Excel's functions, but the hyperbolic tangent is (and cotanh = 1/tanh). See Eq. 8.11 in Publ. 16 (page 270). Note that the higher terms are very small indeed, and certainly may be neglected (n = 39 as a maximum was chosen rather arbitrarily). We find the F(x) by taking double the sum of all Series terms: **Put** this equation in cell **N14** of the Calculation procedure screen.

7. Calculate the value of the equivalent depth, d, in cell **N15** according to the given equation (which is Eq. 8.9 of Publ. 16).

8. Now calculate the value of h in cell **N17**, and the value of $8*K_b*d*h+4*K_t*h^2$ ($=q*L^2$) in cell **N18**. Divide it by q (watch the units !) and take the square root in cell **N20**. Make the contents of N20 appear in cell **E20** of the original template.

9. The computation model is now ready. To use it, change the initial value of 20 in the first template to something closer to 60 and keep on changing until the two are equal (this is demonstrating the **iteration** process). The final value should be 76 m, the same as we found with the Fortran program.

10. Your simple Hooghoudt calculation program is now ready, apart from a possible protection against accidental overwriting. You may protect the worksheet, but you have to unprotect ranges E9..E15 and D20, otherwise you cannot enter input data. Note that, upon opening the file you see nothing of the Calculation procedure screen, nor of the Series calculation columns. You do not have to bother about them from now on. The only thing you do is **enter input data** and then **change assumed L-values** until you get identical values: that is your drain spacing.

11. You may find that you have invested quite some time in making a simple calculation

program: that is correct, but your benefit lies in the time-saving you will realise if you have to calculate drain spacings for many different sets of variables. If you only have to calculate an occasional value, writing a computer program **does not make sense** !

12. Save your Hooghoudt program as A:\HOOG\HOOG_2 on your floppy. You now have HOOG_1.XLS, HOOG_2.XLS, and HOOG.EXE on your floppy under subdirectory A:\HOOG\.

13. There are ways to avoid the manual iteration, as we may demonstrate later.

At the end of this exercise, you may be aware that embellishments (adding colour, adding graphs, avoiding impossible input data, etc.) are possible. You can do that on your own. An example is given on your floppy as A:\HOOG\HOOG_4.XLS. A print of the template page is shown on page 27 (Figure 6).

You may also realise that similar templates can be made for other drain-spacing equations. A draft of such other templates may be given to you later (called SPACING.XLS), which contains templates for different drain-spacing equations in different sheets of the same file (Hooghoudt, Ernst, Glover-Dumm, and De Zeeuw-Hellinga). NOTE that this is a draft version, which may not work error-free !!!

	A	B	C	D
1				
2	**Hooghoudt's steady-state drain-spacing equation (ILRI publication 16 of 1994, page 268, equation 8.8)**			
3				
4–5		$L = +\sqrt{\dfrac{8k_b dh + 4K_t h^2}{q}}$		
6				
7	Validity	1) one soil layer over impervious		
8		2) two-layered soil; drain at interface		
9	**Input data:**			
10	***Soil***	K-top	1.00	m/d
11		K-bottom	0.70	m/d
12		aquiclude at	6.20	m - s.s.
13	***System***	drain depth	1.20	m
14		drain radius r0	0.05	m
15	***Agric.crit.***	allowed w.t.	0.40	m -s.s.
16	***Recharge***	R = q	8.0	mm/d
17				
18	**Derived data:**			
19	***Soil***	D	5.00	m
20		d	2.40	m
21	***Agric.crit.***	w.t. height = h	0.80	m + d.d.
22				
23	**Output:**			
24				
25		spacing L =	40.8	m
26				
27	**Type input data in light-green area; then click "Find L" under Output**			**Calculations are to the right**
28				

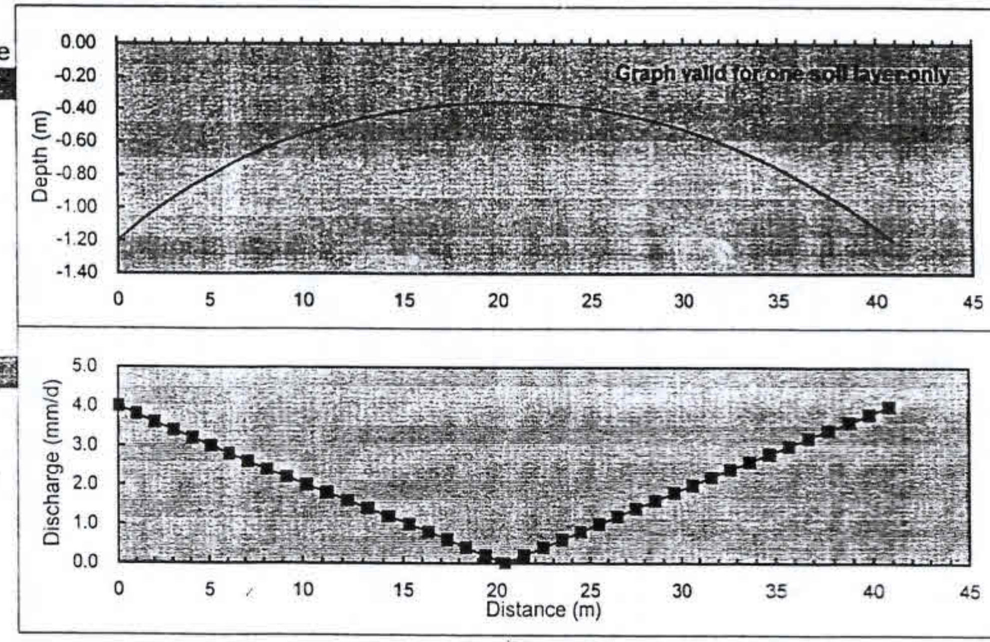

Figure 6 A possible Excel calculation template for Hooghoudt's drain-spacing equation

8 EXERCISE SUB-SURFACE DRAINAGE

Input data

To apply drainage equations we need three sets of input data:

- the agricultural criteria: these are the criteria which are used to translate the agricultural objectives in parameters that can be used in the design;
- the technical criteria: these are the criteria which specify the type of drainage system that we want to install, and;
- the soil characteristics, which specify the soil and soil's hydrological conditions.

Fixed inputs

Design variables

For a design engineer, the agricultural criteria and the soil characteristics are data, which can not be changed: they are fixed input data. On the other hand, the technical criteria are the design tools for the engineer: for an area with fixed soil characteristics, the design engineer can design alternative systems by selecting different types of drainage systems, different construction methods or materials, each satisfying the same agricultural criteria. For more information on drainage criteria, see Publication 16, Chapter 17.

Simplification

For this design, the engineer needs the drainage equations. These drainage equations do not describe the complex reality of a drainage problem, as we find it in the field, but they only describe a simplified situation. In other words, we have to simplify the complex reality before we can apply a drainage equation (Figure 7).

Judgement

To select the appropriate equation and to make the correct simplifications requires a thorough knowledge of the basics of groundwater flow and the assumptions and boundary conditions on which the equations are based. This is the most difficult part of a design.

Exercise

In this chapter of the workbook a drainage exercise is given, in which you can see that the final result of your calculations depends very much on the assumptions and simplifications you have to make in order to apply the appropriate drainage equation.

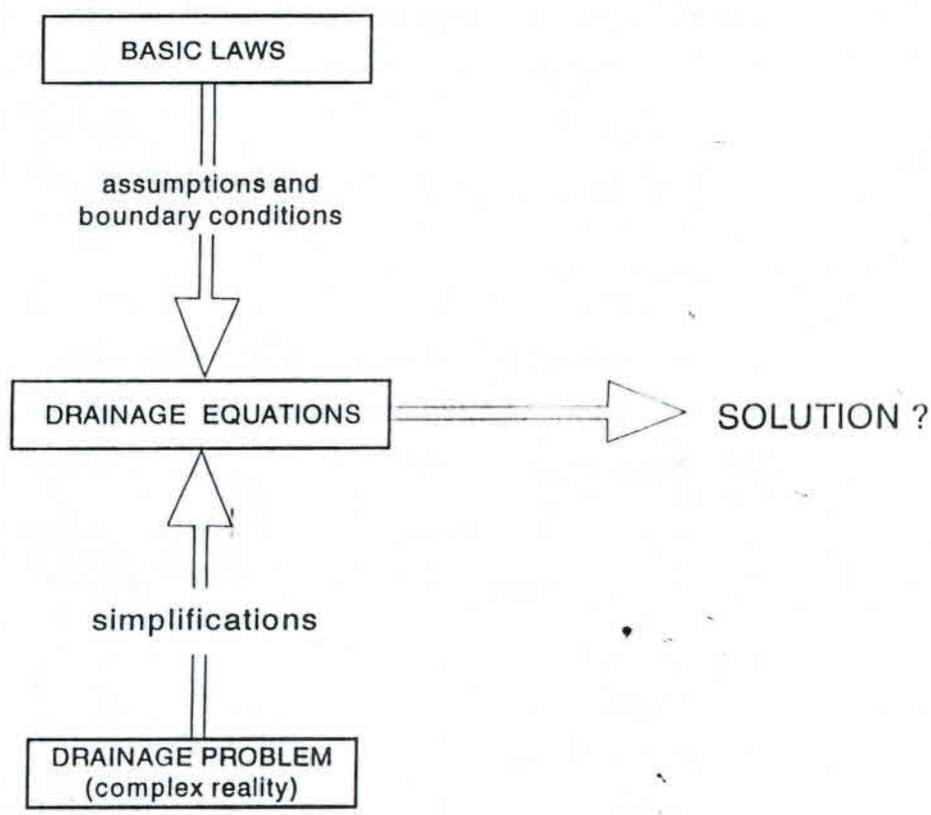

Figure 7 Application of the drainage equations in a complex situation

Table 3 *Hydraulic conductivity measurements*

N	*Auger-hole bottom (m -ss)*	*Water depth in auger hole (m)*	*Water table elevation (m -ss)*	*Hydraulic conductivity (m/d)*
1	*2.00*	*0.86*	*1.14*	*0.07*
2	*2.00*	*0.87*	*1.13*	*0.02*
3	*2.00*	*0.49*	*1.51*	*0.09*
4	*2.00*	*0.90*	*1.10*	*0.02*
5	*2.00*	*0.79*	*1.21*	*0.11*
6	*2.00*	*0.90*	*1.10*	*0.08*
7	*2.00*	*0.85*	*1.15*	*0.03*
8	*2.00*	*0.90*	*1.10*	*0.09*
9	*2.00*	*0.47*	*1.53*	*0.04*
10	*2.00*	*1.17*	*0.83*	*0.10*
11	*2.00*	*0.82*	*1.18*	*0.08*
12	*2.00*	*0.50*	*1.50*	*0.05*
13	*2.00*	*0.85*	*1.15*	*0.05*
14	*2.00*	*1.35*	*0.65*	*0.05*
15	*2.80*	*0.98*	*1.82*	*2.00*
16	*3.00*	*1.38*	*1.62*	*0.03*
17	*3.00*	*1.42*	*1.58*	*2.27*
18	*3.00*	*1.32*	*1.68*	*2.64*
19	*3.03*	*1.00*	*2.03*	*0.01*
20	*3.03*	*1.00*	*2.03*	*0.02*
21	*3.03*	*1.20*	*1.83*	*0.02*
22	*3.10*	*1.10*	*2.00*	*0.92*
23	*3.10*	*0.96*	*2.14*	*2.10*
24	*3.10*	*1.13*	*1.97*	*1.60*
25	*3.20*	*1.16*	*2.04*	*0.01*
26	*3.45*	*1.05*	*2.40*	*0.12*
27	*3.50*	*0.95*	*255*	*1.10*
28	*3.50*	*1.10*	*2.40*	*1.04*
29	*3.50*	*1.12*	*2.38*	*0.88*
30	*3.80*	*1.00*	*2.80*	*0.73*

Exercise sub-surface drainage: Application of the drainage equations

In an irrigated area, high water tables occur due to the recharge by irrigation water losses.

[] *Design a pipe drainage system to control the water table under the following conditions:*

Agricultural drainage criteria:

- *a steady design discharge of 1 mm/d;*
- *the water table should be controlled at 1.0 m below soil surface.*

Technical criteria:

- *drains will be installed at 2.0 m depth;*
- *pvc pipe drains with a radius (r_0) of 0.10 m will be used.*

In the area the following soil investigations have been conducted:

- *the texture of the soil has been established from samples of an augering up to the impermeable layer (Table 2);.*
- *thirty auger-hole measurements at a depth ranging from 2.0 to 3.8 m below soil surface (Table 3).*

Table 2 *Soil texture analysis*

Depth (m -ss)	*Sand (%)*	*Silt (%)*	*Clay (%)*	*Texture*
0.0 - 0.5	6	34	60	clay
0.5 - 1.5	8	20	72	clay
1.5 - 2.0	11	20	69	clay
2.0 - 2.5	34	29	37	clay loam
2.5 - 3.0	26	41	33	clay loam
3.0 - 4.0	6	61	33	silty clay loam
4.0 - 5.0	15	65	20	silt loam
5.0 - 6.0	8	44	48	silty clay
6.0 - 6.8	23	8	69	clay
> 6.8	3	12	85	clay

To complete the exercise, apply the following procedure:

1. *Make a drawing of the simplified soil profile:*
   a) How many different soil layers can you distinguish?
   b) What is the thickness of the different soil layers?
   c) Calculate the "average" hydraulic conductivity of each soil layer in two ways, i.e. by using the geometric and the arithmetic means.
   d) Calculate the ratio of the hydraulic conductivity above/below drain level.
   e) What will be the geometric and arithmetic means if we assume that the soil is homogeneous?
   f) Which value(s) of the hydraulic conductivity is (are) representative?

   If you want, you may use Excel to do your computations. The data of Table 2 and Table 3 are in a file named A:\COND\COND_1.XLS on your Excel floppy.

2. *Proceed to calculate the drain spacing:*
   a) Select the appropriate drainage equation.
   b) Select representative values of the hydraulic conductivity.
   c) Calculate the drain spacing.

3. *Can you also solve the problem by using the simplified Hooghoudt equation?*
   a) Select a representative value of the hydraulic conductivity.
   b) Calculate the drain spacing.

4. *Which spacing do you obtain if you assume that the soil profile is homogeneous?*
   a) Select a representative value of K for the homogeneous soil profile.
   b) Calculate the drain spacing.
   c) What will be the drain spacing if you use the arithmetic mean of the hydraulic conductivity?

5. *Now compare the drain spacings calculated in questions 2c, 3b, 4b, and 4c and draw your conclusions. You may also want to know that, if we would (erroneously) use the Ernst equation for this situation, we would find L = 77 m. What conclusion would that lead to? Which equation is the most appropriate for this case and why?*

6. *Let us now, for this question only, assume that the available drainage machines can only install drain pipes up to a **maximum** depth of 1.50 m below the soil surface. Then the technical criteria change: you have to reduce the drain depth from 2.0 m to 1.5 m. The width of the trench made by this machine is 0.25 m.*
   a) Which drainage equation should now be used?
   b) Calculate the drain spacing.
   c) Calculate the drain spacing with the same equation, assuming a homogeneous soil profile (although it is an unrealistic exercise).
   d) Calculate the drain spacing assuming a homogeneous soil profile and using Hooghoudt.
   e) Compare the results and comment.

7. *In questions 2, 3, 4, 5, and 6 you have calculated the drain spacings assuming **steady-state** conditions. Now check if the calculated drain spacing can also cope with **unsteady-state** conditions. For applying the unsteady-state approach an additional agricultural criterion is required:*
   - *the maximum permissible height of the water table is 0.75 m below the soil surface (whereas in the steady-state equations we used an average depth of 1.00 m).*

   Furthermore, the following information is available:
   - *during the rainy season, an observation well was installed in the area. It was observed that in a rainy period a single rainstorm of 15 mm caused the water table to rise 0.30 m;*
   - *during the irrigation season water is applied every 20 days.*

   Calculate:

a) the drainable pore space μ.

b) the instantaneous recharge assuming that the steady-state drainage criterion (equalling 1 mm/d) over a irrigation cycle can be transformed into an instantaneous recharge.

8. *Select an equation to calculate the fluctuation of the water table and enter the known parameters, so that the water table depth only depends on day t.*

9. *Calculate the fluctuation of the water table for days 0, 5, 10, 15, 20, assuming that the water table is at 0.75 m below soil surface after the first irrigation (which gives you h_0). Note the height of the water table at day 20, just before the next irrigation.*

10. *Check if there is a relation between the steady-state conditions (considering the simplified Hooghoudt equation) and the unsteady-state conditions (considering the reaction factor).*

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9 SHORT TEST

To check your knowledge on the subject a test is included in this series of lectures. To assess your current level of understanding yourself, try to answer the following questions.

1. What are the three components of the total energy head? Which one of the three can be neglected in groundwater flow problems?

2. Why do we need the Dupuit-Forchheimer assumptions to solve most groundwater flow problems?

3. The viscous fluid model can be used to simulate the flow of groundwater to parallel drains. How can we simulate a flow problem in a soil with a lower hydraulic conductivity than in the video?

4. How did Hooghoudt account for the extra head loss caused by the converging flow near the drainpipe?

5. In the Hooghoudt equation the square of the spacing, L^2, is proportional to 1/q. What is the reason that, when q is taken 4 times larger, L does not become exactly half?

6. Why have we used the Hooghoudt equation in Problem 6 and the Ernst equation in Problem 7?

7. What is the reason that steady-state equations can also be used for drainage problems in irrigated areas, where the flow is highly unsteady?

8. Which two equations can be used to relate a steady-state criterion with a unsteady-state criterion? Derive that relationship.

9. A farmer has determined that his crop will give the highest yield if the water table is

maintained at 0.50 m below the soil surface. He has engaged a contractor to install pipe drains using a trencher, which makes trenches of 0.20 m wide. Corrugated plastic pipes, r_0 = 0.06 m, wrapped with a 7-mm thick envelope will be used. The drains will be installed at a depth of 1.0 m. The design discharge is 7 mm/d and the soil has a uniform hydraulic conductivity of 1.5 m/d up to a depth of 7.0 m. Below this depth, the soil is considered to be impervious.

Determine the drain spacing with and without considering the drain trench.

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INTERNATIONAL COURSE ON LAND DRAINAGE ICLD

Workbook
2.2 GROUNDWATER SURVEY
AQUIFER TEST

DRAINAGE

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Workbook

2.2. GROUNDWATER SURVEY
AQUIFER TEST

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Lecture notes for the International Course on Land Drainage are not official publications. They may be altered from year to year. Lecture notes have been published as: Drainage Principles and Applications, ILRI Publication 16, Wageningen 1974, and as a revised version in 1994.

Subject: Single-Well and Aquifer Tests

Lecture notes & references:
- ILRI-Publication 16, Chapter 10 (1994);
- ILRI-Publication 48 (1989);
- prepared exercises and solutions.

Time schedule:
- one block of 3 hours: lectures;
- one block of 4 hours: exercises and ILRI-software demonstration;
- one block of 3 hours: exercises with ILRI-software.

Contents of lectures:
- overview of different types of aquifer systems and their hydraulic characteristics (definitions and order of magnitude);
- general aspects concerning preparation and performance of single-well and aquifer tests;
- time-drawdown analysis methods for unconfined aquifers;
- time-recovery analysis methods for unconfined aquifers;
- special ILRI-software on the subject.

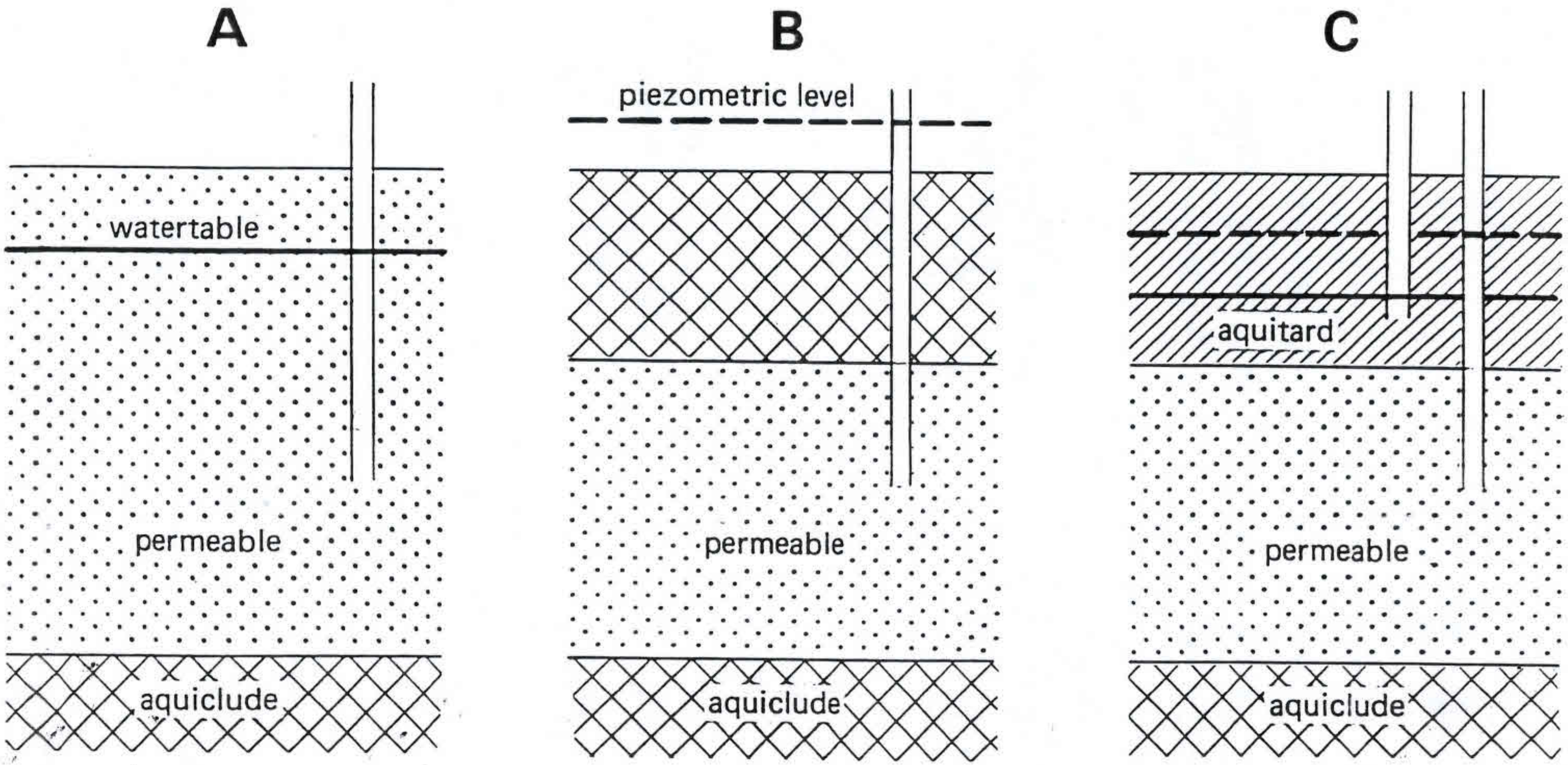
Teaching method:
- lectures using overhead sheets;
- ILRI-software;
- exercises to be made by hand;
- exercises to be made by using ILRI-software.

Teaching aims:
- to acquaint participants with the preparation and performance aspects of aquifer tests, so that they are able to supervise these types of tests in the future;
- participants should have acquired a thorough knowledge and understanding of the treated analysis methods and will be able to analyze these types of tests;
- participants should be able to apply the other analysis methods which were not treated during the lectures, after self-study of the lecture notes;
- participants should have acquired a basic knowledge of the ILRI-software and will be able to apply it in the future.

WHY AN AQUIFER TEST

There are numerous examples of groundwater-flow problems whose solution requires a knowledge of the hydraulic characteristics of waterbearing layers. These characteristics were defined in Chapter 2. In drainage investigations, this knowledge is required for two purposes:

- To assess the net recharge to an aquifer in groundwater-balance studies (Chapter 16);
- To determine the long-term pumping rate and the well spacing for tubewell drainage (Chapter 22).


A
B
C
watertable
piezometric level
aquitard
permeable
permeable
permeable
aquiclude
aquiclude
aquiclude

HYDRAULIC CHARACTERISTICS

Hydraulic Conductivity

The hydraulic conductivity, K, is the constant of proportionality in Darcy's law 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 (e.g. m/d). Its order of magnitude depends on the texture of the soil (Chapter 3) and is affected by the density and viscosity of the groundwater (Chapter 7).

HYDRAULIC CHARACTERISTICS

Saturated Thickness

For confined aquifers, the saturated thickness, H, is equal to the physical thickness of the aquifer between the aquicludes above and below it (Figure 2.10B). The same is true for a semi-confined aquifer bounded by an aquiclude and an aquitard (Figure 2.10C). In both these cases, the saturated thickness is a constant. Its order of magnitude can range from several metres to hundreds or even thousands of metres. For unconfined aquifers (Figure 2.10A), the saturated thickness, D', is equal to the difference in level between the watertable and the aquiclude. Because the watertable is free to rise and fall, the saturated thickness of an unconfined aquifer is not constant, but variable. It may range from a few metres to some tens of metres.

HYDRAULIC CHARACTERISTICS

Transmissivity

The transmissivity, KH, 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 and over the whole saturated thickness of the water-bearing layer. It has the dimensions of $length^2/time$ and can, for example, be expressed in m^2/d. Its order of magnitude can be derived from those of K and H.

Drainable Pore Space

The drainable pore space, μ, is the volume of water that an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline of the watertable. Small pores do not contribute to the drainable pore space because the retention forces in them are greater than the weight of water. Hence, no groundwater will be released from small pores by gravity drainage.

Drainable pore space is sometimes called specific yield, drainable porosity, or effective porosity. It is a dimensionless quantity, normally expressed as a percentage. Its value ranges from less than 5 per cent for clayey materials to 35 per cent for coarse sands and gravelly sands (Chapter 3).

HYDRAULIC CHARACTERISTICS

Storativity

The storativity, S, of a saturated confined aquifer is the volume of water released from storage per unit surface area of 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 decline distance. The storativity is a dimensionless quantity. It is the algebraic product of an aquifer thickness and specific storage and its value in confined aquifers ranges from 5×10^{-5} to 5×10^{-3}.

HYDRAULIC CHARACTERISTICS

Specific Storage

The specific storage, S_s, of a saturated confined aquifer is the volume of water that a unit volume of the aquifer releases from storage under a unit decline in head. This release of water under conditions of decreasing hydraulic head stems from two mechanisms:

- The compaction of the aquifer due to increasing effective stress;
- The expansion of water due to decreasing water pressure (see also Chapter 9).

For a certain location, the specific storage can be regarded as a constant. It has the dimension of $length^{-1}$.

HYDRAULIC CHARACTERISTICS

Hydraulic Resistance

The hydraulic resistance, c, 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 and is thus defined as

$$c = \frac{D'}{K} \tag{2.1}$$

The dimension of hydraulic resistance is time; it can, for example, be expressed in days. Its order of magnitude may range from a few days to thousands of days. Aquitards with c-values of 1000 days or more are regarded as aquicludes, although, theoretically, an aquiclude has an infinitely high c-value.

HYDRAULIC CHARACTERISTICS

Leakage Factor

The leakage factor, L, describes the spatial distribution of leakage through an aquitard into a semi-confined aquifer, or vice versa. It is defined as

$$L = \sqrt{KHc} \qquad (2.2)$$

High values of L originate from a high transmissivity of the aquifer and/or a high hydraulic resistance of the aquitard. In both cases, the contribution of leakage will be small and the area over which leakage takes place, large. The leakage factor has the dimension of length and can, for example, be expressed in metres.

WHAT IS AN AQUIFER TEST

Performing an aquifer test is one of the most effective ways of determining the hydraulic characteristics. 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 pumped well itself and in a number of piezometers or observation wells in the vicinity.

AQUIFER TEST VERSUS SINGLE-WELL TEST

Owing to the high costs of aquifer tests, the number that can be performed in most drainage studies has to be restricted. Nevertheless, one can perform an aquifer test without using observation wells, thereby cutting costs, although one must then accept a certain, sometimes appreciable, error. To distinguish such tests from normal aquifer tests, which are far more reliable, they are called single-well tests. In these tests, measurements are only taken inside the pumped well.

ANALYZING AQUIFER TEST DATA

After a single-well or an aquifer test, the data collected during the test are substituted into an appropriate well-flow equation. In this chapter, we shall confine our discussions to the basic well-flow equations. For well-flow equations that cover a wider range of conditions, see Kruseman and De Ridder (1990).

PREPARING FOR AN AQUIFER TEST

10.2.1 Site Selection

Although, theoretically, any site that is easily accessible for manpower and equipment is suitable for a single-well or an aquifer test, a careful selection of the site will ensure better-quality data and will avoid unnecessary complications when the data are being analyzed. The factors to be kept in mind when selecting an appropriate site are:

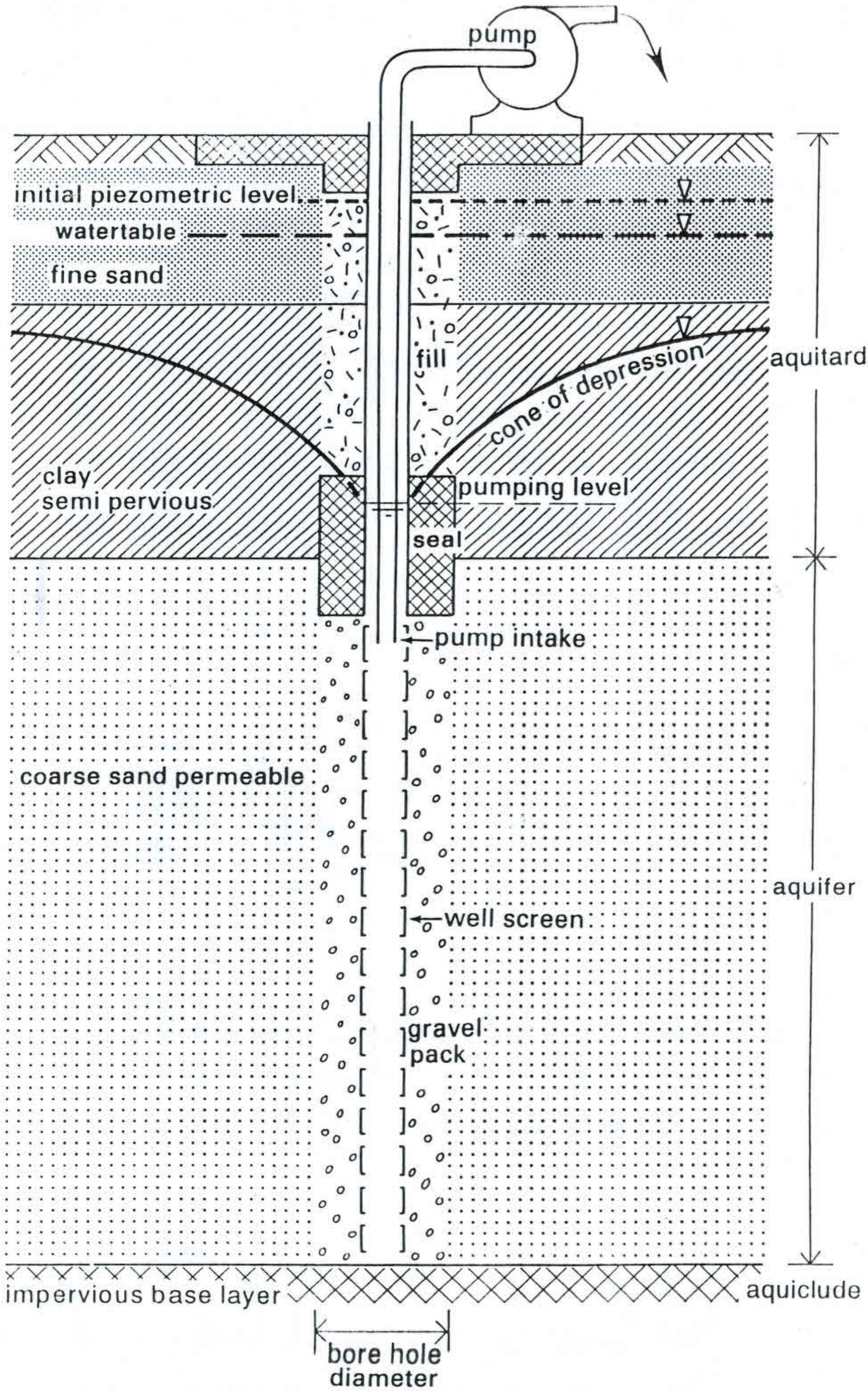
- The hydrological conditions should be representative of the area;
- The watertable gradient should be small;
- The aquifer should extend in all directions over a relatively large distance (i.e. no recharge or barrier boundaries should occur in the vicinity of the test site);
- The pumped water should be discharged outside the area affected by the pumping to prevent it from re-entering the aquifer.

If not all these conditions can be satisfied, techniques are available to compensate for any deviations.

10.2.2 Placement of the Pumped Well

At the site selected for the test, the well that is to be pumped is bored into the aquifer. Its diameter is generally between 0.10 and 0.30 m, depending on the type of pump that will be used; the type of pump depends on the desired discharge rate and the allowable maximum pumping lift.

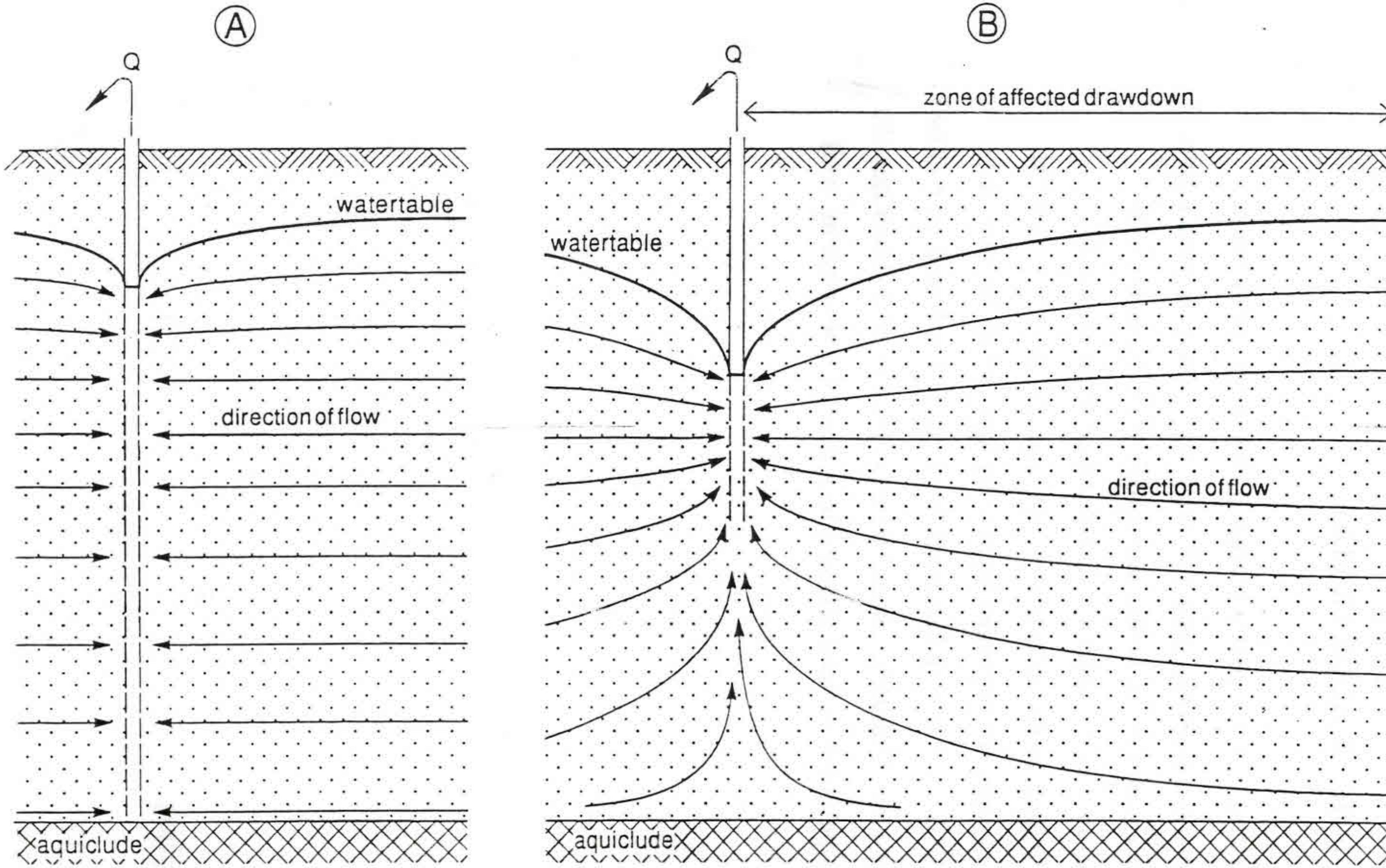
After the well has been drilled, it must be fitted with a screen, the length of which depends on the type of aquifer being tested. In unconfined aquifers, the bottom one-third to one-half of the aquifer should be screened to prevent the well screen from falling dry if appreciable drawdowns occur. In semi-confined (leaky) aquifers, the well should be screened over at least 70 to 80 per cent of the aquifer thickness. When such a well is pumped, the flow to the well will be essentially horizontal, and there will be no need to correct the drawdown data of any nearby observation wells. To prevent downward flow along the well from overlying layers, a seal of bentonite clay or very fine clayey sand may be required above the well screen (Figure 10.1).



pump
initial piezometric level
watertable
fine sand
fill
cone of depression
aquitard
clay
semi pervious
pumping level
seal
pump intake
coarse sand permeable
aquifer
well screen
gravel
pack
impervious base layer
aquiclude
bore hole
diameter

PREPARING FOR AN AQUIFER TEST

Thick aquifers can only be partly screened, say their upper 50 m, because the cost of screening their full thickness would be prohibitive. In such partially-penetrating wells, vertical flow components will influence the drawdown within a radial distance from the well approximately equal to the thickness of the aquifer. As these vertical flow components are accompanied by a head loss, all drawdown data from wells sited within this radius must be corrected before they can be used to calculate the hydraulic characteristics. Figure 10.2 illustrates the flow to a fully-penetrating well (A) and to a partially-penetrating well (B).

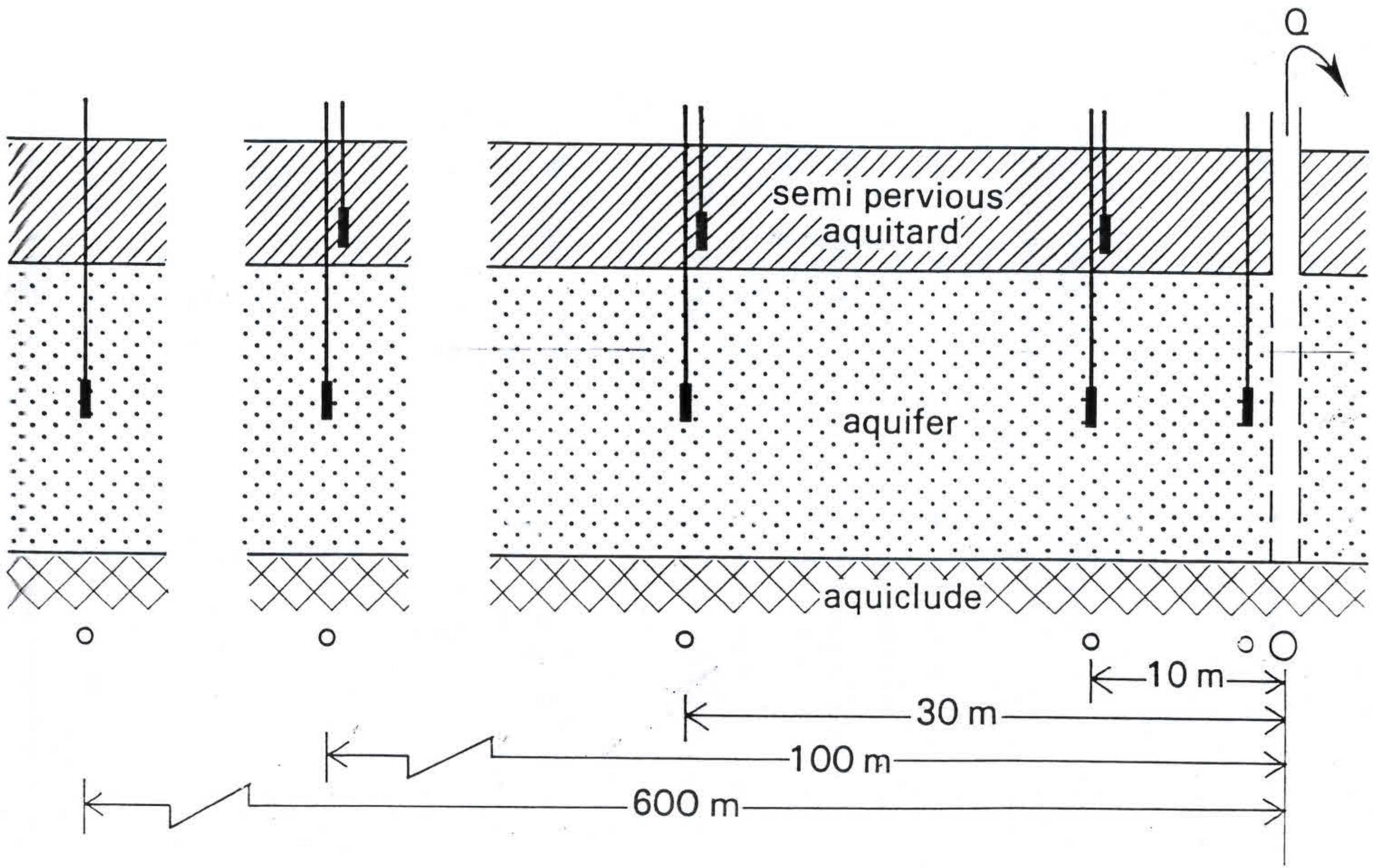


A
Q
watertable
direction of flow
aquiclude
B
Q
zone of affected drawdown
watertable
direction of flow
aquiclude

10.2.3 Placement of Observation Wells

The observation wells need only be of small diameter, and each should be fitted with a screen, 1 to 2 m long, placed at about the same depth as the middle of the screen of the pumped well. Such an observation well is also called a piezometer. Figure 10.3 shows an example of the arrangement of observation wells in a semi-confined aquifer that is being tested with a fully-penetrating well. Deep observation wells are placed in the aquifer and shallow ones are placed in the overlying semi-pervious layer. Other observation wells could be placed in the sandy material below the impervious base layer (aquiclude) to check whether that layer is indeed impervious.

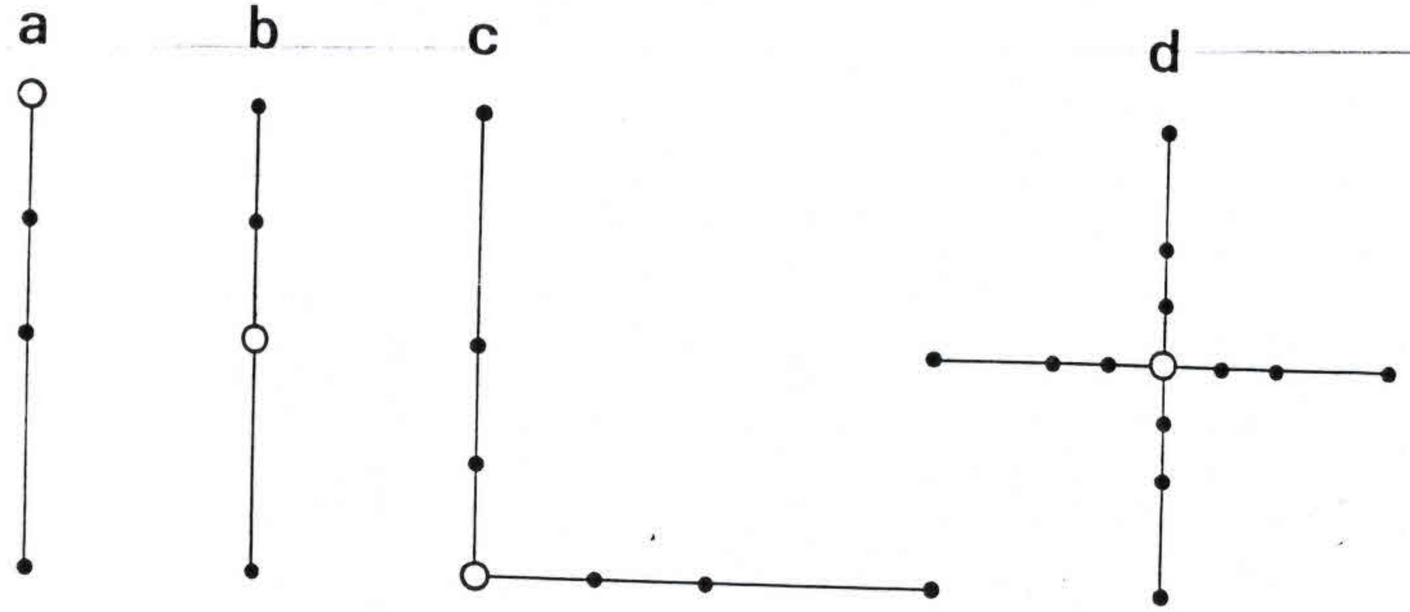
In unconfined aquifers, observation wells placed at distances of, say, 3, 10, 30, and 100 m from the pumped well will be appropriate in most cases. In confined and semi-confined aquifers, if thick and stratified, the distances must be greater, say, 100 to 300 m from the pumped well.


Q
semi pervious
aquitard
aquifer
aquiclude
10 m
30 m
100 m
600 m

10.2.4 Arrangement and Number of Observation Wells

The number of observation wells depends on the amount and accuracy of information that is required and on the funds available for the test. The water-level data from one single observation well will allow the hydraulic characteristics to be calculated, but the data from two or more such wells will allow the test results to be analyzed in different ways. These different analyses provide a check on the accuracy of the results obtained from the test. Besides, since an aquifer is seldom homogeneous, it is always best to have as many observation wells as circumstances permit.

Figure 10.4 shows four different arrangements of observation wells and the pumped well. For drainage studies, arrangements A, B, or C will usually be appropriate.


a
b
c
d

10.3.1 Time

The time measurements are started at the beginning of the test; they can be recorded either as "time of day" or as "time since the test started". Because water levels are dropping fast during the first hour or two of the test, readings should first be taken at brief intervals. As pumping continues, water levels will drop less and less fast and the intervals between readings can gradually be lengthened. Since, in all the analysis procedures, the time is plotted on a logarithmic scale, it is recommended to have the same number of readings in each log cycle of time. Table 10.1 shows an example of the sequence in time for taking water-level measurements, based on ten readings in each log cycle and resulting in approximately equidistant plotting positions.

Table 10.1 Sequence in time for taking water-level measurements

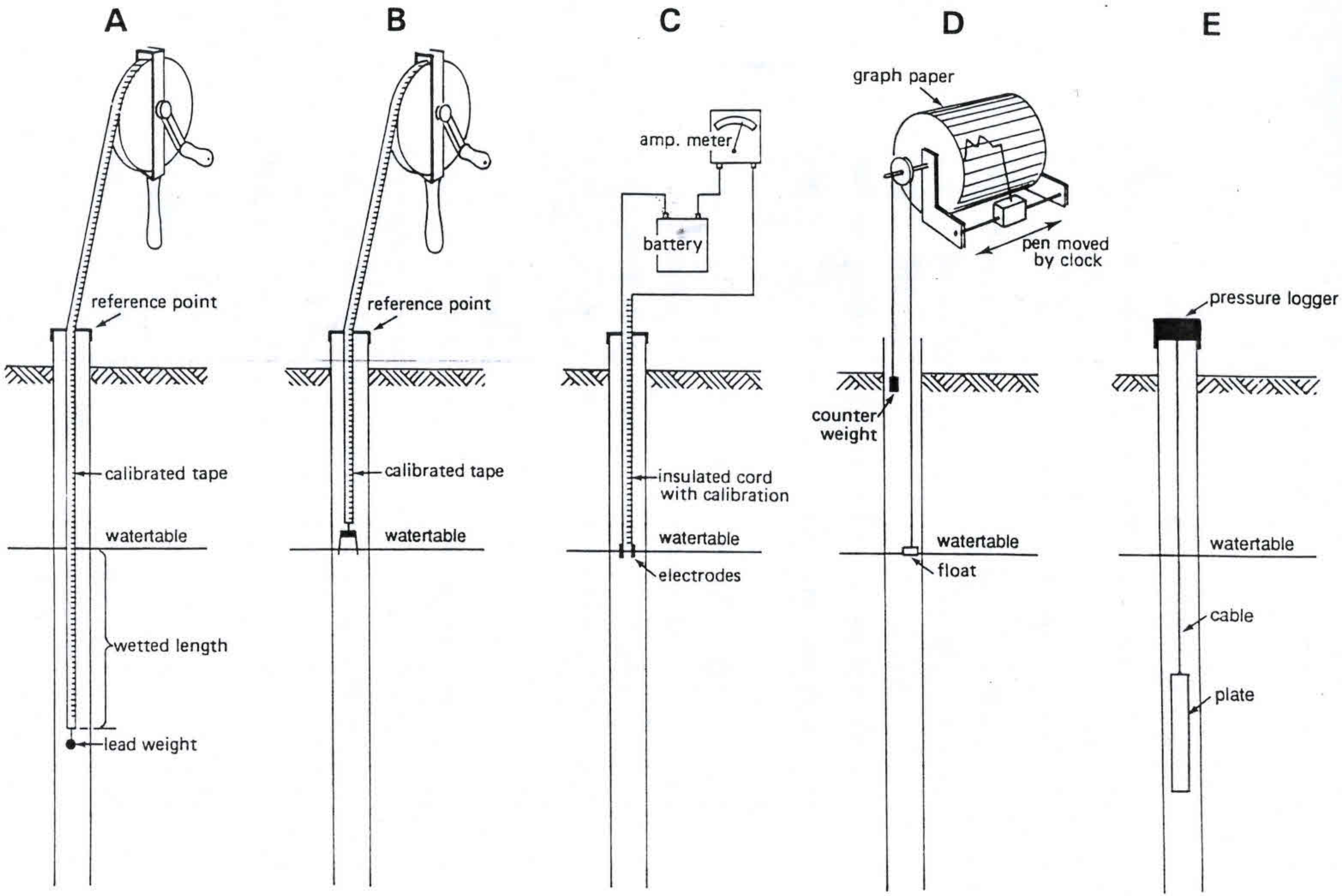
Time (s)	Time (min)	Time (min)	Time (h)	Time (h)
10	2.5	20	2.5	22
20	3.0	25	3.0	27
30	4.0	30	4.0	33
40	5.0	40	5.0	42
50	6.5	50	7.0	53
60	8.0	65	8.5	67
80	10.0	80	11.0	83
100	13.0	90	13.0	108
120	16.0	120	17.0	133

10.3.2 Head

Before pumping starts, the water levels in all the wells should be measured from a chosen reference (e.g. the rim of the pipe).

Water-level measurements can be taken in various ways: with the wetted-tape method, mechanical sounder, electric water-level indicator, floating-level indicator or recorder, pressure gauge, or pressure logger. (For information on these devices, see Chapter 2.) Fairly accurate measurements 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 2 mm.

For piezometers close to the well, the wetted-tape method cannot be used because of the rapid water-level changes, and the mechanical sounder is not suitable because of the noise of the pump. Although the pressure-gauge method is less accurate than the other methods (within 0.06 m), it is the most practical method of measuring water levels in a pumped well. It should not be used, however, in observation wells.



A
B
C
D
E
reference point
calibrated tape
watertable
wetted length
lead weight
reference point
calibrated tape
watertable
amp. meter
battery
insulated cord
with calibration
watertable
electrodes
graph paper
pen moved
by clock
counter
weight
watertable
float
pressure logger
watertable
cable
plate

10.3.3 Discharge

The discharge rate is usually determined in the field. Several days before the test is to be conducted, the test well should be pumped for several hours. In most tests, a major portion of the drawdown occurs in the first few hours of pumping, so this preliminary testing will reveal the maximum expected drawdown in the well. Also, for aquifer tests, it will reveal whether the discharge rate is high enough to produce good measurable drawdowns - at least some decimetres - in all the observation wells.

To avoid unnecessary complications when the test is being analyzed, the discharge of the well should be kept constant. It should therefore be measured at least once every hour and, if necessary, adjusted.

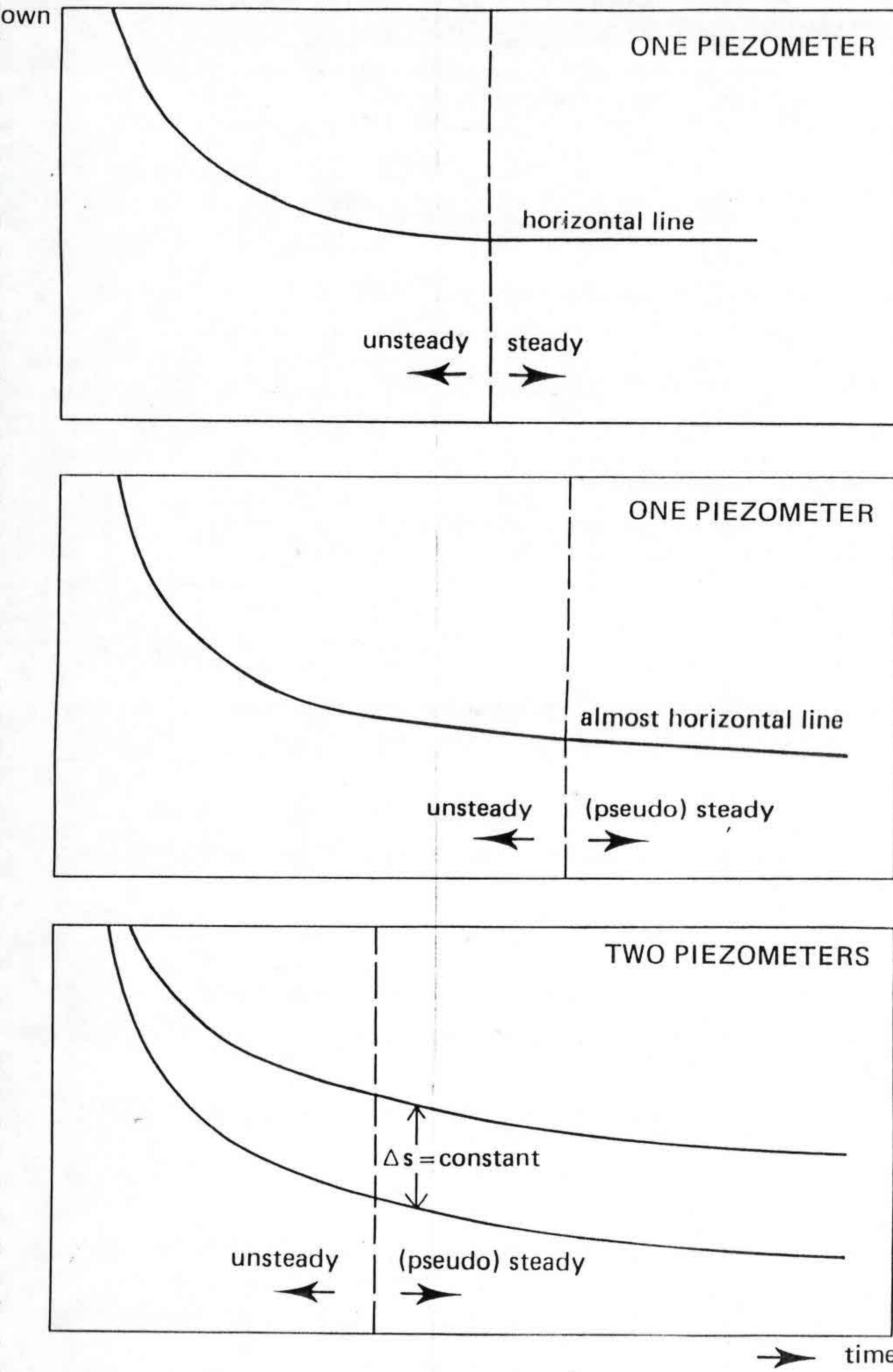
There are various ways of measuring the discharge. If the outflow pipe is running full, accurate measurements can be made with a water meter of appropriate capacity. It can also be measured by recording the time required to fill a container of known volume, or, if the pumped water is conveyed through a channel or small ditch, by means of a flume or weir.

10.3.4 Duration of the Test

The question of how long the test should run depends on the type of aquifer being tested. With all the effort and expense that is put into an aquifer test, it is not wise to economize on the time of pumping because this constitutes only a small fraction of the total cost. It is therefore advisable to continue the test until the water levels in the observation wells have stabilized (i.e. until the flow has reached a steady or pseudo-steady state).

Steady-state flow is independent of time (i.e. the water level, as observed in piezometers, does not change with time). Because real steady-state conditions seldom occur, it is said in practice that a steady state is reached when the changes in water level are negligibly small, or when the hydraulic gradient has become constant (pseudo steady-state).

To establish whether unsteady or (pseudo) steady-state conditions prevail, the changes in head during the pumping test should be plotted. Figure 10.5 shows the different plots and their interpretations.


own
ONE PIEZOMETER
horizontal line
unsteady
steady
ONE PIEZOMETER
almost horizontal line
unsteady
(pseudo) steady
TWO PIEZOMETERS
Δs = constant
unsteady
(pseudo) steady
time

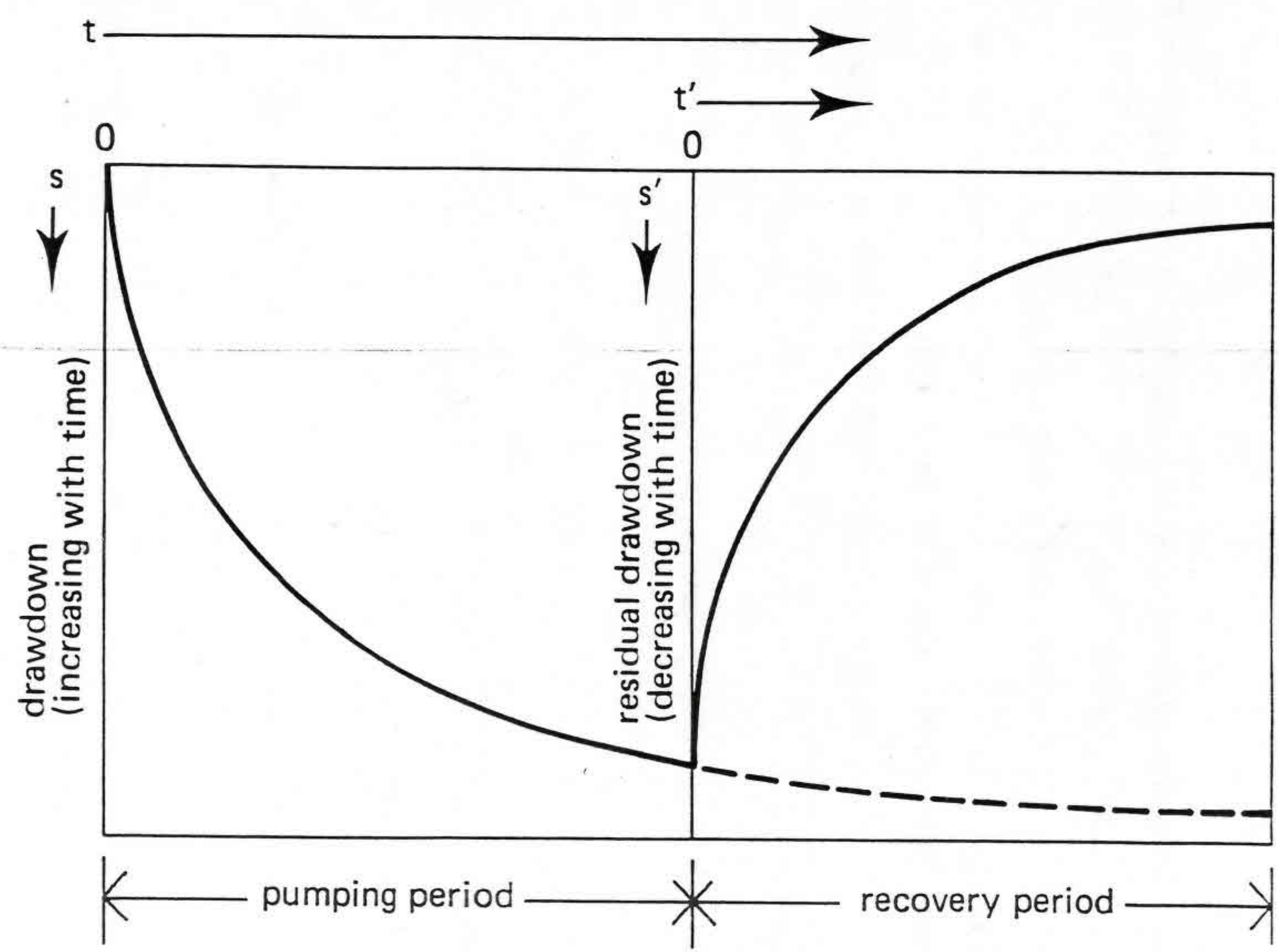
10.4 Methods of Analysis

As already stated, the principle of a single-well or 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/or in a number of observation wells in the vicinity. The change in water level induced by the pumping is known as the drawdown. In literature, tests based on the analysis of drawdowns during pumping are commonly referred to as "pumping tests".

The hydraulic characteristics can also be found from a recovery test. In such a test, a well that has been discharging for some time is shut down, after which the recovery of the aquifer's hydraulic head is measured, in the well and/or in the observation wells. Figure 10.6A gives the time-drawdown relationships during a pumping test, followed by a recovery test.

Analyses based on time-drawdown and time-recovery relationships can be applied to both single-well tests and aquifer tests.

A


t
t′
0
0
s
s′
drawdown
(increasing with time)
residual drawdown
(decreasing with time)
pumping period
recovery period

GENERAL ASSUMPTIONS AND CONDITIONS

All the methods presented 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 horizontal (or nearly so) over the area that will be influenced by the test;
- The pumped well penetrates the entire thickness of the aquifer and thus receives water by horizontal flow;
- The aquifer is pumped at a constant-discharge rate;
- The water removed from storage is discharged instantaneously with decline of head (see Section 10.5.1);
- 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.

THEIS DRAWDOWN EQUATION

10.4.1 Time-Drawdown Analysis of Unconfined Aquifers

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

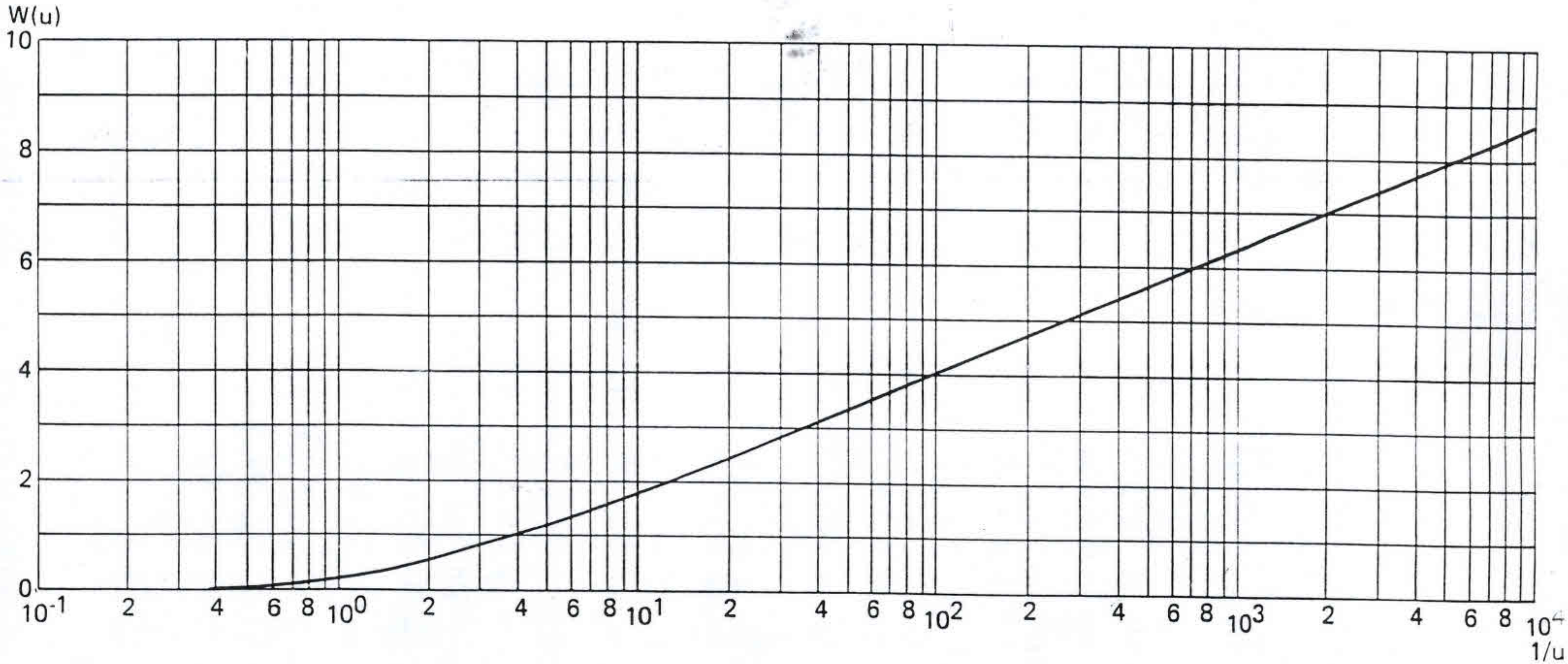
$$s = \frac{Q}{4\pi KH} \int_u^\infty \frac{1}{y} \exp(-y)\, dy = \frac{Q}{4\pi KH} W(u) \qquad (10.1)$$

and

$$u = \frac{r^2 \mu}{4KHt} \qquad (10.2)$$

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)
- μ = specific yield of the aquifer (-)
- t = time since pumping started (d)
- u = help parameter (-)
- $W(u)$ = Theis well function (-)



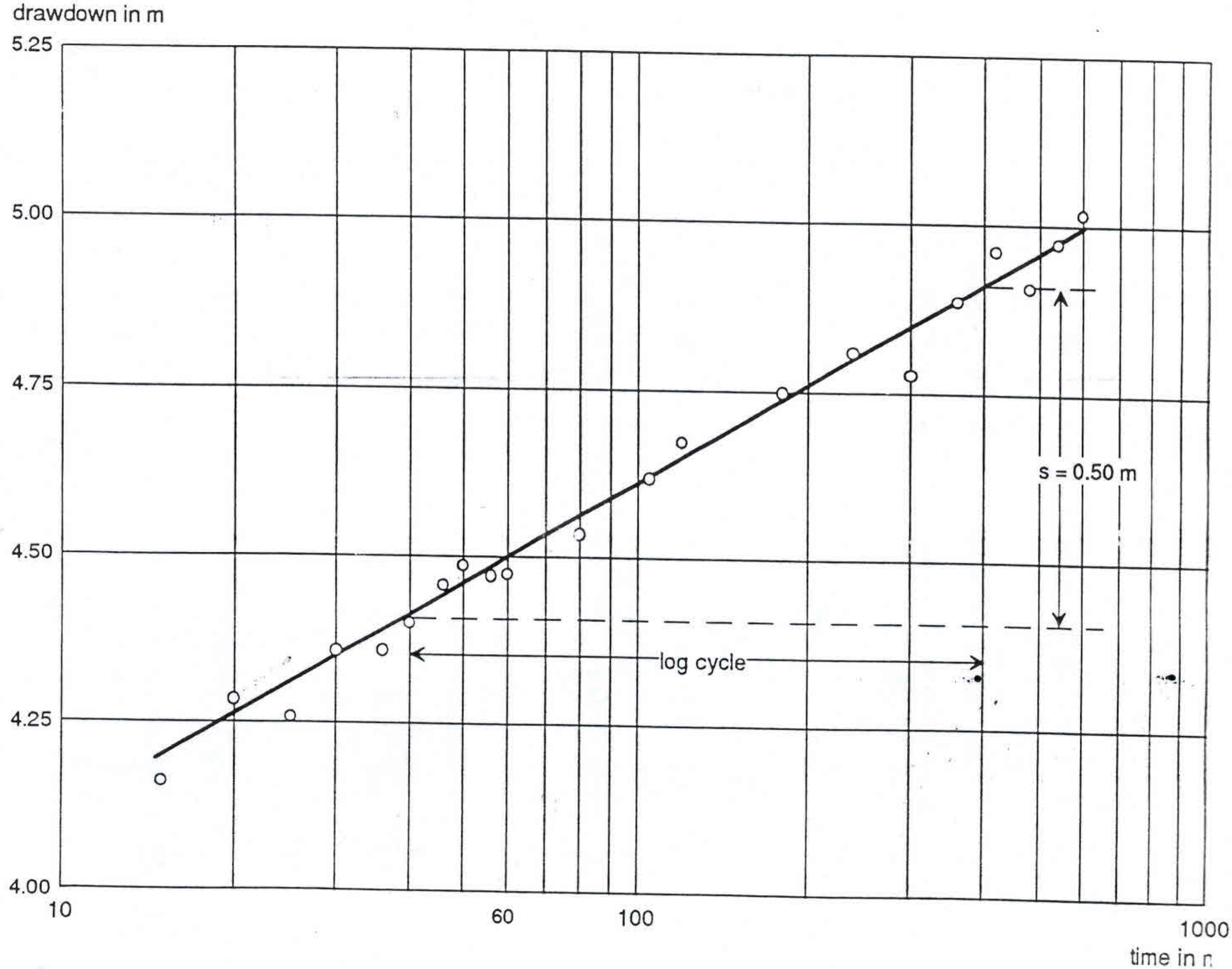
W(u)
10
8
6
4
2
0
10-1
2
4
6
8
100
2
4
6
8
101
2
4
6
8
102
2
4
6
8
103
2
4
6
8
104
1/u

JACOB DRAWDOWN EQUATION

It can be seen in Figure 10.7 that, for large values of 1/u, 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 10.1 can be approximated by

$$s = \frac{2.3Q}{4\pi KH} \log \frac{2.25KHt}{r^2\mu} \qquad (10.3)$$

with an error of less than 10, 5, 2, and 1 per cent for 1/u values larger than 7, 10, 20, and 30, respectively. For all practical purposes, Equation 10.3 can thus be used for 1/u values larger than 10.



drawdown in m
5.25
5.00
4.75
4.50
4.25
4.00
10
60
100
1000
time in n
s = 0.50 m
log cycle

CALCULATION OF HYDRAULIC CHARACTERISTICS

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 10.3 gives

$$KH = \frac{2.3Q}{4\pi\Delta s} \qquad (10.4)$$

If the straight line is extended until it intercepts the time-axis where $s = 0$, the interception point has the coordinates $s = 0$ and $t = t_0$. Substituting these values into Equation 10.3 gives $\log [2.25KHt_0/r^2\mu] = 0$ or $[2.25KHt_0/r^2\mu] = 1$ or

$$\mu = \frac{2.25KHt_0}{r^2} \qquad (10.5)$$

Jacob's straight-line method is based on the assumptions listed in Section 10.4 and on the limiting condition that the pumping time is sufficiently long for a straight-line segment to be distinguished in a time-drawdown plot on semi-log paper.

CALCULATION PROCEDURE BASED ON JACOB EQUATION

Procedure 1

- For one of the observation 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 10.4 and solve for KH;
- Extend the straight line until it intercepts the time-axis where $s = 0$, and read the value of t_0;
- Substitute the values of KH, t_0, and r into Equation 10.5 and solve for μ;
- Substitute the values of KH, μ, and r into Equation 10.2, together with $1/u = 10$, and solve for t. This t value should be less than the time range for which the straight-line segment was selected (see Example 10.1);
- If drawdown values are available for more than one well, apply the above procedure to the other wells also.

10.4.3 Time-Recovery analysis

Unconfined Aquifers

Theis developed his recovery method for confined aquifers. For unconfined aquifers, after a constant-rate pumping test, the residual drawdown s' during the recovery period is given by

$$s' = \frac{Q}{4\pi KH}\{W(u) - W(u')\} \qquad (10.14)$$

and

$$u = \frac{r^2\mu}{4KHt} \quad \text{or} \quad u' = \frac{r^2\mu'}{4KHt'} \qquad (10.15)$$

where

s' = residual drawdown (m)

μ' = specific yield during recovery (-)

t = t_{pump} + t' = time since pumping started (d)

t' = time since pumping stopped (d)

JACOB RECOVERY EQUATION

In Figure 10.13, the expression W(u)-W(u') is plotted versus u'/u on semi-log paper. This shows that, for small values of u'/u, the expression exhibits a straight-line segment.

When u' is sufficiently small (u' < 0.1) - the value of u is then also smaller than 0.1, provided that $\mu'/\mu = 1$ - Equation 10.14 can be approximated by

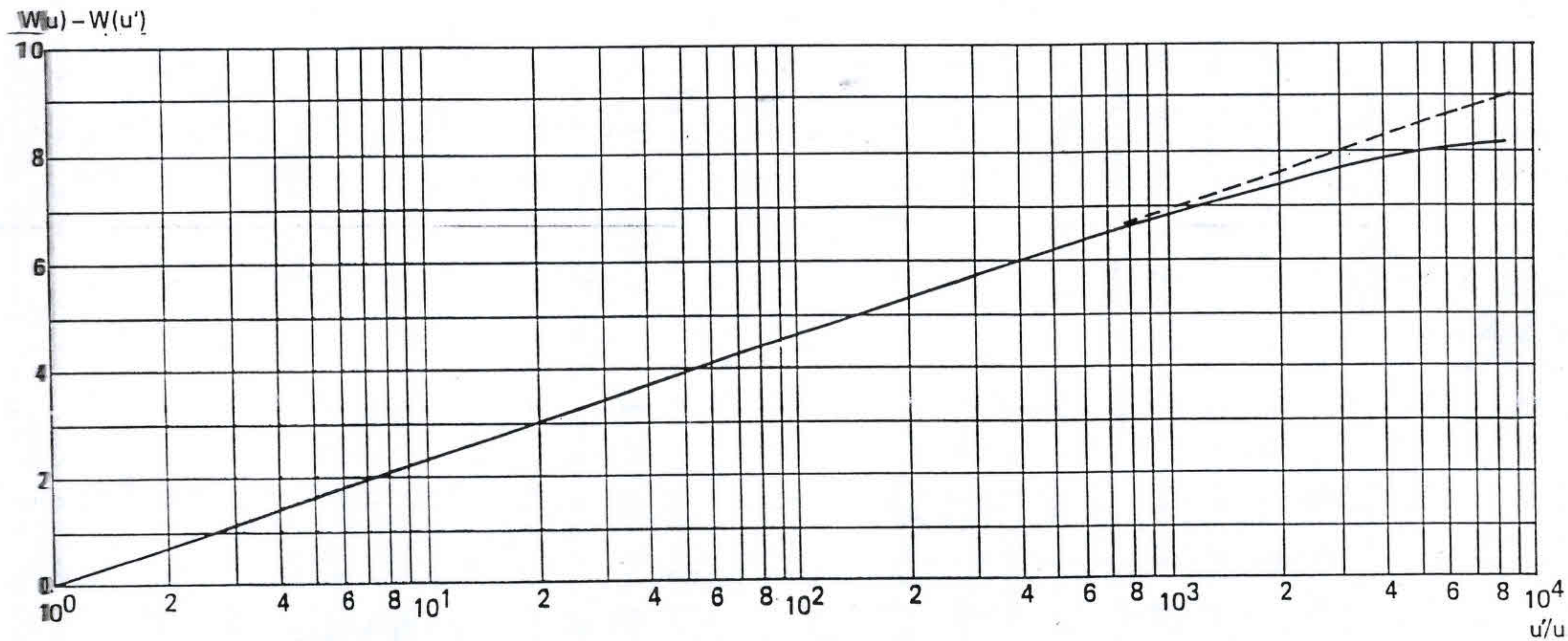
$$s' = \frac{2.3Q}{4\pi KH} \log \frac{\mu' t}{\mu t'} \qquad (10.17)$$

If we use residual-drawdown observations at a particular distance r from the pumped well and plot the residual drawdown s' versus the logarithm of the time ratio t/t', we obtain a straight line, provided that the time of pumping t_{pump} was long enough. If we express the slope of this straight-line segment as the drawdown difference ($\Delta s' = s_1' - s_2'$) per log cycle of the time ratio, rearranging
Equation 10.17 gives

$$KH = \frac{2.3Q}{4\pi\Delta s'} \qquad (10.18)$$

If we extend the straight line until it intercepts the time-axis where $s' = 0$, the interception point has the coordinates $s' = 0$ and $t/t' = (t/t')_0$. Substituting these values into Equation 10.17 gives $\log[\mu' t/\mu t'] = 0$ or $[\mu' t/\mu t'] = 1$ or

$$\mu' = \frac{\mu}{(t/t')_0} \qquad (10.19)$$



W(u) – W(u')
10
8
6
4
2
0
10^0
2
4
6
8
10^1
2
4
6
8
10^2
2
4
6
8
10^3
2
4
6
8
10^4
u'/u

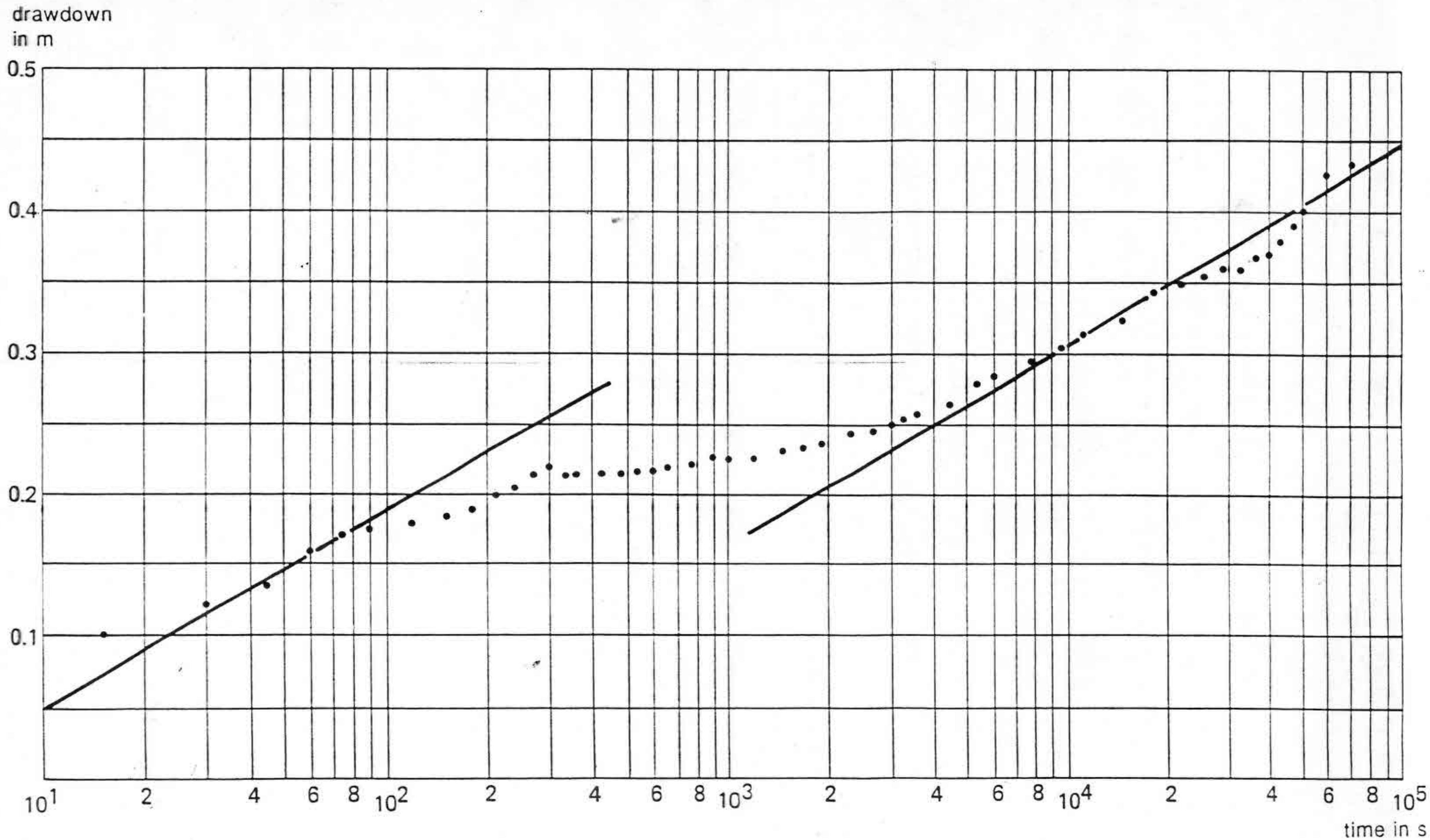
CALCULATION PROCEDURE BASED ON JACOB EQUATION

Procedure 3

- 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 Δs' per log cycle of time ratio t/t');
- Substitute the values of Q and Δs' into Equation 10.18 and solve for KH;
- Extend the straight line until it intercepts the time-ratio axis where s' = 0, and read the value of $(t/t')_0$;
- Substitute this value and that of the specific yield obtained from analyzing the drawdown data into Equation 10.19 and solve for μ';
- Substitute the values of t_{pump}, KH, r, and μ' into Equation 10.16 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 the above procedure to the other wells also.

10.5.1 Delayed-Yield Effect in Unconfined Aquifers

The general assumption that water removed from storage is discharged instantaneously with decline of head is not always met. Drawdown data in an unconfined aquifer often show 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. When the time-drawdown curve is plotted on semi-log paper, it shows a typical shape: a relatively steep early-time segment, a flat intermediate segment, and a relatively steep segment again at later times (Figure 10.18).

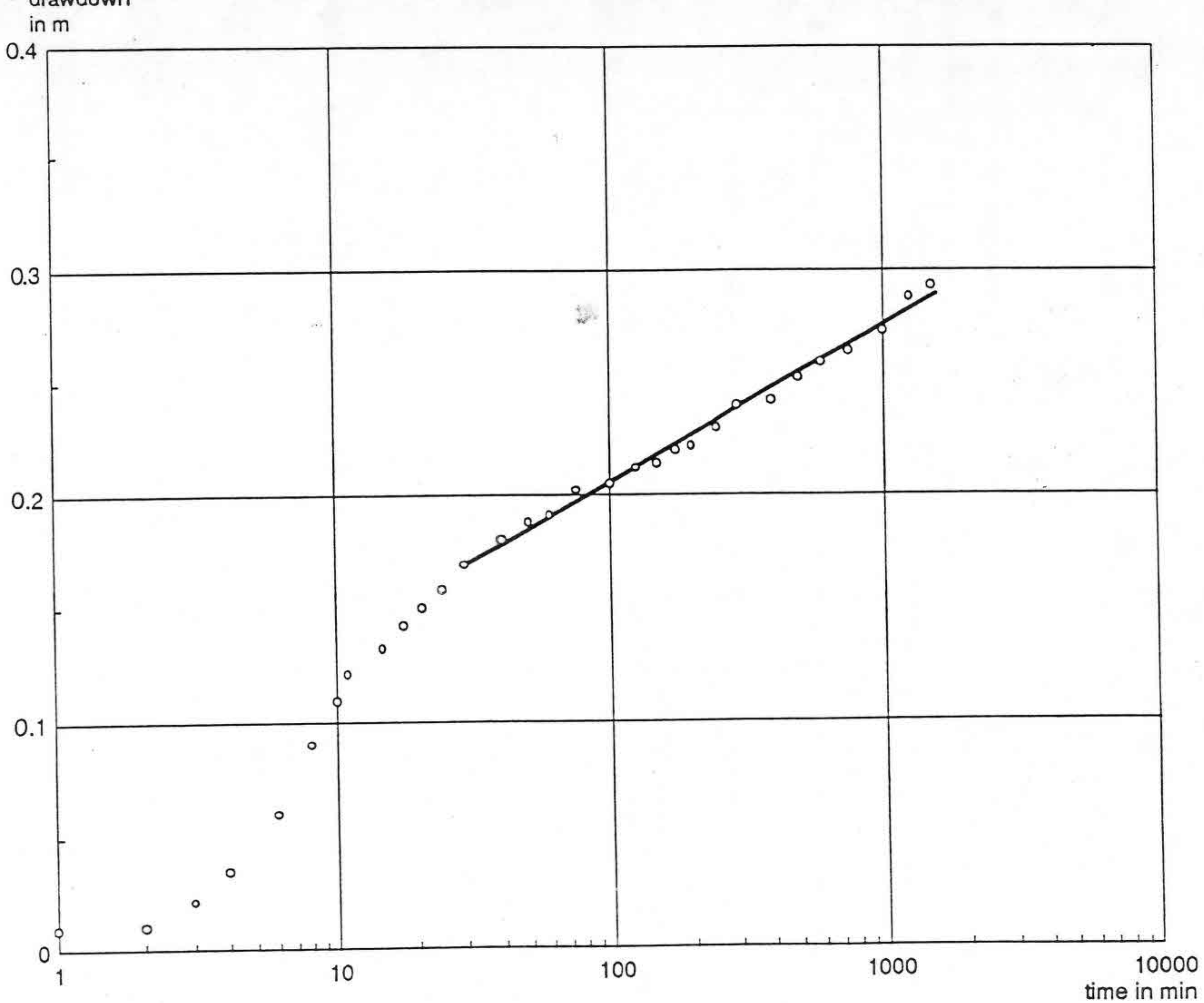


drawdown
in m
0.5
0.4
0.3
0.2
0.1
10^1
2
4
6
8
10^2
2
4
6
8
10^3
2
4
6
8
10^4
2
4
6
8
10^5
time in s

10.5.2 Partially-Penetrating Effect in Unconfined Aquifers

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 degree of penetration.

Hantush (1962) presented a solution for partially-penetrating wells in confined aquifers. Because of the large aquifer thickness, the induced drawdowns are usually relatively small, so Hantush's solution can also be applied to unconfined aquifers. Figure 10.19 shows the typical time-drawdown shape of a confined or unconfined aquifer pumped by a partially-penetrating well. The curve shows a curved-line segment, an inflection point, a second curved-line segment, and finally a straight-line segment under a slope.


drawdown
in m
0.4
0.3
0.2
0.1
0
1
10
100
1000
10000
time in min

10.5.3 Deviations in Late-Time Drawdown Data

Steepening of Late-Time Slope

All real aquifers are limited by geological or hydrological boundaries. If, however, 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 (e.g. a fault or an impermeable valley wall), it can expand no farther in that direction. The cone must expand and deepen more rapidly at the fault or valley wall to maintain the yield of the well.

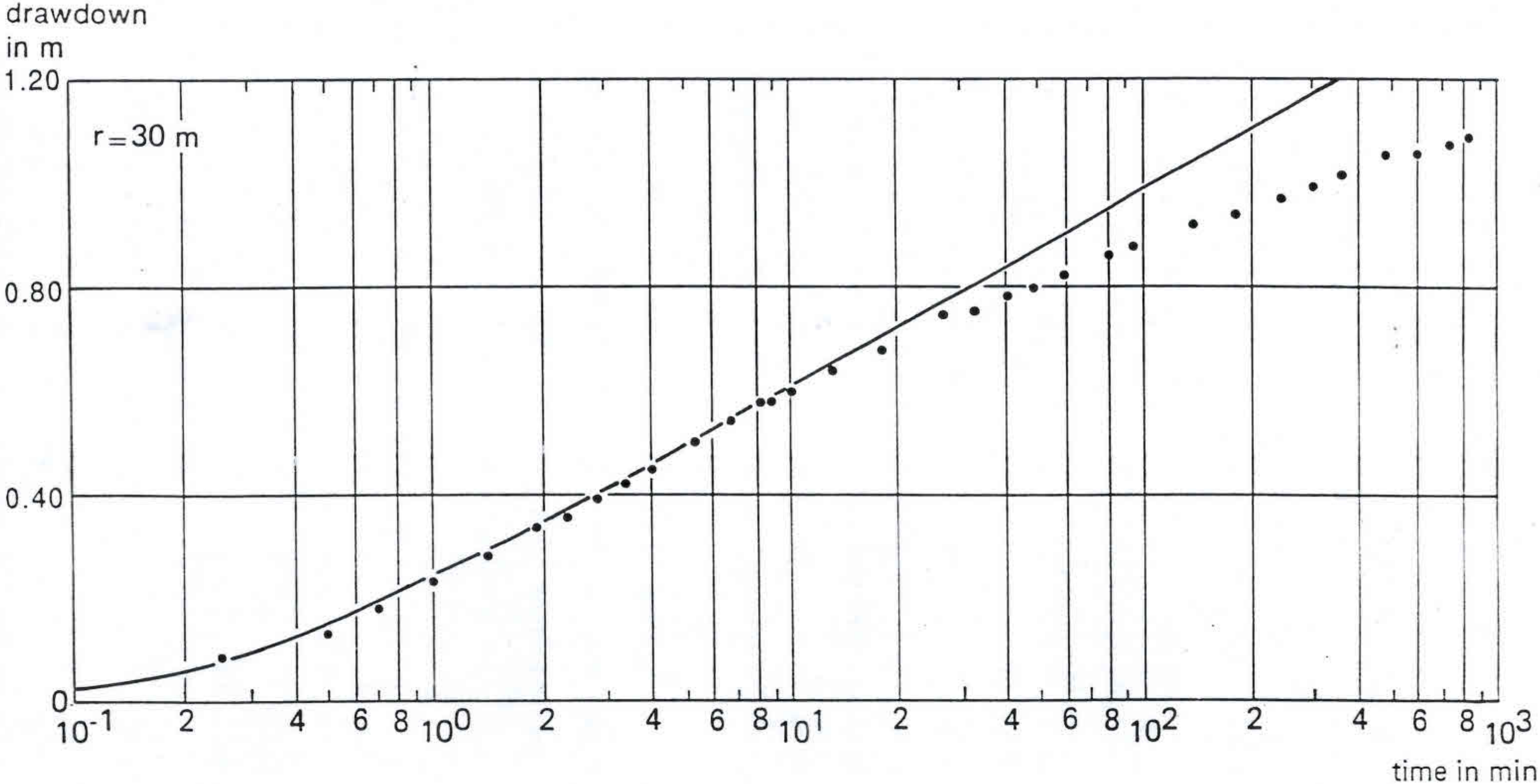
All the methods we have presented also assume that the tested aquifer is homogeneous within the area influenced by the pumping. This condition is never fully met. When, in one of the directions, the sediments become finer and the hydraulic conductivity decreases, the slope of the time-drawdown curve will become steeper when the cone of depression spreads into that area. The typical shape resulting from this phenomenon is identical to that of an impervious boundary. Well interference will also result in a similar phenomenon.

SPECIAL PHENOMENA

Flattening of Late-Time Slope

An opposite phenomenon is 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 (Figure 10.20). As a phenomenon, it resembles the recharge that occurs in a semi-confined aquifer. The same phenomenon occurs when, in one of the directions, the hydraulic conductivity or the aquifer thickness increases.

The above cases will result in time-drawdown plots in which the last part of the late-time drawdown data will deviate from a straight line under a slope. This part of the plot should be disregarded when the slope of the straight-line segment is being determined.



drawdown
in m
1.20
0.80
0.40
0
r = 30 m
10^{-1}
2
4
6
8
10^{0}
2
4
6
8
10^{1}
2
4
6
8
10^{2}
2
4
6
8
10^{3}
time in min

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INTERNATIONAL COURSE ON LAND DRAINAGE ICLD

Workbook

2.3 GROUNDWATER SURVEY

BALANCES

DRAINAGE

From 19 August to 6 December 2002, Wageningen, The Netherlands

FORTYFIRST INTERNATIONAL COURSE ON LAND DRAINAGE
Wageningen – The Netherlands, 2002

Workbook

2.3. GROUNDWATER SURVEY BALANCES

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1995

Lecturer ICLD 2002

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ASSESSMENT OF DRAINABLE SURPLUS BY GROUNDWATER BALANCE ANALYSIS

1 Introduction

Analyses of water balances are necessary to calculate an area's drainable surplus (drainage requirement), which we define here as the quantity of water that flows into the groundwater reservoir in excess of the quantity that flows out under natural conditions. Removing the drainable surplus has two advantages: it prevents waterlogging by artificially maintaining a sufficiently deep watertable and it removes enough water from the root zone so that any salts brought in by irrigation cannot reach a concentration that would be harmful to crops.

Calculating the drainable surplus is a major problem in many irrigation and reclamation areas. The natural conditions in these areas are diverse, and different water resources may be involved in the calculations. It is therefore necessary to do field work on the general features of the groundwater regime and to study the water regime and its balances. A proper understanding of this regime allows the drainage engineer to predict how they will be affected by drainage and reclamation works.

The factors involved in calculating the drainable surplus are derived from analysis of the overall water balance of the study area. The balance method, however, can be used only if it is possible to determine directly all components of the water balance with sufficient accuracy. If the results of several independent balance analyses do not agree, the drainage engineer can compare the degree of discrepancy to get an idea of the reliability of the obtained data and to see if further observation and verification are necessary.

2 Water Balances

The water balance is defined by the general hydrologic equation, which is basically a statement of the law of conservation of mass as applied to the hydrologic cycle. In its simplest form, this equation reads

$$\text{Inflow} = \text{Outflow} + \text{Change in Storage} \tag{1}$$

The water balance method has four characteristic features. They are:
- A water balance can be assessed for any subsystem of the hydrologic cycle, for any size of area, and for any period of time;
- A water balance can serve to check whether all flow and storage components involved have been considered quantitatively;
- A water balance can serve to calculate the one unknown of the balance equation, provided that the other components are known with sufficient accuracy;
- A water balance can be regarded as a model of the complete hydrologic process under study, which means it can be used to predict what effect the changes imposed on certain components will have on the other components of the system or subsystem.

It is worth noting that the word 'area' is commonly used in the professional jargon to mean 'volume', i.e. a certain part of a three-dimensional flow domain. The process of 'making an overall water balance for a certain area' thus implies that an evaluation is necessary of all inflow, outflow, and water storage components of the flow domain as bounded by the land surface, by the impermeable base of the underlying groundwater reservoir, and by the imaginary vertical planes of the area's boundaries.

2.1 Time and Flow Domain

Water balances are often assessed for an average year. But waterlogging and salinity problems are not of the same duration or frequency throughout the world. In some regions, they are permanent: in marshy areas, which are topographic depressions with a permanently high watertable caused by a combination of surface and subsurface inflow. In others, they are temporary: in areas of incidentally high rainfall or in irrigation areas that receive large quantities of surface water only during the irrigation season. In both cases, the watertable rises to an unacceptable level because the natural drainage of the area cannot cope with the excessive recharge of the groundwater reservoir.

If the watertable remains high for long periods, crop yields will diminish. In areas where waterlogging occurs, it is necessary to assess water balances not only for an average year, but also for specific years and even for specific seasons (e.g. the growing season, the irrigation season, or, in irrigation areas in arid and semi-arid climates, the period of leaching the soil to prevent salinization).

Let us say that we want to make a water balance study of a certain surface area. We can choose from two types of flow domains. They are:

- Flow domains comprising physical entities: river catchments and physical groundwater reservoir;
- Flow domains comprising only parts of physical entities: irrigation schemes and areas with shallow watertables).

Irrigation areas and areas in need of drainage usually cover only part of a river catchment or groundwater reservoir. Therefore, it is necessary to account for surface and subsurface inflow and outflow across the vertical planes of the boundaries of these areas. If we determine all their inflow, outflow, and water storage components, we can assess the overall water balance. This is how water balance studies for water resources study are usually done.

In overall water balances, we consider the flow domain vertically - from the soil surface to the impermeable base of the groundwater reservoir. The impermeable base may consist of massive hard rock or of a clay layer whose permeability for vertical flow is so low that it can be regarded as impermeable. Three reservoirs occur in this flow domain: at the surface itself, in the zone between the surface and the watertable, and in the zone between the watertable and the impermeable base. Because the reservoirs are hydraulically connected, it is often necessary to assess partial water balances for each of them in order to specify the drainable surplus. These water balances are referred to here as the surface water balance, the water balance of the unsaturated zone, and the groundwater balance. We shall discuss them in more detail in the sections that follow.

It is important to note that, at certain depths, there can be clay layers that behave more like aquitards than like aquicludes. The occurrence of these aquitards implies the presence of one or more confined aquifers underneath. In principle, then, it is possible to consider either a multiple aquifer system as a whole or the shallow aquifer alone. In water balance studies for subsurface drainage, it is common to consider only the shallow aquifer. This approach makes it necessary to consider the possible interaction between the deeper, confined water and the shallow, unconfined water.

2.2 Water Balance of the Unsaturated Zone

For any water resources study, it is absolutely essential to understand the water regime in the unsaturated zone, which extends from the land surface to the watertable. It is in this zone that favourable conditions for crop growth must be created. Some components of a water-balance study of the unsaturated zone are:

- Determine the soil-water storage;
- Assess the soil-water balance and define the relation between it, the water balance of the underlying saturated zone (zone below the watertable), and the hydrometeorlogical factors;
- Assess the infiltration, evaporation and evapotranspiration, seepage and percolation, and groundwater movement.

Figure 1 shows the three subzones of the unsaturated zone: the soil-water zone, the intermediate vadose zone, and the capillary fringe. The soil-water zone extends from the surface down through the major root zone of crops and vegetation. It is not saturated except for the times when the land surface receives water from precipitation or (in irrigated areas) for irrigation. Its thickness varies with soil type and with the types of crops and vegetation, ranging from less than one metre to several metres.

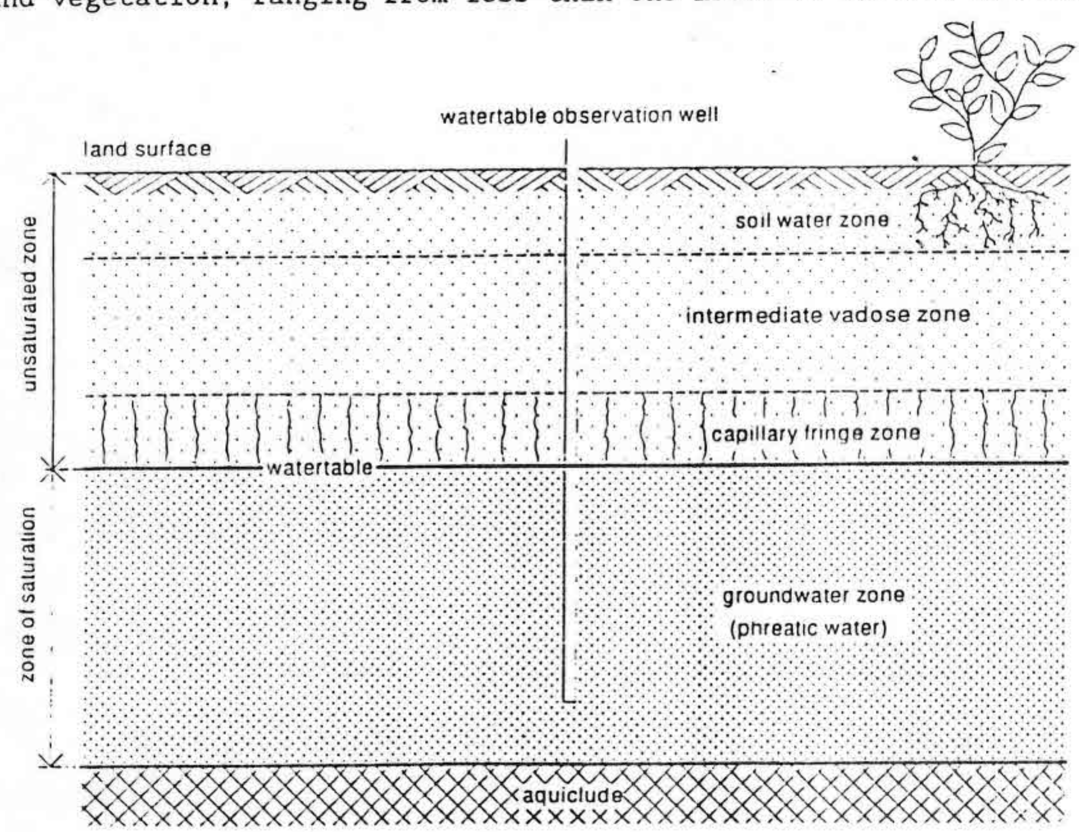

Figure 1 Three different subzones of the unsaturated zone

In areas with a shallow watertable, the capillary fringe may extend into the root zone of the crops and vegetation. A vertical flux from the saturated zone may then develop and move up into the unsaturated zone, from where it is removed by evapotranspiration. The rate of capillary rise, and the subsequent evaporation at the surface, decrease as the depth of the watertable increases.

Infiltrating rain and irrigation water increase the soil-water content and can cause the watertable to rise. The time required for the infiltrating water to reach the watertable increases in proportion to the depth of the watertable. Clearly then, if we want to assess the water balance of the unsaturated zone, we must consider all waters that infiltrate into it due to precipitation, irrigation, and seepage. We must know not only the maximum water-holding capacity of the soil, but also the amount of moisture stored in the zone, the actual rate of evapotranspiration of the crops, the percolation to the groundwater, and the rate of capillary rise from the groundwater. The water balance of the unsaturated zone reads

$$I - E + G - R = \frac{\Delta W_u}{\Delta t} \tag{2}$$

where

I	=	the rate of infiltration into the unsaturated zone (mm/d)
E	=	the rate of evapotranspiration from the unsaturated zone (mm/d)
G	=	the rate of capillary rise from the saturated zone (mm/d)
R	=	the rate of percolation to the saturated zone (mm/d)
ΔW_u	=	the change in soil water storage in the unsaturated zone during the computation interval of an equivalent layer of water (mm)
Δt	=	the computation interval of time (d)

The common assumption is that the flow direction in the zone is mainly vertical, so no lateral flow components occur in the water balance. Note that in areas with deep watertables, the component G will disappear from the water balance equation of the unsaturated zone.

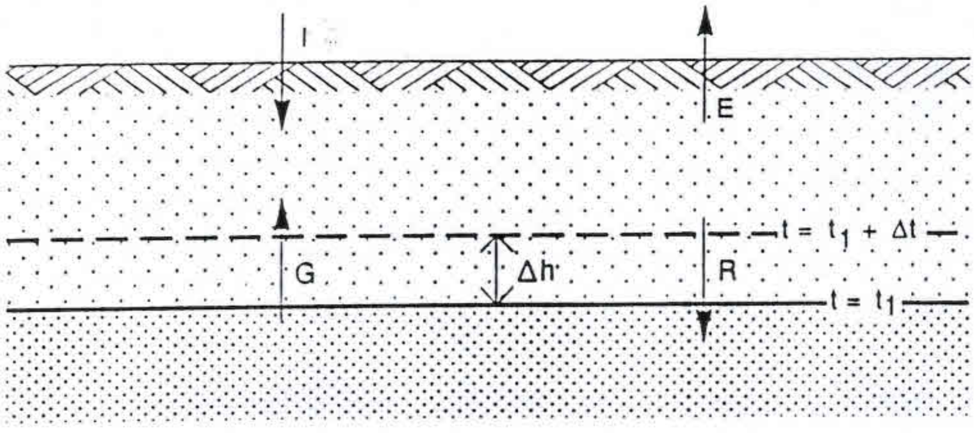

Figure 2 Water-balance components of the unsaturated zone

In Figure 2, a rise in the watertable Δh (due to downward flow from, say, infiltrating rainwater) is depicted during the time interval Δt. Conversely, during a period of drought, we can expect a decline in the watertable due to upward flow from capillary rise and to subsequent evapotranspiration by the crops and natural vegetation. In both situations, it should be certain that the position of the watertable at the beginning and the end of the time interval is what accounts for the change in the volume of the unsaturated zone and for the inherent change in soil-water storage.

Most of the components of Equation 2 cannot be measured in the field. Some components can be assessed only from combinations of other, partial water balances.

2.3 Water Balance at the Land Surface

Because the rate of infiltration (I) in Equation 2 is the recharge into the unsaturated zone, its value is related to the inflow and outflow components of the surface water balance. These components are:

- Water that reaches the land surface from precipitation;
- Water that enters the water balance area by lateral surface inflow and leaves it by lateral surface outflow;
- Water that evaporates from the land surface.

The difference between the components is due to changes in surface water storage. Infiltration in the unsaturated zone can therefore be expressed by the following equation

$$I = P - E_o + 1000\,\frac{Q_{si} - Q_{so}}{A} - \frac{\Delta W_s}{\Delta t} \qquad (3)$$

where

- P = precipitation for the time interval Δt (mm)
- E_o = evaporation from the land surface (mm/d)
- Q_{si} = lateral inflow of surface water into the water balance area (A) (m^3/d)
- Q_{so} = lateral outflow of surface water from the water balance area (A) (m^3/d)
- A = the water balance area (m^2)
- ΔW_s = the change in surface water storage (mm)

In irrigated areas, the major input and output of a water balance are usually determined by two artificial components, namely the application of water for irrigation and in arid zones for leaching the soil, and the removal of excess irrigation water (surface drainage) and excess groundwater (subsurface drainage).

Figure 3 shows the components of the surface water balance in an area of basin irrigation. On the left, an irrigation canal delivers surface water to an irrigation basin (Q_{ib}). A portion of this water is lost through evaporation to the atmosphere (E_{ob}). Another portion infiltrates at the surface of the basin (I_b), increasing the soil-water content in the unsaturated zone. Any surface water that is not lost through either

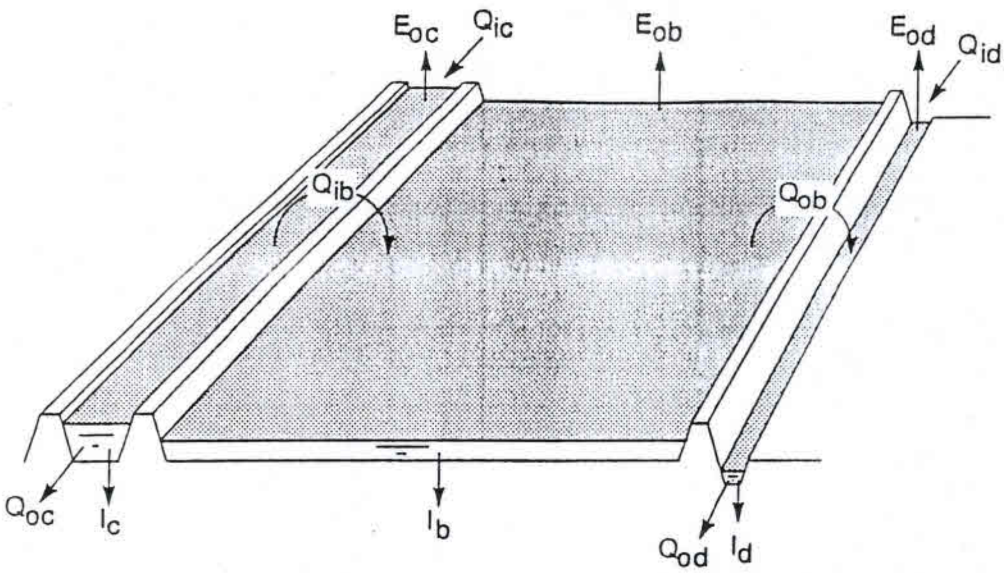

Figure 3 Surface water balance components for a basin-irrigated area

evaporation or infiltration is discharged downslope by a surface drain (Q_{ob}). Both the irrigation canals and the surface drains lose water through evaporation (E_{oc} + E_{od}) to the atmosphere and through seepage to the zone of aeration (I_c + I_d).

We can still describe the surface water balance in this area with Equation 3 if we substitute (Q_{ic} + Q_{id}) for Q_{si}, and (Q_{oc} + Q_{od}) for Q_{so}. Note that infiltration (I) now comprises the combined effect of the infiltration of rainfall, the infiltration of irrigation water at the fields, and the seepage losses of the irrigation canals and the surface drains to the unsaturated zone. Note also that E_o comprises not only evaporation of rainwater that did not infiltrate into the soil, but also evaporation of water in canals, basins, and drains.

2.4 Groundwater Balance

The water balance for the saturated zone, also called the groundwater balance, can generally be expressed as follows (see Figure 4)

$$R - G + 1000\,\frac{Q_{gi} - Q_{go}}{A} = \mu\,\frac{\Delta h}{\Delta t} \qquad (4)$$

where

- Q_{gi} = Q_{gih} + Q_{giv} = the total rate of groundwater inflow into the shallow unconfined aquifer (m^3/d)
- Q_{go} = Q_{goh} + Q_{gov} = the total rate of groundwater outflow from the shallow unconfined aquifer (m^3/d)
- Q_{gih} = the rate of horizontal groundwater inflow into the shallow unconfined aquifer (m^3/d)
- Q_{goh} = the rate of horizontal groundwater outflow from the shallow unconfined aquifer (m^3/d)
- Q_{giv} = the rate of vertical groundwater inflow from the deep confined aquifer into the shallow unconfined aquifer (m^3/d)

Q_{gov} = the rate of vertical groundwater outflow from the shallow unconfined aquifer into the deep confined aquifer (m^3/d)
μ = the specific yield or effective porosity, as a fraction of the volume of soil (-)
Δh = the rise or fall of the watertable during the computation interval (mm)

and the other symbols as defined earlier.

When the layer beneath the shallow unconfined aquifer is impermeable, the rates of vertical groundwater inflow and outflow equal zero, the total groundwater inflow equals the horizontal groundwater inflow, and the total groundwater outflow equals the horizontal groundwater outflow.

The base of an unconfined aquifer is, in reality, seldom impermeable; it is the first clay layer struck at some depth during borehole drilling. In sandy areas, groundwater underlying the 'impermeable' base is confined. In discharge areas of the groundwater system, the aquifer receives confined water from beneath, and the quantity of inflow per computation interval of time must be included in the water balance. The total groundwater inflow is then equal to the sum of horizontal and vertical inflow.

In irrigation areas, the watertable in the unconfined aquifer can be appreciably higher than the piezometric surface in the deep aquifer. The resulting downward seepage from the shallow aquifer to the deep aquifer, over the time interval Δt, must then be included in the water balance. The total groundwater outflow then equals the sum of horizontal and vertical outflow. This flow constitutes what is called the 'natural drainage' of the area. In areas with an operational field drainage system, the drain discharge should be a separate component of the water balance.

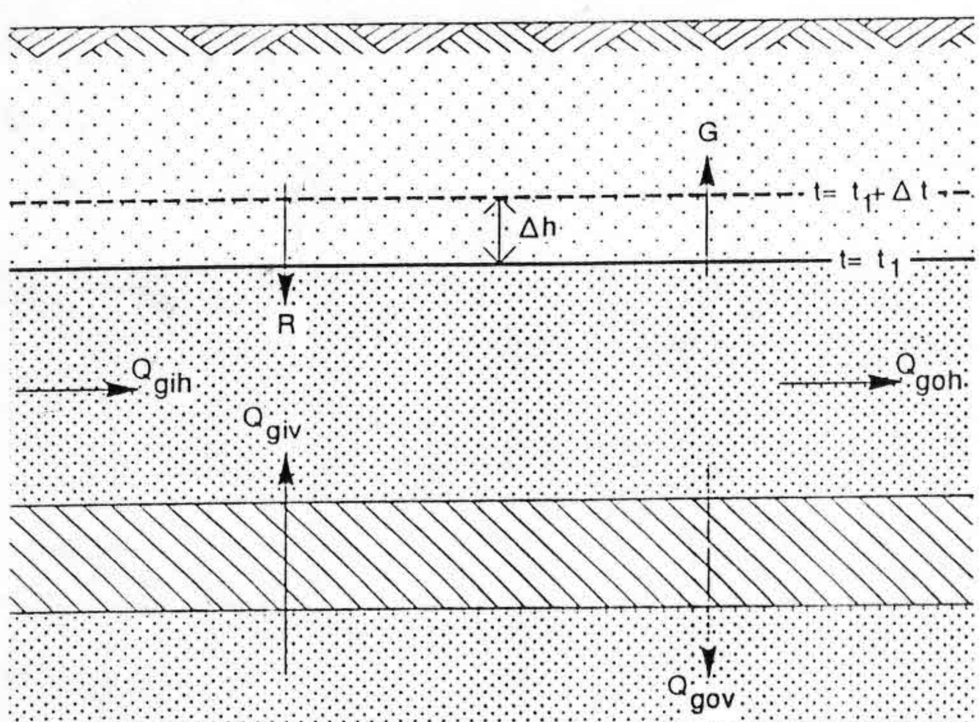

Figure 4 Groundwater balance components of the shallow aquifer of a multiple aquifer system

We can determine the horizontal groundwater inflow and outflow through the boundaries of the area by using watertable contour maps, which show the direction of groundwater flow and the hydraulic gradient, and by considering transmissivity at the boundary. We can determine upward and downward seepage through an underlying semi-confined layer by considering vertical gradients and the shallow aquifer's hydraulic resistance. And we can calculate the change in storage by using groundwater hydrographs and the specific yield or drainable pore space of the shallow aquifer.

To get the data necessary for these direct calculations of horizontal and vertical groundwater flow, and of the actual amount of water going into or out of storage, we must install deep and shallow piezometers and conduct aquifer tests.

In some areas with limited surface water resources, groundwater is used both for human consumption and for irrigation. When this occurs, the rate of groundwater abstraction must be accounted for in the water balance. If pumped wells provide irrigation water, we must keep track of the amount of return flow, i.e. the portion of the total groundwater abstraction that returns to the deeper layers and so recharges the groundwater reservoir. Return flow must also be accounted for in the water balance.

According to Equation 4, we can calculate the value of the net recharge as $Q_n = R - G$. In areas with deep watertables, there is no upward flux by capillary rise, and so the actual percolation equals the calculated net recharge. In areas with shallow watertables, it is possible to determine only the net recharge.

2.5 Integrated Water Balances

The partial water balances that we discussed in the three previous sections are often combined to form integrated water balances. For example, by combining Equations 2 and 3, we get the water balance of the topsoil

$$P - E_o - E + G - R + 1000\ \frac{Q_{si} - Q_{so}}{A} = \frac{\Delta W_s + \Delta W_u}{\Delta t} \qquad (5)$$

To assess the net recharge $Q_n = R - G$, we can use Equation 5. We can also assess this value from the groundwater balance (Equation 4). And, if sufficient data are available, we can use both of these methods and then compare the net recharge values obtained. If the values do not agree, the degree of discrepancy can indicate how unreliable the obtained data are and whether or not there is a need for further observation and verification.

Another possibility is to integrate the water balance of the unsaturated zone with that of the saturated zone. Combining Equations 2 and 4, we get the water balance of the aquifer system

$$I - E + 1000\ \frac{Q_{gi} - Q_{go}}{A} = \frac{\Delta W_u}{\Delta t} + \mu\ \frac{\Delta h}{\Delta t} \qquad (6)$$

We can assess the infiltration from Equation 6, provided we can calculate the total groundwater inflow and outflow, the change in storage, and the actual evapotranspiration rate of the crops. We can also assess the infiltration from the surface water balance (Equation 3). And, if sufficient data are available, we can follow the same procedure we followed above.

Finally, let us integrate all three of the water balances described in the previous sections. This overall water balance reads

$$P - E_o - E + 1000 \frac{Q_{si} - Q_{so}}{A} + 1000 \frac{Q_{gi} - Q_{go}}{A} = \frac{\Delta W_u}{\Delta t} + \frac{\Delta W_s}{\Delta t} + \mu \frac{\Delta h}{\Delta t} \quad (7)$$

Equation 7 shows that the vertical flows I, R, and G (all important linking factors between the partial water balances) disappear in the overall water balance. Nevertheless, these linking factors determine to a great extent whether there are drainage problems or not.

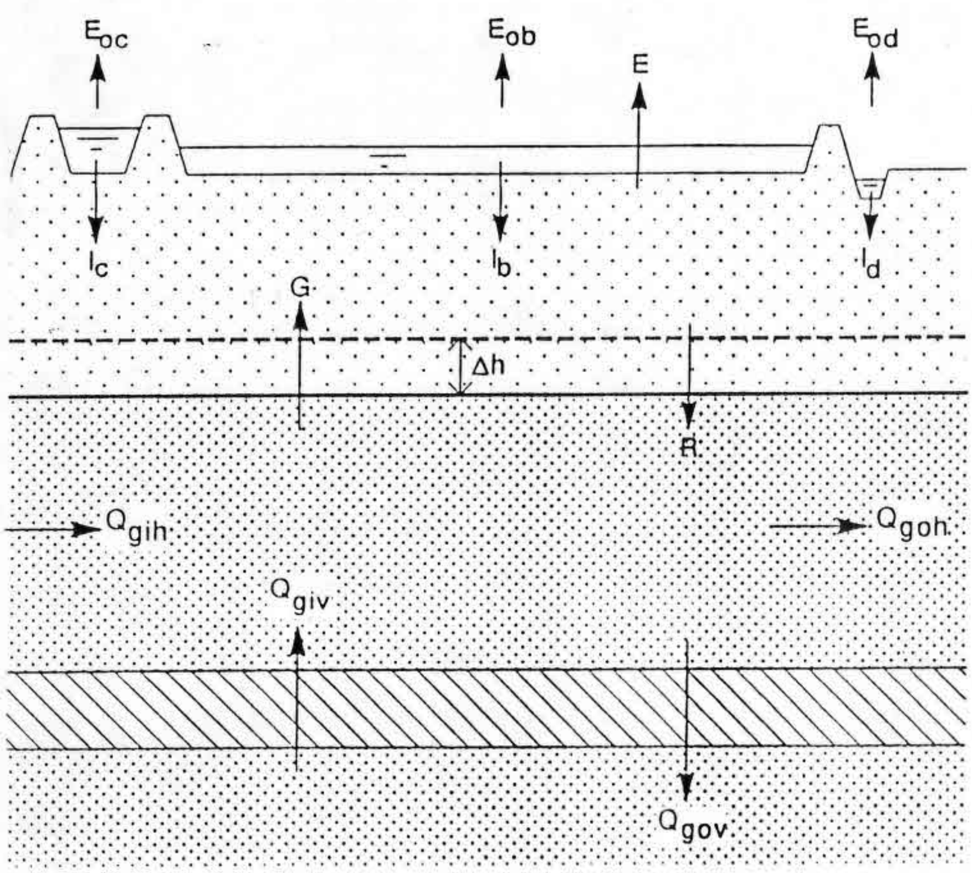

Figure 5 Overall water balance components for a basin-irrigated area

For an example, let us look at Figure 5, which shows all the terms of the overall water balance for an area with basin irrigation. The overall water balance can be described by Equation 7 if we make the following substitutions:

- $E_o = E_{oc} + E_{ob} + E_{od}$
- $Q_{si} = Q_{ic} + Q_{id}$
- $Q_{so} = Q_{oc} + Q_{od}$
- $Q_{gi} = Q_{gih} + Q_{giv}$
- $Q_{go} = Q_{goh} + Q_{gov}$

When water balances are assessed for a hydrologic year, changes in storage in the various partial water balances can often be ignored or reduced to zero if the partial balances are based on long-term average conditions. In Equations 2 to 7, the sum of the various inflow components then equals the sum of the various outflow components.

3 Numerical Groundwater Models

The process of setting up various water balances can be complicated and time-consuming. Spatial variation in the contributing components can make it necessary to split up the study area into various sub-areas. Each of the sub-areas will require a separate water balance, and all of these balances will have to be aggregated. In addition, the sub-areas may require a monthly water balance, and these will also have to be aggregated if a seasonal or annual water balance is needed.

These problems of spatial and temporal variation are quite often oversimplified or even neglected when water balances are being set up manually. To avoid the risk of oversimplification, it is recommended to use numerical groundwater models to solve the problems.

A groundwater model can be defined as a simplified version of the real groundwater system, describing the features essential to the purpose for which the model was developed and including various assumptions and constraints pertinent to the system. It expresses the conceptual representation of the system in causal relationships among the system's various components and between the system and its environment.

The model should at first be used principally as a tool to synthesize data, to match, for instance, known responses to pumping, and to test various hypotheses of how the real hydrologic system may function. Subsequently, it may be developed into, or used conjunctively with, decision models to aid in planning and management more directly. Alternative development schemes can be tested in a search for optimal ones.

Groundwater models are based on two well-known equations: Darcy's equation and the equation of conservation of mass. The combination of these two equations results in a partial differential equation that can be solved by numeric approximation. The two best-known approximation methods are the finite difference method and the finite element method. Both require that space be divided into small but finite intervals. The sub-areas thus formed are called nodal areas, as they each have a node that connects it mathematically to its neighbours. The nodal areas make it possible to replace the partial differential equation with a set of algebraic equations.

3.1 Types of Models

There are many types of groundwater models, but for our purposes let us start with a description of steady-state and unsteady-state models. As their name suggests, steady-state models assume that groundwater flow is in steady state, i.e. that the hydraulic heads do not change with time, and that the change in storage is equal to zero. Steady-state models are often used in situations where the hydrologic conditions are either average or do not change much over time. Unsteady-state models assume that the hydraulic heads change with time. Although these models are better at simulating the actual behaviour of groundwater systems, they require far more input data than do steady-state models. Because these data are scarce, unsteady-state models are not used as often as steady-state models.

For both types of models, we must input the geometry of the aquifer system, the type of aquifer, and the hydraulic characteristics of the aquifer. Although there may be variation from one node to another, we can assume that within a nodal area these data are constant and time-independent.

For steady-state models, we must prescribe net recharge values for the internal nodes and boundary conditions for the external nodes. Components of net recharge are recharge of the groundwater system by rainfall and/or irrigation, and discharge from the groundwater system by tubewell pumpage, capillary rise, and/or artificial drainage. As boundary conditions, we must prescribe either a constant head or a constant flux.

Time simulation in unsteady-state models is a succession of small but finite intervals. For each of these time steps, specific values of net recharge and boundary conditions must be prescribed, as they may change with time. Initial conditions must also be prescribed. Usually, we can interpolate the values of the head at the internal nodes from a watertable contour map.

Now that we have considered these models, let us look at prediction models. Prediction models simulate the behaviour of the groundwater system and its response to net recharge. They are categorized as either unsaturated-zone models, saturated-zone models, or integrated models.

Unsaturated-zone models simulate vertical, one-dimensional flow. They use a succession of different soil layers, usually extending from the land surface to the saturated zone, to represent a vertical soil column. To each of these soil layers, they attribute a soil-moisture retention curve and values of the hydraulic conductivity as a function of soil-moisture content. In addition, they require values for the initial moisture content in the profile and for the boundary conditions at the top and bottom of the column. The boundary conditions at the top are described by values of rainfall, potential soil evaporation, and potential evapotranspiration. The boundary conditions at the bottom are described by pressure head or flux conditions. The soil layers themselves may consist of various compartments. Each compartment is represented by a nodal point; the values for pressure head, unsaturated hydraulic conductivity, and soil moisture content are calculated at these points.

Saturated-zone models simulate the horizontal, two-dimensional flow. They discretize the aquifer system into a network of nodal areas. To each nodal area, they attribute values for the thickness, the saturated hydraulic conductivity, the specific yield, and the storage coefficient. In addition, they require values for the initial hydraulic heads in each nodal area and for the boundary conditions at the top and sides (lateral boundary conditions). We can obtain a value for the boundary conditions at the top by calculating the net recharge to the aquifer system from setting up a water balance for the unsaturated zone. To define the lateral boundary conditions, we can use hydraulic head conditions and flux conditions, but it is more common to use hydraulic head conditions.

A third type of prediction model is the integrated model. These models can integrate the flow in the unsaturated zone with the flow at the land surface, with the flow in the saturated zone, with both of these flows, and with crop production.

3.2 Inverse Modelling by SGMP

The present groundwater model is an updated version of SGMP. Appendix A gives a short summary on its features and restrictions, together with an overview of its input parameters. For more detailed information on its background, reference is made to Boonstra and de Ridder (1990).

Usually, hydraulic heads at the internal nodes are calculated as function of prescribed net recharge values which may vary in space and time. Based on these calculated hydraulic heads, the various relevant water-balance components - horizontal subsurface incoming and outgoing groundwater flow, change in groundwater storage - are calculated for each internal nodal area. When SGMP is run in this manner, it is referred to as running it in normal mode.

In the so-called inverse mode, SGMP calculates net recharge values for the internal nodal areas as function of prescribed, historical hydraulic heads at these nodes. These values are based on the following groundwater balance, which SGMP calculates for each nodal area separately (see Figure 6):

$$Q_{nb} = - \sum_{i} (h_i - h_b) \frac{W_{i,b} K_{i,b} D_{i,b}}{L_{i,b}} + A_b \mu_b \frac{\Delta h_b}{\Delta t} \qquad (8)$$

where

Q_{nb}	= net recharge to aquifer in nodal area b
h_b	= absolute watertable elevation at node b
h_i	= absolute watertable elevations at nodes i
$W_{i,b}$	= length of nodal area side between nodes i and b
$K_{i,b}$	= horizontal hydraulic conductivity of aquifer along $W_{i,b}$
$D_{i,b}$	= saturated thickness of aquifer along $W_{i,b}$
$L_{i,b}$	= distance between nodes i and b
μ_b	= specific yield of aquifer in nodal area b
A_b	= area associated with node b
Δh_b	= increase in absolute watertable elevation over Δt
Δt	= size of time step

It should be noted that with groundwater balances the convention is that recharge to the aquifer, i.e. downward flow towards the watertable and horizontal groundwater flow entering a nodal area, is taken positive, while discharge from the aquifer, i.e. upward flow from the watertable and horizontal groundwater flow leaving a nodal area, is taken as negative. Absolute watertable elevations are expressed with respect to mean sea level. This implies that watertable elevations are expressed in a coordinate system with the vertical axis positive upward. So, $\Delta h > 0$ indicates a rise in watertable due to recharge from rainfall and/or irrigation, whereas $\Delta h < 0$ indicates a drop in watertable due to discharge from capillary rise and/or tubewell pumping.

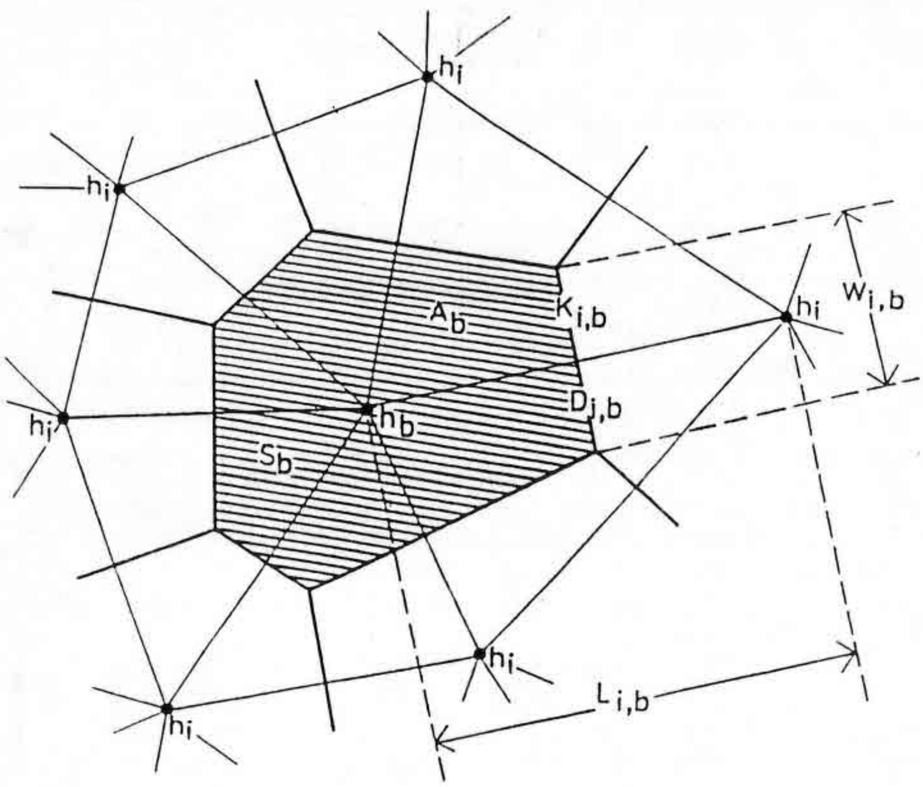

Figure 6 Nodal geometry

The application of SGMP in inverse mode also requires that both space and time should be discretized. To discretize the project area into nodal areas, a network of rectangles, squares, or polygons is superimposed on it. It is impossible to give any hard and fast rules on what network to apply and how to design it. Because of different geological and hydrogeological conditions, a network that is appropriate in one project will be inappropriate in another; similarly, a network appropriate for one problem will be inappropriate for another. In designing a nodal network, the following factors should be considered: the type of problem to be solved; the required accuracy of the results; the homogeneity or heterogeneity of the aquifer; the availability of data.

With respect to the discretization in time, the availability of historical, observed watertable elevations as function of time will determine to a large extent the selection of the time steps. If, for instance, the watertable observation network is monitored for groundwater depth on a monthly basis, we will run SGMP in successive time steps of one month. If such a network is monitored only twice a year as is commonly practiced in India and Pakistan, SGMP will be run one a seasonal basis, i.e. a succesion of one time step of four month representing the monsoon period and the other of eight months representing the non-monsoon period.

Inverse modelling with SGMP will thus result in monthly, sesasonal or yearly average net recharge values on a nodal basis, depending upon the time interval of watertable measurements. As simulation period, we advise a period of at least a few years. Summarizing, the following data are required for inverse modelling:

- topographical map with sufficiently small contour intervals. If such a map is not available for the project area, a special topographical survey will be required.
- type and extent of the aquifer system underlying the project area: this information can be obtained from the geological department, reports on tubewell exploration, and/or from previous groundwater resources studies.
- values for the hydraulic characteristics of the aquifer system like hydraulic conductivity, saturated thickness, specific yield and storativity. This information can be obtained from the analysis of so-called aquifer tests and/or well tests. For information on this subject, reference is made to Boonstra (1989).
- watertable depth data of an observation network. Because SGMP needs absolute watertable elevations, the observation wells need to be levelled, i.e. reduced levels should be available for all observation wells.

The advantage of assessing the net recharge using the groundwater approach is that rather limited data are required. For instance, assessing the same net recharge using an integration of the water balance for the unsaturated zone with the water balance at the land surface as was discussed in Section 2.5 requires considerably more data (see also Figure 7):

- rainfall data like location of rainfall stations; daily rainfall data; calculation of areal rainfall;
- irrigation data like daily head delivery discharges of main branch canals, distributaries, minors; discharge capacities and location of outlets and their command areas;
- loss rates of rivers, various types of irrigation canals, drains;
- crop data like types of crop and their areas; fallow lands and their rotation;
- capillary rise data like classification of representative soil types; relationships between watertable depth and capillary rise; watertable depth data; climatological data for calculation evaporation;
- tubewell data like location of tubewells; assessment of draft by horse power engine, fuel consumption, electricity consumption, operating hours.

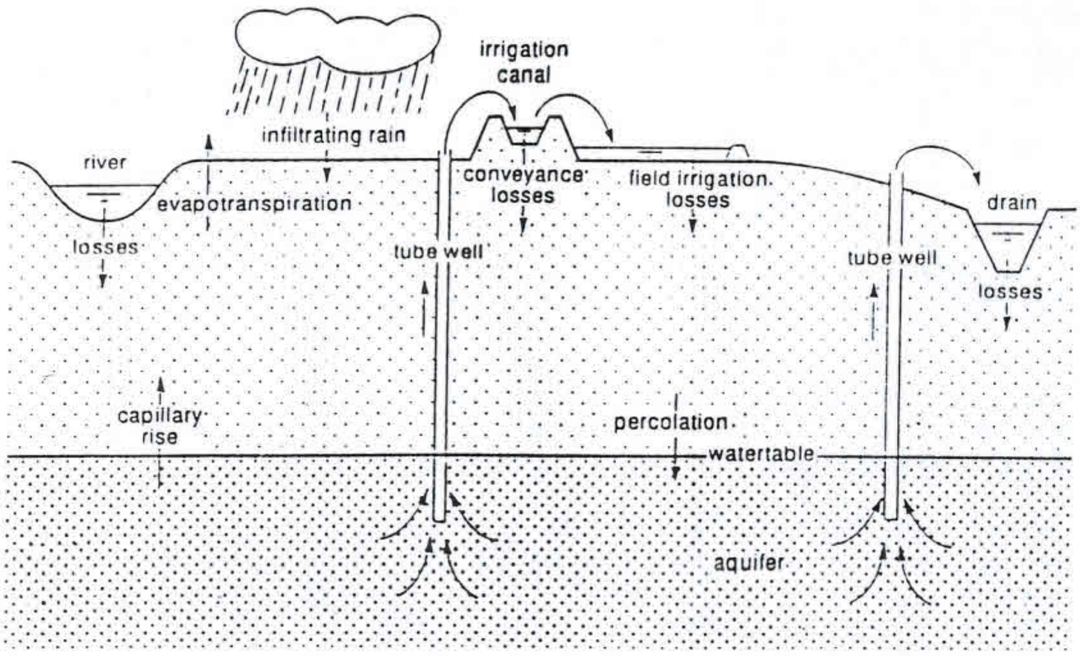

Figure 7 Flow components for an irrigated area with artificial drainage

The process of collecting and processing the above data, many of which vary in space and time, is rather time consuming and its reliability is also sometimes questionable. In that respect, it can be stated that assessing the net recharge to an aquifer system using a groundwater approach deserves more attention. Moreover, it can also serve as a check on the result of the above, integrated water balance approach.

References

Boonstra, J. and N.A. de Ridder, 1990. Numerical Modelling of Goundwater Basins. ILRI-Publication 29 (2nd ed.), Wageningen, The Netherlands, 226 pp.

Boonstra, J., 1989. SATEM: Selected Aquifer Test Evaluation Methods. ILRI-Publication 48, Wageningen, The Netherlands, 80 pp.

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41th INTERNATIONAL COURSE ON LAND DRAINAGE ICLD

2.3 GROUNDWATER BALANCES
CASE STUDY HANSI

DRAINAGE

From 19 August to 6 December 2002, Wageningen, The Netherlands

2.3 GROUNDWATER BALANCES CASE STUDY HANSI

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Lecture notes for the International Course on Land Drainage are not official publications. They may be altered from year to year. Lecture notes have been published as: Drainage Principles and Applications, ILRI Publication 16, Wageningen 1974, and as a revised version in 1994.

Subject: CASE STUDY HANSI (GROUNDWATER FLOW)

Schedule: Preferably in blocks of 2 or 4 hours on consecutive days.

Lecture notes: Hand out (Exercise + Solutions)

Objectives:
- To exercise the preparation of watertable contour, depth to watertable and groundwater salinity maps in the irrigated Hansi farm (136 ha)
- To exercise the Thiessen polygon for aquifer transmissivities
- To exercise the preparation of a flow net
- To analyze the groundwater flow
- To calculate natural drainage and to make the relation with depth to watertable and soil salinity

Method of instruction:
Learning while doing. Participants elaborate the excercise described in the hand out. The lecturer gives explanations and background information while the exercise is in progress.

Material requirements:
- Pen/pencil, ruler, calculator and linear graphic paper for each participant.
- Overhead sheets of lecture notes, problems and solutions.
- Overhead projector in the classroom.
- Blackboard/whiteboard with markers in classroom
- Coffee and tea

Related subjects:
- Publ. 16, ILRI 1994, Chapter 2: Groundwater Investigations
- Publ. 16, ILRI 1994, Chapter 16: Analysis of Water Balances

INTRODUCTION

The aim of this case study is to give you some experience in:

- Drawing a depth-to-watertable map;
- Drawing a groundwater contour map;
- Drawing a groundwater salinity map;
- Analyzing a groundwater regime;
- Applying a flow net analysis;
- Calculating the natural drainage from an area.

For this case study, we have chosen a world-wide problem: the salinization of soil and groundwater as a result of irrigation.

A rectangular farm (Hansi), 1600 m long and 850 m wide (area = 136 ha), is located in a flat alluvial plain (Figure 1). An irrigation canal crosses the farm approximately in the middle. The crops cultivated on the farm are irrigated with water from this canal. Rice is grown in a strip on both sides of the canal, and cereals and other field crops on the remaining parts of the farm.

The lands surrounding the farm are also cultivated, but because of the shortage of irrigation water, they are not supplied with water from the canal. Some farmers have a shallow hand-dug well and use its water to irrigate small patches of the land. The groundwater table in the surrounding lands is deeper than in the Hansi farm. Natural subsurface drainage occurs from the farm to the surrounding lands. The farm has no salinity problems, but the surrounding lands are threatened by salinization.

During the irrigation season it was found that the groundwater table in parts of the farm was rather shallow, and the question arose whether the land needed artificial drainage. Shallow piezometers were placed in a regular grid, and monthly readings were made of their water levels. Groundwater samples were taken from the piezometers and their electrical conductivity was determined.

AVAILABLE DATA

Figure 1 shows the absolute watertable elevations above mean sea level on a certain date n the irrigation season.

Figure 2 shows the transmissivity values ($T = KH$ m^2/day) at the locations where aquifer tests were conducted in the past.

Figure 3 shows the depth to the watertable in the piezometers on the same date as that of Figure 1.

Figure 4 shows the electrical conductivity values of the groundwater in the piezometers on the same date as that of Figures 1 and 3.

ASSIGNMENT

- Make a depth-to-watertable map based on the depth-to-watertable data as shown in Figure 3 using a contour interval of 0.5 m. In drawing lines of equal depth-to-watertables, use the values of 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, and 3.5 metres below land surface. What is your conclusion?

- Make a groundwater contour map based on the absolute watertable elevation data as shown in Figure 1 using a contour interval of 0.5 m. In drawing lines of equal absolute watertable elevations, the so-called groundwater contours, use the values of 6.5, 7, 7.5, 8. 8.5, 9, and 9.5 metres above sea level. What conclusion can be drawn about the direction of groundwater flow?

- Make an electrical conductivity map based on the EC data as shown in Figure 4. In drawing lines of equal EC, use the limits of 1, 2, 4, 8 and 16 millimhos/cm. Compare the three maps you have drawn. What are your conclusions?

- Calculate the rate of natural drainage from the farm. For this purpose, use the groundwater contour map and construct a flow net along the boundaries of the farm (the pairs of equipotential lines and of flow lines should form "squares"). When you have completed the flow net, use the transmissivity values (T = kD) of Figure 2 and apply Darcy's equation to calculate the natural drainage. Express your answer in mm/day;

GUIDELINES IN MAKING A FLOW NET

- To construct the first "square", select a pair of equipotential lines that run along both sides of the boundary of the water-balance area. Draw a first flow line at an arbitrarily chosen location; the smoothly-drawn flow line should intersect both equipotential lines at right angles. Draw a second flow line in such a manner that the distance between the two equipotential lines midway between the two flow lines is equal to the distance between the two flow lines midway between the two equipotential lines. So, a square will generally have four slightly curved sides;
- To construct the next square, use the same pair of equipotential lines if these lines still follow the boundary of the water balance area. Draw the next flow line. If the equipotential lines start to deviate from the area boundary, extend the flow line to another pair of equipotential lines that do follow the boundary. The squares should follow the boundaries of the water balance area as closely as possible;
- Continue this process until the last flow line drawn coincides with the first flow line drawn, i.e. until the water balance area is fully enclosed by squares.

It is advised to start making the first square in the top right corner of the irrigated farm using the pair of groundwater contour lines of 7.5 and 8.0 metres above sea level, and to continue making the subsequent squares in a anti-clockwise direction following the boundaries of the farm.

DISCUSSION OF RESULTS

- Figure 16.12 shows the resulting depth-to-watertable map;
- Figure 16.13 shows the resulting groundwater contour map;
- Figure 16.14 shows the resulting electrical conductivity;
- Figure 16.15 shows the resulting flow net constructed along the farm boundaries.

Analyzing the groundwater regime

Figure 16.12 shows that the watertable in the middle of the farm is the most shallow: less than 1 m below land surface and, along the canal, even less than 0.5 m. This is caused partly by leakage from the canal, but mainly by the heavy percolation from the rice fields near the canal. In the other parts of the farm less irrigation water is supplied (cereals and field crops), percolation is less and the watertable is deeper: 2 to 3 m.

The direction of groundwater flow can be derived from the groundwater contour map (Figure 16.13). The flow direction is perpendicular to the contour lines (equipotential lines). In the middle of the farm near the canal, a groundwater mound has formed from which water flows in all directions. Everywhere along the borders of the irrigated farm groundwater flows away from the farm, except in the south-east where the boundary is nearly perpendicular to the groundwater contour lines. This means that this part of the boundary is a flow line through which, by definition, no groundwater flows. Along the other parts of the farm boundary the watertable gradient varies from about 1:200 to 1:400. This indicates that the underground is more or less homogeneous.

Figure 16.14 shows the electrical conductivity map of the shallow groundwater. The least salty groundwater is found in the middle of the farm, even though the watertable there is at its shallowest. The heavy percolation in this part of the farm prevents capillary rise and since groundwater flows away from this area in all directions, soil and groundwater cannot become salinized. In the direction of flow, however, the salinity increases rapidly, and just beyond the farm boundaries, i.e. in the non-irrigated areas, it reaches its highest values (EC = 20 to 25 millimhos/cm). Farmers in these areas suffer in three ways:

- They do not receive surface water from the canal for irrigation because it is short supply;
- They cannot use groundwater because it has become too salty;
- Their lands are in danger of becoming salinized because the inflow of groundwater from the irrigated farm.

The lesson to be learned here is that in solving the water supply problems for one particular area, new and severe problems can be created for neighbouring areas.

Calculating the natural drainage

To calculate the rate of groundwater outflow through the farm boundaries, we need data on the watertable gradient and on the transmissivity. Since the equipotential lines you have drawn in Figure 16.13 do not coincide with the farm boundaries but cross them obliquely, we must construct a flow net as shown in Figure 16.15. To construct a system of "squares" along the boundaries, it is necessary at some places to reduce the gradient from 0.50 to 0.25 or even to 0.10 (in the east). We can now apply the equation

$$Q = n \, \Delta h \, KH$$

Where n = the number of "squares"

Δh = the difference in hydraulic head

KH = the transmissivity of the aquifer

Starting in the north east and using Figure 2 for the values of KH, we have

$$Q = (1 \times 0.25 \times 250) + (5 \times 0.50 \times 250) + (3 \times 0.50 \times 260) + (7 \times 0.50 \times 170) + (6 \times 0.50 \times 290) + (2 \times 0.10 \times 350) + (1 \times 0.20 \times 350) + (1 \times 0.10 \times 350) = 2718 \text{ m}^3/\text{day}$$

Since the area of the farm A = 136 ha = 136 x 10^4 m^2, the groundwater outflow is equivalent to q = 2718 / (136 x 10^4) = 0.002 m/day = 2 mm/day.

Using the groundwater balance concept and assuming that steady state conditions prevailed in the period of observations, the net recharge towards the aquifer is also 2 mm/day. This value is, of course, an average for the irrigated farm as a whole. It can be expected that it will have a higher value in the middle of the farm because of leakage from the canal and of heavy percolation from the rice fields near the canal. Consequently, the net recharge will then have a lower value than 2 mm/day along the fringes of the irrigated farm.

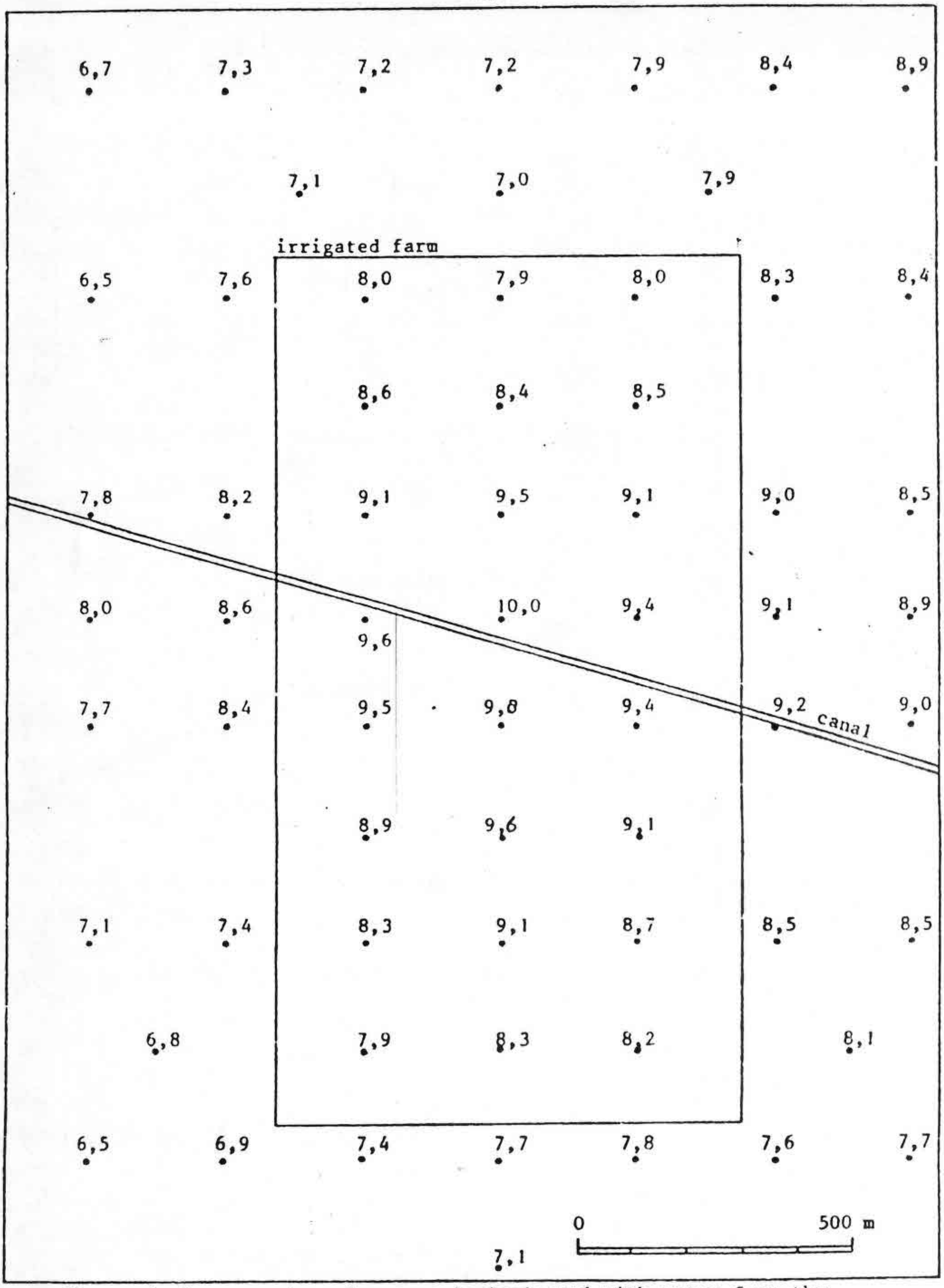

Figure 1 Inner rectangular area is irrigated with water from the canal. 8,0 observation well, watertable elevation 8,0 m above sea level

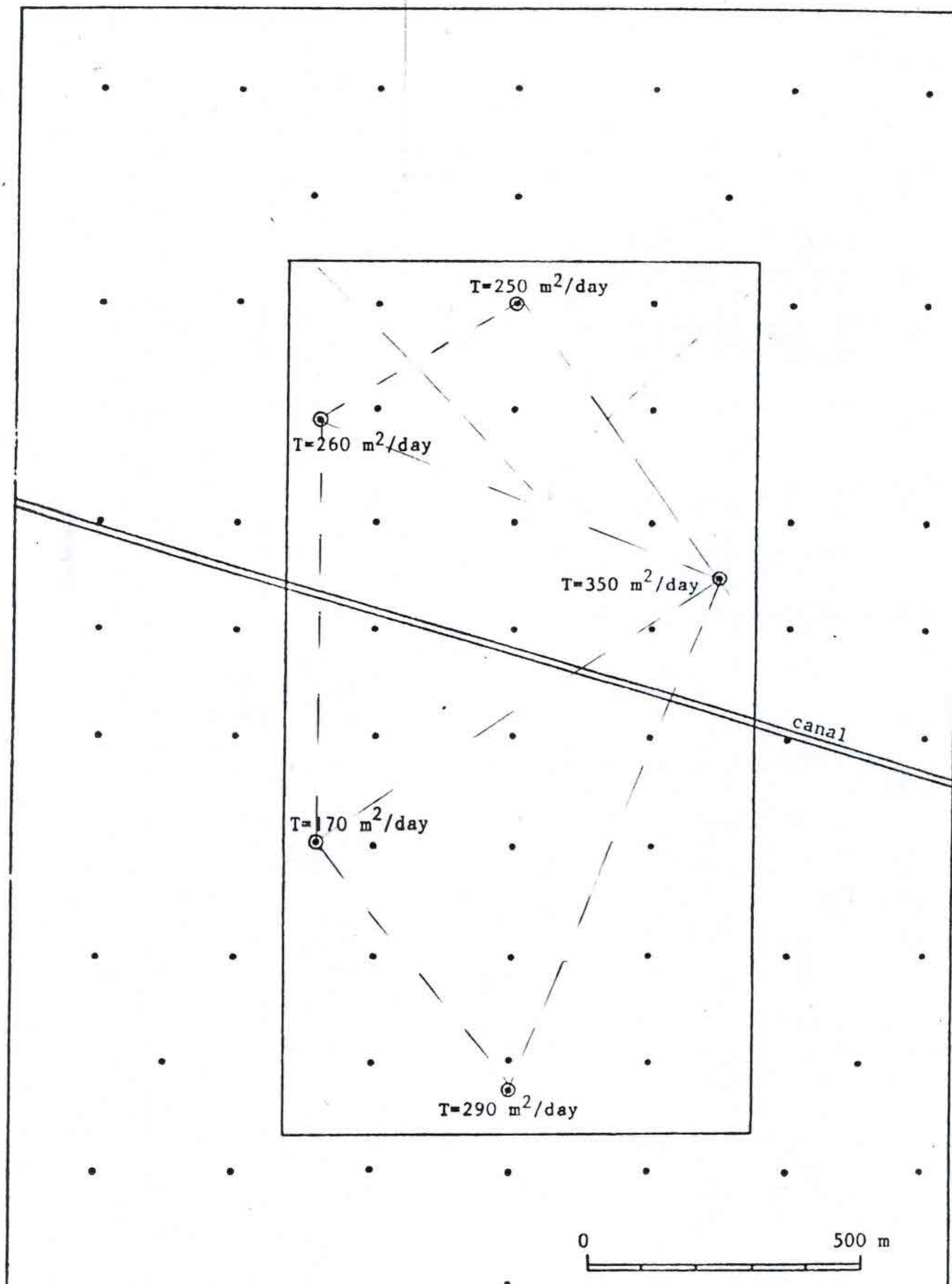

Figure 2 Location of test sites where the aquifer transmissivity has been determined

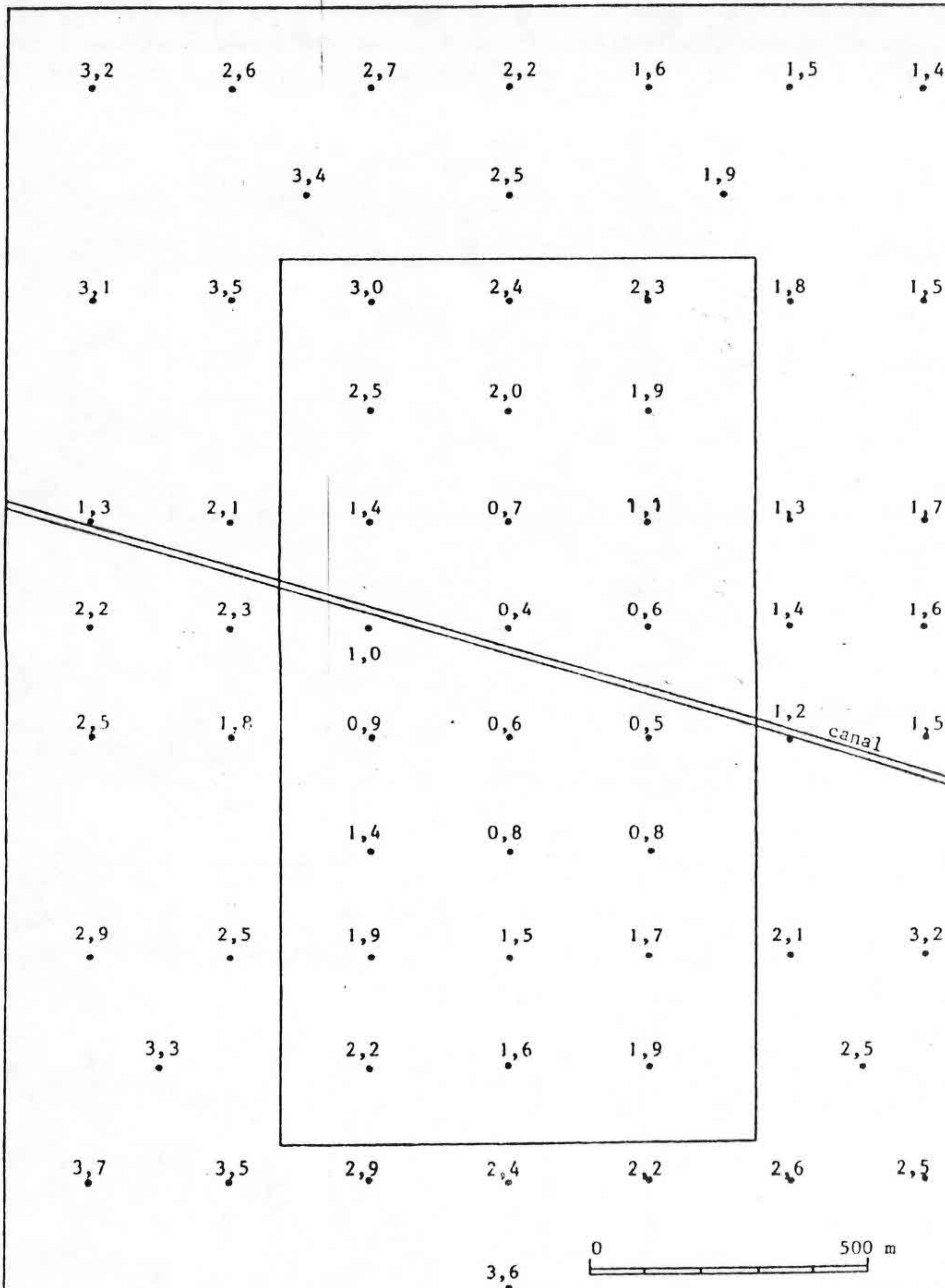

Figure 3 Depth to the watertable, in m below ground surface

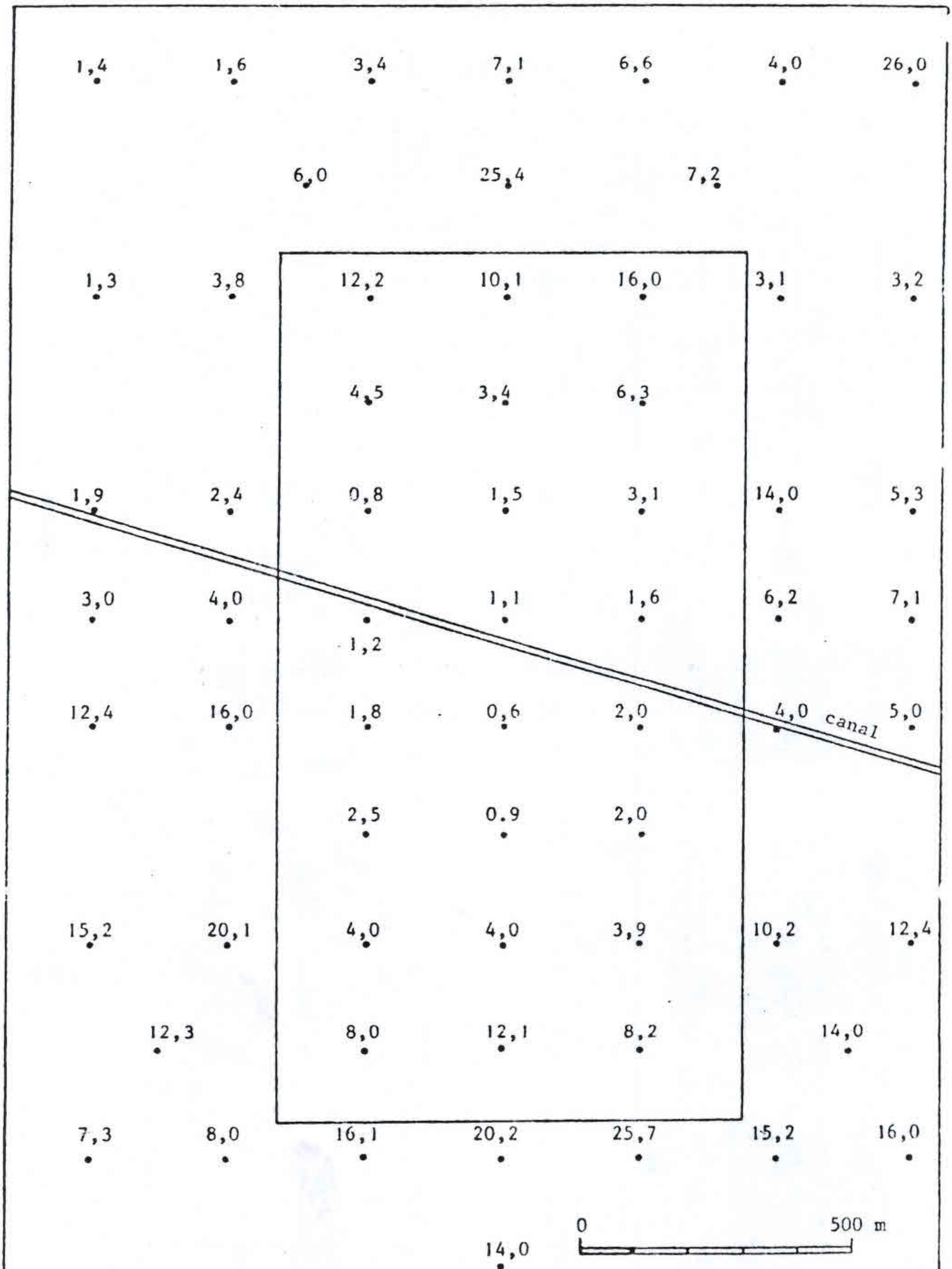

Figure 4 Electrical conductivity of the shallow groundwater, in millimhos/cm

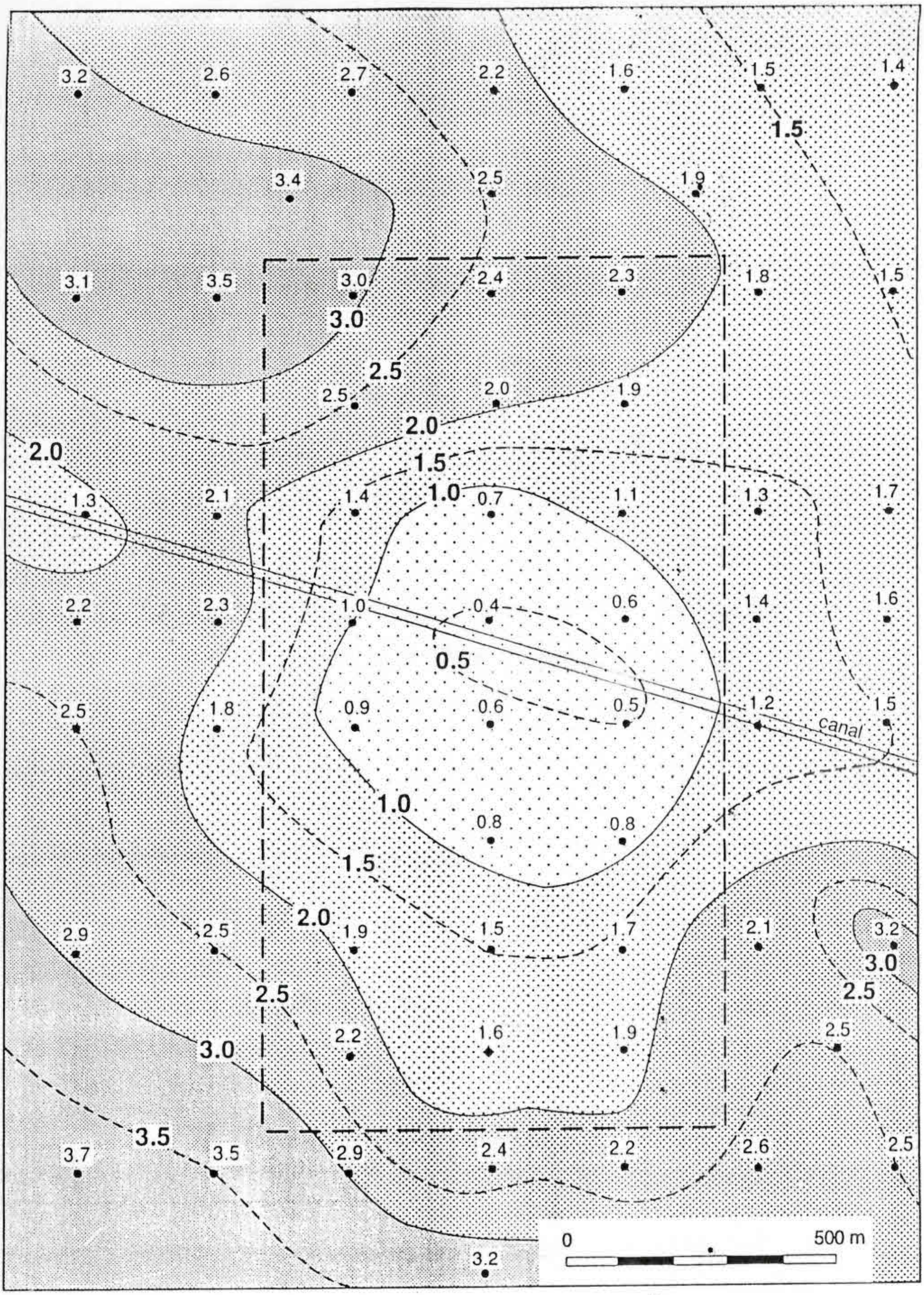

figure 16.12, depth-to-watertable map
1.6 observation well, watertable depth 1.6m below soil surface

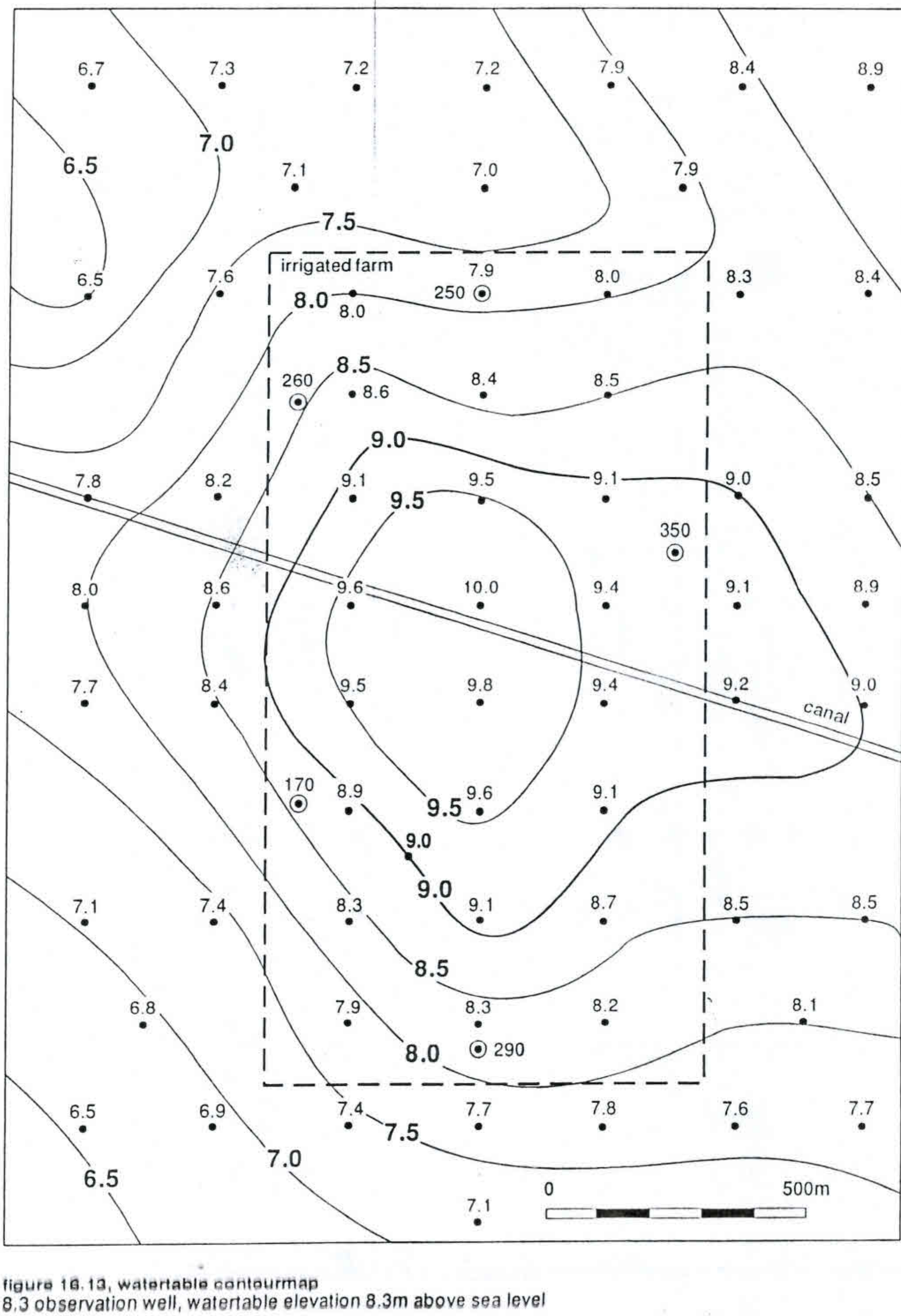

figure 16.13, watertable contourmap

8.3 observation well, watertable elevation 8.3m above sea level

290 aquifer test site, transmissivity KD = 290 m^2/d

figure 16.14
electrical conductivity of the shallow
groundwater in dS/m

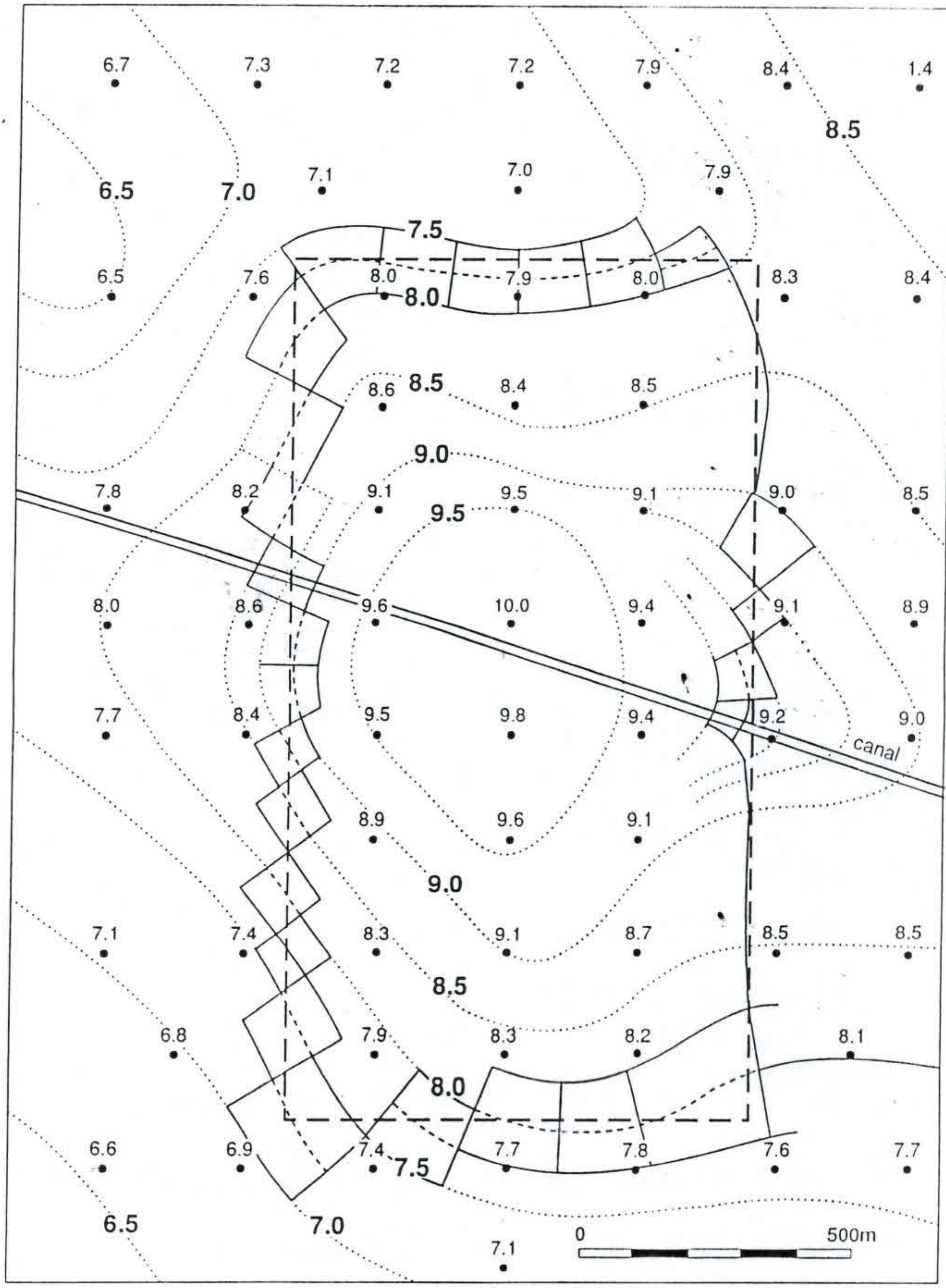

figure 16.15
Watertable contour map with a flow net constructed along the farm boundaries.

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41th INTERNATIONAL COURSE ON LAND DRAINAGE ICLD

Workbook
4.1 DRAINAGE MATERIALS

DRAINAGE

From 19 August to 6 December 2002, Wageningen, The Netherlands

Workbook

4.1 DRAINAGE MATERIALS

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WORKBOOK DRAINAGE MATERIALS

LOUIS C. STUYT

SC-DLO

1 Overview

1.1 Objective of this module

The Lecture module 'Drainage Materials' is embedded in the ICLD Programme as follows:

1	Introductory Subjects	
2	Principles of Land Drainage	**Maintenance**
3	Surveys and investigations	**Environment**
4	**Design of Drainage Systems**	***Drainage Materials***
5	Design Exercises	**Installation of Pipes**
6	Elective Subjects	**Surface Drainage System Design**

The objective of this module is to explain, discuss and illustrate the properties and functioning of drain pipes and envelopes, both in theory and in practice. The participants will be familiarized with physical processes, occurring near drains and the way in which such processes may disable proper functioning of pipe drains. They will be supplied with tools, helping them to select materials which suit their local situation best. The necessary precautions, to be taken to safeguard adequate long-term functioning of drains are summarized.

1.2 Concepts used in this module

In this module of the ICLD, the performance of the drain line is investigated.The associated physical area is pretty small. It comprises the pipe drain and the media bordering it: an envelope (optional) and the backfilled or disrupted soil. By approximation, this area of interest is contained in an imaginary circular cylinder with radius *3r*, coaxially extending around a drain pipe with radius *r*. From such a long cylindrical area of interest, a 0.25 m long section (with a volume of 0.006 m^3 for a 6 cm diameter drain) may be considered representative for making investigations of the relevant physical processes.

The area surrounding a subsurface drain is a crucial yet comparatively unexplored constituent of drainage technology. Crucial because all groundwater must pass along easily, while soil particles nor biochemical processes should clog the drain line. Unexplored because the area is difficult to investigate due to the unstability and the heterogeneity of the media concerned, and because it is difficult to trace it down, monitor its properties, or sample it for further analysis.

At the interface of the soil and the pipe wall, soil aggregates and -particles are subject to the drag force of the water. Substantial hydraulic gradients induce movement of these aggregates and particles towards and into envelope and drain pipe. The spectrum of soil permeability of soil and envelope will be enhanced, particularly in weakly-cohesive soils. Some sections will become virtually impermeable; others will develop into highly-conductive macropore networks. Existing theory does however not account for these phenomena. Hence, the concept of *entrance resistance* is of merely theoretical interest. Other parameters to be discussed are the pore- and particle size distributions of envelopes and soils, the effective opening size of envelope pores (the O_{90}-value), the thickness of envelopes, soil texture and -structure. Some of these parameters are used in design criteria for envelopes.

1.3 Summary of contents of this module

In this series of six lectures, the participants are familiarized with the area in the immediate vicinity of pipe drains. Some properties of this area are profoundly affected by the installation of the drains. After a discussion of physical properties and applications of various types of drain pipes and the water acceptance (≈entrance resistance) of drains, a series of stereoscopic (3-D) slides will be presented and discussed. These slides contain images illustrating the heterogeneity of (partially clogged) envelopes and complex structural features of the abutting soils. The images were obtained by the scanning of field samples using Computed Tomography (CT) x-ray-scanning techniques. The physical processes occurring at the interface between soil, envelope and pipe wall, and the associated risks of drain line malfunctioning are established. Next, the principles of design of granular (i.e. gravel), organic and synthetic envelopes (i.e. geotextiles and Prewrapped Loose Material (PLM) envelopes) are reviewed. Pros and cons of laboratory- and field testing of envelopes are elucidated. Finally, a case will be presented in which the participants will design (a) suitable gravel envelope(s).

1.4 Associated ICLD lectures and activities

Lectures

9 Subsurface flow to drains
20 Maintenance
24 Installation of pipes
33 Subsurface drainage design

Excursions

6 Drainage Machinery
7 Waterboard: Installation and maintenance of drains, including equipment
12 Soil & Water laboratory, Belgium (testing of pipes and envelopes).

2 Subject Matter

2.1 Reference to relevant sections of ILRI Publication 16 (1994)

2.2 Changes or additional information

1 The state of the art concerning properties and application of envelope materials, particularly in the developing countries, is very well documented in the proceedings of the 5th International Drainage Workshop, Lahore, Pakistan, February 1992. In Volume I, pages 151-169, Prof Dr Lyman Willardson, retired from Utah State University, Logan, UT, USA, reports on Technical Session 5, dealing with the use of drainage materials. This material is interesting for engineers working in the field of drainage technology. It is split in three parts: 1) Summary, 2) Synopsis of submitted papers and 3) Discussion, questions and answers separated by paper.

2 In 1991, dr Jan van Schilfgaarde, Editor of ASA Monograph 17 (1974) *"Drainage for Agriculture"* and Prof dr R.W. Skaggs of North Carolina State University, decided to edit a new drainage monograph for the American Society of Agronomy to replace No. 17 (and 7). This monograph will contain 13 sections and 44 chapters, and is scheduled to be pulished in 1995. Chapter 29, entitled 'Drain Envelopes' by L C P M Stuyt and L S Willardson will include information on so-called Prewrapped Loose Material envelopes (PLM's) which will be standardised in the European Community shortly. Regrettably, this important material is not included in ILRI Publication 16 (1994).

3 Section 21.7.1 in ILRI Publication 16, entitled *"Flow Conditions in the Immediate Vicinity of a Pipe Drains"* contains an inconsistency. The concept of entrance resistance is emphasized, yet the validity of this theoretical concept cannot be demonstrated in practice. In scientific work, theoretical development and validation must go hand in hand. In this case, however, this procedure has not been followed. Given the highly complex and largely unknown flow conditions near pipe drains, any computational analysis of effects of 'entrance resistance' on drain performance, though illustrative, is merely of speculative nature. In the text, while discussing non-ideal

drains in a heterogeneous soil, it is acknowledged that (page 895) *"...the hydraulic conductivity of the backfilled soil will vary considerably over short distances. As a result, the flow conditions are heterogeneous and are difficult to predict. A theoretical formulation of the flow pattern is hampered by the fact that equipotential lines do not show a regular pattern."* In the subsequent section, 21.7.2, entitled *"Soil Physical Conditions in the Immediate Vicinity of a Pipe Drain"* the consequences of the physical interaction between groundwater, soil and (wrapped) envelope is elucidated. The obvious result, soil heterogeneity and its associated variables like (saturated hydraulic conductivity) is contradictory to the theoretical discussion in the preceding section. Obviously, flow conditions (21.7.1) and soil physical conditions (21.7.2) are strongly interrelated. It would have been sensible to discuss the physical conditions first, followed by the flow conditions. The inconsistency, created by doing it reversely is confusing.

2.3 Information Concerning Presented Overhead Sheets and Colour Slides

N.B. page numbers in *italics*, like (*page 272*) refer to ILRI-Publication 16.

2.3.1 Drain pipes and Entrance Resistance

2.3.1.1 Introduction
2.3.1.2 Figure 8.6 (*page 272*): Geometry of 2-D flow towards drains, according to Ernst.
2.3.1.3 Drain pipes (*2.1.3.2; page 830-832).*
2.3.1.4 A series of 27 colour slides, entitled 'Drainage Materials: Clay, Concrete, Plastic', prepared by the Department of Agricultural Engineering of the Ohio Cooperative Extension Service (USA).
2.3.1.5 Figure 21.40 (*page 891*): Flow pattern in the vicinity of a drain pipe. Entrance resistance (*21.7.1; page 891-895*). Envelope thickness.
2.3.1.6 Physical conditions near pipe drains (*21.7.2; page 895-898*).

2.3.2 Flow towards Drain Pipes; 3-D Demo

An x-ray CT-scanner was used to investigate 45 field samples of pre-wrapped drains that had been installed in weakly-cohesive, very fine-sandy soils with a d_{90} of approximately 150 μm. Among other things, this research yielded three-dimensional (3D) mappings of heterogeneous patterns of mineral clogging inside envelopes and showed soil structural features in the abutting soil. Much was revealed about the functioning of pre-wrapped envelopes. Effects of soil properties exceeded those of envelope properties. Patterns of water flow into drains were, unlike theoretical concepts, heterogeneous and were strongly correlated with the natural layering and the macropore network in the adjacent soil.

2.3.2.1 Various colour slides showing field sampling of the drain sections.
2.3.2.2 Various colour slides showing CT-scanning of the drain sections.
2.3.2.3 Various colour slides showing computer processing of the images.

Stereoscopic colour slides are shown using dedicated equipment, producing true 3D vision of heterogeneous patterns of mineral clogging inside envelopes and soil structural features in the abutting soils. 3D vision is established by wearing spectacles with polarized glasses. It will be experienced only if both your eyes are functioning normally. All samples are taken at three pilot areas in The Netherlands: Uithuizermeeden, Valthermond and Willemstad. The imaged objects are 15 cm long by approx. 19 cm diameter.

2.3.2.4 A series of sample cores in the field
2.3.2.5 The laboratory with 3-D image processing UNIX Workstation
2.3.2.6 Video editing department of the Winand Staring Centre (SC-DLO)

Raw Data 3D CT Images		*Sample ID*
2.3.2.7	Valthermond/"Typar" nonwoven envelope: macropores in subsoil	V01
2.3.2.8	Uithuizermeeden/"Cerex" nonwoven envelope: layered subsoil	U14

Processed 3D CT Images 1: Envelopes only

2.3.2.9	Uithuizermeeden/PS-LDPE: mineral clogging lower side	U07
2.3.2.10	Valthermond/PP: discharge through macropore lower side	V09
2.3.2.11	Valthermond/PP: mineral clogging lower side	V10
2.3.2.12	Willemstad/Peat-Cocos: partial clogging upper side	W09
2.3.2.13	Valthermond/Cocos: partial clogging lower side	V12
2.3.2.14	Willemstad/Peat-Cocos: partial clogging both sides	W03

Processed 3D CT Images 2: Layered Subsoils; Low-Permeable Trenches

2.3.2.15	Willemstad/"Cerex" nonwoven envelope	W07
2.3.2.16	Willemstad/Glass Fibre Membrane envelope	W02
2.3.2.17	Willemstad/Big "O" Fabric envelope	W08

Processed 3D CT Images 3: Highly-Permeable Trenches; Subsoils with Macropore Networks

2.3.2.18	Valthermond/PP envelope	V10
2.3.2.19	Valthermond/PS-LDPE envelope	V07
2.3.2.20	Uithuizermeeden/Big "O" Fabric envelope	U12
2.3.2.21	Valthermond/Cocos envelope	V11
2.3.2.22	Valthermond/"Typar" nonwoven envelope	V01
2.3.2.23	Valthermond/PP envelope	V09
2.3.2.24	Valthermond/"Cerex" nonwoven envelope	V06

Processed 3D CT Images 4: Macropore Networks in Trench Backfill

2.3.2.25	Uithuizermeeden/Peat-Cocos envelope	U11
2.3.2.26	Uithuizermeeden/Peat-Cocos envelope	U08
2.3.2.27	Uithuizermeeden/"Cerex" nonwoven envelope	U14
2.3.2.28	Uithuizermeeden/Peat-Cocos envelope	U18
2.3.2.29	Willemstad/PS-LDPE envelope	W06
2.3.2.30	Uithuizermeeden/Big "O" Fabric envelope	U13

2.3.3 Envelopes 1
2.3.3.1 Principles of Envelope Design
2.3.3.2 Design of Granular Envelopes
2.3.3.3 Design of Synthetic Envelopes
2.3.3.4 Design of Geotextile Envelopes
2.3.3.5 Design of PLM Envelopes

3 Learning by Doing

3.1 Guided Exercise

In this exercise you will design a gravel envelope, to be installed in silty and fine sandy soils near Khaipur, Pakistan, following the United Kingdom Road Research (RRL) Criteria (Spalding, 1970; Boers & van Someren, 1979).

3.2 Points of discussion

To be included after ICLD #33 (1994).

4 Sources and Applications

4.1 Description of slides and video-presentation

- ***Colour Slides*** will be presented concerning drainage materials, analog laboratory models, field research including video-inspection of drain pipes and high-technological laboratory research (x-ray imaging using a CT-scanner).

- ***Stereoscopic Colour Slides*** will be presented concerning 3-D flow patterns near drains, soil aggregate configuration, the effect of soil layering on flow into drains, clogging patterns of envelopes etc..

- ***Video Movies*** are available of field- and laboratory research, and rotating 3-D CT-images of drain sections and associated macropore systems.

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Contents of Lecture Series:

Realization of Drainage System:-

- excavation machinery
- construction materials: pipes, envelopes

Envelopes: Serious Gap in Knowledge

- Complexity of Problem:
- Large Variability Soil Types
- Large Variability Envelopes
- Difficult to predict necessity
- Trends are acknowledged ⇒

  Recommendations, Test Procedures, Design Criteria
- Use Locally Available Materials

Drain Pipes

Criteria for pipe quality & selection:

- resistance to mechanical damage
- resistance to chemical damage
- service life
- costs

Clay Tiles

- ±1850 - 1965
- good quality: excellent properties
- manufacturing is difficult
- expensive

Concrete Tiles

- still in use
- large diameters
- susceptible to acidity and sulphates
- manufacturing is easy

Plastic pipes

- since ±1965 smooth; ±1970 corrugated
- advantages over clay & concrete obvious
- resistant to chemical agents
- materials: PVC, PE (PP)
- UK & USA: PE; Continental Europe: PVC

■ high temperature	PVC✓	PE
■ deformation	PVC✓	PE
■ low temperatures	PVC	PE✓
■ UV radiation	PVC	PE✓

Quality Standards

- **C**omité **E**uropéenne de **N**ormalisation (CEN): '**EN**'-Standards in Europe (1995)
- ISO (International Standard Organization)

mechanical, chemical properties; dimensions; perforations; weight etc..

☞ *Hydraulic Design: Cavelaars (22a)*

- Drain spacing formula (Ernst)

$$\Delta h_{tot} = \Delta h_{ver} + \Delta h_{hor} + \Delta h_{rad} \; (+ \; \Delta h_e)$$

☞ assume ideal drain: no entry resistance

Real drain:

- inlet area ≈ 1.5 % wall area (perforations)
- streamlines converge to perforations

$$\Delta h_e = q W_e$$

where

$$W_e = \frac{\alpha_e}{k}$$

- α_e = entrance constant [-]

Entrance constant of unwrapped drain pipes

Pipe category	α_e
Clay & Concrete	1.0 - 3.0
Smooth Plastic	0.6 - 1.0
Corrugated plastic	0.3 - 0.6

- soil- and envelope properties crucial:

α pipe
⇓
placement envelope
⇓
approximate 'ideal drain' $\rightarrow \alpha \downarrow$

- Envelope thickness $\downarrow \rightarrow \alpha \downarrow$

☞ too much makes no sense!

Account for entry head loss due to W_e

Effective Radius r_{eff} of drain pipe:

W_e of *existing* drain pipe with radius r_p

↓

replace by / identical to

↓

W_e of *imaginary*, 'ideal' drain with $r = r_{eff}$

$$r_{eff} < r_p$$

- use r_{eff} in drain spacing formulae

☞ See Fig. 8.4, page 271, Publ. 16 ILRI

$$d = \frac{\frac{\pi L}{8}}{\ln \frac{L}{\pi r_{eff}} + F(x)} \qquad (8.9)$$

Clogging of drains: siltation
chemical deposits
root penetration

Function of envelopes:

- prevent siltation
- facilitate water entry
- protection of pipes
- protection of collectors ('wet' installation)

Criteria for *application* are ambiguous
related to soil
and the region

e.g. **no** envelope required:

Egypt: ≥ 30% clay,
Netherlands: ≥ 25% clay.

☞ **always** envelope required:

soils without inherent structural stability

Envelope Categories

Raw Material: mineral, organic, synthetic

Structure: granular, fibrous

Mineral envelopes: sand, gravel,
glass fibre sheet,
glass- & rock wool.

Organic envelopes: fibrous peat, flax straw,
coconut fibres, hay,
wood chips, sawdust,
rice straw, cereal straw

Synthetic env.: (non)woven fibres of
polyamide,
polyethylene (PE),
polypropylene (PP),
polystyrene (PS)

☞ envelope ≠ filter !

Problem Soils

low cohesion, low structural stability

= f (particle size distribution) = *soil texture*

= f (chemical composition)
sodic soils: *dispersion*
calcareous soils: stability

Soil Structure = rate of *aggregation* between elementary soil particles into *soil aggregates*

Factors: *texture, organic matter, cation ratio*

Structure destroyed by 'wet' installation !

Mineral Clogging

- contact process at soil/envelope interface
  - ⇒ contact erosion
  - ⇒ natural filter buildup ✓

Hydraulic Aspects

Envelope lowers Entrance Resistance:-

- increase effective radius r_{eff}
- flow to perforations easier

Influence envelope thickness smaller than theory suggests

assumption: homogeneous, isotropic soil

↕

reality: heterogeneity, macropores in soil

Chemical & Microbiological Aspects

clogging due to iron, lime and sulphates

= f (chemical composition soil & water, microbiological activity in soil, aerobic / anaerobic conditions, envelope properties)

Chemical Composition Soil & Water

- iron compound very risky
- Kuntze/Eggelsmann (1974); Ford (1983)
- temporary / permanent ?
- treatment: drain jetting (van Zeijts)

Microbiological Activity in Soil

- iron compound→*bacteria*→slimy products
- O_2-rich environment (aerobic)

Envelope Properties

- qualitative, empirical knowledge only
- voluminous envelopes less risky

Envelope Design Fundamentals

1. *Gravel*

"Filter criteria" for pervious granular materials by Terzaghi (1922); Civil Engineering

- filter: very coarse & pervious (k_{SAT})
- not too coarse: particle movement

Terzaghi: basis for gravel envelope design

2. *Prewrapped Loose Materials*

- gravel criteria inapplicable
- Holland & Belgium: design & application criteria (field/lab/theoretical research)

Hydraulic Failure Gradient (HFG)

- Willardson (USA); 1979
- analogue modelling (permeameters)
- soil 'fails' at internal water flow gradient
- HFG correlates with k_{SAT} and PI of soil

$$PI = (\theta_{soil,\ liquid\ limit} - \theta_{soil,\ plastic\ limit})$$

$$HFG = e^{(0.102 - 0.108 k_{SAT} + 1.09 \ln PI)}$$

Reduce HFG by:-

- increase $\boldsymbol{r_{eff}}$ (envelope)
- more pipe perforations
- reduce depth & spacing

☞ effect soil loosening & backfilling on HFG

☞ local experience & field observations crucial; HFG 'just another tool'

Design of Gravel Envelopes

Gravel envelope should:-

1. safely operate between *pipe perforations* and *soil* (no particle invasion into gravel and pipe), *[Mechanical Function]*
2. be internally stable; no erosion,
3. certify hydraulic conductivity.
   [Hydraulic Function]

Design criteria: **characteristic particle sizes of soil & gravel**

Design Procedure:-

1. Make mechanical analysis of soil;
2. Make mechanical analysis of gravel;
3. Apply criterion ('compare') & decide.

RRL: British **R**oad **R**esearch **L**aboratory
SCS: USDA **S**oil **C**onservation **S**ervice
USBR: U.S. Bureau of **R**eclamation

USBR coarser envelopes than **SCS**

USBR: (semi)arid zones western-USA

☞ *large-scale projects*: great L, depth etc. emphasis is on *hydraulic* function

SCS: humid eastern areas USA

☞ small scale (*farms*); *filter* function

Example **USBR** (1978)

USBR Surround Design; hydraulic conductivity, Table 21.2, page 836, ILRI Publication 16

Base material 60 %passing (diameter of particles in mm)	Gradation limits for gravel envelope (particle diameter, mm)					
	lower limits percentage passing					
	100	60	30	10	5	0
0.02 - 0.05	9.52	2.0	0.81	0.33	0.3	0.074
0.05 - 0.10	9.52	3.0	1.07	0.38	0.3	0.074
0.10 - 0.25	9.52	4.0	1.30	0.40	0.3	0.074
0.25 - 1.00	9.52	5.0	1.45	0.42	0.3	0.074

Base material 60 %passing (diameter of particles in mm)	Gradation limits for gravel envelope (particle diameter, mm)					
	upper limits percentage passing					
	100	60	30	10	5	0
0.02 - 0.05	38.10	10.0	8.7	2.5	---	0.590
0.05 - 0.10	38.10	12.0	10.4	3.0	---	0.590
0.10 - 0.25	38.10	15.0	13.1	3.8	---	0.590
0.25 - 1.00	38.10	20.0	17.3	5.0	---	0.590

USBR: only 1 criterion: d_{60} size of soil

= 60% size of soil

= particle diameter, such that 60% of soil particles by weight has smaller diamater

☞ sieve opening sizes where 60% of soil particles by weight pass through sieve

Soil Gradation Curve Figure 21.3

0.215 mm sieve opening:100% through☞ d_{100}
0.150 mm sieve opening: 90% through☞ d_{90}
0.131 mm sieve opening: 85% through☞ d_{85}
0.090 mm sieve opening: 60% through☞ d_{60}
0.080 mm sieve opening: 50% through☞ d_{50}
0.045 mm sieve opening: 30% through☞ d_{30}
0.018 mm sieve opening: 15% through☞ d_{15}

for **USBR** we need d_{60} = 0.09 mm = 90 μm
→ use table 21.2, page 836.

Hydraulic Properties of Envelope:

$\mathbf{D_{15}/d_{15} \geq 4}$: $\mathbf{k_{SAT,\ ENV} \geq 10\ k_{SAT,\ SOIL}}$

☞ hydraulic conductivity determined by small particle diameters

Filtering Properties of Envelope:

$\mathbf{D_{15}/d_{85} \leq 4}$: fine particles don't wash into the pipe

☞ small envelope particles are crucial for filtering properties; should not be too big

Problems:-

- gravel specifications uncertain;
- rounded & angular particles;
- no uniform quality;
- segregation during transport, installation;
- flowability problems in supply tube;
- unequal distribution around pipe.

Consequences:-

1☞Improve selection & design (Pakistan); Willem Vlotman;

2☞Search for synthetic substitutes (Egypt); Louis Stuyt [NL] & Willy Dierickx [B].

Thin, fine **Geotextiles**:

■ clog easily; ■ may have wetting problems.

Criteria:-

■ soil retention ■ ~~prevent clogging~~
■ ~~hydraulic conductivity~~

Retention criterion = filter criterion
= bridging factor

☞ provide *mechanical support* to soil

$$\frac{CHARACTERISTIC\ \ PORE\ \ SIZE\ \ ENVELOPE}{CHARACTERISTIC\ \ PARTICLE\ \ SIZE\ \ SOIL} = \frac{O_{90}}{d_{90}}$$

thin geotextile [≤ 1 mm]	voluminous geotextile [thickness ≥ 5 mm]
$\mathbf{O_{90}/d_{90} \leq 2.5}$	$\mathbf{O_{90}/d_{90} \leq 5}$

$\mathbf{O_{90}/d_{90} \leq 1}$ inappropriate: internal clogging

Table 21.4, page 838 Publication 16

Table 21.4 Existing filter criteria for geotextiles.

Reference	Geotextile	Soil	Criteria	Remarks
Calhoun (1972)	woven	cohesionless ($d_{50} \geq 74$ mm)	$O_{95}/d_{85} \leq 1$	dry sieving, glass bead fractions
		cohesive ($d_{50} < 74$ mm)	$O_{90} \leq 200$ µm	
Ogink (1975)	woven nonwoven	sand sand	$O_{90}/d_{90} \leq 1$ $O_{90}/d_{90} \leq 1.8$	dry sieving, sand fractions
Zitscher (1975) in Rankilor (1981)	woven	$C_u \leq 2$ 100 µm $\leq d_{50} \leq$ 300 µm	$O_{50}/d_{50} \leq 1.7\text{-}2.7$	
Sweetland (1977)	nonwoven	$C_u = 1.5$ $C_u = 4.0$	$O_{15}/d_{85} \leq 1$ $O_{15}/d_{15} \leq 1$	
ICI Fibers (1978) in Rankilor (1981)	nonwoven	20 µm $\leq d_{85} \leq$ 250 µm $d_{85} >$ 250 µm	$O_{50}/d_{85} \leq 1$ $O_{15}/d_{15} \geq 1$	
Schober and Teindl (1979)	woven and thin nonwoven ($T_g \leq 1$ mm)	sand	$O_{90}/d_{50} \leq B_1\ (C_u)$	dry sieving, sand fractions $B_1(C_u) < B_2\ (C_u)$ and are factors depending on the coefficient of uniformity C_u $B_1\ (C_u) = 2.5 - 4.5$; $B_2\ (C_u) = 4.5 - 7.5$)
	thick nonwoven ($T_g \geq 1$ mm)	sand	$O_{90}/d_{50} \leq B_2\ (C_u)$	
Millar, Ho and Turnbull (1980)	woven and nonwoven		$O_{50}/d_{85} \leq 1$ $O_{50}/d_{15} \geq 1$	
Giroud (1982)	needle-punched nonwoven	cohesionless less dense $1 < C_u < 3$ $C_u > 3$	 $O_{95}/d_{50} < C_u$ $O_{95}/d_{50} < 9/C_u$	
		moderate dense $1 < C_u < 3$ $C_u > 3$	 $O_{95}/d_{50} < 1.5\ C_u$ $O_{95}/d_{50} < 13.5/C_u$	
		dense $1 < C_u < 3$ $C_u > 3$	 $O_{90}/d_{50} < 2\ C_u$ $O_{95}/d_{50} < 13.5/C_u$	
	woven and heat bonded nonwoven	$1 < C_u < 3$ $C_u > 3$	$O_{95}/d_{50} < C_u$ $O_{95}/d_{50} < 9/C_u$	
Heerten (1983)	woven and nonwoven	cohesionless ($d_{50} \geq 60$ µm) $C_u > 5$	 $O_{90}/d_{50} < 10$ $O_{90}/d_{90} < 1.0$	wet sieving, graded soil
		$C_u < 5$	$O_{90}/d_{50} < 2.5$ $O_{90}/d_{90} < 1$	
		cohesive ($d_{50} \leq 60$ µm)	$O_{90}/d_{50} < 10$ $O_{90}/d_{90} < 1$ $O_{90} \leq 100$ µm	
Carroll (1983)	woven and nonwoven.		$O_{95}/d_{85} \leq 2\text{-}3$	
Cristopher and Holtz (1985)		dependent on C_u	$O_{95}/d_{85} \leq 1\text{-}2$ $O_{95}/d_{15} \geq 3$	

Prewrapped Loose Material (PLM) is:

- loose fibres (polypropylene (pp) and coconut fibres, peat fibres
- loose granules (polystyrene beads) in synthetic netting

prewrapped in factory.

Design & application in Holland & Belgium:

- theoretical studies;
- mathematical modelling;
- pilot area research;
- analogue models (permeameters);
- practical experience (30 years).

Relevant factors for envelope functioning:-

- soil structural stability;
- soil texture;
- ripening of a soil (rate & depth);
- organic matter content;
- Fe-content soil and groundwater.

PLM types, used in the Netherlands

PLM type	average thickness (mm)	minimum thickness (mm)	average weight (kg.m^{-2})	O_{90} (μm)
Cocos 700	11.0	6.5	1.0	700
Cocos 1000	8.0	4.0	0.75	1000
PS-1000 polystyrene	10.0	8.0	12 kg.m^3	1000
PP 300 polypropylene	5.0	3.0	0.475	300
PP 450 polypropylene	5.0	3.0	0.475	450
PP 700 polypropylene	6.0	4.0	0.6	700
PP 700 heavy polypropylene	10.0	6.0	0.9	700

Source: Horman Drainagefilter BV, 's-Gravendeel, the Netherlands

Thickness tolerances:-

- Cocos and PP: ±25%
- PS: ±10%

Weight tolerance: ±25% (all categories)

Pore size (O_{90}) tolerances:

- Cocos and PS: ±100 μm
- PP: ±150 μm

Evaluation of Drainage Materials through:-

1. Theoretical investigations
2. Laboratory investigations
3. Experimental fields
4. Combinations of 1+2+3.

1. Theory - Period 1950-1980.
Dierickx (1980), Stuyt (1991).

2. Laboratory - 1960++ Analogue models:
sand tanks & flow permeameters
world-wide.

3. Experimental Fields - Period 1960-1990.
crucial yet expensive. Stuyt (1992).

4. Combinations - Lab + field + internal TV
inspection + 3D x-ray analysis
(Stuyt, 1992).

European ('EN') standard for

Geotextile: a permeable, polymeric (synthetic or natural) textile material, in the form of manufactured sheet (which may be woven, non woven or knitted) used in geotechnical and civil engineering applications.

Prewrapped Loose Material (PLM): A permeable structure consisting of loose, randomly oriented yarns, fibres, filaments, grains, granules or beads, surrounding corrugated drain pipe, assembled within a permeable surround or retained in place by appropriate netting and used in drainage applications.

Two classes of PLM envelopes:

PLM-F 300 μm $\leq O_{90} <$ 600 μm (**F**ine)

PLM-S 600 μm $\leq O_{90} \leq$ 1100 μm (**S**tandard)

General Requirements for EN-standard

Geotextile

- appearance
- colour
- thickness (2 kPa; ISO/DIS 9863; ±10%)
- mass per unit area
  (2 kPa; ISO/DIS 9863; ±10%)
- porometry (±30%)
- wettability (water head ≤ 5 mm)

Prewrapped Loose Material (PLM)

- minimum thickness e_{min} (±25%)

Synthetic PLM		Organic PLM	
Fibrous	Granular	Fibrous	Granular
3 mm	8 mm	4 mm	8 mm

- mass per unit area: *not specified*;
<25% deviation from specs of manufacturer

PLM - cont'd

- porometry: all measured O_{90}'s within class limits (fine or standard)
- marking of coils: fully prescribed

Testing Procedures:

1. ***Geotextiles***

- wettability = initial resistance of a dry geotextile to water penetration

2. **Geotextiles and *PLM's***

- thickness
- minimum thickness (PLM)
- mass per unit area
- porometry : O_{95} and O_{90}

Established 30 December 1993

Fig. 1 *2 grading curves*

☞ identify:
- well-graded soil
- uniform soil

☞ estimate: D_{10} and D_{60} of both soils

Fig 2 *RRL Filter Design*

☞ use Table 21.2 (page 836) to determine the *finest* and *coarsest* possible grading curves of gravel envelopes conforming the RRL criteria (D_{15}, D_{50}, D_{85}?)
☞ sketch both grading curves

Use Fig. 3 as an example; you are supposed to produce a similar result.

Fig 4 *USBR Filter Design*

☞ use Table 21.2 (page 836) to determine the *finest* and *coarsest* possible grading curves of gravel envelopes conforming the USBR surround design
☞ sketch lower and upper grading curves

Fig 5 *Filter Limits SCS, RRL & USBR*

☞ sketch lower and upper filter limits following the SCS, RRL & USBR criteria, using Fig. 2, 3 and 4

Fig 6 *Grading curves of soil samples from Khaipur East Pilot Area*

☞ Note the variability of the 12 soil samples. Which curves should we select for the design of the gravel envelope?

Fig 7 *RRL lower & upper filter limits*

☞ calculate and sketch the lower and upper filter limits for soils A and B. Use Figs. 8 and 9 as examples; you are supposed to produce a similar result.

Fig 10 *Combination of Filter Limits*

☞ Shade the area in which the grading curve of a gravel envelope must lie, conforming SCS, RRL and USBR

Fig 11 *Proposed range of Filters*

☞ Verify the proposed range of filters for soils in the Khaipur Pilot Area

Fig 12 *Gravel Supply Quarries*

☞ Familiarize yourself with gravel supply quarries in Pakistan. Note the great distances, leading to very high transportation costs.

Fig 13 *Grading Curves of Gravels*

☞ Select the most appropriate gravel(s) for application in the Khaipur pilot area.

Gravel from Shadi Shaheed is most suitable, considering:

- grading curve
- distance to pilot area (10 km)
- performance in sand tank model

Boers, Th.M. & C.L. Van Someren. 1979. **Design of gravel envelope for silty and fine sandy soils in Pakistan.** ILRI Publ. 25:713-731.

Conclusions

1. Silty Clay Loams & Fine Sandy Soils: **SCS** criteria are best;

☞ RRL: too many fine particles

☞ USBR: too coarse envelope

2. USBR & RRL-ranges merge in SCS-range

☞ more info on pages 730-731, Publ. 25.

Fig. 1 *2 grading curves*

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Use Fig. 3 as an example; you are supposed to produce a similar result.

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ANNEX

Granular Envelopes

Design of a granular (sand-gravel) filter for a drain envelope is different from design of granular filters for hydraulic structures in that a drain envelope needs to satisfy both the demand for the filtering function and the demand for a high permeability at the same time.

It is assumed, at this point, that from the pre-drainage soil investigation a base soil bandwidth for soils in need of a drain envelope has been determined (Figure 4). The finer boundary of the base soil bandwidth will be used for the filter/retention criteria and the coarser boundary to satisfy the permeability or hydraulic criteria.

The criteria will result in control points on the Particle Size Distribution (PSD) curve through which the coarse and fine boundaries of a granular envelope bandwidth can be drawn (subscripts c and f mean coarse and fine boundary respectively):

Control points for the coarse boundary:

1. $D_{15c} < 7*d_{85f}$ — control point 1, filter criterion, d_{85} is that of the fine boundary of the base soil;
2. $D_{60c} = 5*D_{15c}$ — control point 2, gradation curve guide. Based on SCS (1994) guideline that $D_{15} / D_{10} = 1.2$ and that $C_u = 6$;
3. $D_{100c} < 9.5$ mm — control point 3, segregation criterion.

Control points for the fine boundary:

4. $D_{15f} > 4*d_{15c}$ — control point 4a, hydraulic criterion, d_{15c} is that of the coarse boundary of the base soil.;
5. $D_{15f} = D_{15c}/5$ — control point 4b, bandwidth guide. This point is the counter part of control point 2 combining control of the bandwidth and controlling $C_u \leq 6$. If control point 4b > 4a use 4b. If 4b < 4a then it will depend on the degree by which 4b is smaller then 4a to decide on what to do (Figure 4);
6. $D_5 > 0.074$ mm — control point 5, hydraulic criterion. This is intended originally to prevent too low hydraulic conductivity, but will also control the amount of fine sediments that will pass into the pipe immediately after construction;

7. $D_{60f} = D_{60c}/5$ control point 6, bandwidth guide. The bandwidth of the specified envelope gradation should not exceed the ratio of 5 below 60% passing;

8. $D_{85} > D_{opening}$ control point 7, retention (bridging) criterion. $D_{opening}$ is the perforation size of the pipe. This control point generally will mean $D_{85} > 2$ mm, and no difficulty will be met to satisfy this generally.

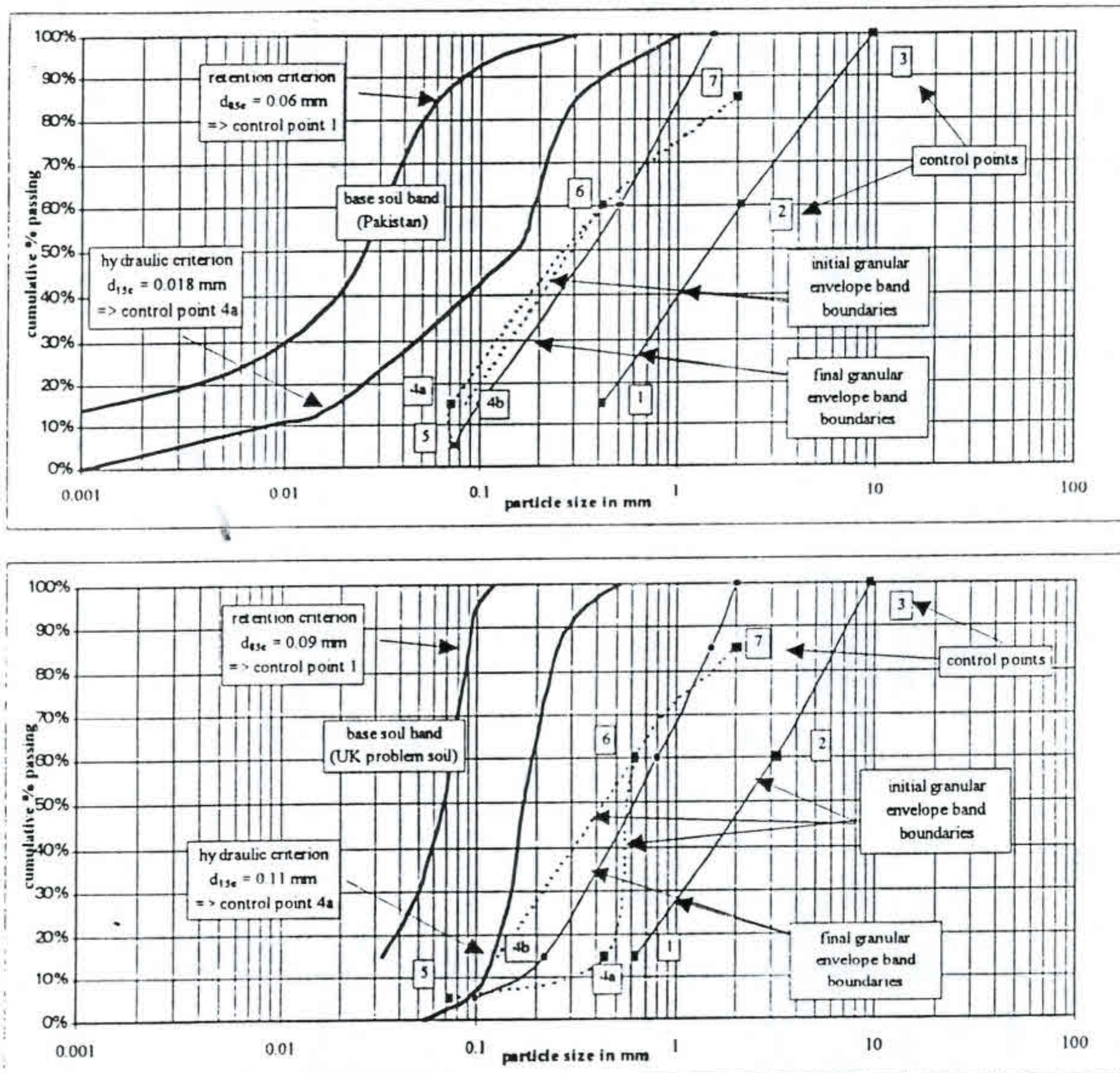
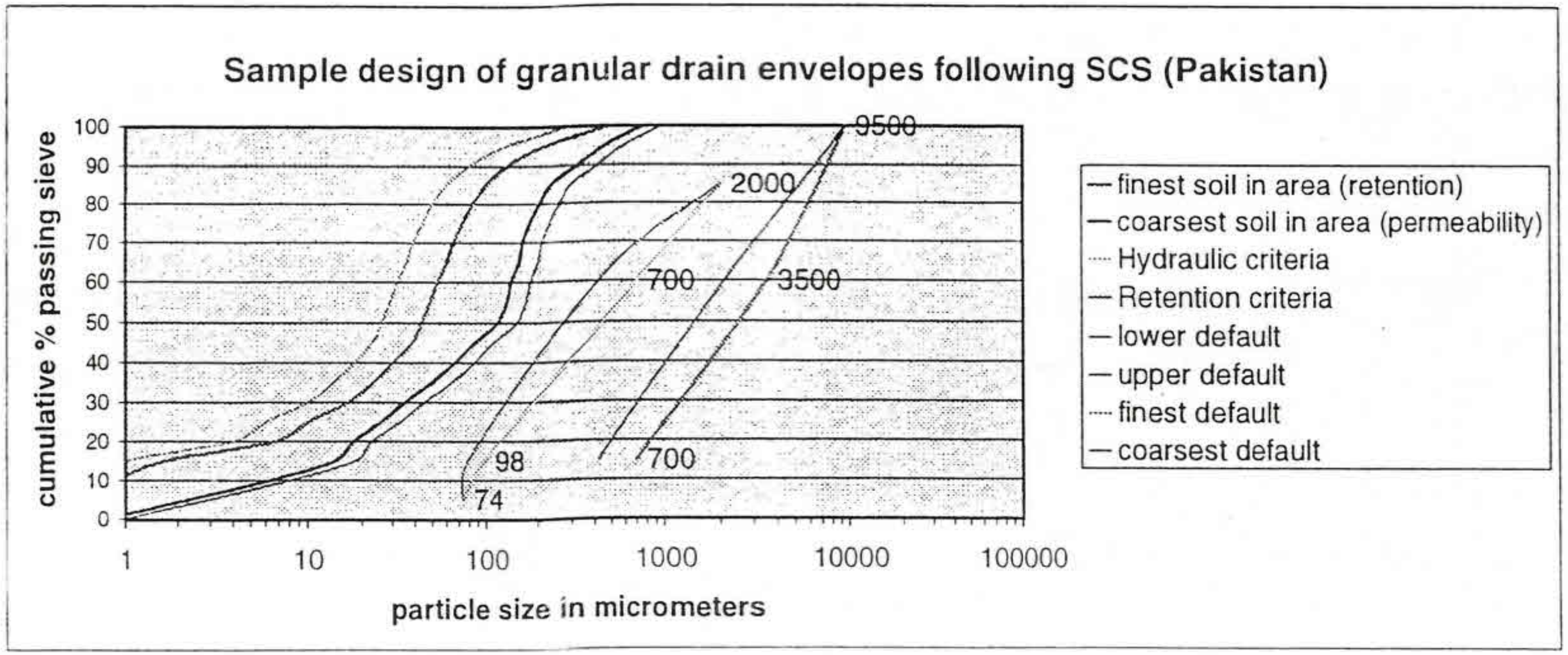


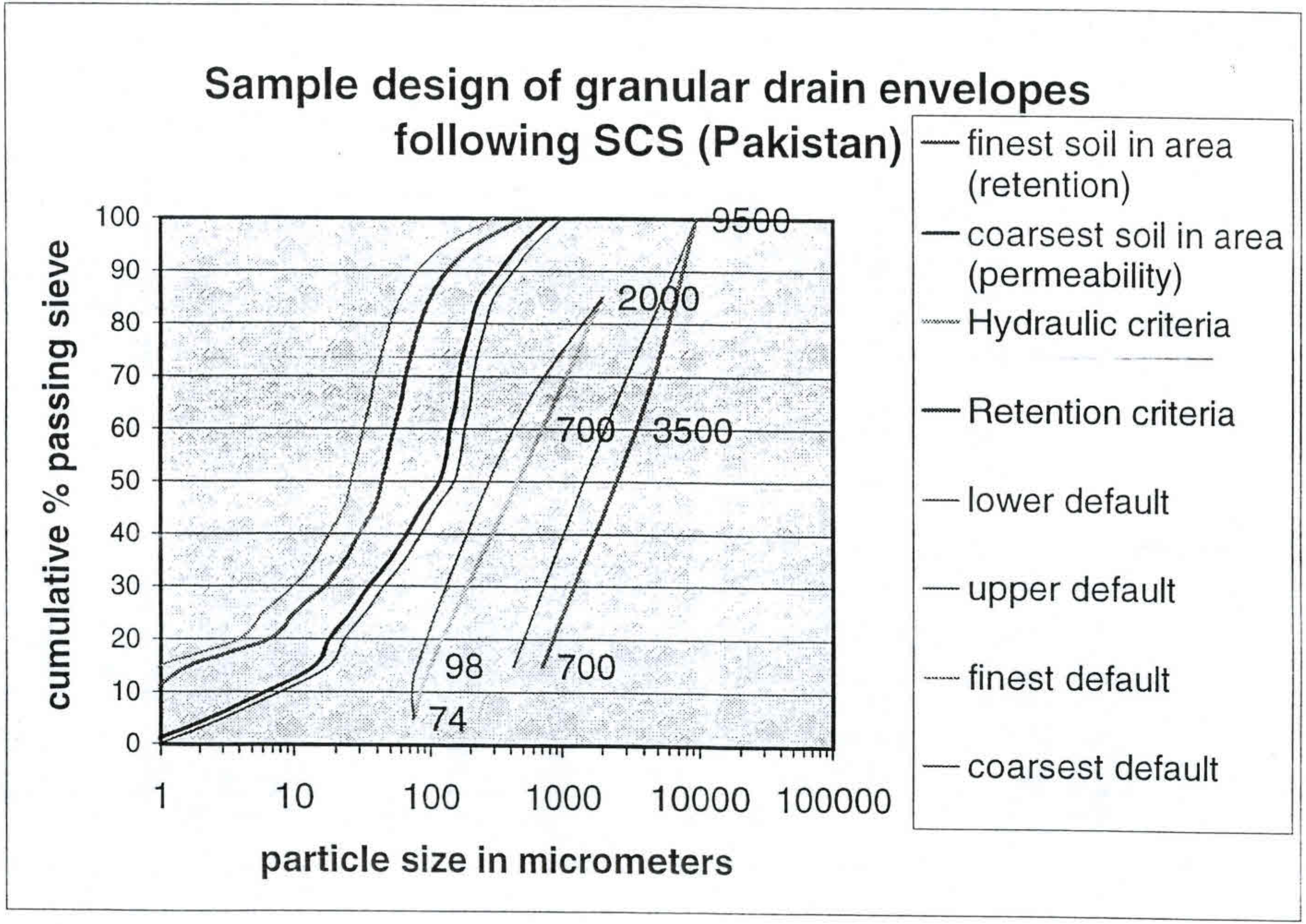
Figure 4   Sample designs of granular drain envelopes.

Sample design of granular drain envelopes - Pakistan (SCS, 1974)

Source: SCS, 1994. Gradation design of sand and gravel filters. NEH Part 633-26. Nat. Eng. Publ from the US SCS. Water resources Publications, Highlands Ranch, CO USA
Spreadsheet developed by DLO-Winand Staring Centre (SC-DLO), October 1997 (L.C.P.M. Stuyt)

cumulative % passing		finest soil in area (retention) retention criteria ("Filter")	finest default		coarsest soil in area (permeability) hydraulic criteria ("permeable constraint")	coarsest default		'permeability limit' of gravel envelope Hydraulic criteria 'Finest' possible envelope Envelope may not be finer because k would be too low		lower default		'retention limit' of gravel envelope Retention criteria 'Coarsest' possible envelope Envelope may not be coarser because filtering action would be redi		upper default	
100	d100f	500	300	d100c	778	1000						D100c	9500	9500	Step 3: segregation criterion
95	d95f	217	130	d95c	467	400									very large gravel particles must
90	d90f	133	80	d90c	327	420									
85	d85f (60)	100	60	d85c	233	300		D85f	2000	2000	Step 8: at least 15% of particles				
80	d80f	83	50	d80c	202	260		retention (bridging)			by weight must exceed size of				
75	d75f	73	44	d75c	179	230		criterion: 2 mm perforations			pipe perforations (2 mm typical)				
70	d70f	65	39	d70c	163	210									
65	d65f	60	36	d65c	154	200									
60	d60f	53	32	d60c	140	180		D60f	700	420	Step 7: bandwidth Guide; envelope	D60c	3500	2100	Step 2: Gradation curve Guide (
55	d55f	48	29	d55c	132	170		bandwidth guide			ratio coarse/fine at 60% passing				requirements: D15/D10 = 1.2 an
50	d50f	43	26	d50c	117	150					should be smaller than 5				
45	d45f	38	23	d45c	86	110									
40	d40f	30	18	d40c	66	85									
35	d35f	23	14	d35c	50	64									
30	d30f	17	10	d30c	35	46	d15c'4	56							
25	d25f	10	6	d25c	26	33	D15c/5	140							
20	d20f	7	4	d20c	18	23									
15	d15f	2	1	d15c (18)	14	18		D15f	98	78	Steps 4+5: hydraulic criterion	D15c	700	420	Step 1: D15<7*d85f; filter criteri
10	d10f	0.8	0.5	d10c	6	8					plus bandwidth Guide				15% of gravel particles should b
5	d5f	0.3	0.2	d5c	2	3		D5f	74	74	Step 6: hydraulic criterion				than 85% of particles of the fine
0	d0f	0.2	0.1	d0c	0.77	6.99					prevent k env too low				





Sample design of granular drain envelopes following SCS (Pakistan)
cumulative % passing sieve
100
90
80
70
60
50
40
30
20
10
0
1
10
100
1000
10000
100000
particle size in micrometers
9500
2000
700
3500
98
700
74
finest soil in area (retention)
coarsest soil in area (permeability)
Hydraulic criteria
Retention criteria
lower default
upper default
finest default
coarsest default

THE SHEETS OF THE POWERPOINT PRESENTATION

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Drainage Materials

Pipes and envelopes

Louis Stuyt (Alterra, Wageningen, NL)
Willem F. Vlotman (Alterra-ILRI, Wageningen, NL)

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Contents

1 General information on drain envelopes
2 Displays of drainage materials
3 Drain pipes
4 Pipe connectors
5 Testing of drain pipes
6 Hancor pipe (USA)
7 Drain envelopes ('filters')
8 Water flow into drains
9 Problems with envelopes

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Contents (cont'd)

10 Laboratory research (analog models)
11 Problem analysis 'old style'
12 Video inspection of lateral drains
13 Checking the slope of lateral drains
14 Sampling of drain sections with surrounding soil
15 X-ray analysis of sampled sections
16 Data analysis of 3 D X-ray images + conclusions
17 Books

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General Information on drain envelopes

- Common Terms
  - Envelope Functions
  - Envelope Terms
  - Proper Naming
- Drain Envelope Need
- Drain Envelope Design
  - Granular envelopes (gravel)
  - Synthetic envelopes (fabric)
- Drain Envelope Construction
- Quality Control

Envelope Terminology

Envelope

a generic name for any material placed on or around a pipe drain without specifying the reason for its use

Filter

an envelope used specifically to prevent fine soil particles from entering the drain.

Permeable surround

material specifically selected to provide a zone of high hydraulic conductivity around the drain

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41th INTERNATIONAL COURSE ON LAND DRAINAGE ICLD

Workbook

4.2 INSTALLATION OF DRAIN PIPES AND MAINTENANCE

DRAINAGE

From 19 August to 6 December 2002 Wageningen, The Netherlands

Books compared

Agricultural Drainage (ASA)

(>30 authors; Dierickx, Stuyt, Willardson) - $90

- concise Handbook; virtually all topics in 1 volume

Materials for subsurface land drainage systems (FAO)

(Stuyt, Dierickx, Martinez Beltran) - $20

- pipes, envelopes, standards, laboratory apparatus

Envelope design for subsurface drains

(Vlotman, Willardson, Dierickx) - $35

- envelopes, historical review of research findings

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FORTYFIRST INTERNATIONAL COURSE ON LAND DRAINAGE
Wageningen – The Netherlands, 2002

Contents

Author

Various authors

Lecturer ICLD 2002

Ing. J. Penninkhof
Lelystad, The Netherlands

Lecture notes for the International Course on Land Drainage are not official publications. They may be altered from year to year. Lecture notes have been published as: Drainage Principles and Applications, ILRI Publication 16, Wageningen 1974, and as a revised version in 1994.

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Envelope Functions 1-2-3-4

Filter function

limit the movement of soil particles into the drain pipe

Hydraulic function

provide a porous medium of relatively high permeability around the pipe and thus reduce entry resistance to water flow

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Envelope Functions 1-2-3-4

Mechanical function

provide support to the pipe in order to prevent excess deflection and damage to the pipe due to soil load

Bedding function

provide a stable base on which to support the pipe in order to prevent vertical displacement due to soil load during and after construction

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Proper Naming of Envelope

Envelope materials should be named and classified according to the material that they are made from, because...

...envelope properties are largely determined by the material that they are made from.

Correct name	Wrong name
• synthetic envelope	• filter envelope
• gravel envelope	• synthetic filter
• peat envelope	

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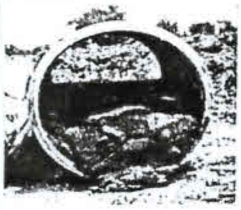
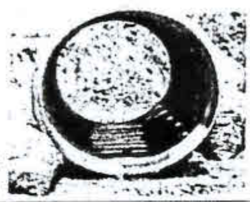
When should I install a drain envelope? (1)

pipe clogged shortly after construction





a properly selected envelope prevented mineral clogging

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When should I install a drain envelope? (2)

- if unstable soils at drain level cause sediment to flow into the drains
- if drain construction takes place below the water table
- if soil chemical status causes dispersion

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When should I install a drain envelope? (3)

Determine the need from soil parameter(s):

- clay percentage of the soil < 25 - 30%;
- Plasticity Index (PI) < 15;
- Coefficient of Uniformity (Cu) of the Particle Size Distribution (PSD) < 12;
- Sodium Absorption Ratio (SAR) > 8-12, and clay % < 40%;
- Hydraulic Failure Gradient (HFG) < the expected exit gradient of the water entering the drain

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Design of granular (gravel) envelopes

- D15 < 7*d85 (filter criterion)
- D15 > 0.3 mm (filter and hydraulic criterion)
- D15 > 4*d15 (filter criterion)
- D5 > 0.074 mm (hydraulic criterion: prevents too low hydraulic conductivity)
- D40 < 4.8 mm (construction criterion: to prevent segregation)
- D100 < 19 mm (construction and hydraulic criterion: to prevent segregation and macro pores)
- All openings should be covered by at least 76 mm (3") of filter material (construction criterion)

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Retention & hydraulic criteria for synthetic envelopes

1 ≤ O90/d90 ≤ 2.5 for envelopes thickness ≤ 1 mm (retention)

1 ≤ O90/d90 ≤ 5 for envelopes thickness 5 mm (retention)

O90 > 200 μm (200 μm = 0.2 mm, hydraulic criterion)

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Mechanical (strength) criteria for synthetic envelopes

Tensile strength > 80 lbs *(ASTM 1682)* or > 6 kN/m

Tensile strength of joints > 6 kN/m

Tear strength > 45 lbs *(ASTM D-1777)*

CBR puncture resistance > 1000 N

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Wrapping of a large diameter (collector) pipe in the field

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Envelope stitching should be done properly

Single overlap stitching will not prevent sediment passing through

no sediment passing

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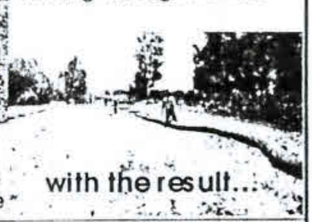
Drain Envelope Construction

the wrapped collector pipe 'winding' through the field



to move it, staff typically grabs the envelope "

with the result...

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Drain Envelope Construction

tearing of the envelope!

If the pipe is lifted by grabbing the fabric, it may tear easily if the tensile strength is not sufficient!

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Testing of synthetic envelopes

- Thickness and Denier or dtex of the base material;
- Mass per unit area (at 2kPa = 0.29 psi);
- Tensile strength of the material;
- Tensile strength of the joints (if applicable);
- Static puncture resistance;
- Water absorption;
- Resistance to chemicals (acid and saline water);
- Characteristic opening size (soil retention capability);
- Water permeability normal to the plane without load;
- Water flow characteristics in the plane;
- Water penetration resistance;
- Resistance to material deterioration (UV resistance, etc.).

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Transport, storage and handling on site

Lifting by grabbing the envelope is forbidden!

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Displays of drainage materials

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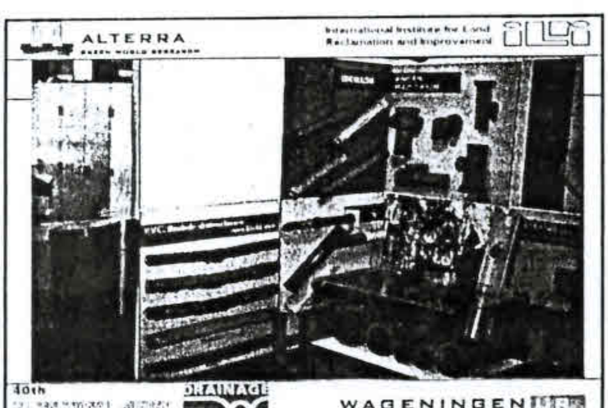

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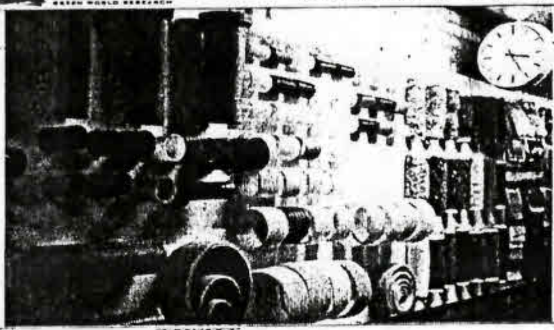

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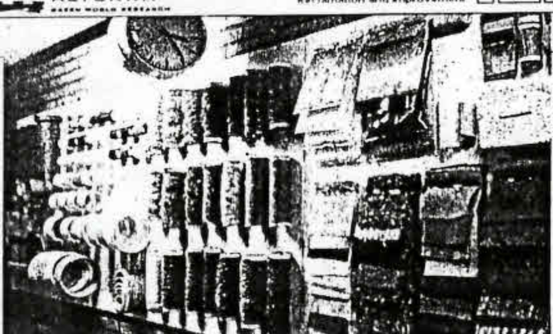

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Drain pipes

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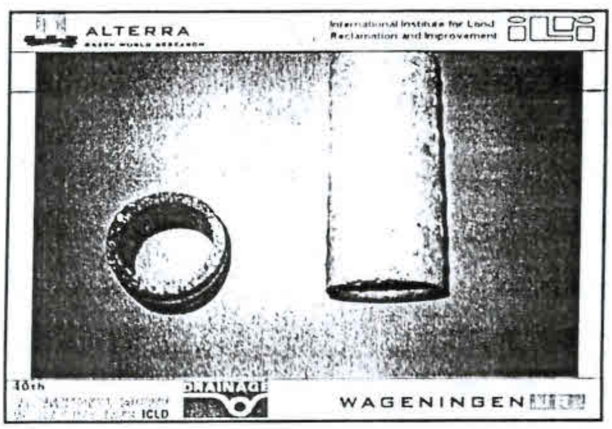
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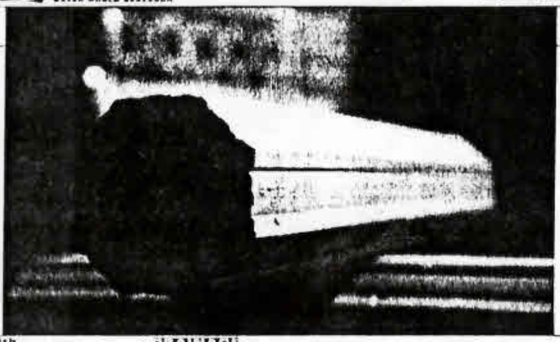

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ADVANTAGES OF CLAY OR CONCRETE TILE

- Low Hydraulic Roughness
- Rigid and Durable
- Fire and Rodent Resistant
- Easy to Locate in Field

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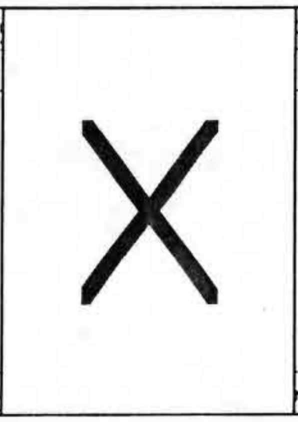

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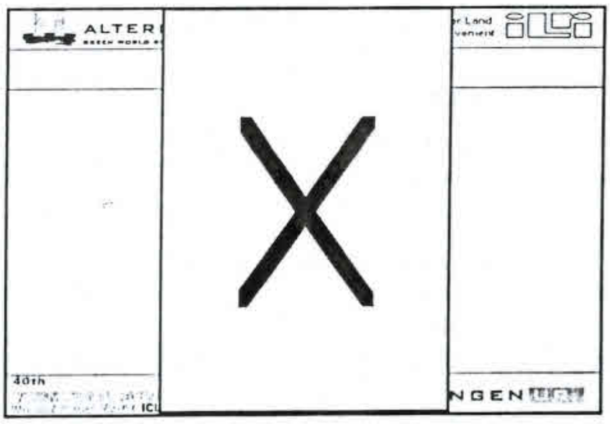
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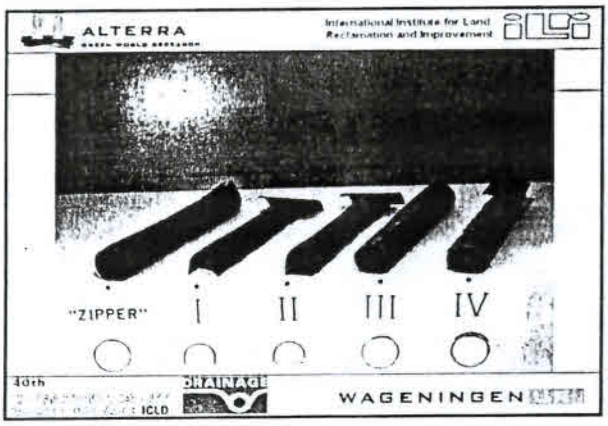
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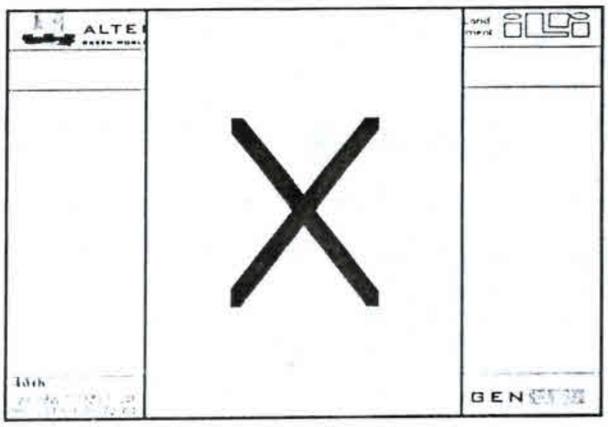
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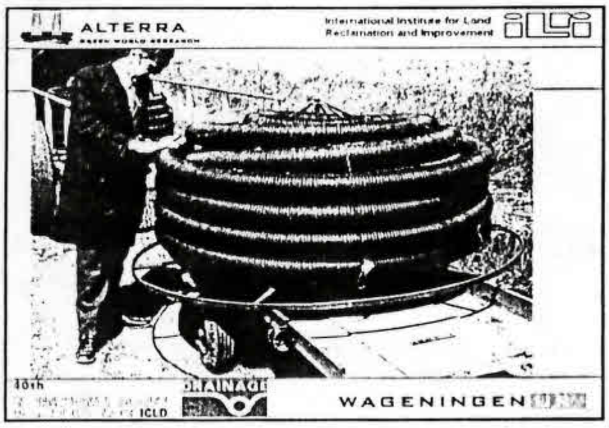

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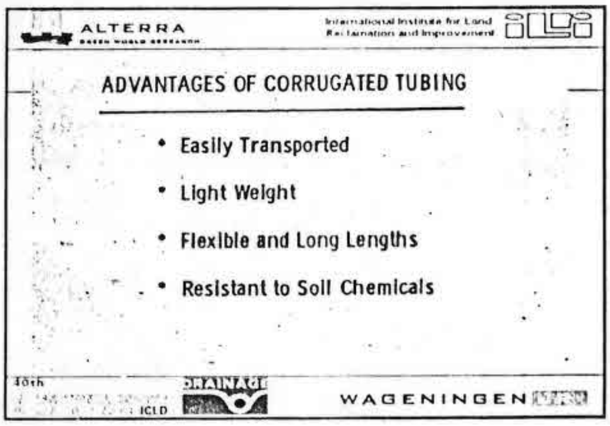

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ADVANTAGES OF CORRUGATED TUBING
• Easily Transported
• Light Weight
• Flexible and Long Lengths
• Resistant to Soil Chemicals
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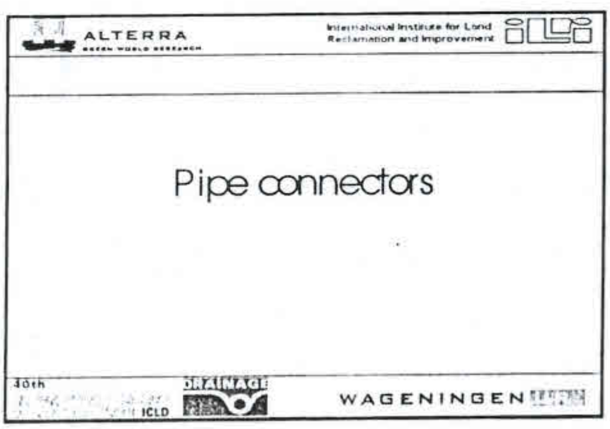
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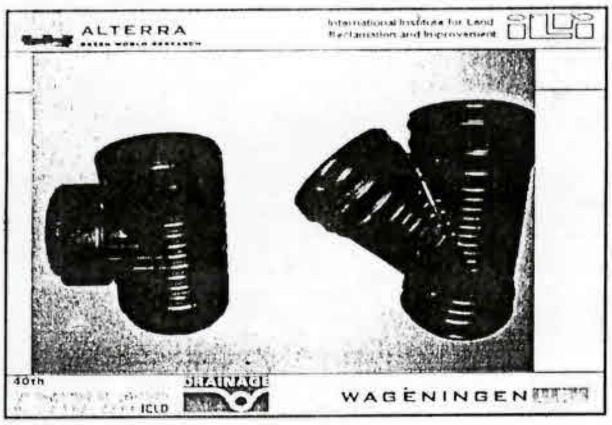
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Testing of drain pipes

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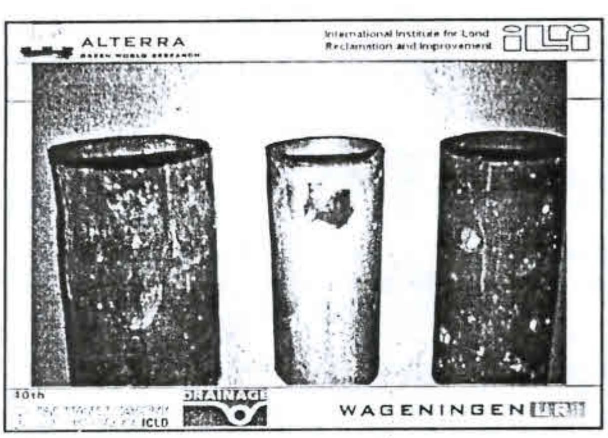

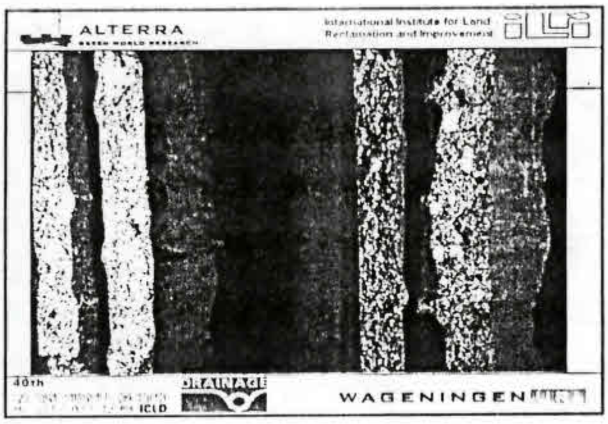

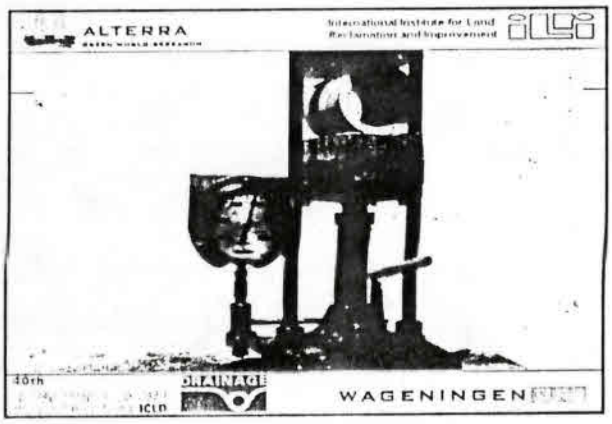

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CORRUGATED TUBING

Temperature °F	Relative Stiffness
35	170%
50	139%
70	100%
85	79%
100	62%
140	43%

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Hancor drain pipe (USA)

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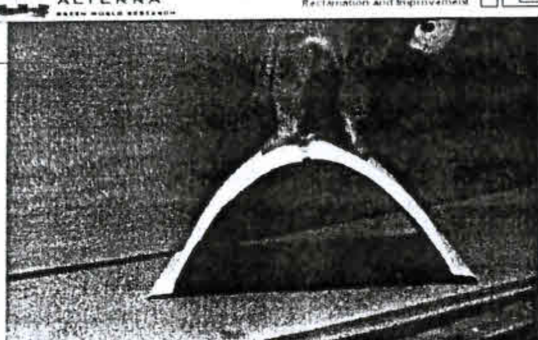

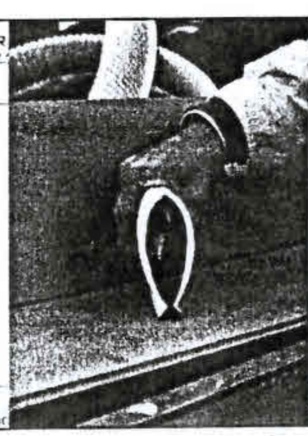


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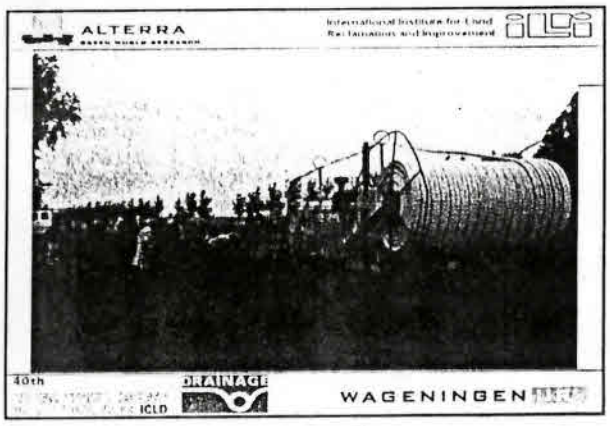
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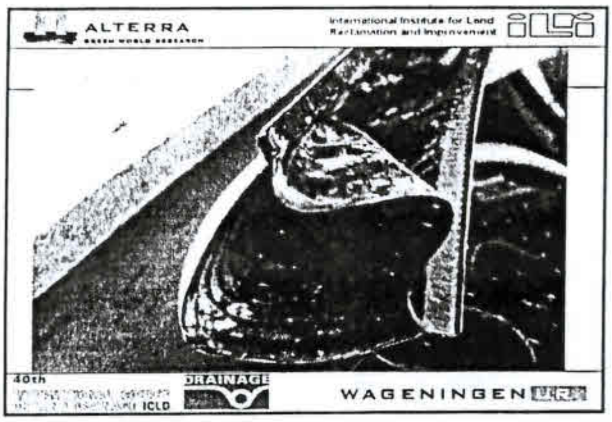

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Installation of lateral drains

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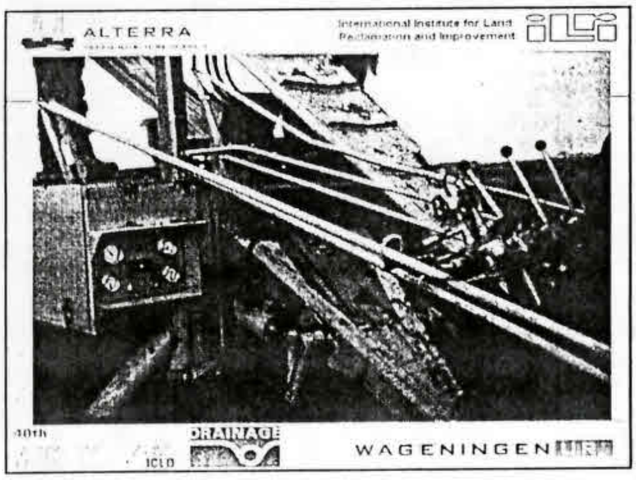
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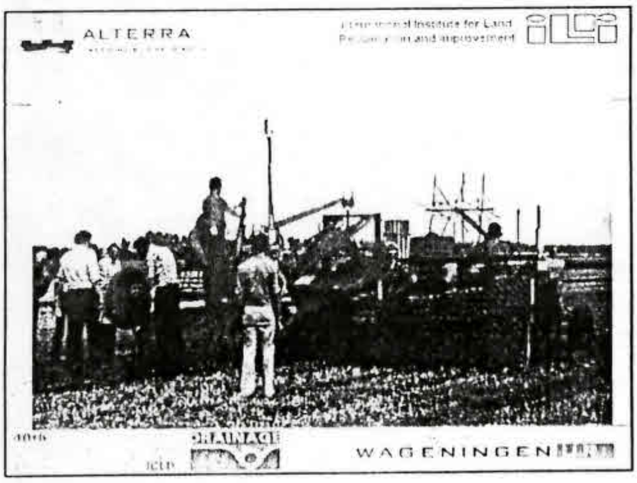
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Drain envelopes

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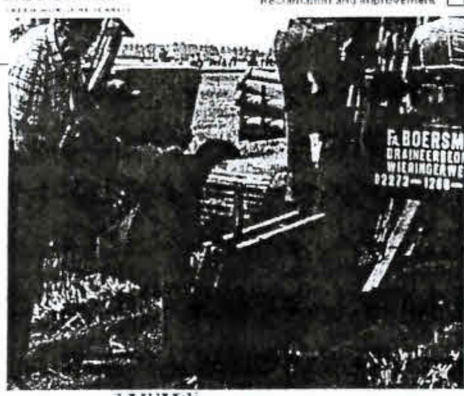

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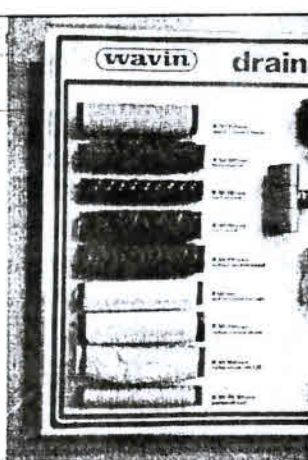

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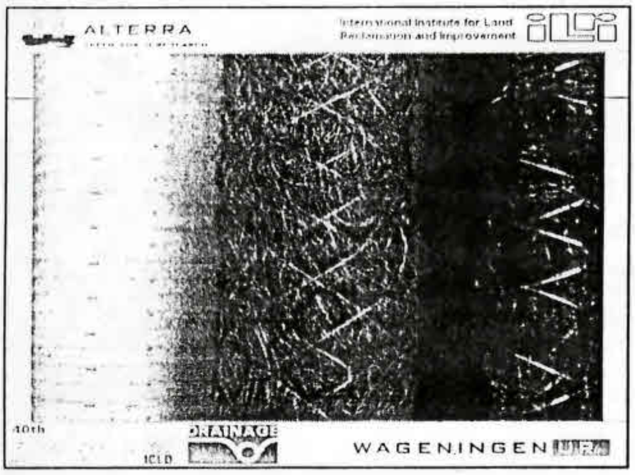
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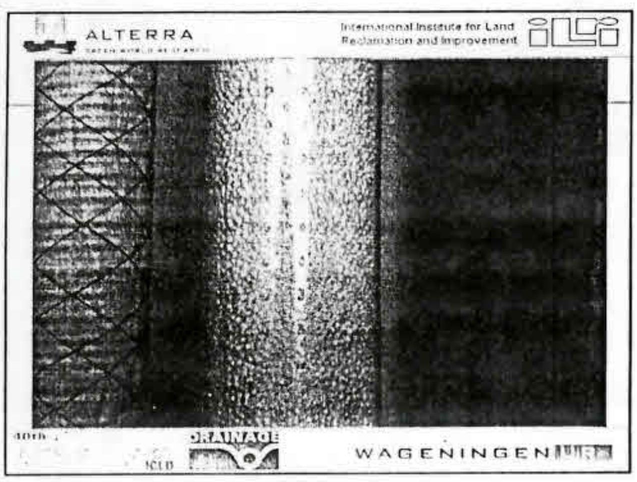
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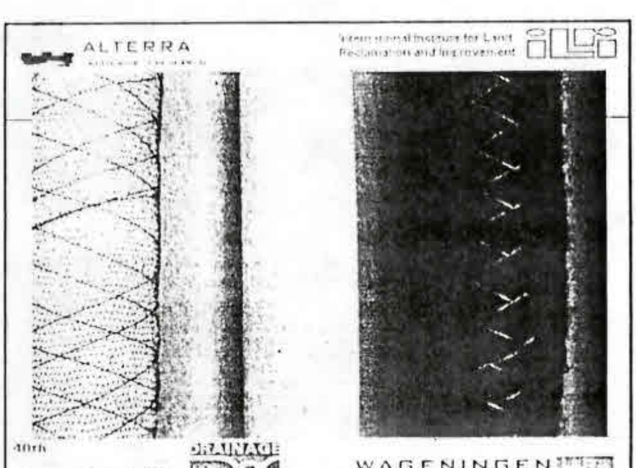
International Institute for Land
Reclamation and Improvement
40th
ICLD
DRAINAGE
WAGENINGEN UR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International Institute for Land
Reclamation and Improvement
40th
ICLD
DRAINAGE
WAGENINGEN UR

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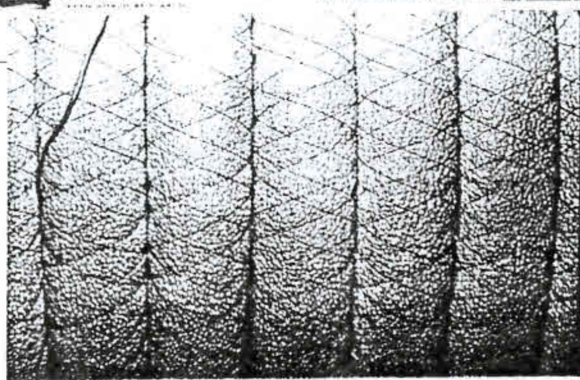

40th ICLD DRAINAGE

WAGENINGEN UR

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Water flow into drains

40th ICLD DRAINAGE

WAGENINGEN UR

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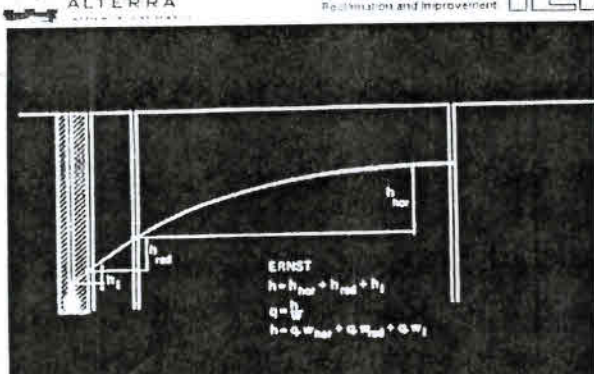
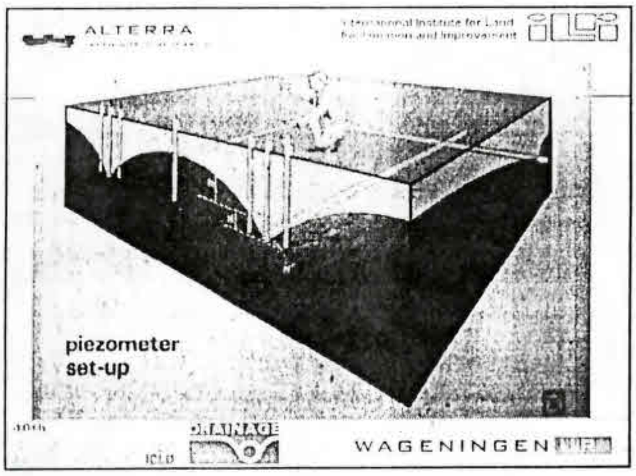


40th ICLD DRAINAGE

WAGENINGEN UR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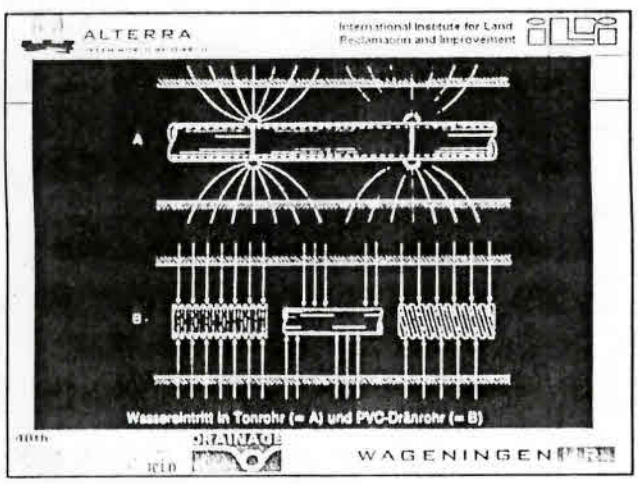
piezometer set-up
DRAINAGE
WAGENINGEN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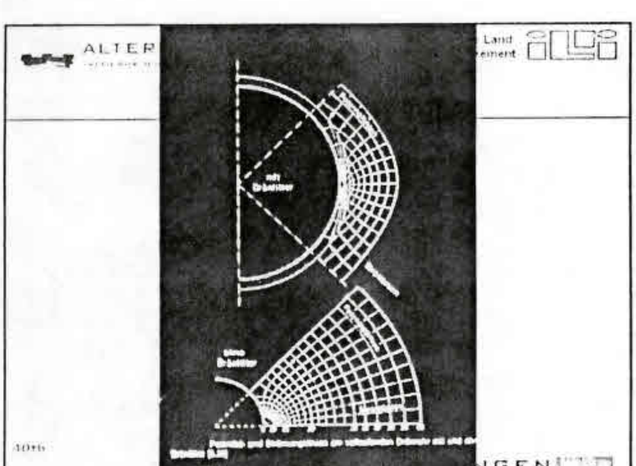
International Institute for Land Reclamation and Improvement
A
B.
Wassereintritt in Tonrohr (= A) und PVC-Dränrohr (= B)
DRAINAGE
WAGENINGEN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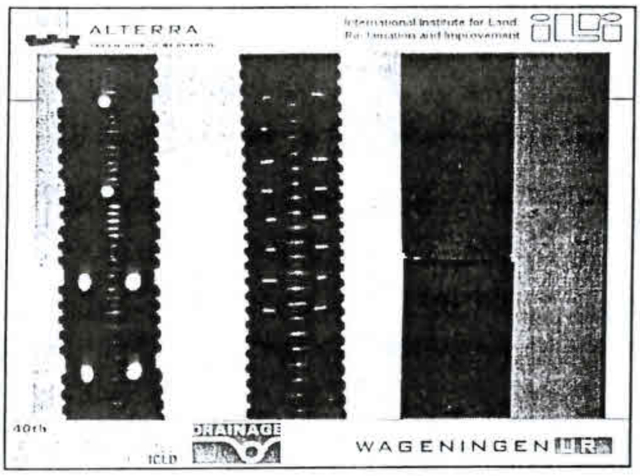

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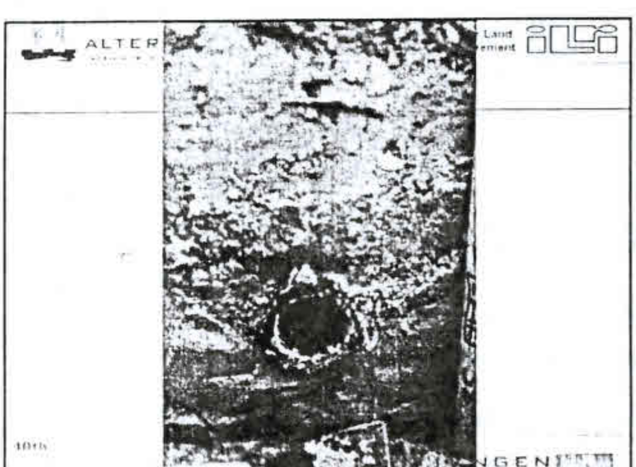
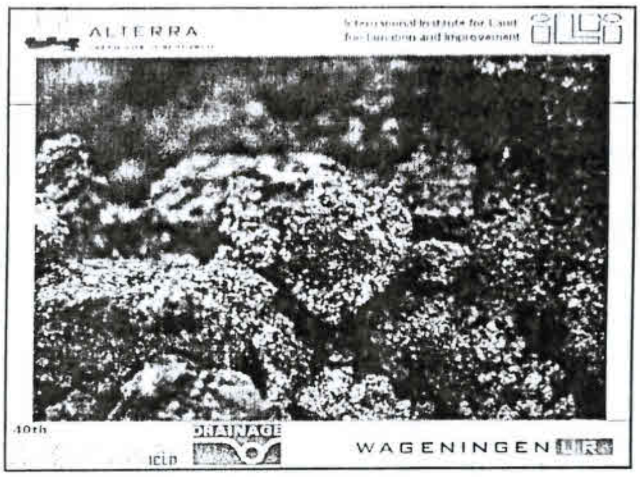
INFLOW RATE INTO DRAINS

Opening	Relative Inflow
Gravel Filter	100%
1/16 Inch Joint Per Foot	40%
1/4 Inch Joint Per Foot	49%
18 - 1 x 1/16 Inch Slits Per Foot	40%
36 - 1 x 1/16 Inch Slits Per Foot	51%

40th ICLD DRAINAGE WAGENINGEN UR



Problems with envelopes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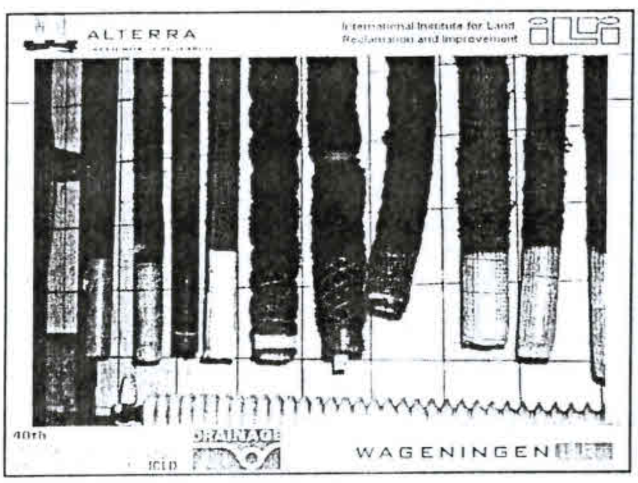
International Institute for Land Reclamation and Improvement
40th
DRAINAGE
ICLD
WAGENINGEN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International Institute for Land Reclamation and Improvement
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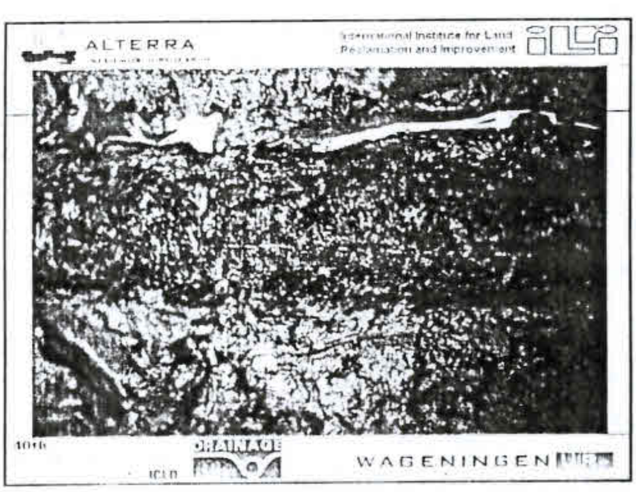
DRAINAGE
ICLD
WAGENINGEN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International Institute for Land Reclamation and Improvement
40th
DRAINAGE
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Reclamation and Improvement
40th
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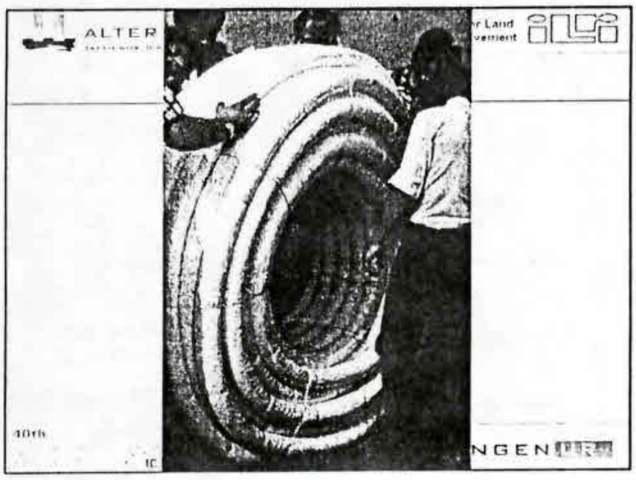
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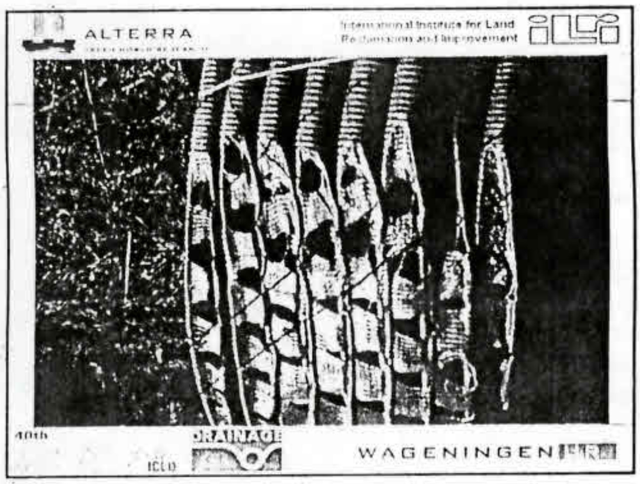
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WAGENINGEN UR

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Laboratory research

40th ICLD DRAINAGE

WAGENINGEN UR

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40th ICLD DRAINAGE

WAGENINGEN UR

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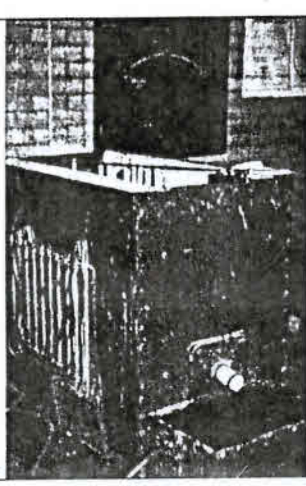

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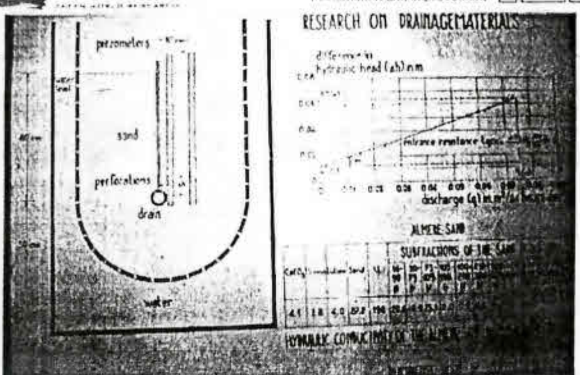

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40th ICLD DRAINAGE

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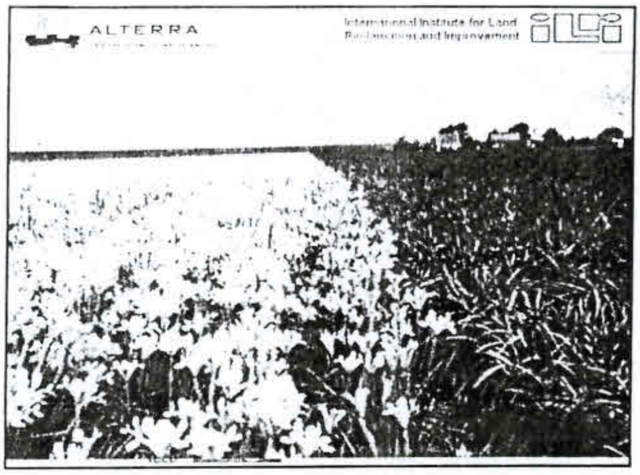
Problem analysis 'old style'

40th ICLD DRAINAGE

WAGENINGEN UR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Reclamation and Improvement

Video inspection of laterals

40th

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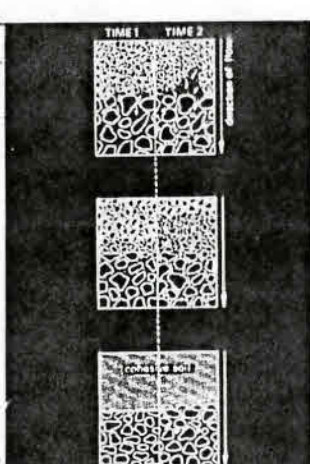

40th

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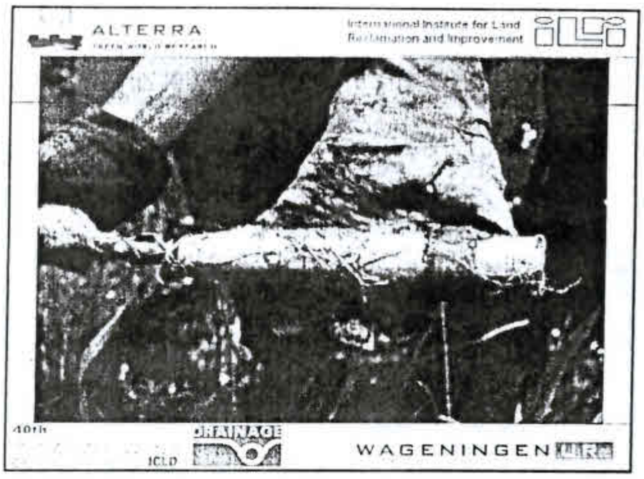
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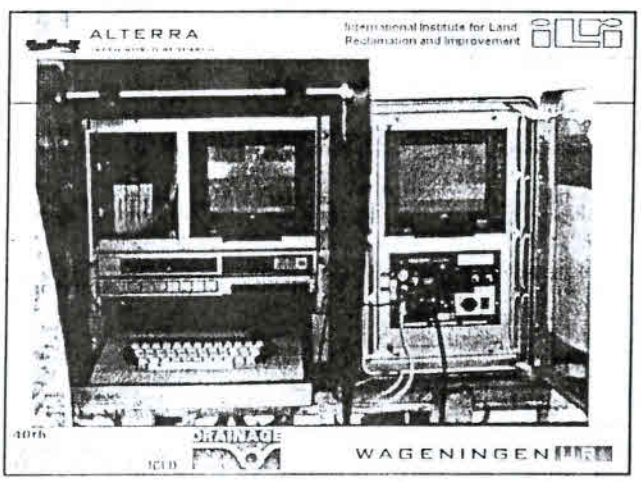
International Institute for Land
Reclamation and Improvement
40th
DRAINAGE
ICLD
WAGENINGEN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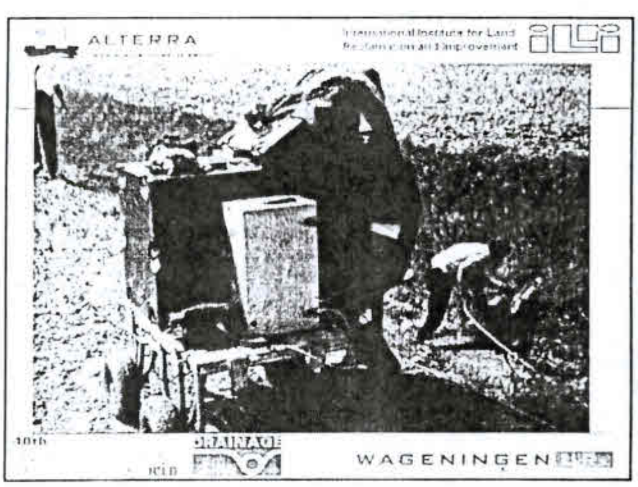
Reclamation and Improvement
40th
DRAINAGE
ICLD
WAGENINGEN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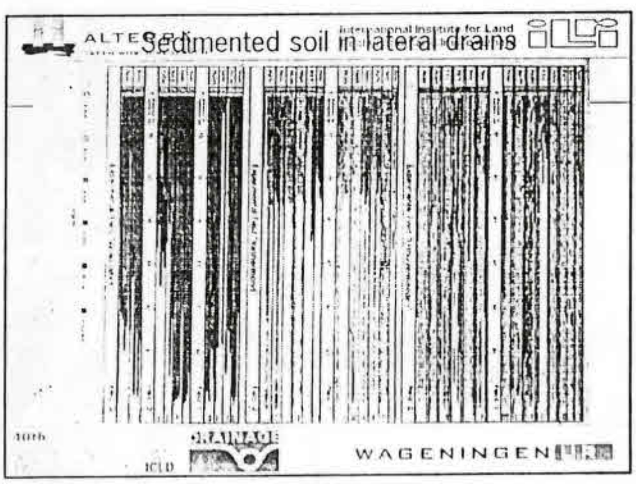
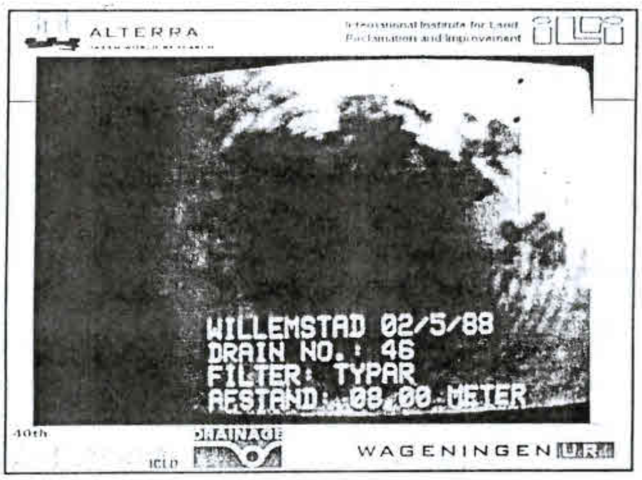
International Institute for Land
Reclamation and Improvement
40th
DRAINAGE
ICLD
WAGENINGEN


ALTERRA
International Institute for Land Reclamation and Improvement
WILLEMSTAD 02/5/88
40th
DRAINAGE
ICLD
WAGENINGEN UR


ALTERRA
Sedimented soil in lateral drains
International Institute for Land Reclamation and Improvement
40th
DRAINAGE
ICLD
WAGENINGEN UR


ALTERRA
International Institute for Land Reclamation and Improvement
WILLEMSTAD 04/5/88
DRAIN NO.: T/O 46/45
FILTER: POLYSTYREEN
40th
DRAINAGE
ICLD
WAGENINGEN UR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International Institute for Land Reclamation and Improvement
WILLEMSTAD 02/5/88
DRAIN NO.: 46
FILTER: TYPAR
AFSTAND: 08.00 METER
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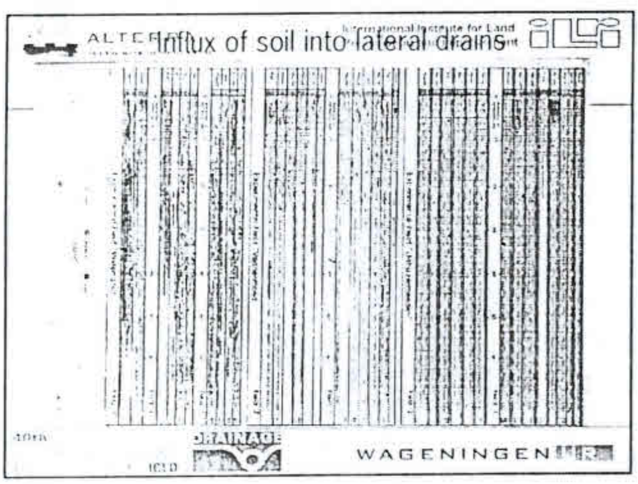
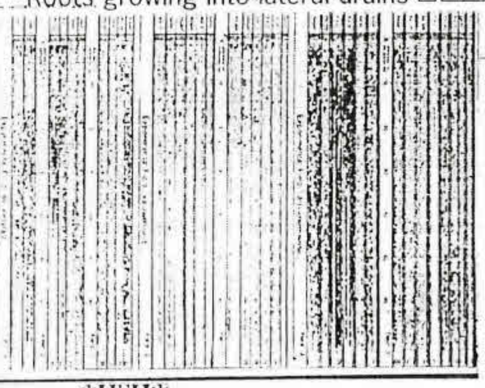
DRAINAGE
ICLD
WAGENINGEN UR

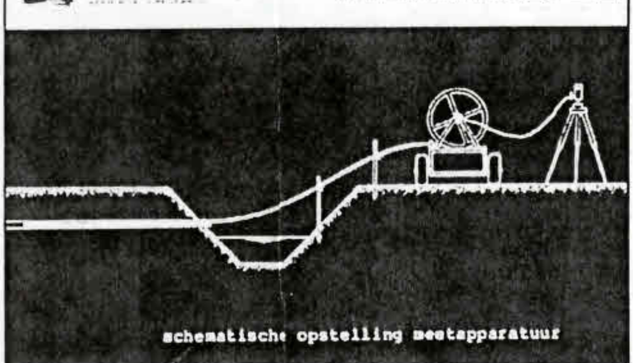

ALTERRA
Influx of soil into lateral drains
International Institute for Land
40th
DRAINAGE
ICLD
WAGENINGEN UR


ALTERRA
International Institute for Land Reclamation and Improvement
WILLEMSTAD 02/5/88
DRAIN NO.: 41
FILTER: GLASVLIES
AFSTAND: 40.00 METER
40th
DRAINAGE
ICLD
WAGENINGEN UR

Roots growing into lateral drains



Slope of installed laterals

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Checking of pipes in situ
40th
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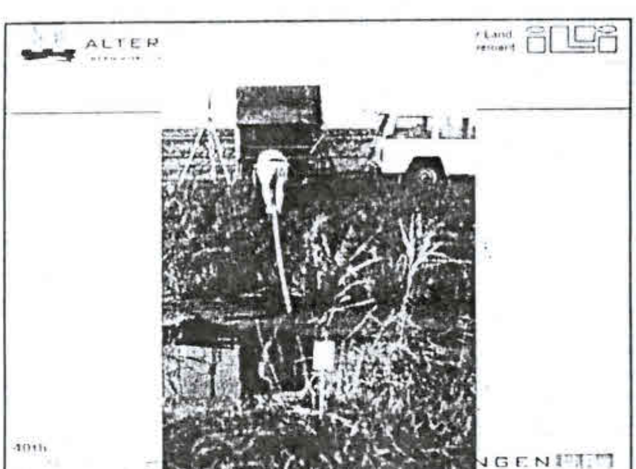
WAGENINGEN UR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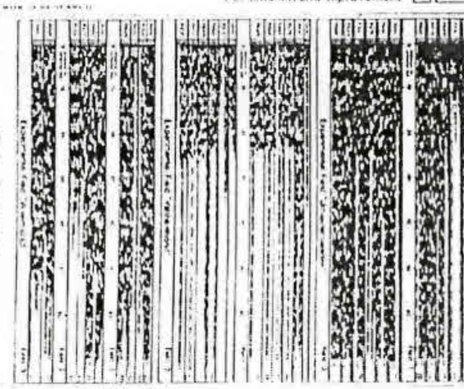
Reclamation and Improvement



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DRAINAGE

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Sampling of drain sections

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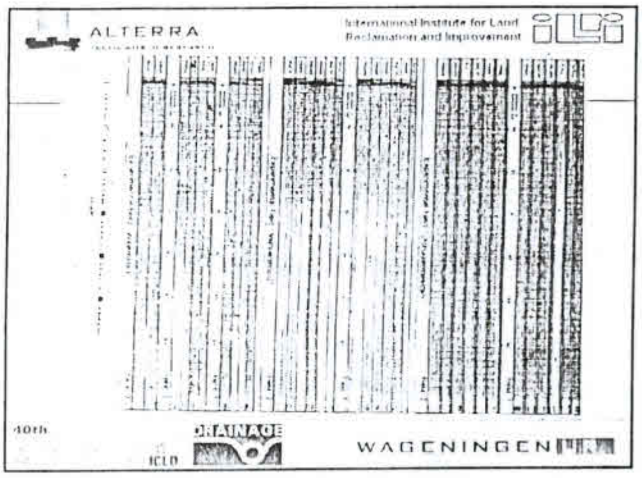
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Reclamation and Improvement
40th
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Reclamation and Improvement
40th
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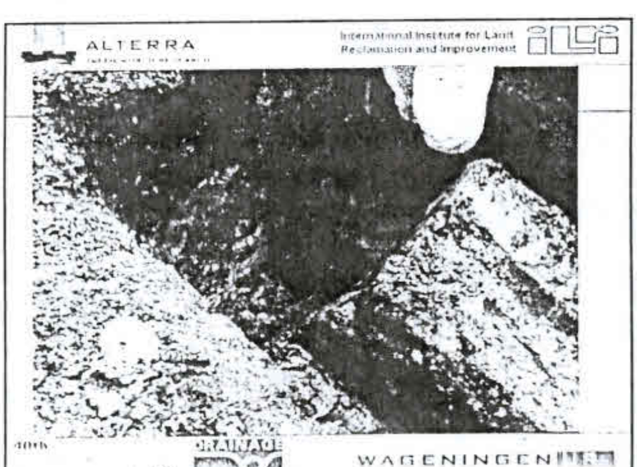
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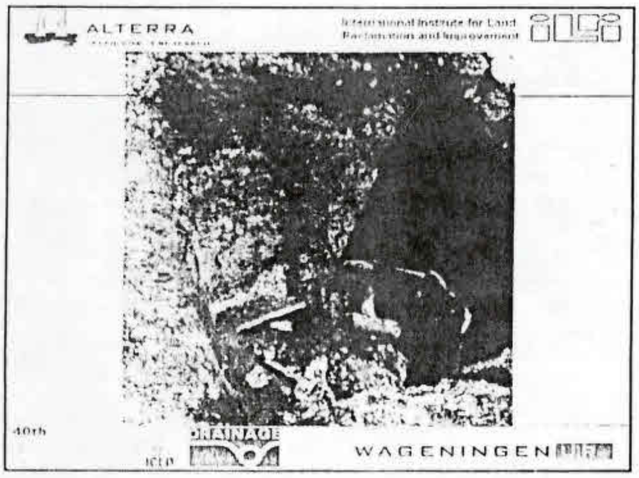
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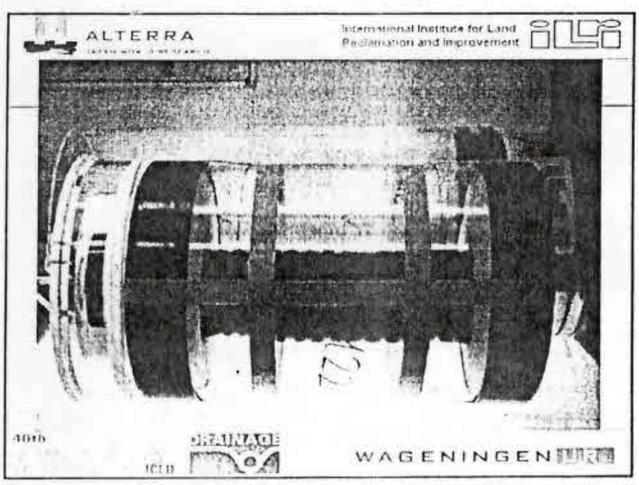
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International Institute for Land Reclamation and Improvement
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WAGENINGEN


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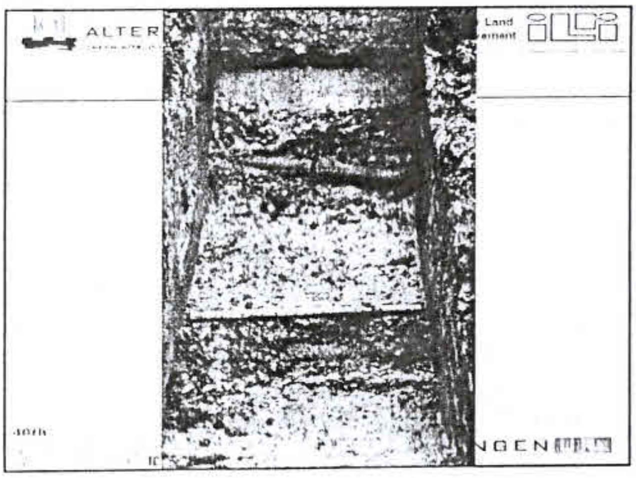

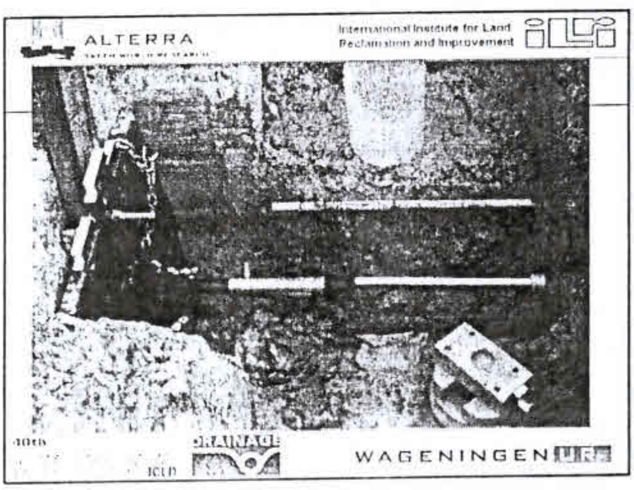
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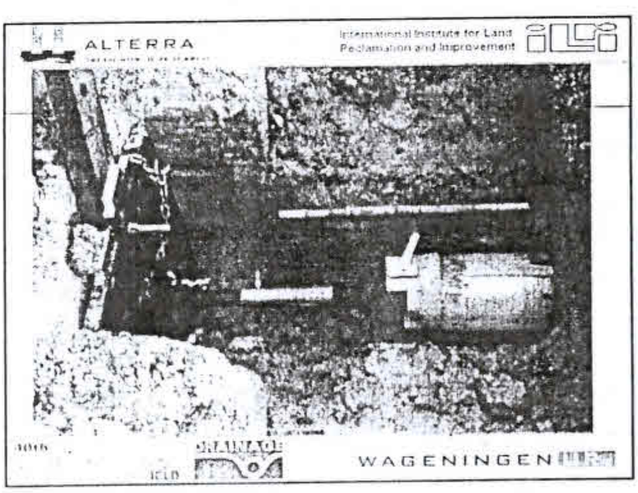
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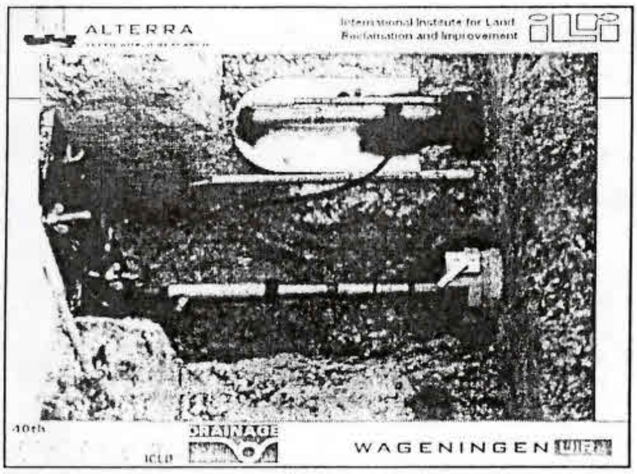
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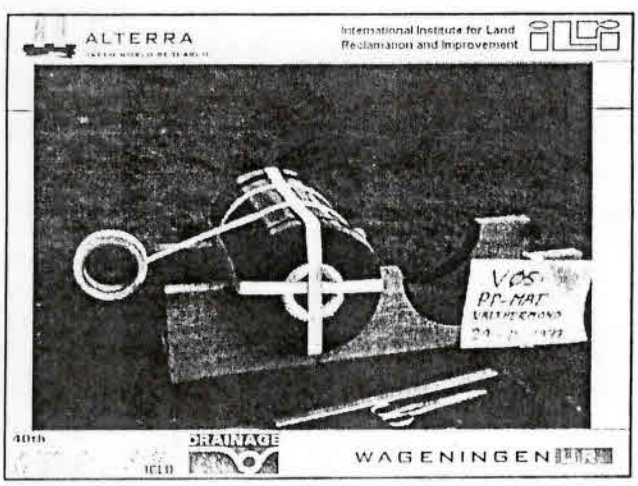
40th
DRAINAGE
WAGENINGEN UR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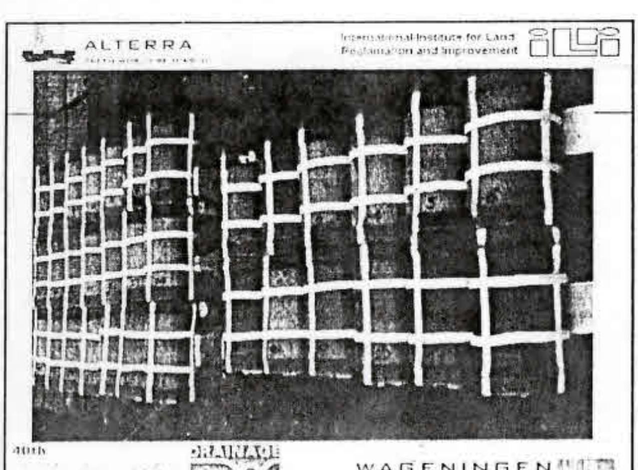
WAGENINGEN UR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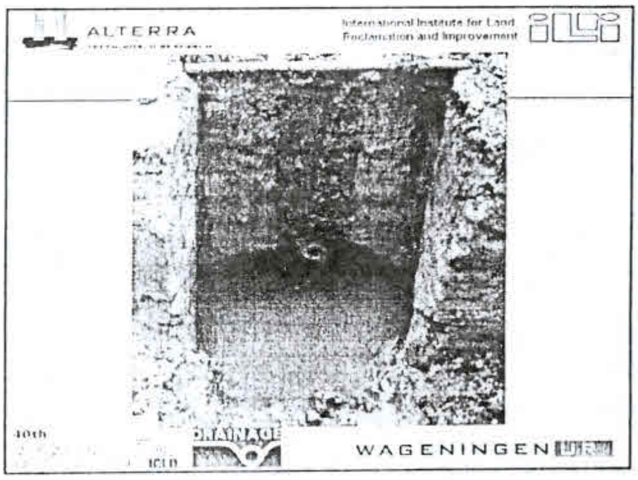
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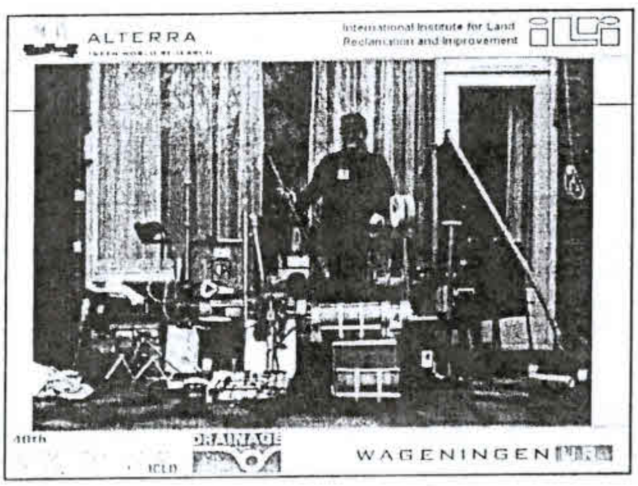
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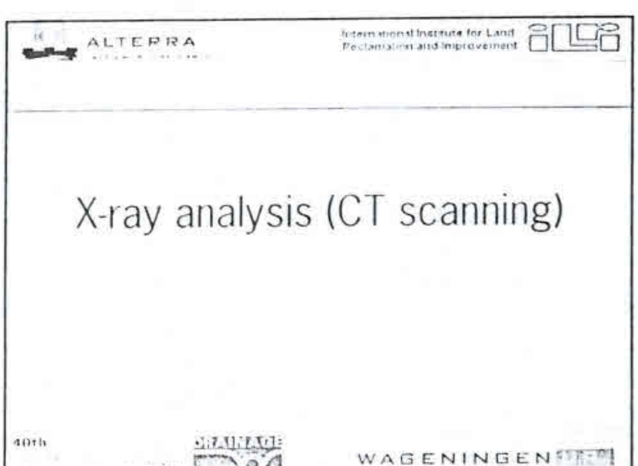
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X-ray analysis (CT scanning)
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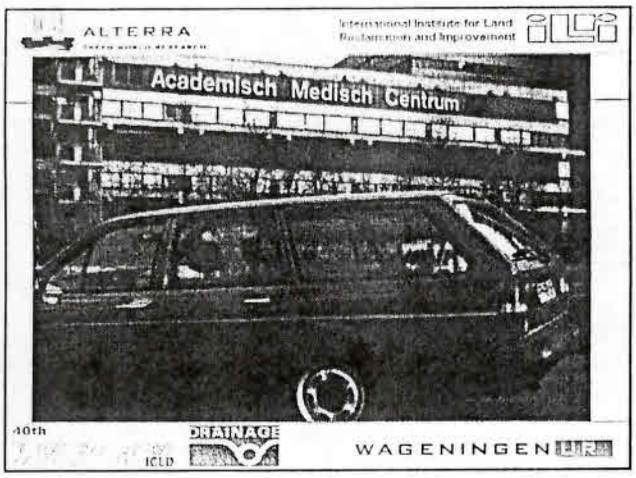
DRAINAGE
WAGENINGEN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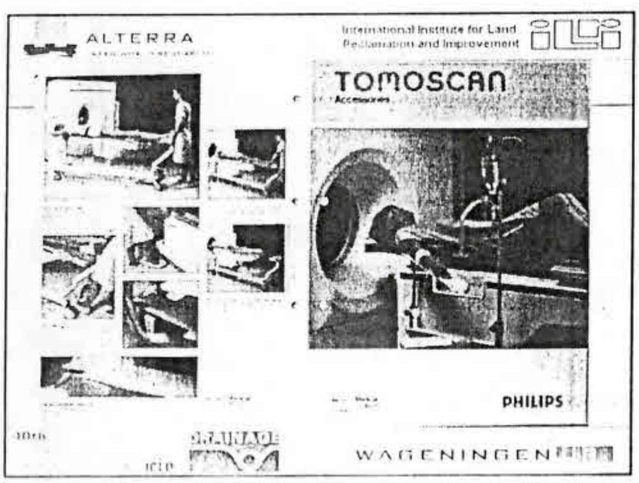
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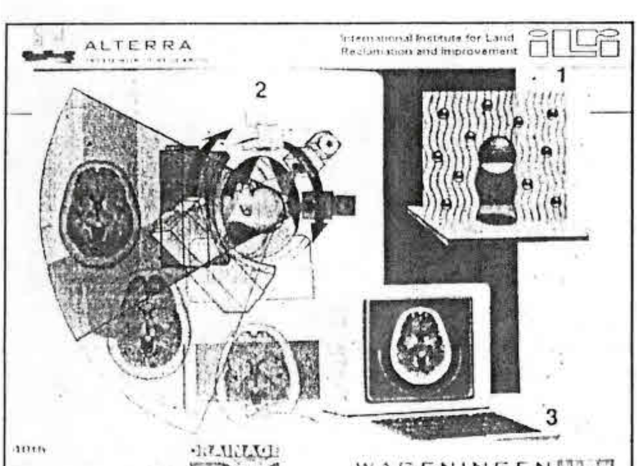
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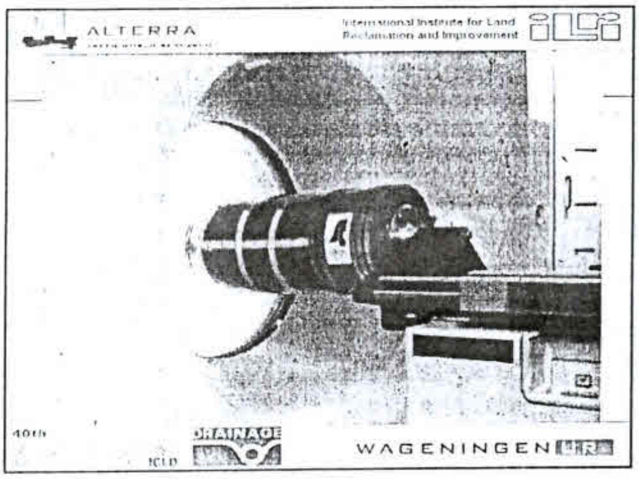

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Data analysis with workstation

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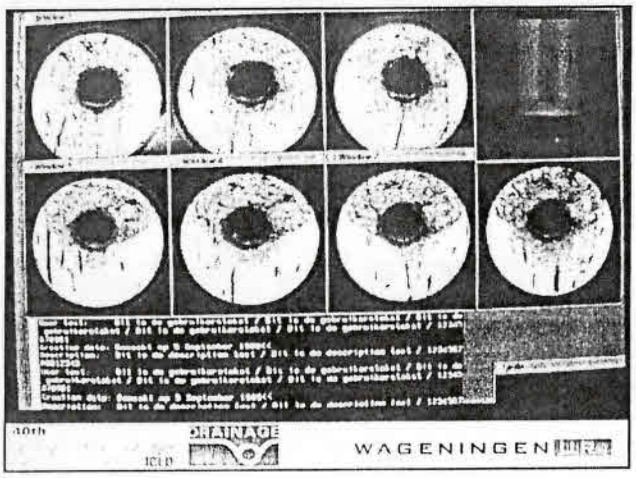
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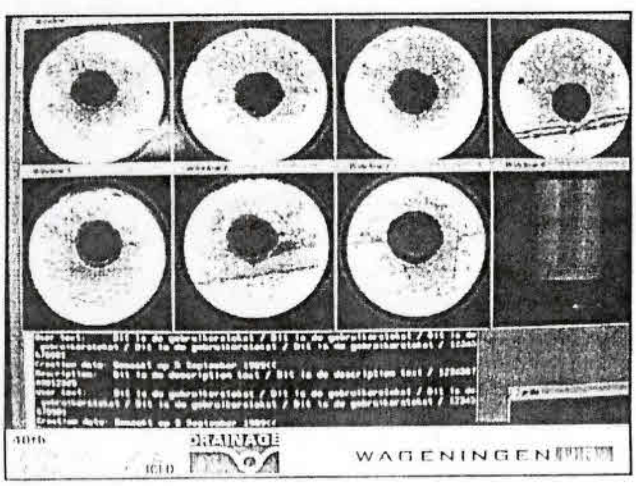
WAGENINGEN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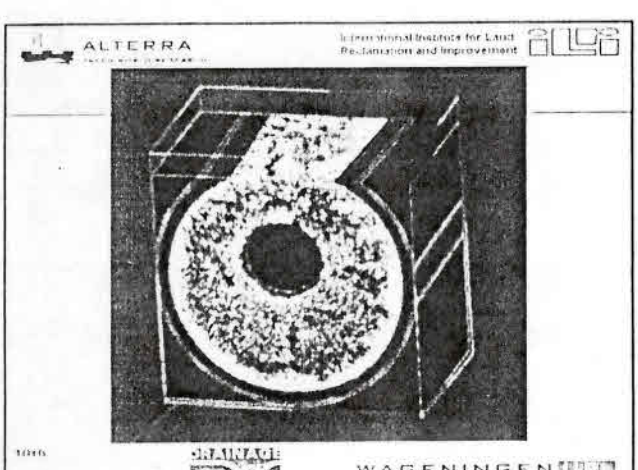
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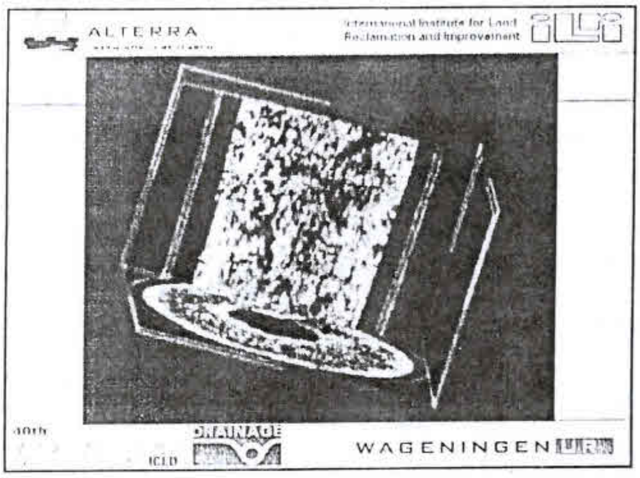
WAGENINGEN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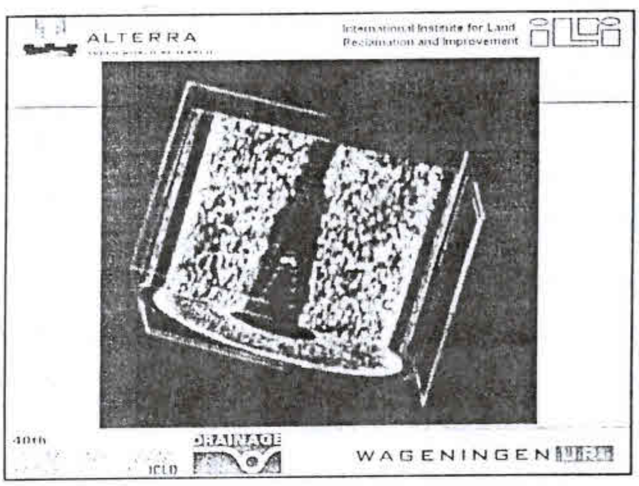
DRAINAGE
WAGENINGEN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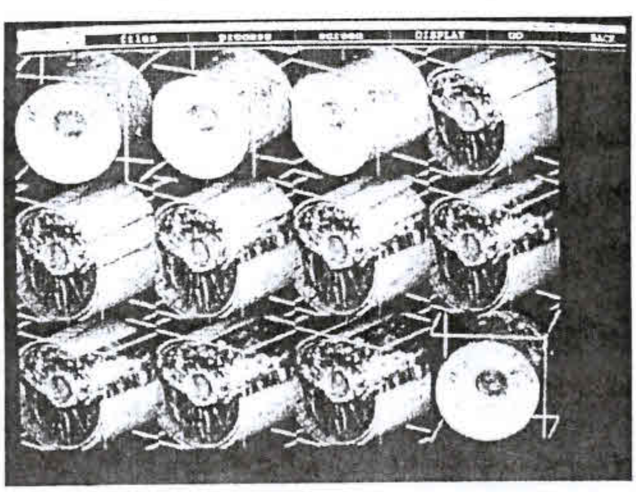
DRAINAGE
WAGENINGEN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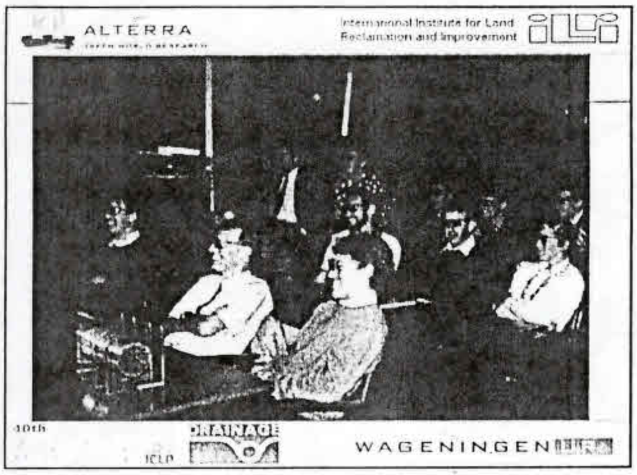
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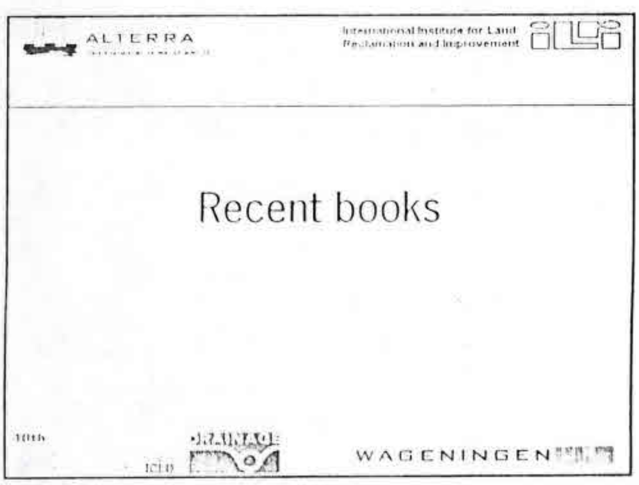
DRAINAGE
WAGENINGEN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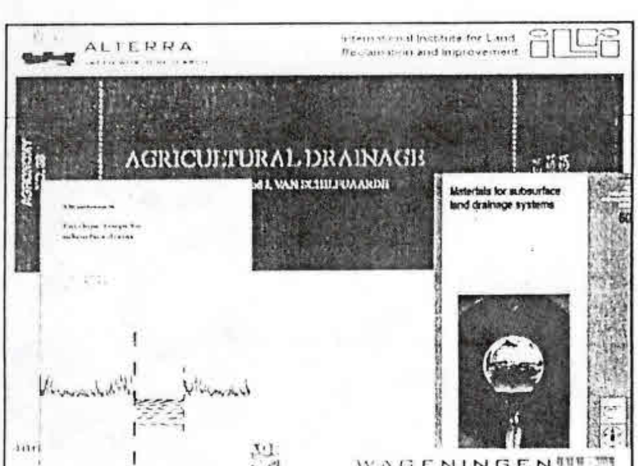
International Institute for Land Reclamation and Improvement
Recent books
DRAINAGE
WAGENINGEN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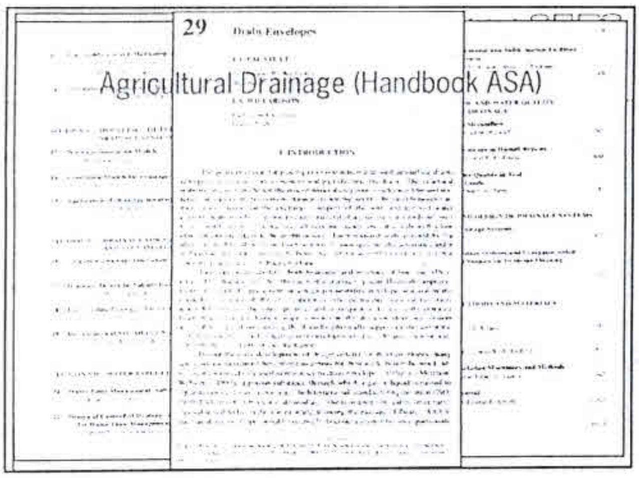
International Institute for Land Reclamation and Improvement
AGRICULTURAL DRAINAGE
Materials for subsurface land drainage systems
WAGENINGEN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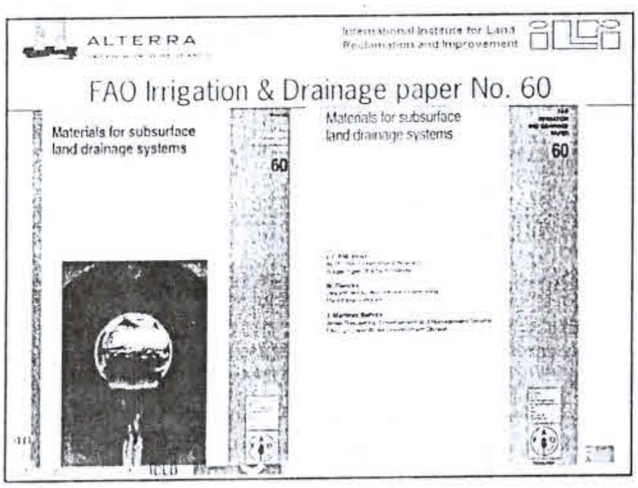
Agricultural Drainage (Handbook ASA)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Materials for subsurface land drainage systems
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Materials for subsurface land drainage systems
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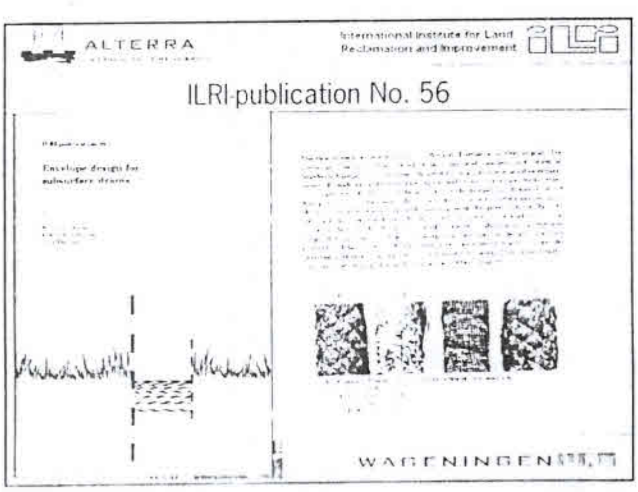
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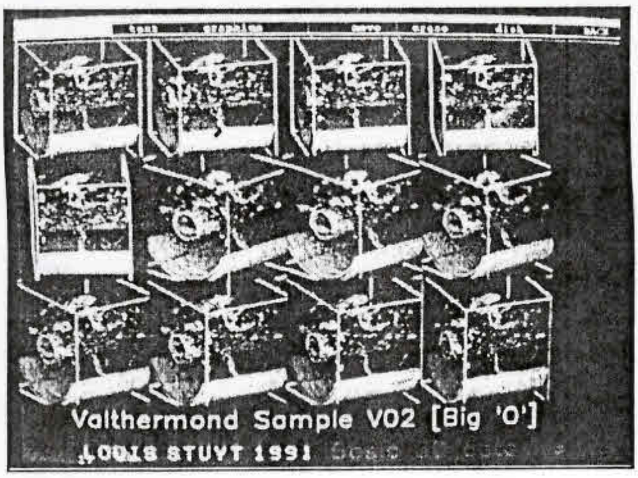
International Institute for Land Reclamation and Improvement
ILRI-publication No. 56
WAGENINGEN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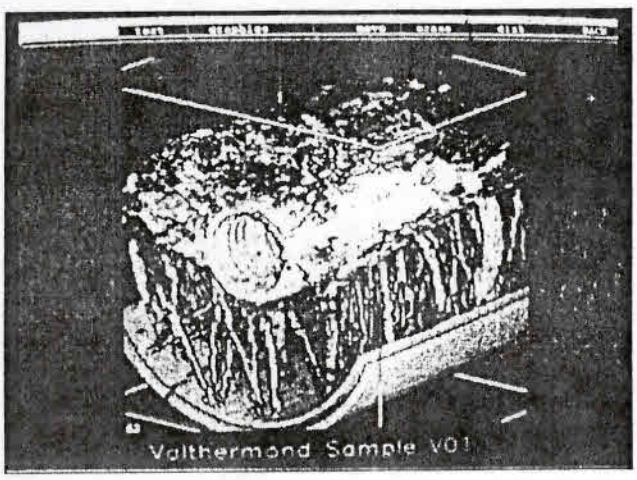
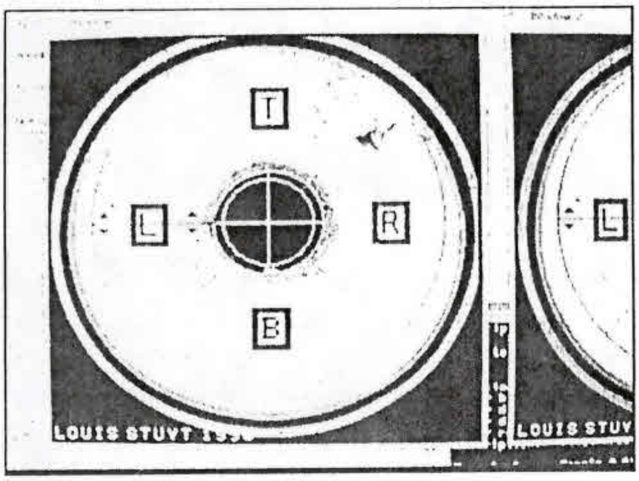
LOUIS STUYT 1991


Valthermond Sample V01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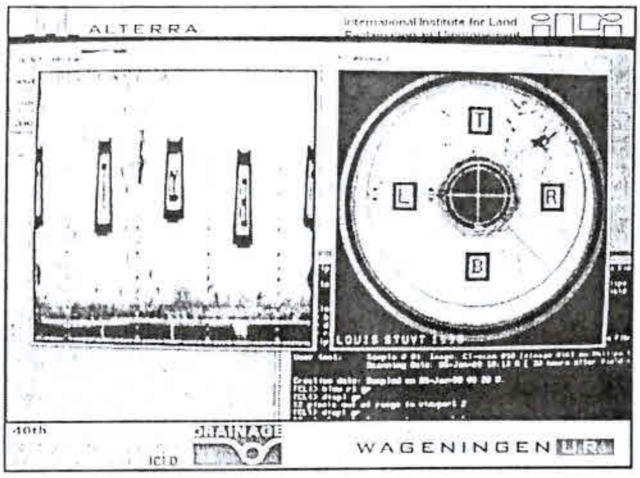
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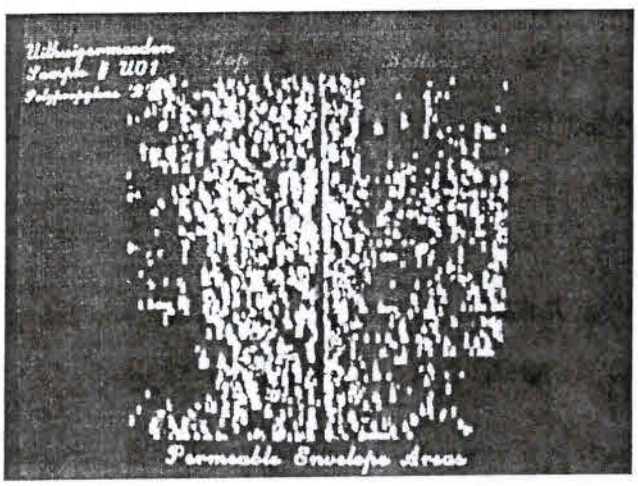
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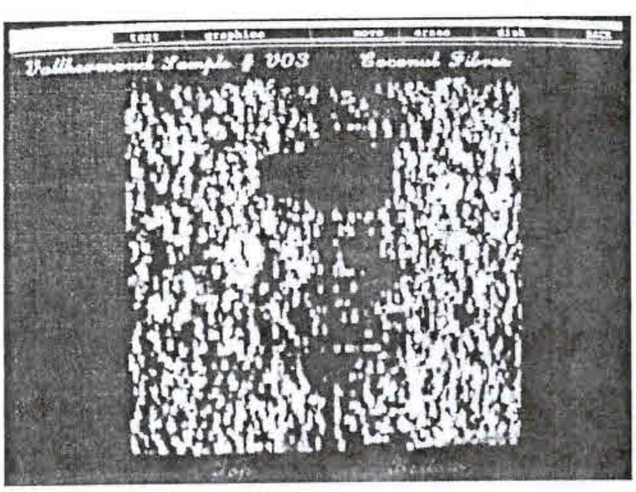
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erase
disk
Sample # V03
Coconut Fibres

INTERNATIONAL INSTITUTE FOR LAND RECLAMATION AND IMPROVEMENT
P.O. Box 47, 6700 AA WAGENINGEN, THE NETHERLANDS, PHONE: +31 317 495549, FAX: +31 317 495590, E-MAIL: ILRI@ILRI.NL

INSTALLATION OF DRAIN PIPES AND MAINTENANCE

Workbook
Installation and maintenance of pipe drains

part 1: Overview

1.1 Subject
This subject is dealing with mechanical installation and maintenance of horizontal pipe drains.

1.2 Lecturer

name:	Toni van Zeijts,
profession:	ecological and drainage engineer, retired since 2000 from *Dienst Landelijk Gebied (DLG) for sustainable land and water management*, Utrecht , The Netherlands.
address:	Buntlaan 93, 3971 JC Driebergen, The Netherlands.
phone:	-- 31 343 512883
E-mail:	t.zeijts@wxs.nl

Former responsibility :
- in general: co-ordinator of the technical developments in the execution of land improvement projects in The Netherlands;
- more specific related to land drainage: co-ordinator of the technical developments in installation and maintenance of pipe drain in The Netherlands in the period 1970 – 1995

Specific expertise:
- installation and maintenance of pipe drains;
- systems for checking quality of drain installation works;
- application of drain envelopes based on local field conditions;
- ground works
- nature management
- cost calculations
- farmers participation in project planning
- consultant in introduction of trenchless installation in Egypt and Portugal.
- trainer EPADP-staff (Egyptian Authority on Drainage Projects)

1.3 Learning objectives / aims
After this part of the course the participants:

1. are able to identify:
   - installation methods
   - relation: field conditions ←→ installation methods

2. have an idea about installation costs

3. are able to identify advantages and drawbacks of cleaning pipes by jet flushing

1.4 Programme
These learning objectives are to be reached in the following steps:

1st day: Introductional lectures and exercises to installation and maintenance

Homework / study

2nd day: Field demonstrations installation and maintenance
(and visit to a pipe factory as well as an envelope factory)

Homework / study

3rd day: Discussions on field demonstration and on homework,
additional lectures and
evaluation

1.5 Teaching methods
The teaching method is based on interaction between participants and lecturer. Lectures will be short and limited. Discussions are important. Many mainlines and important details will be showed with help of slides and sheets. Participants are expected to do some exercises during the evenings; co-operation is recommended.

1.6 Participants work-load
All participants are expected to:
- join in the scheduled activities and to do some exercises as homework.
- study the following papers:
  1. Drainage machines
  2. Effects of Jet Flushing on Drain Performance and Sustainability.

The total work-load for homework will be about 5 hours.
Besides that participants are advised to study the paper: Possibilities and Limitations of Trenchless Pipe Drain Installation in Irrigated Areas.

1.7 Reference to written information
- ILRI-publication 16:
  - 21.4 Installation of Pipe Drains
  - 21.5.3 Operation and Maintenance – Cleaning Pipe Drains with Flushing Machines
- Papers in this workbook

Part 2: Learning and doing

Points for discussion and excercises

2.1 Installation

1a Suppose you have to buy a new drainage machine for installion of lateral pipe drains. What would be the best type, related to the field conditions in your own country:
- a trencher or a trenchless machine?
- by choosing a trenchless machine:
  - a V-plough or
  - a vertical plough

b What is the motivation of your choice?

2 What do you prefer: a drainage machine on tires or on tracks? Mention the advantages and drawbacks of both.

3 In the design of drainage machines **engine capacity** (in Kw) is one of the main parameters. What are the most important factors (derived from field conditions and from the required output of the machine) you have to think of, determining engine capacity, for a trencher as well as for a trenchless machine?

4 Calculate the total cost (in Dlf/ha) of installation of a lateral pipe drain system (gen. drain depth 1.00m) in a clay soil in the Netherlands, with a trencher as well as trenchless.
Data:
- 600 m lateral drain pipes per ha.
- Material: corrugated pvc-pipe with a PP 450-envelope (dfl 1.50,--/m)
- One installation unit exists of:
  - 1 installation machine provided with laser (trencher 160 Kw: dfl 200,--/h, trenchless 200 Kw: dfl 240,--/h),
  - 1 tractor with trailer for transportation of material in the field and equipped with a blade for filling the trenches (dfl 15,--/h),
  - 2 drivers (dfl 40,--/h)
  - and one extra laborer (dfl 40,--/h).
- The production (in m/h) per unit can be found in table 1 of the paper "Possibilities and Limitations of Trenchless Pipe Drain Installation in Irrigated Areas" (lecture notes: 23).

5 What would be the total cost (in Dlf/ha) if the system would be installed manually (average production per laborer: 2m/h)?

6 Compare the installation cost (in dfl/m) (trencher installation, trenchless installation and installation manually) in a imaginary country with lots of laborers and little money. Use the same data on production and prices as in The Netherlands; however the cost of the drivers and other laborers is dfl 2.50/h).

2.2 Maintenance

1 a For cleaning pipe drains by means of jet flushing the accessibility and the maximum length of the drains is important. Why?
b Can we flush composite pipe systems as well as sigular systems? Give a motivation.

2 What is the cleaning effect of jet flushing?
a removing sand, silt, clay, ochre, roots out of the pipe;
b cleaning the perforations in the pipe wall;
c cleaning the envelope around the pipe.
(Underline the right answers.)

3 What are the disadvantages of jet flushing? In wich soil types do you expect these disadvantages?

4 In what circumstances is jet flushing useful?

5 In what circumstances jet flushing is not good for the drain performance?

6 The tabel on page .... presents data of three different groups of jet flushers, based on the water pressure at the pump: Low, Medium and High. What is your opinion on the performance of these 3 groups on the **cleaning effect** and on the risks of **damage** to the soil structure around the drain pipe? What is your opinion on the suitability of these 3 types? (Where can we apply which flusher type?)

7 If farmers are complaining about wet spots in an area, which is provided with a pipe drainage system, how do you know whether flushing can improve the system or not.

2.3 Quality Control

1. Why is it important, that grade deviations are limited?

2. Mention different reasons why too large grade deviations can occur, even when the machines are provided with laser.

3. What will a good supervisor inspect <u>before</u> the installation works and what <u>after</u>? Make a checklist.

Part 3: Appendix

Literature

Zeijts, T.E.J. van (1990). **Introduction on Land Drainage in The Netherlands.** Information paper nr 14 of the Government Service for Land and water Management, Utrecht, The Netherlands

de Boer. K.S. (1987). **Grading Precision of Subsurface Drains.** Mededelingen landinrichtingsdienst nr. 158a. A report dealing with the grading precision requirements of subsurface drains; the extent to which these requirements are complied with and developments necessary for further improvements. (Government Service for Land and Water Management, Utrecht, The Netherlands)

Bons, Arie and Toni van Zeijts (1991). **Jet flushing, a method for cleaning subsurface drainage systems.** A report dealing with:
- causes of malfunctioning of subsurface drainage systems;
- identification of drainage problems
- cleaning pipe drains by jet flushing
- main functions of jet flushing
- application jet flushing in arid countries
- guidelines for flushing

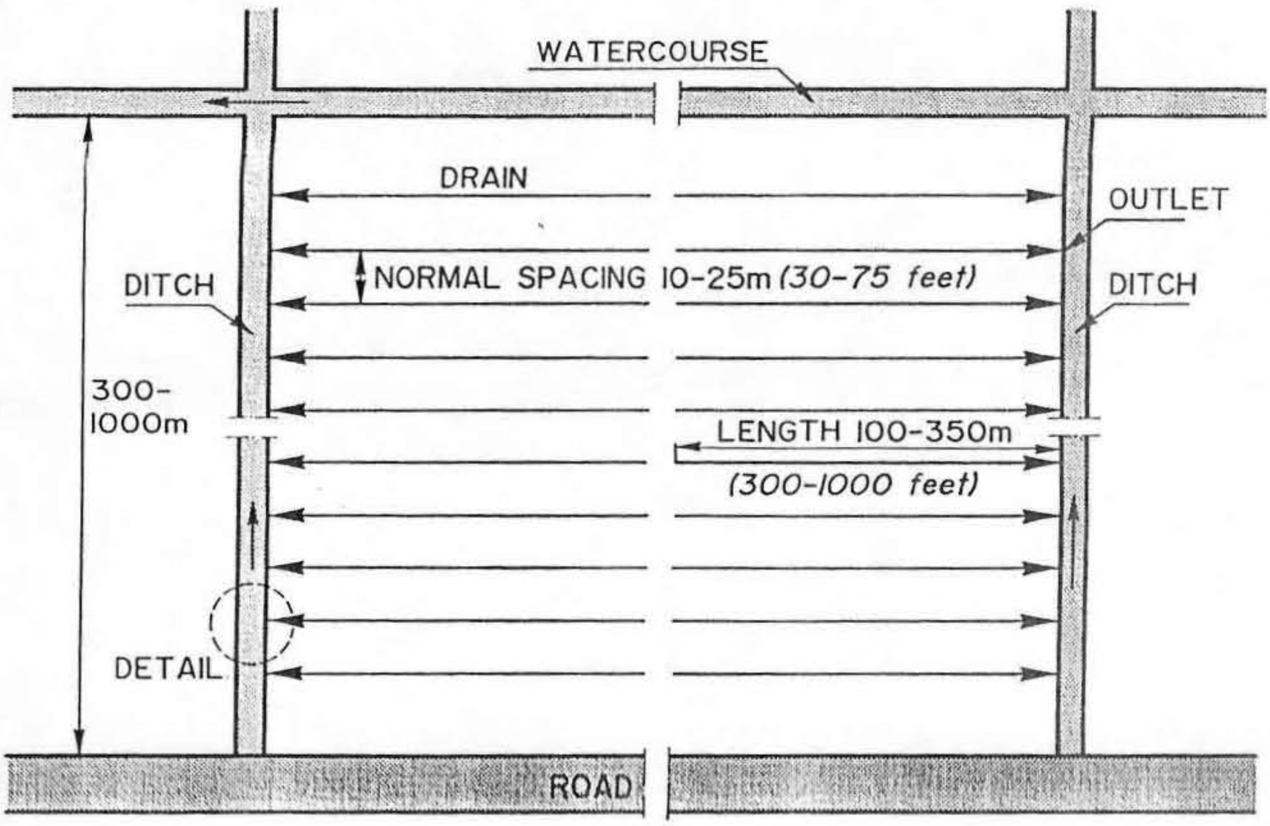
Government Service for Land and Water Management, Utrecht, The Netherlands.

Zeijts, T.E.J. van (1995). **Introduction of Trenchless Drain Installation in Egypt.** Mission Report to the Drainage Research Institute, Caïro, Egypt

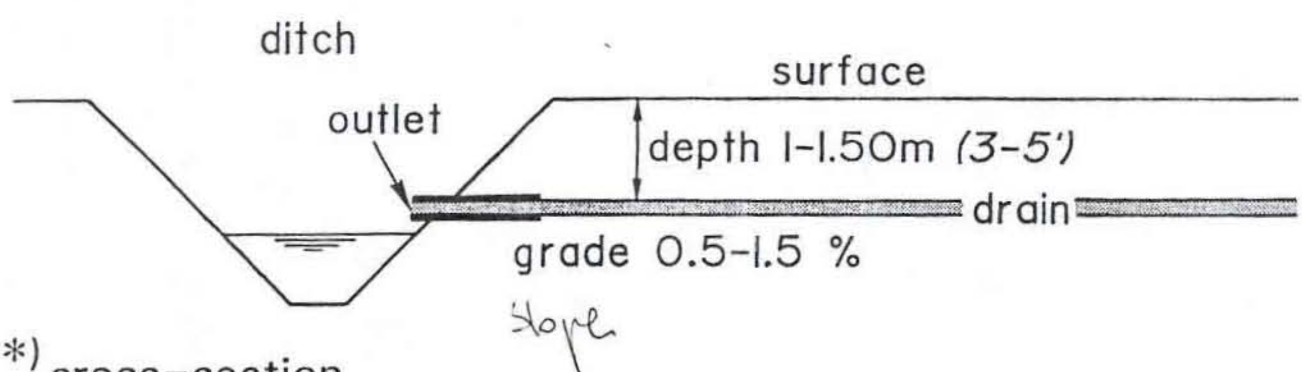
Drainage Research Institute (1997). **Practical Experiences with Trenchless Drainage (V-plow) in Egypt.** Caïro, Egypt

Part 4: Copies of overhead sheets

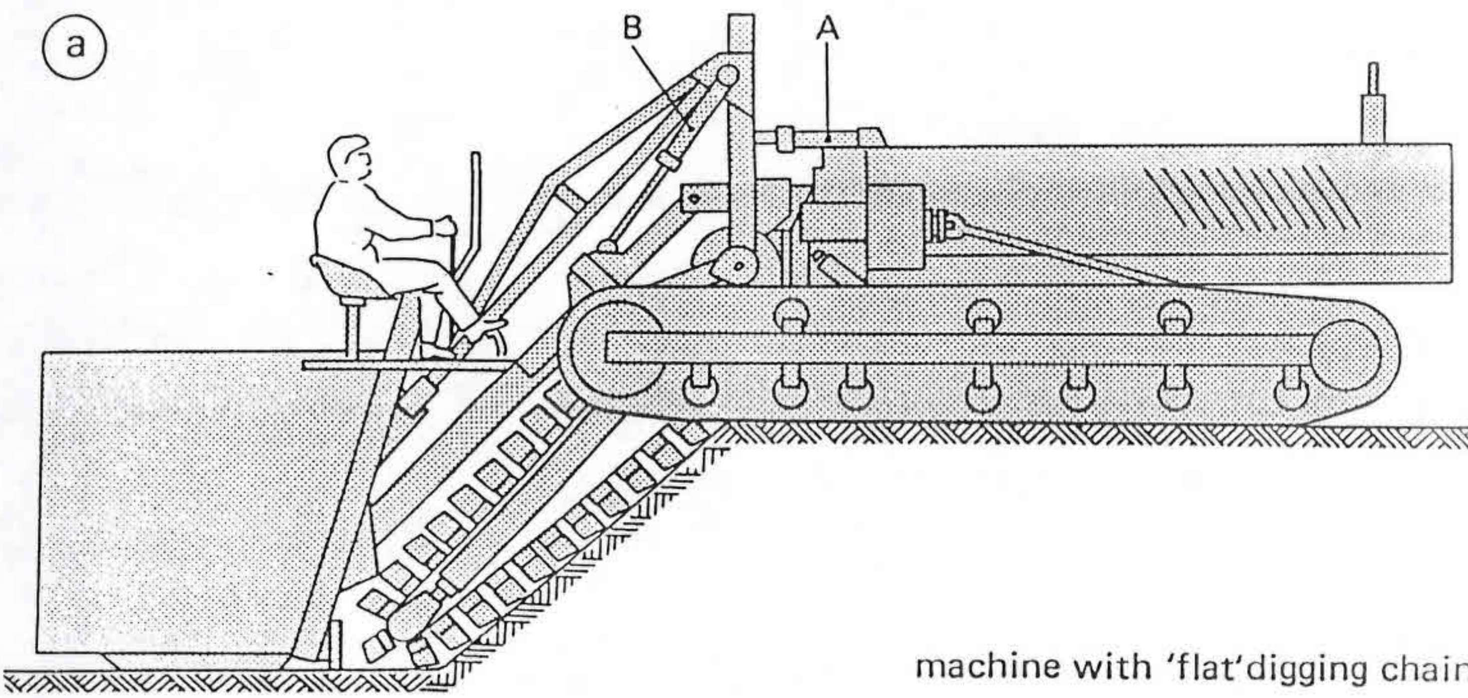
EXAMPLE OF A DRAINAGE SYSTEM



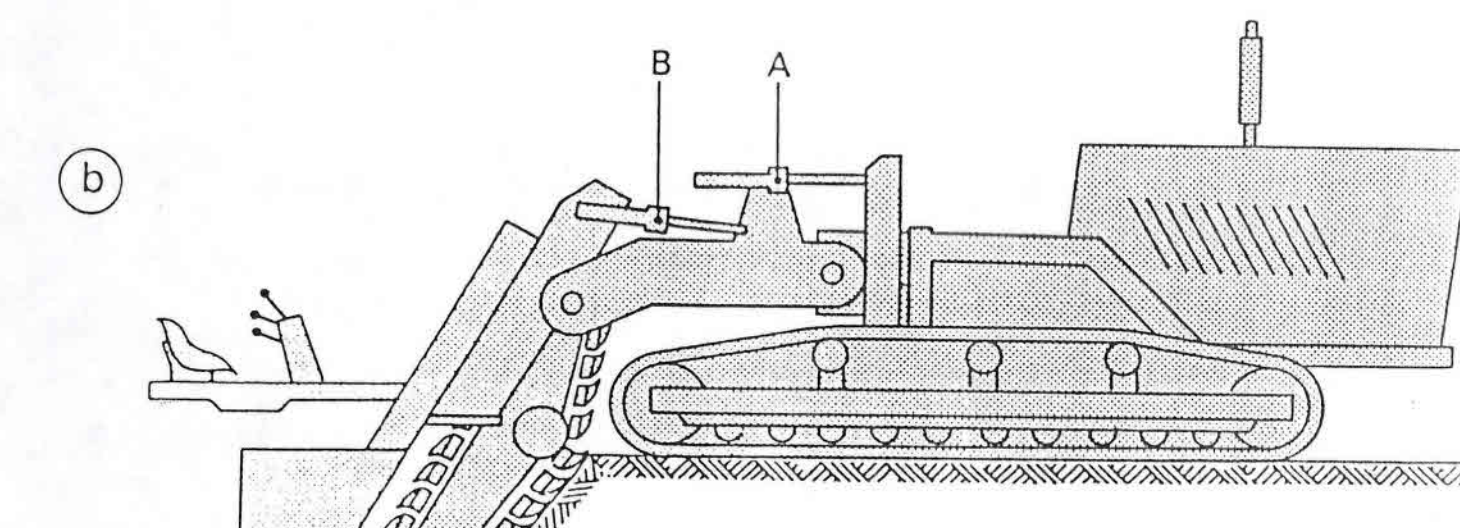
DRAIN OUTLET IN DETAIL*)



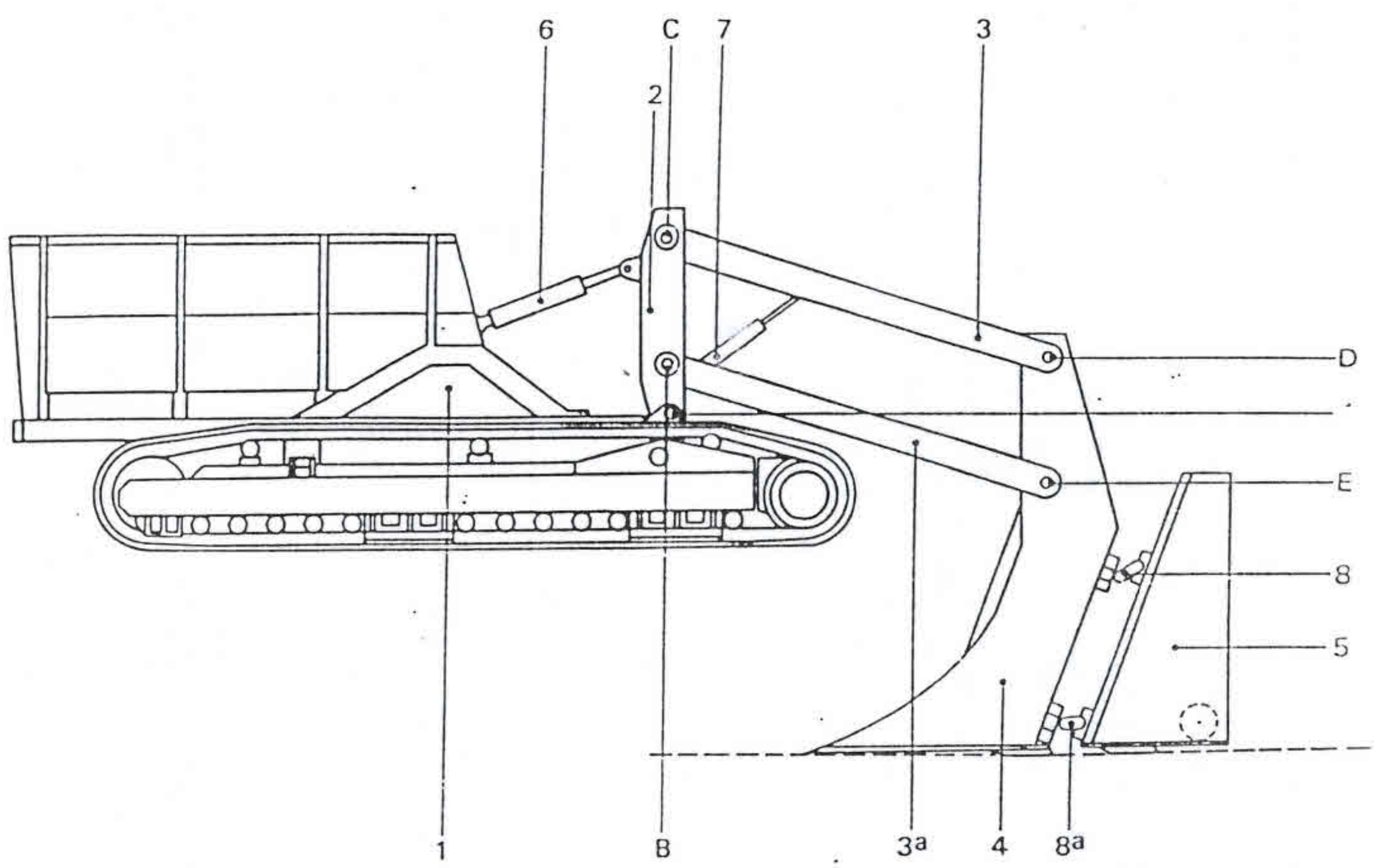
*) cross-section



machine with 'flat' digging chain



machine with 'steep' digging chain



1 - tractor or machine carrier
2 - tilting arm
3 - upper and lower parallellogram arm
4 = plow
5 = pipe box
6 = stabilizing cylinder
7 = main cylinder
8/8a = arms of pipe box suspension (different lenghts)

Figure 12. Diagram of the grade control system of a trenchless machine.

Coarse summary of devel opment in production
at drain installation in The Netherlands

Year	Method	Engine (kW)*	Weight (tons)	Production (m'/hour)
1950	manual	-	-	1-2
1960	chaindigger	75	8	150
1970	chaindigger	125	10	300
1980	chaindigger	175	15	500
1990	trenchless	225	27,5	650

*1 kW = 1,34 HP

5 Check points for a good machine

(machine construction)

Caracteristisc	related to requirements
1 stable	3c
2 provided with tracks	1, 3c,
3 proper power	1
4 proper grade control	3c
5 proper conduction through the machine for drain material	3a
6 Long live time	2
6 Few repair and maintenance	2

However:
No good performance
without a good driver !

International Course on land Drainage

5 Requirements for a good machine

(Job)

1 high capacity
2 low cost per working hour
3 good installation quality:
  a no damage to drain
  b straight line
  c few grade deviations
  d few damage to soil surface
  e few damage to soil around pipe

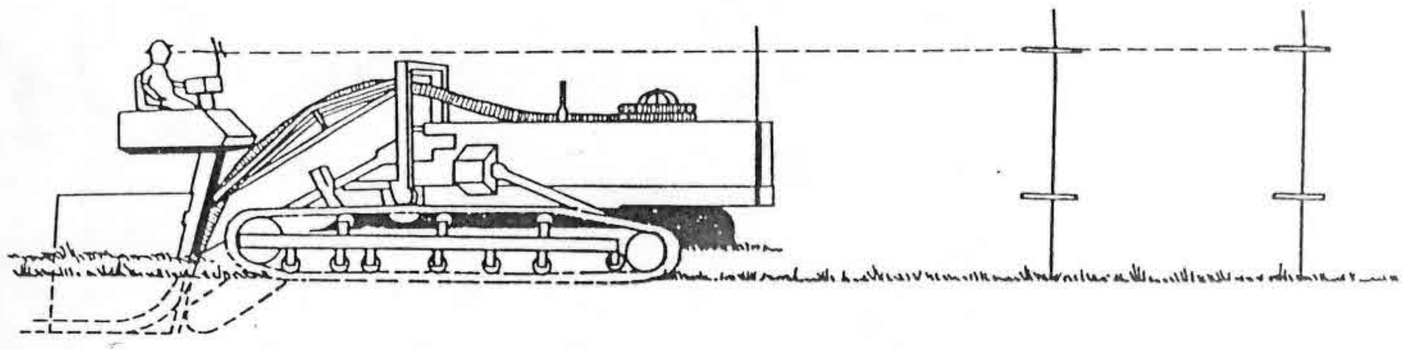


Figure 11. Originally, grade control occurred by hand.

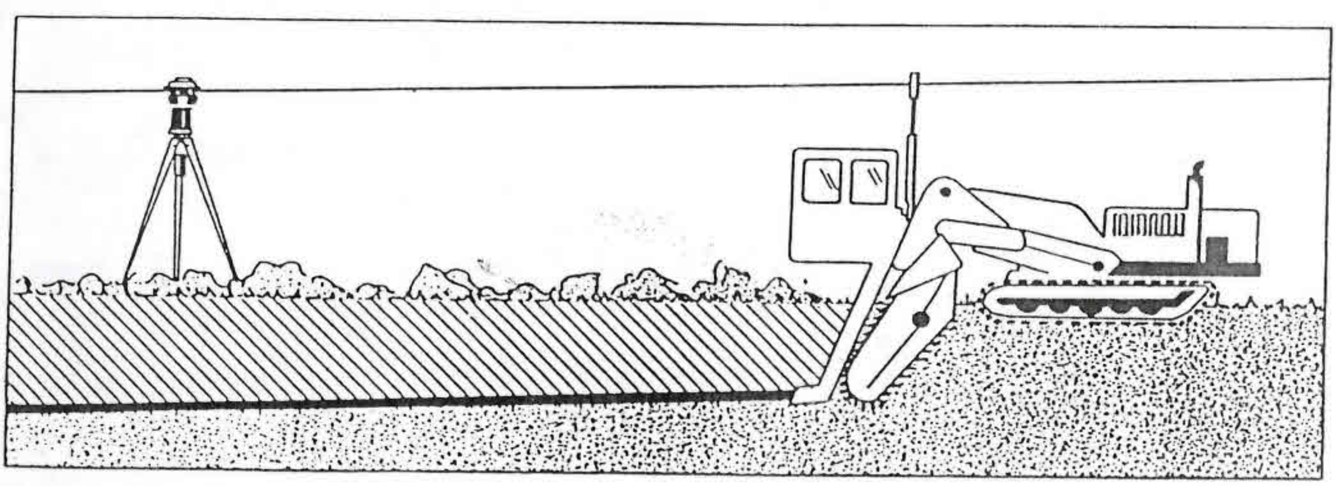
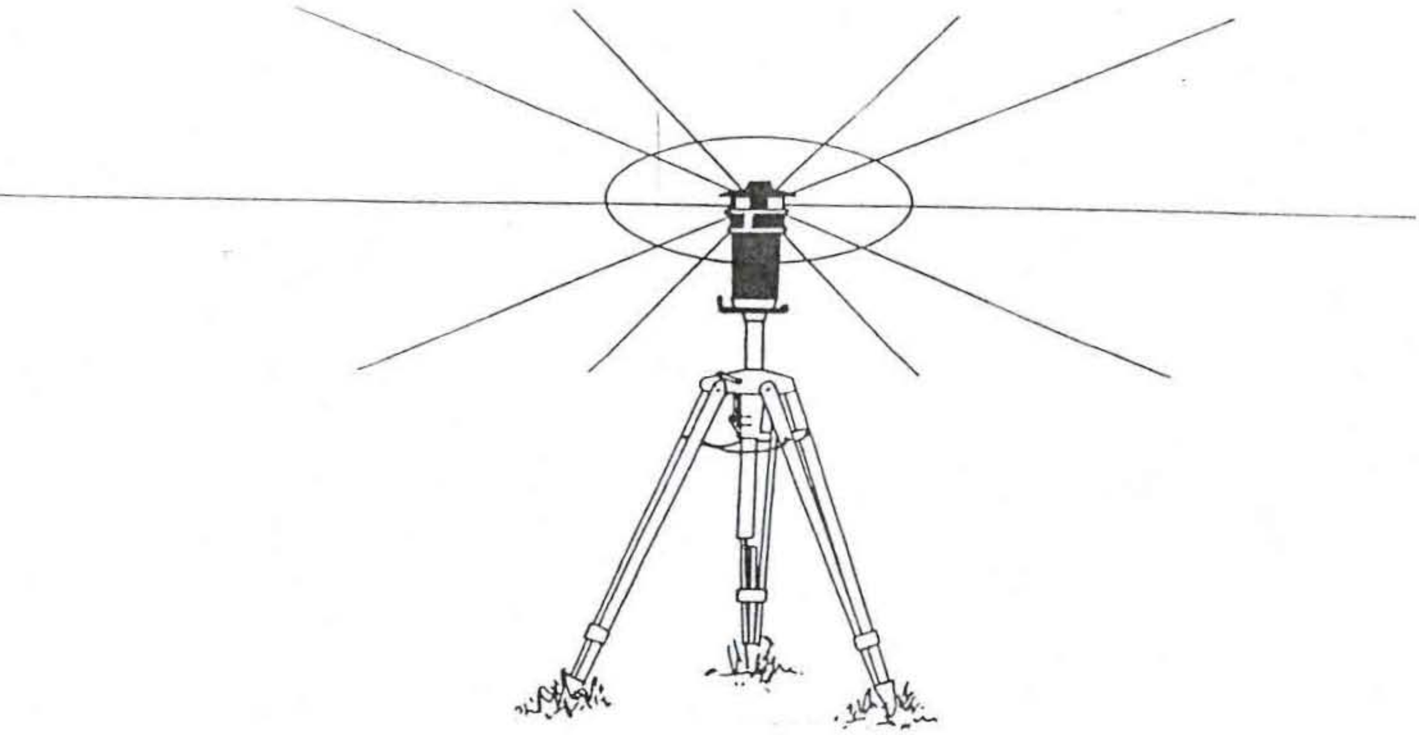


Figure 19. Trencher controlled with a laser.



igure 17. Laser transmitter which transmits a plane of light.

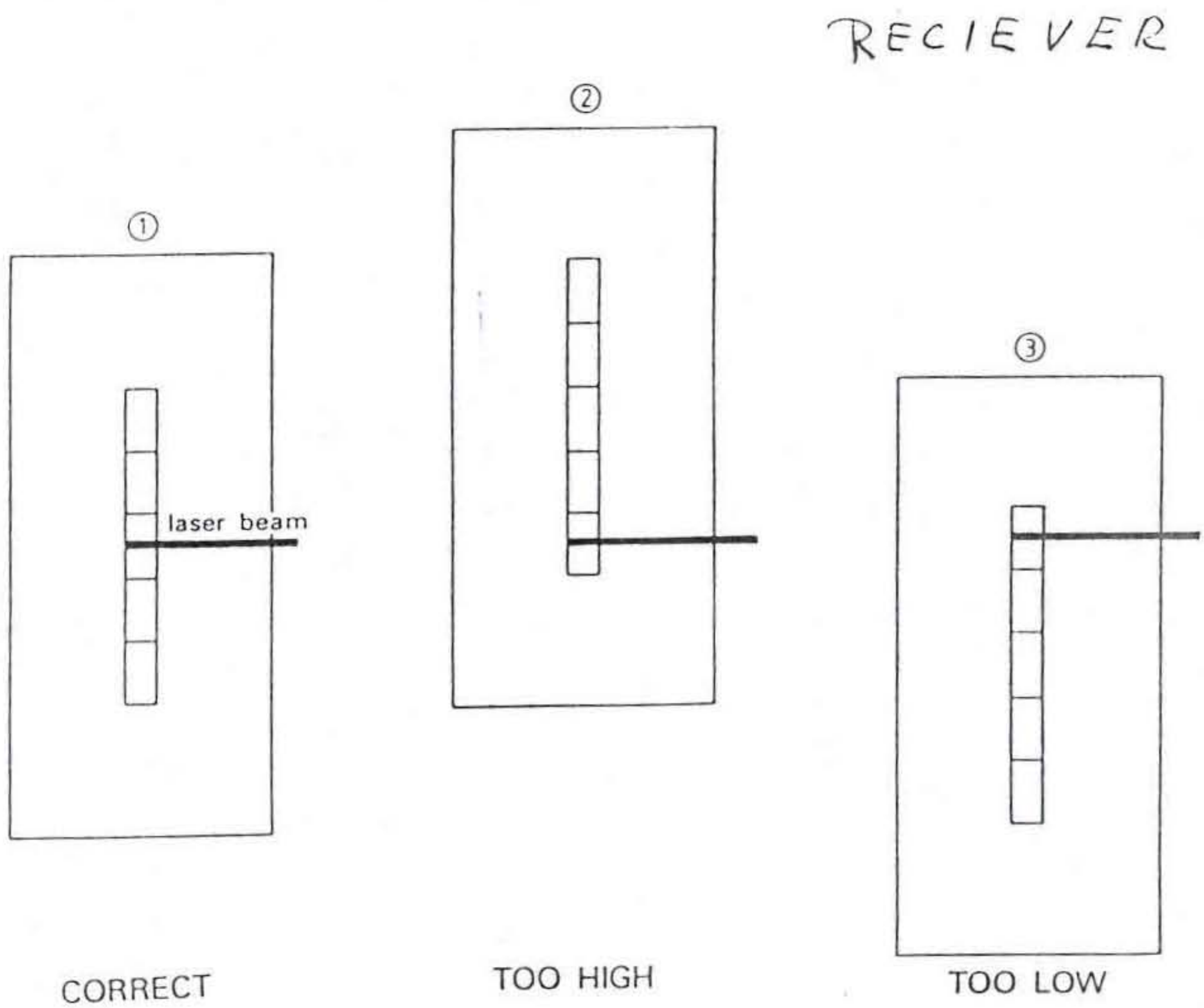


Figure 18. The laser beam hits the photocells. In the first case, the height is correct, in the second case, the machine is too high and, in the third case, the machine is too low.

GRADE CONTROL SYSTEMS:

- can't avoid grade deviation but
- they are reacting on deviations
- their accuracy depends on:
  - *interaction soil - machine*
  - *grade control system*
  - *human factor (driver)*

INCORRECT USE OF LASER EQUIPMENT

__laser equipment__

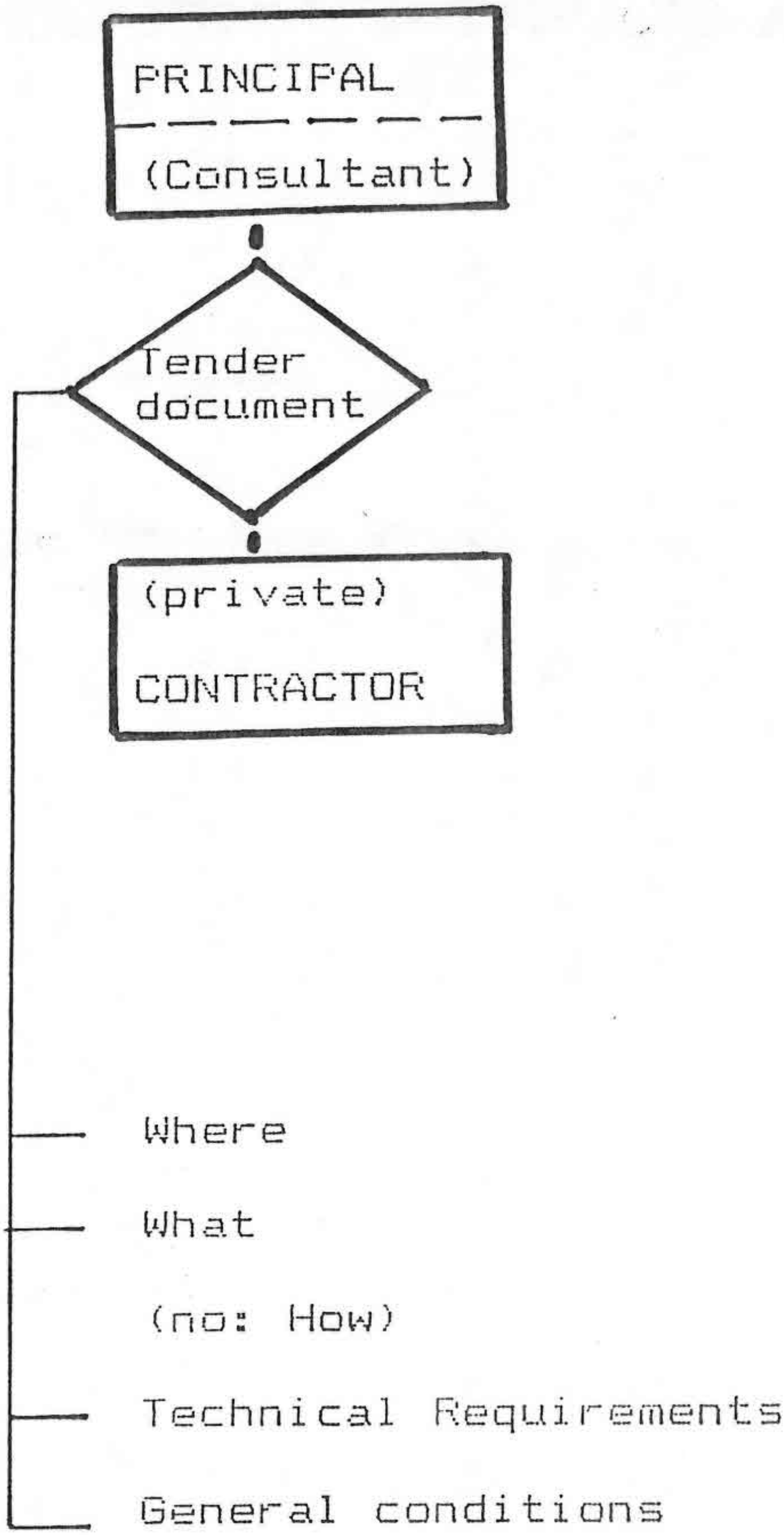
- transmitter (stability,
  grade calibration, grade direction)
- reciever (sensitivety)
- relation transmitter - reciever
  (wind, fog, temperature, radar, etc)

__drainage machine__

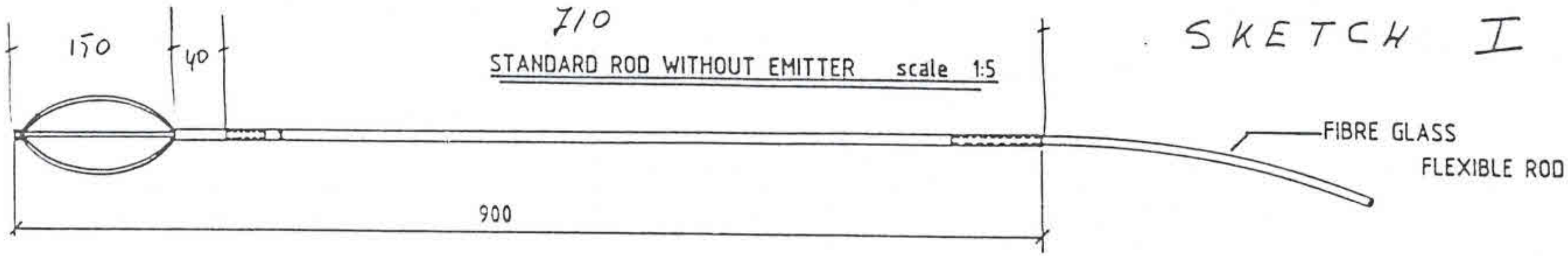
- machine design
- relation reciever - digging equipment
- relation electric - hydraulic system

__human factors__ (operator)

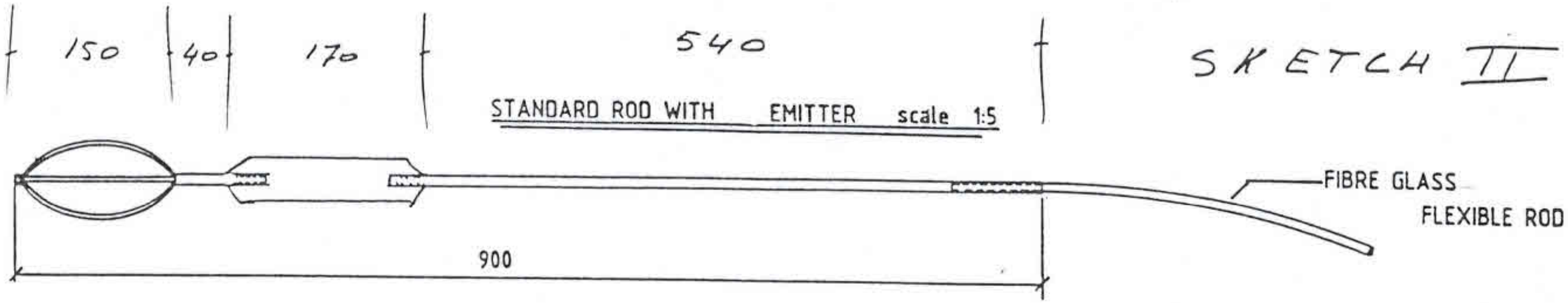
- failures at the beginning
- installation speed
- knowledge on the subsoil
- stops during installation
- blinding


PRINCIPAL
(Consultant)
Tender document
(private)
CONTRACTOR
Where
What
(no: How)
Technical Requirements
General conditions

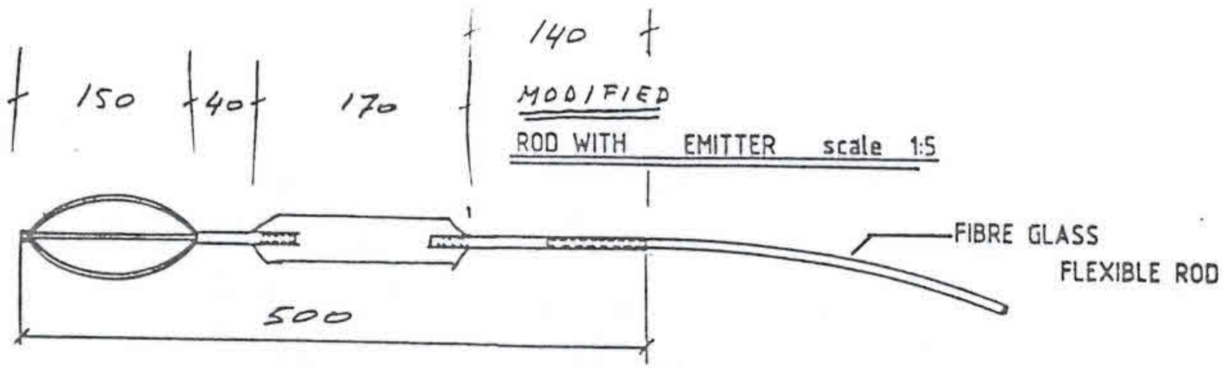
SKETCH I



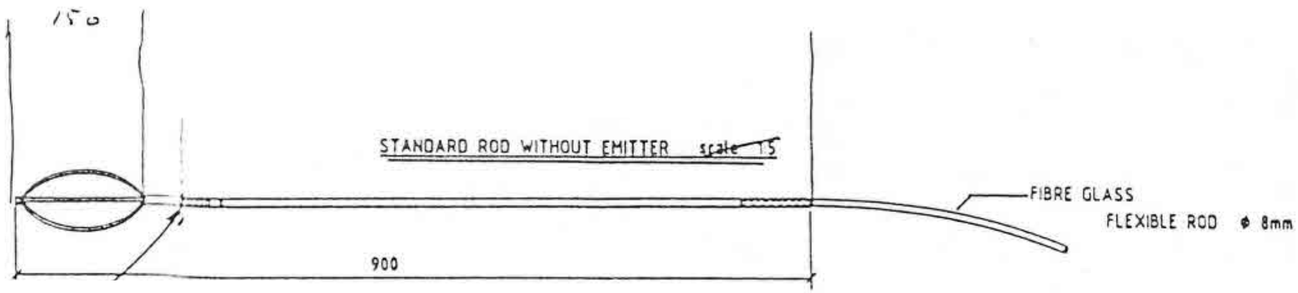
SKETCH II

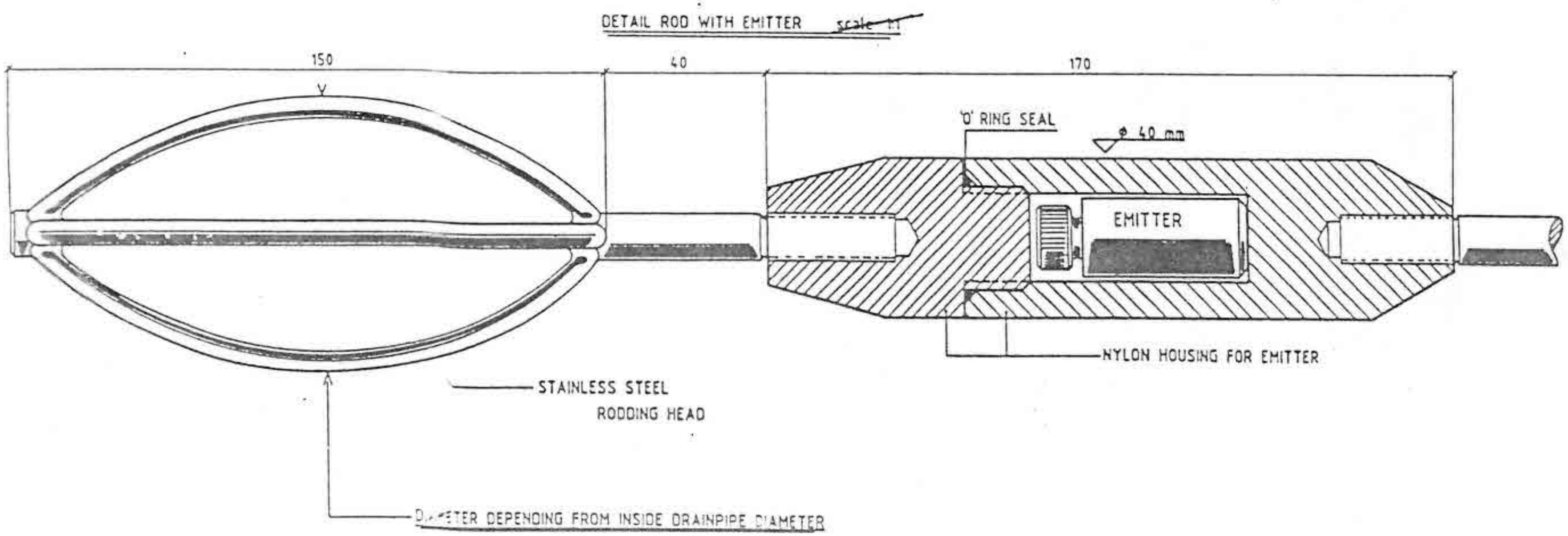


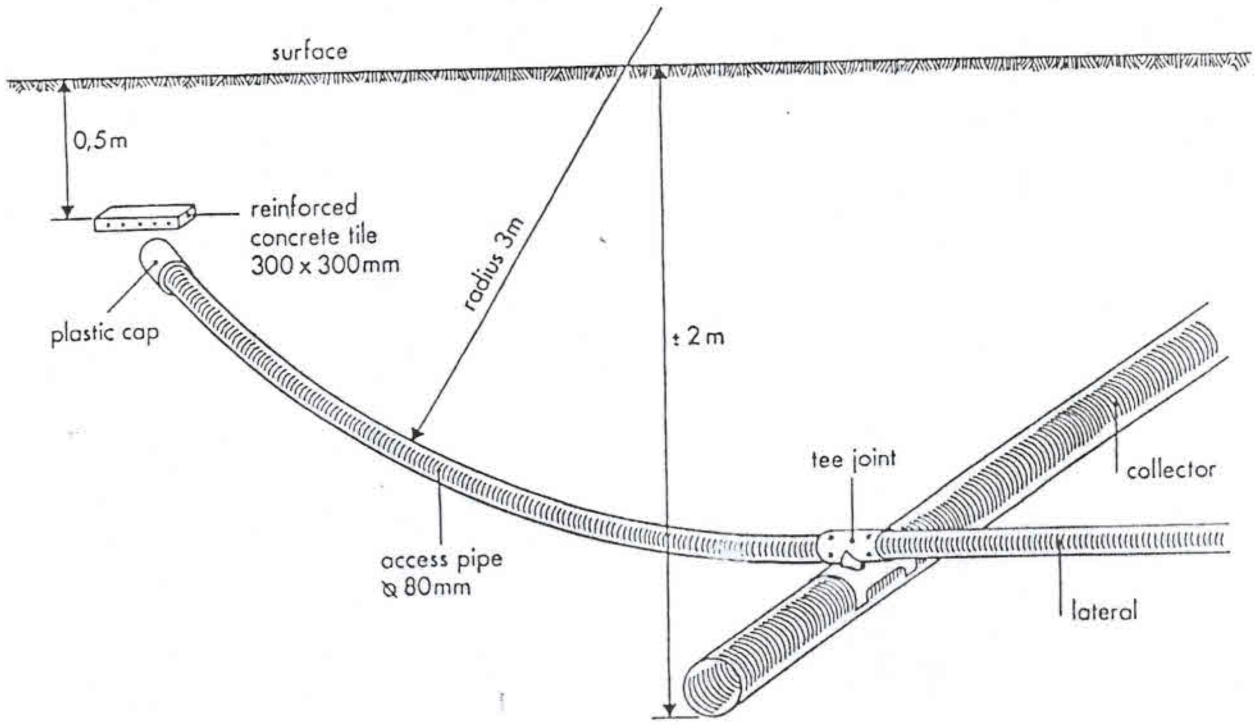
SKETCH III

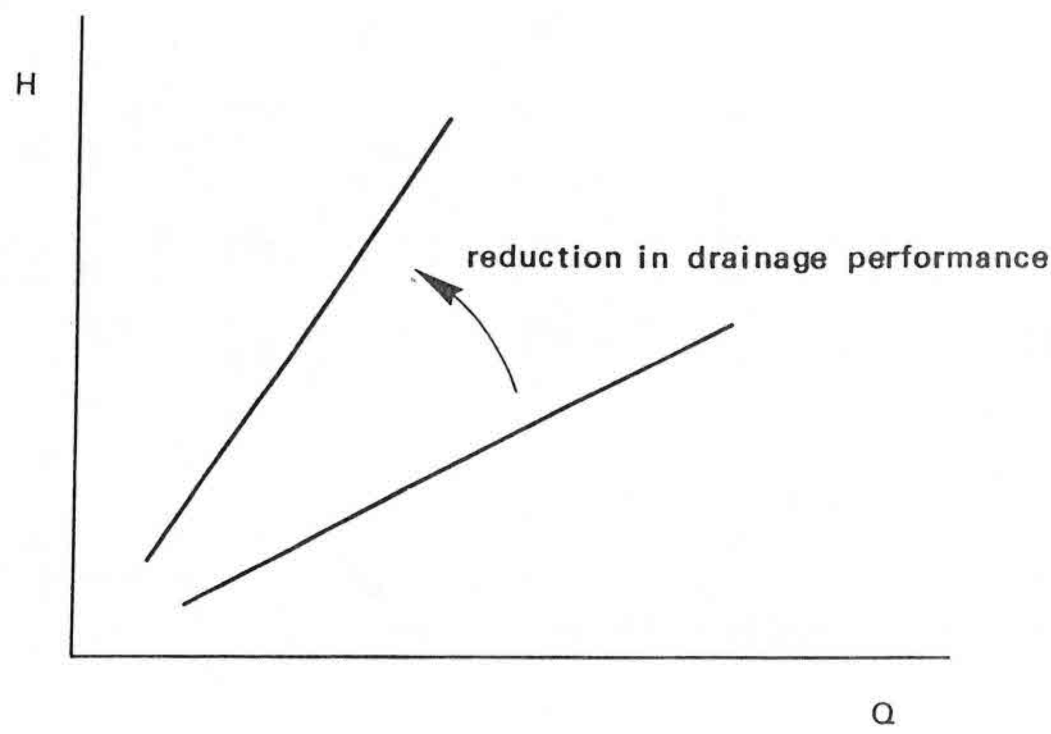


STEENBERGEN HOLLANDDRAIN RODHEAD WITH EMITTER 34.2.0653.01






surface
0,5m
reinforced
concrete tile
300 x 300mm
plastic cap
radius 3m
± 2 m
tee joint
collector
access pipe
⌀ 80mm
lateral


H
reduction in drainage performance
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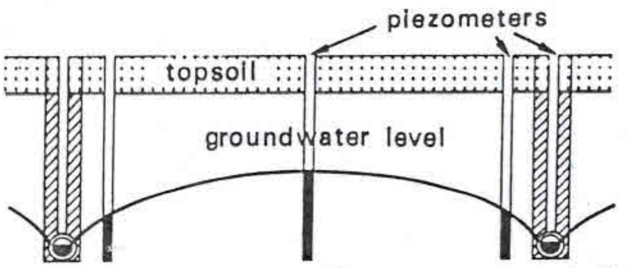
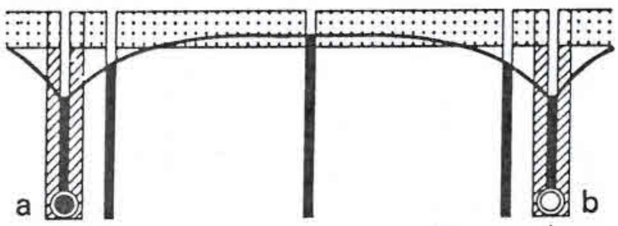
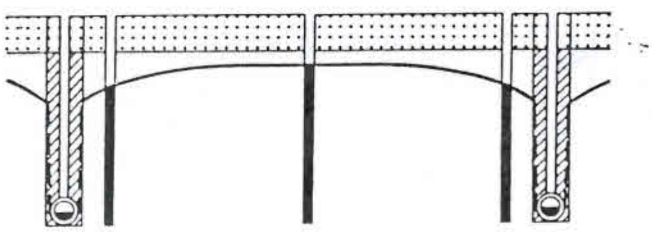


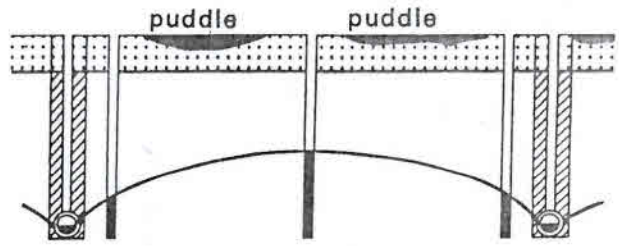
A. Drainage performs well.



B. Drainage does not perform well
(a) outfall end submerged or blocked pipe
(b) pipe perforations or envelope clogged.

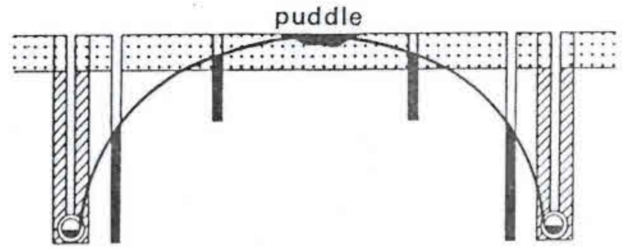


C. Drainage does not perform well permeability of dain trench is very low.



D. Drainage system good but does not perform due to very low permeability of top soil.

E. Drainage system good but does not perform due to soil layer with very low permeability.



F. Drainage system is good but doe' not perform well due to too wide drain spacing.

lco363

Comparison between different Types of Jet Fluçhers

aspect	pressure		
	low	medium	high
Connection with tractor	mounted at 3 point linkage	mounted at 3 point linkage	trailer
Pressure (bar)			
.at pump	< 20	20 - 50	> 50
(.at nozzle (?)	10	10 - 25	> 25)
Yield (l/min)	+/- 80	+/- 80	+/- 100
Moving hose in the drain pipe			
. forwards	rolls ((jet f.))	rolls (jet f.)	jet forces
. backwards	rolls and reel	rolls and reel	reel
Judgement			
cleaning effect			
risk of damage			
Suitable			

MATERIALS & EQUIPMENT
Drainage machines and auxiliaries

CONTENTS

Page

1. INTRODUCTION

1.1. Drain installation by hand

Until the 1950's the installation of tile drains in most countries was done entirely by hand.

- Very labour intensive: 230-300 manhours per 1000 m drain

1.2. Mechanization

- Large areas to be tile drained
- Wages increased
- Scarcity of experienced labour

Mechanization started in the USA in the 1920's.
In Europe drainage machines were introduced in the 1950's.

In 1954 a BUCKEYE drainage machine was imported in The Netherlands from the USA.

First: Trench excavated by machine, but laying of pipes by hand
Later: Excavating the trench and pipe laying both by the machine

Dutch machine constructors developed drain laying machines

- The first drainage machines manufactured were built onto a farm tractor
- Digging wheel replaced by digging chain with cutter blades (lighter and compact construction, higher laying capacity)
- Hydraulic control system for depth digging depth regulation
- The machine was built as an integral unit on a special frame with long and wide tracks

Labour input at mechanized drain laying:

- Concrete and/or clay drain pipes: 25-30 manhours per 1000 m drain
- Flexible corrugated PVC drain pipes: 4-7 manhours per 1000 m drain

Specialized drainage contractors

2. TYPES OF DRAINAGE MACHINES

A. Trench excavating drainage machine

B. Trenchless drainage machine

C. Horizontal dewatering machine

A. TRENCH EXCAVATING DRAINAGE MACHINE

General characteristics

* DISTINCTION

- "Normal Duty" machine (lateral drain installation)
- "Heavy Duty" machine (collector drain installation)

The distinction is, however, not sharp as many machines are adjustable to the type of job. Certain parts, mainly digging chain and trench box can be replaced for different trench widths and excavation depths.

* MOVEMENT

- Crawler tracks
- Rubber wheels
- "Half-tracks"
- Attached to normal farm tractors

The track width of some crawler-type machines can be adjusted. **Narrow** for transport on the road and **wide** for digging to provide space for the disposal of the excavated soil. The minimum width for transport on the road is approximately 2.50 m. In the field the width can be extended to a maximum of 5 m.

* GROUND PRESSURE

The ground pressure ranges between 0.2 and 0.3 kg/cm^2; the variation being much less than the variation in machine weights (12 - 40 tons) as heavier machines have larger tracks. The ground pressure is low, so that the machines can work under rather adverse conditions on wet and soft land.

* EXCAVATION

- Revolving wheel
- Chain with digging knives

The digging chain type is predominant. It is easier and cheaper to maintain and to repair. There are two types:

- "Flat" digging chain type
- "Steep" or "Semi-vertical" digging chain type

The "flat" digging chain type has a digging boom and trench box connected to the machine frame by a parallelogram construction. With this system the angle of the digging boom varies according to the working depth (figure 1).

The "steep" or "semi-vertical" digging chain type machine has an intermediate frame which connects the digging boom and the trench box to the machine. While trenching, the digging boom is at an approximately constant angle of 60° from horizontal, irrespective of working depth (figure 2).

Hard soil layers
For hard soil layers the cutters on the digging chain are placed by very hard steel points (so-called rockbits) to cut through rock layers (e.g. in the Nubariya Area in Egypt).

* TRENCH WIDTH

Standard 0.20 -0.25 m. Wider trenches up to 0.60 m (for collectors) are also possible.

* EXCAVATION DEPTH

Standard: approximately 1.8 m

HD-machines: up to 3.5 m

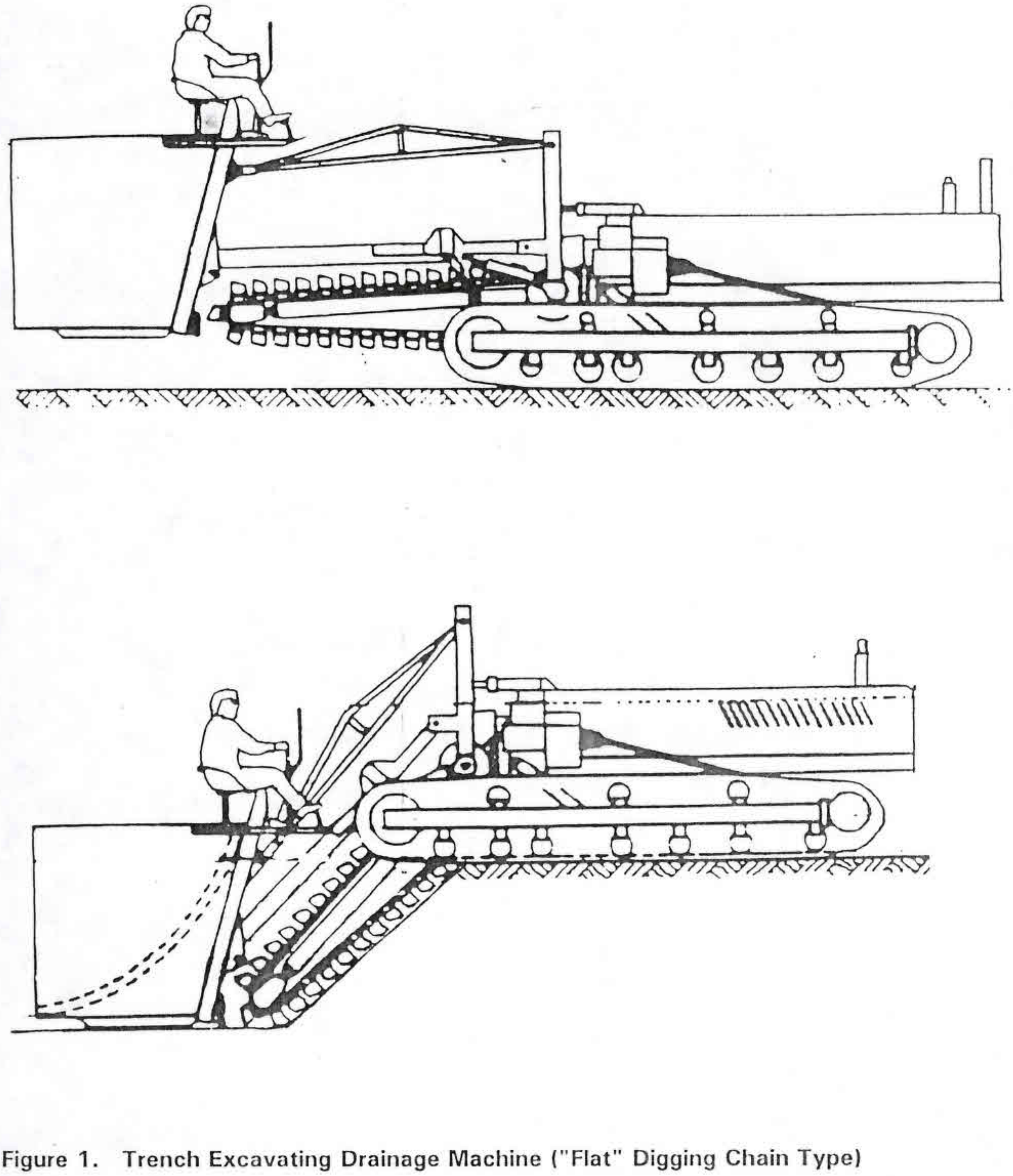


Figure 1. Trench Excavating Drainage Machine ("Flat" Digging Chain Type)

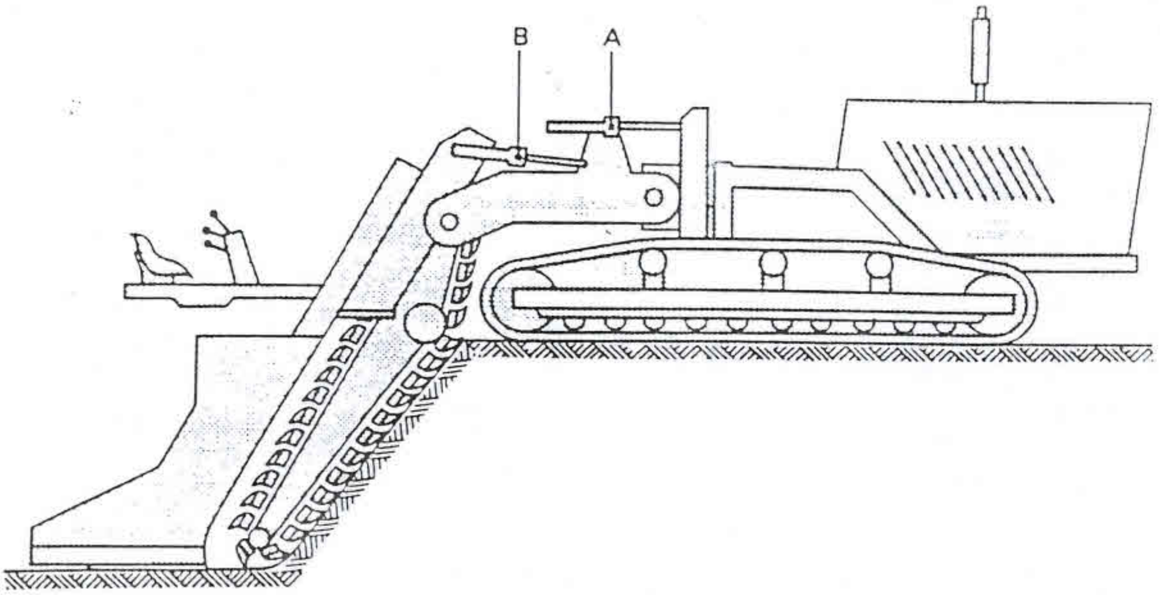


Figure 2. Trench Excavating Drainage Machine ("Steep" or "Semi-vertical" Digging Chain Type). Principle of depth regulation: while trenching the shoe rests on the trench bottom and the lifting cylinders A are in float postion; depth is regulated by expanding and retracting cylinders B

* DEPTH REGULATION

- Manual (Sighting targets)
- Automatic control system (Laser)

Manual

The depth and grade of the drains was initially controlled by the machine driver. Sighting targets are installed on each drain line at a constant height above the drain alignment. The machine driver's position is attached to the digging mechanism. He keeps a sighting bar, in front of him on the machine, in line with the targets by actuating the switch for the hydraulic valve of the depth control cylinder as required (figure 3).

The accuracy depends very much on:

- Constant attention of the driver
- Good visibility conditions

The manual system limits the speed of the whole operation of drain installation.

Automatic control system

Nowadays the grade control by sighting targets has largely been replaced by an automatic control system. The laser system, developed in USA, consists of:

- A command post mounted on a tripod in the field (transmitter)
- A receiver and control box mounted on the machine

The receiver is hit by laser signals from a rotating transmitter at the command post in the field. The plane of rotation can be tilted at the command post according to the required drain gradient (slope). The entire set-up is programmed in such a way that the receiver is kept in the plane the laser beam is describing (figure 4).
The receiver consists of a vertical series of five photoelectric cells. Its height is adjusted before digging starts, so that the laser beam hits the middle cell when the trencher is at the correct depth.

When the laser beam hits the receiver at a higher or a lower cell during digging, the machine is digging too low or too high, and the signal is processed in the control box to actuate the hydraulic valve of the depth control cylinder, which will automatically adjust the digging depth.

A set of lights on the control box indicates the position of the digging mechanism continously. The digging depth is constantly checked in this way, small deviations are immediately detected and automatically corrected.

The system is effective in a radius of 300 metres, so that several drains can be installed without having to move the command post.

The process of staking out the drains is very much simplified.

The setting and resetting of sighting targets of each drainline is completely eliminated.

* ENGINE

The engine power ranges from 100 to 400 HP. In recent years there has been a tendency towards increased engine powers. The major part of the engine power is used in excavating the trench while the machine moves forward.

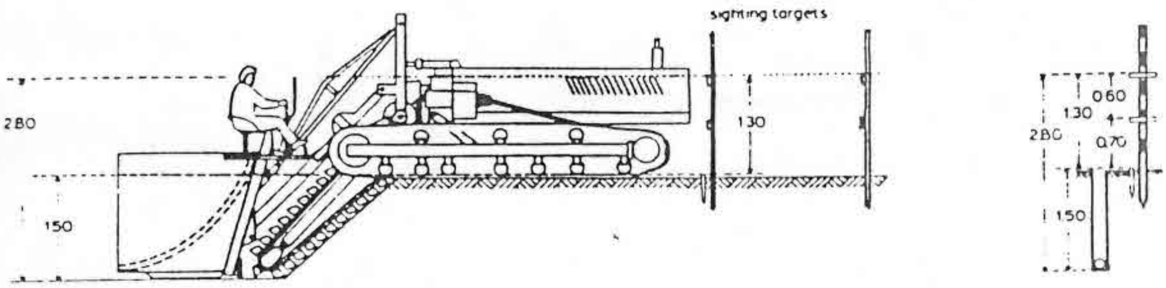


Figure 3. Manual control of excavation depth by sighting targets

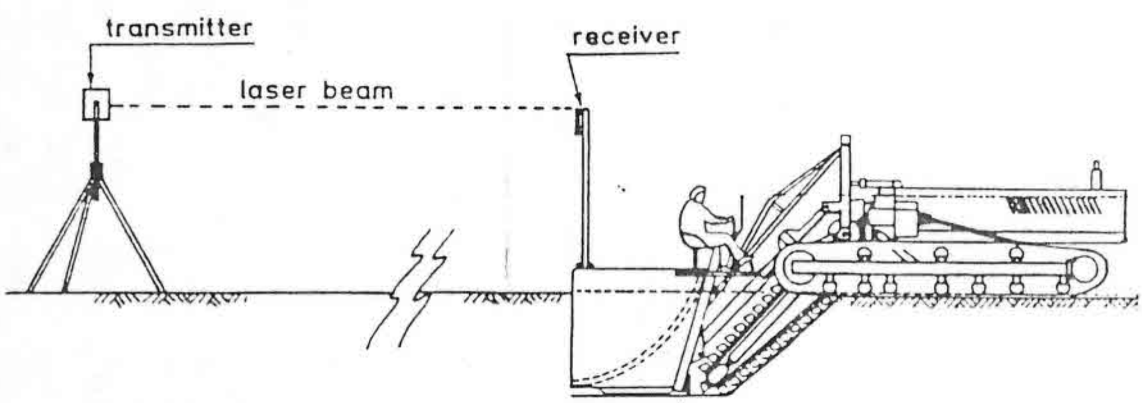


Figure 4. Excavation depth controlled by laser

* WORK OUTPUT

The work output varies widely as a function of:

- Machine power
- Depth of drain
- Soil and working conditions
- Logistics (timely supply of pipes and cover materials, maintenance, etc.)

Maximum working speed is in the range of 1000 to 2000 m per hour, depending of engine power and digging depth.
A good average output over a longer period (e.g. a week) is in the order of 200- 400 m per hour.

* SPECIAL ATTACHMENTS

Special attachments may be mounted on the machine for a variety of purposes. Examples are:

- Water tank and spraying installation to spray water on the chain and the trench box sides to avoid clogging of clay in heavy soils and to reduce resistance of the trench box sides sticking against the trench wall;

- Platform to carry clay tiles or concrete pipes

- Gravel container with provisions to apply gravel both below and on top of the pipe;

- Conveyor belt for disposal of excavated soil. This is used on HD-machines (wide and deep trench). The amount of excavated soil is too much to be put on either side of the trench between the tracks, like with "normal duty"-machines;

- Reels for corrugated PVC pipe coils;

- Trench backfilling attachment.

B. TRENCHLESS DRAINAGE MACHINE

The technique of trenchless pipe drainage was developed from the idea of lining mole drains. As the name implies no trench is excavated to lay the pipe.
The installation of a ready-made pipe without a trench having to be dug became practically feasible with corrugated plastic pipes. The corrugated plastic pipes are flexible enough to make the rather sharp curve at the spot where the pipe leaves the machine.

Two main types are operational at present:

- Subsoiler type (figure 5)
- V-plough type (figure 6)

* **Subsoiler**

A subsoiler blade is pulled through the ground to break and lift up the soil to make room for the pipe. The pipe is guided into position through a hollow part of the blade or through a pipe guide, trailed behind the blade. The trenchless machine is manufactured either as an attachment to a standard heavy crawler tractor (e.g. Caterpillar D8 or Komatsu), or as one unit together with the tractive part as is common with trench excavating machines.

Depth regulation is always by laser as manual control by the driver would be too difficult due to:

- Comparatively high speed
- Vibrations of the machine

Maximum attainable depth is 1.8 - 2.0 m. The required traction increases sharply with depth and depends very much on texture and moisture conditions of the soil. Egine power mav be up to 400 HP. For heavy jobs a second crawler tractor is sometimes used. Installation becomes very difficult under conditions of a wet clayey top soil.

* **V-plough**

With the V-plough type machine a "beam" of soil with triangular cross section is temporarily lifted. The corrugated drain pipe is conveyed through one "leg" of the V-plough. With this type the problem of soil compaction does not arise. The required traction is somewhat less than with the subsoiler-type.

Advantages of trenchless drainage are:

- Less wear of the pipe laying implement as there are no revolving parts;
- High installation speed (more than double that of a trench excvator);
- No trench backfilling necessary;
- More suited to stony soils than a trencher.

Disadvantages (especially at greater installation depths) are:

- High traction required;
- Possible compaction of soil around the pipe (subsoiler type). Below a certain "critical depth" the soil is no longer lifted, but rather pressed aside. This may reduce the hydraulic conductivity of the soil in the vicinity of the drain pipe and hamper the entry of water, especially in clayey soils where the water flow depends on the continuity of large pores like rootholes and cracks. As a measure to overcome the compaction, one or two subsoiler blades may be pulled through the soil ahead of the "pipe laying subsoiler";
- Not well suited to the application of a gravel filter around the drain pipe;
- Limited depth range.

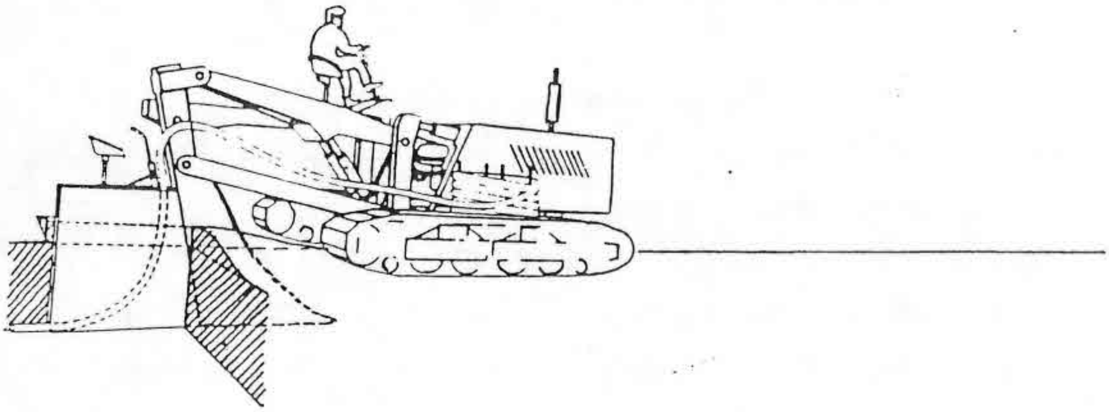
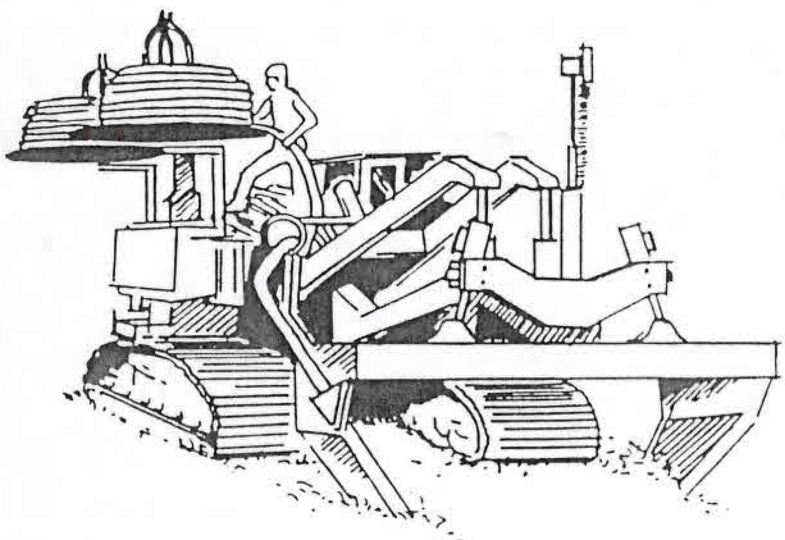


Figure 5. Trenchless pipe drainage machine (Subsoiler type)



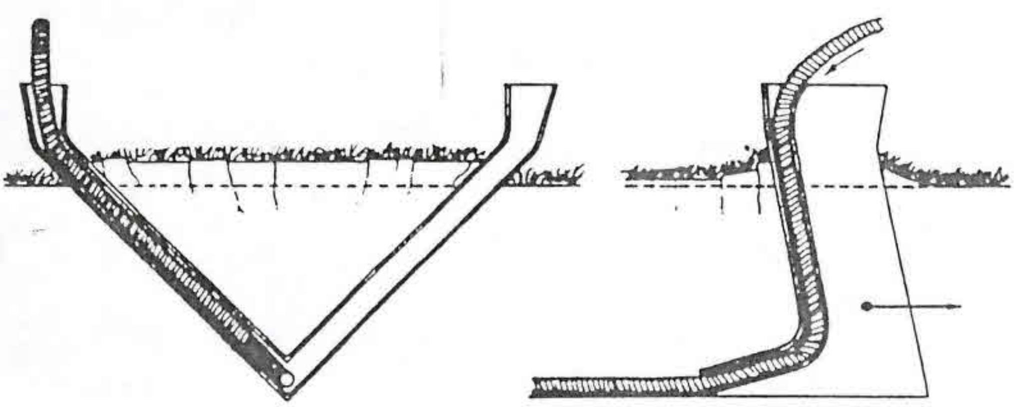


Figure 6. Trenchless pipe drainage machine (V-plough type)

C. HORIZONTAL DEWATERING MACHINE

The horizontal dewatering technique is applied to temporarily lower the watertable. This will permit excavating a trench under dry conditions for installation of e.g. oil and gas pipe lines, sewage pipes and collector drains.
A corrugated perforated pvc-pipe is installed with a trench-type drainage machine (figure 7). This drain pipe is installed at a depth lower than the bottom of the collector drain. The specific features of the horizontal dewatering machine are:

- The very long (up to 6 m) boom with digging chain is in a vertical position while working;
- The machine has no sophisticated regulation of installation depth. It is not very important for the pipe to be in a straight line, as it is not discharging through gravity but through pumping;
- There is no arrangement for disposal of excavated soil; consequently the trench normally caves in immediately behind the boom, which again is no problem;
- At certain intervals (e.g. 30-50 m) the drain pipe is connected with a pump through an unperforated pipe section.

Horizontal dewatering adds considerably to the costs of collector installation, but it is still cheaper than the traditional vertical well-point system. Collector installation without previous dewatering would in many cases not result in acceptable quality of work.

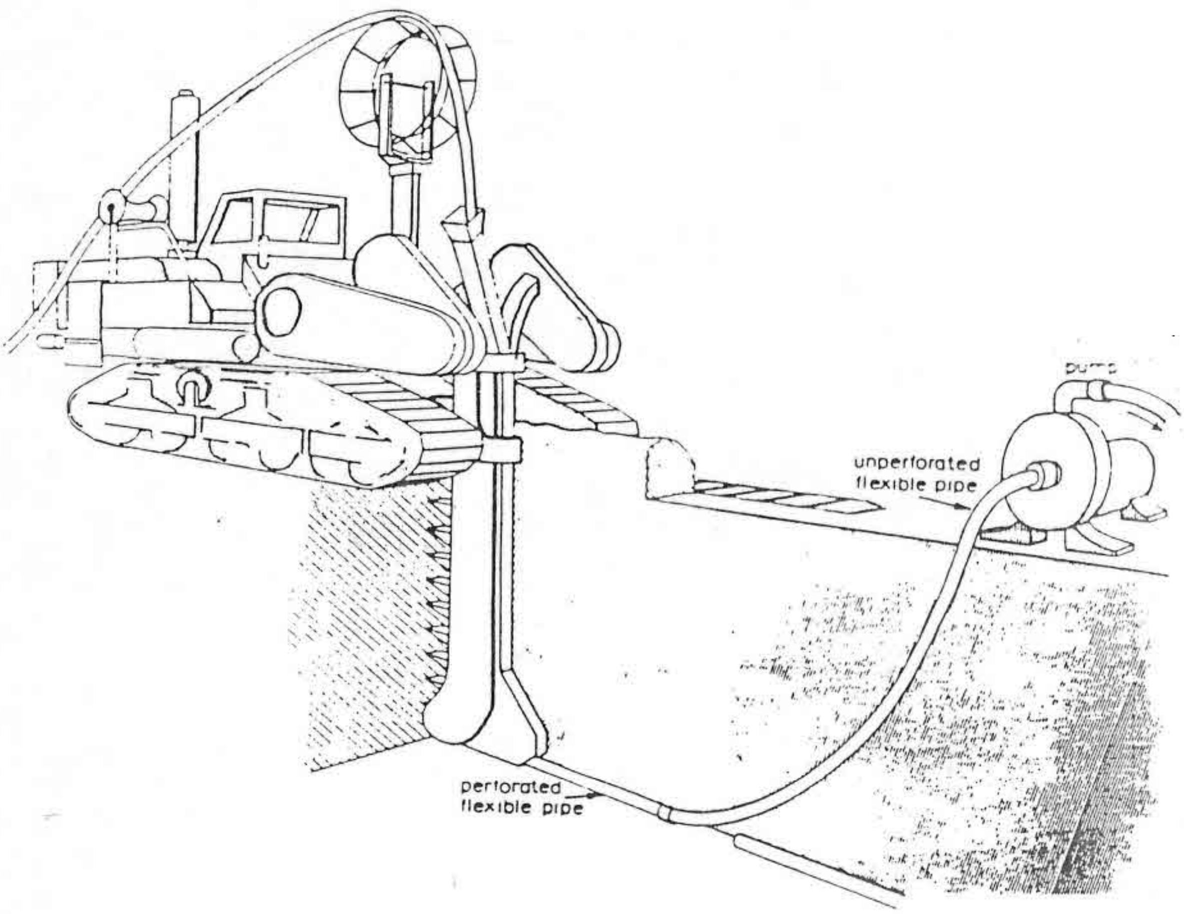


Figure 7. Horizontal dewatering machine installing pipe

AUXILIARIES

* Excavator

* Gravel trailers

* Bulldozers for backfillig of the trench

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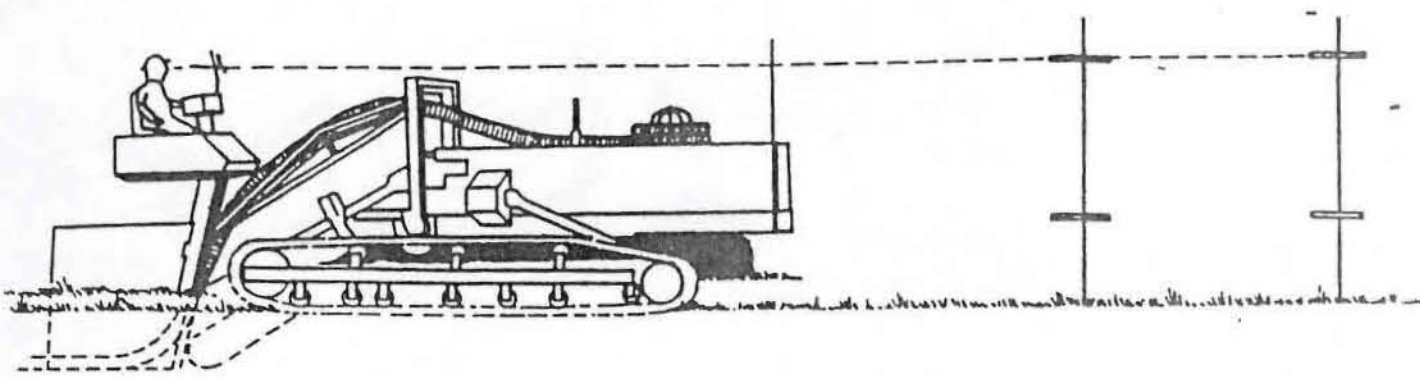
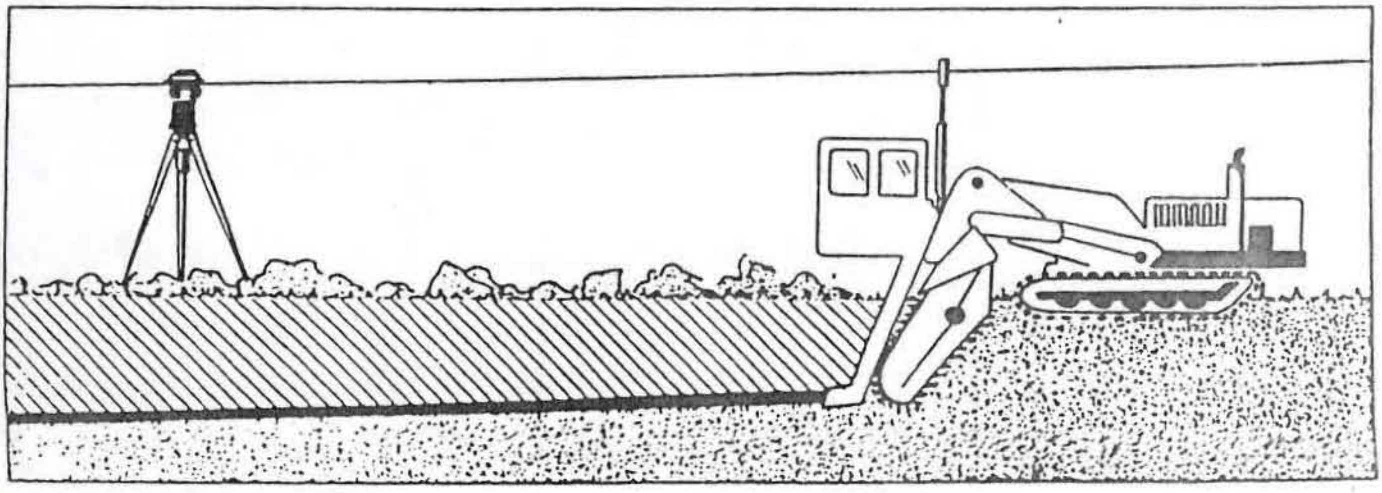
Zijlstra, G. Drainage machines. In:

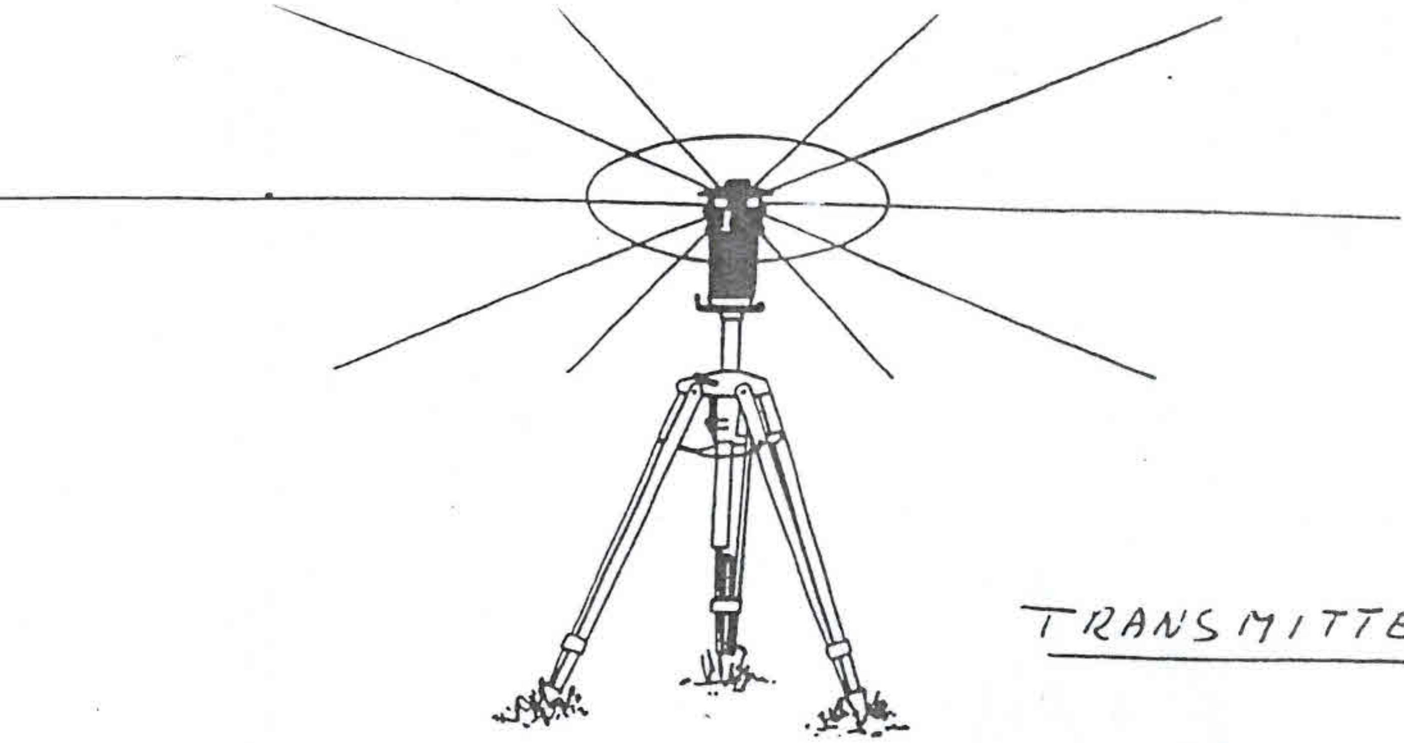
LASER USE IN DRAINAGE



Originally, grade control occurred by hand.



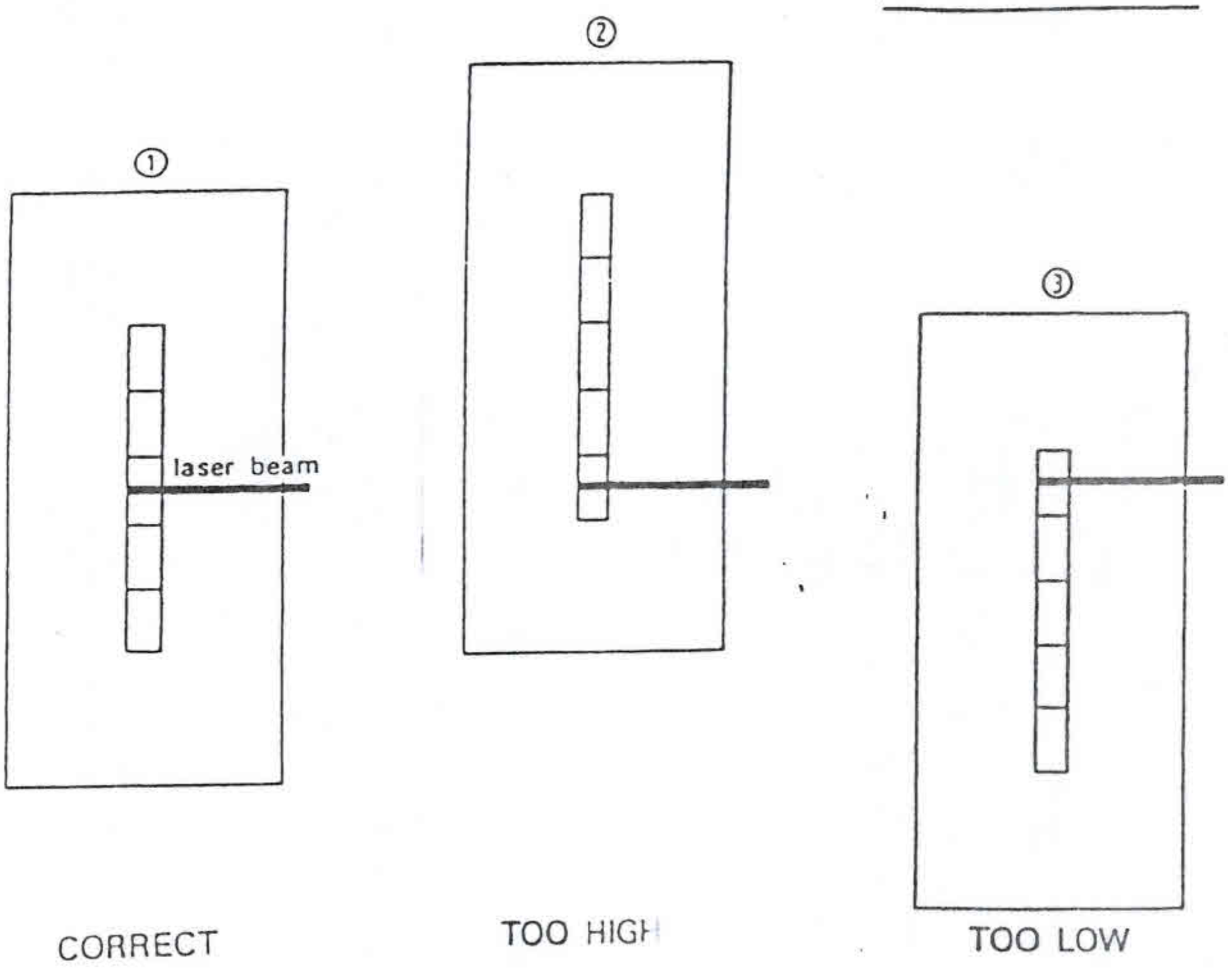
Trencher controlled with a laser.



TRANSMITTER

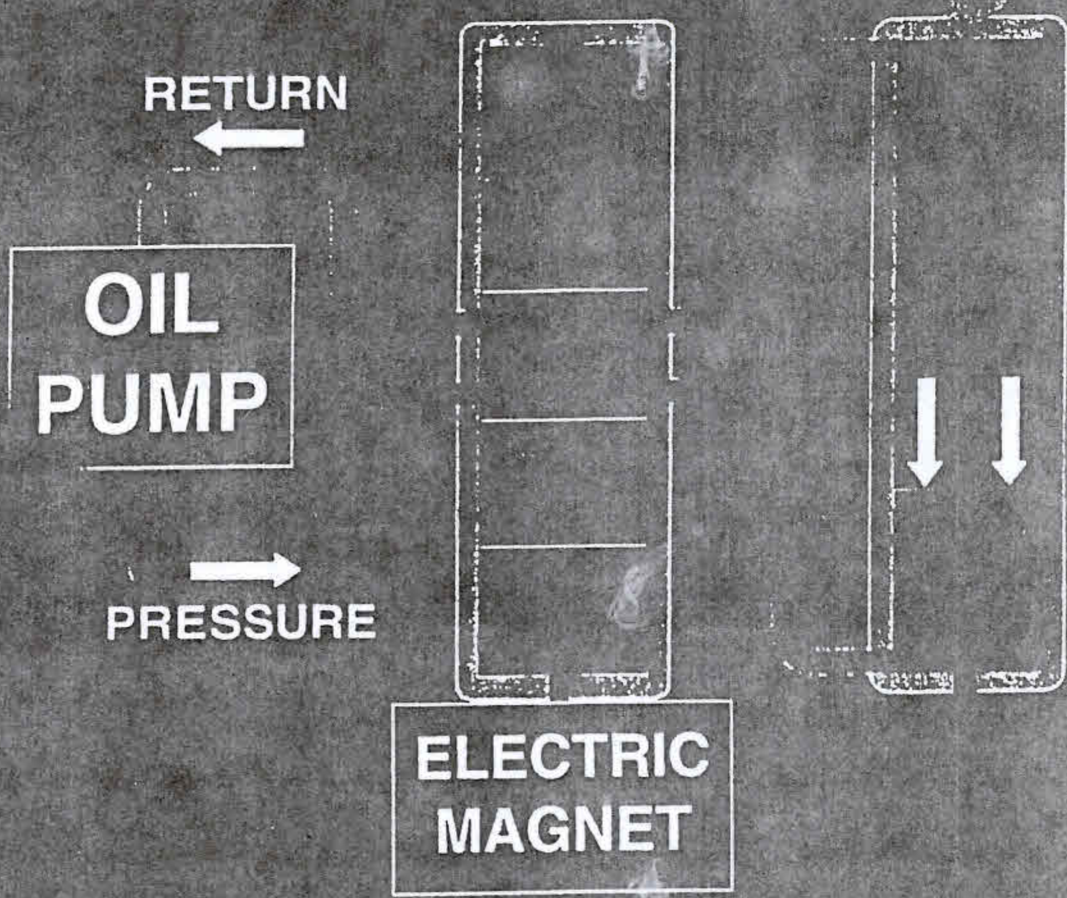
Laser transmitter which transmits a plane of light.

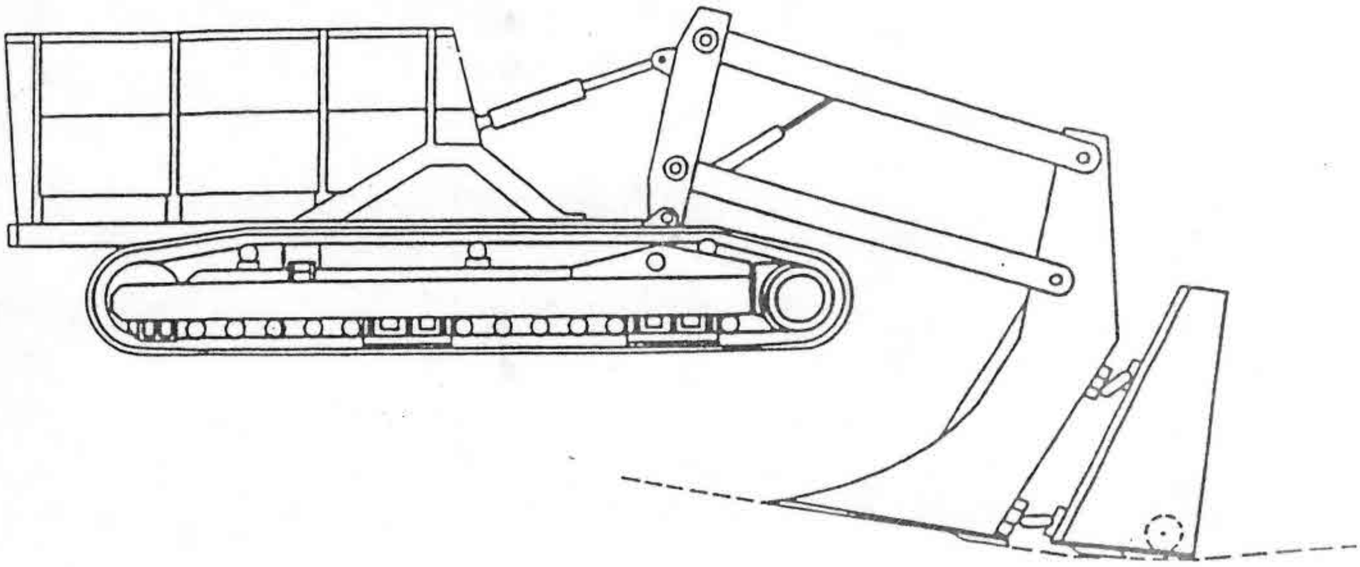
RECIEVER



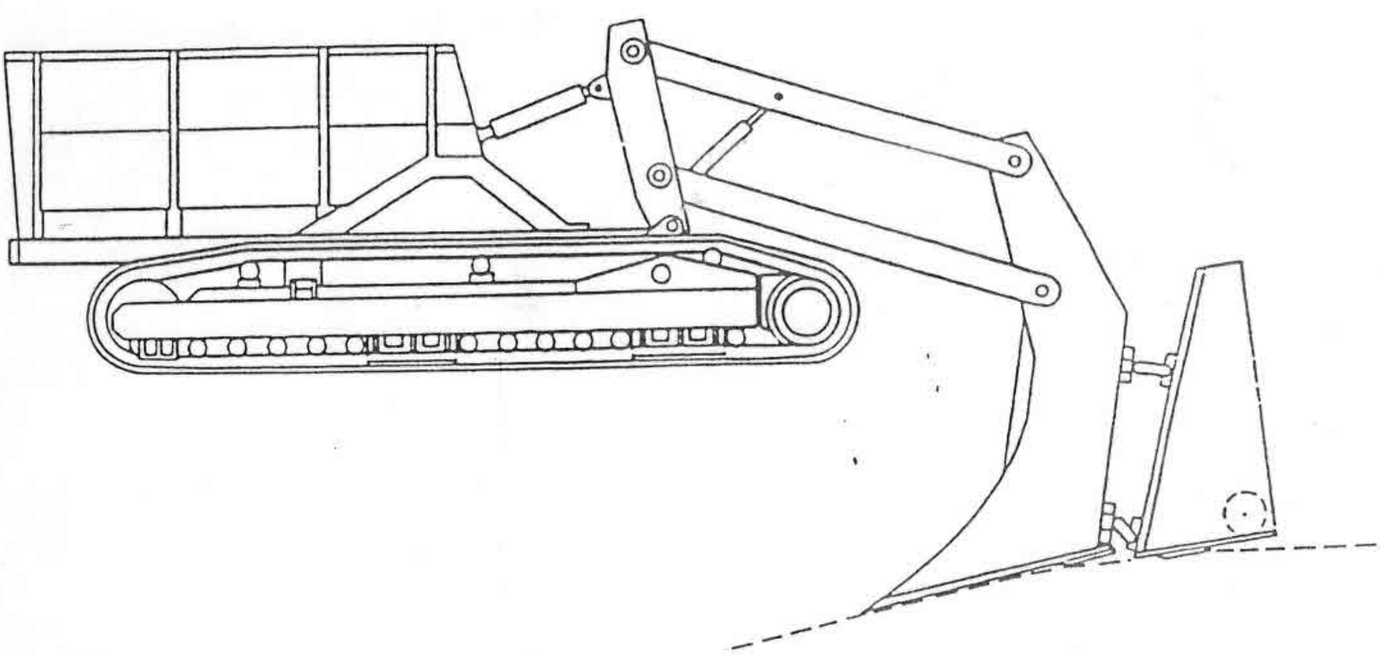
The laser beam hits the photocells. In the first case, the height is correct, in the second case, the machine is too high and, in the third case, the machine is too low.

SCHEMATIC PRESENTATION OF A VALVE MOVING DOWNWARD





The tipping backwards of the plow exagerated.



The tipping forwards of the plow exagerated.

GRADE CONTROL SYSTEMS:

. can't avoid grade deviation but
. they are reacting on deviations
. their accuracy depends on:
    - *interaction soil - machine*
    - *grade control system*
    - *human factor (driver)*

Grade control is depending on the interaction between soil and machine

Soil	⟺	Machine
bearing capacity *surface flatness* *soil resistant*	⟺	*soil pressure* *stability* *depth control*

INCORRECT USE OF LASER EQUIPMENT

<u>laser equipment</u>

- transmitter (stability, grade calibration, grade direction)
- reciever (sensitivety)
- relation transmitter - reciever (wind, fog, temperature, radar, etc)

<u>drainage machine</u>

- machine design
- relation reciever - digging equipment
- relation electric - hydraulic system

<u>human factors</u> (operator)

- failures at the beginning
- installation speed
- knowledge on the subsoil
- stops during installation
- blinding

Incorrect use of laser

Laser equipment :

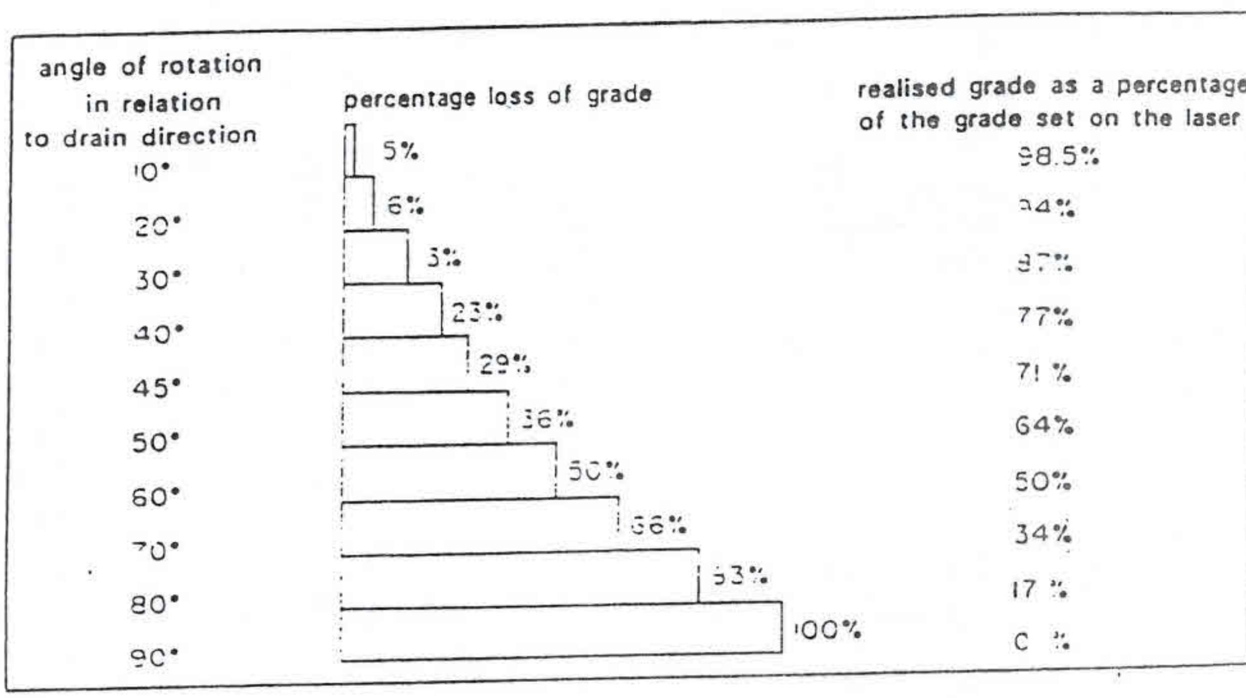
- transmitter.
  stability : soft soils , to near to working machines (trembling).
  grade calibration : the transmitter should be calibrated on the laboratory. If a laser is not calibrated, this can mean that the beam of light which comes out of the tube does not hit the prism vertically. The result, the laser beam can have an upwards or downwards deviation.
  grade direction : The laser is set up in such a way that the direction of the grade of the laser does not correspond with the drain direction. (see figure)
- receiver.
  sensitivity: bandwidth of the green signal is too big.:
  -relation transmitter- receiver: wind (see diagram) , fog , radar (see diagram), high tension, temperature .

Drainage machine

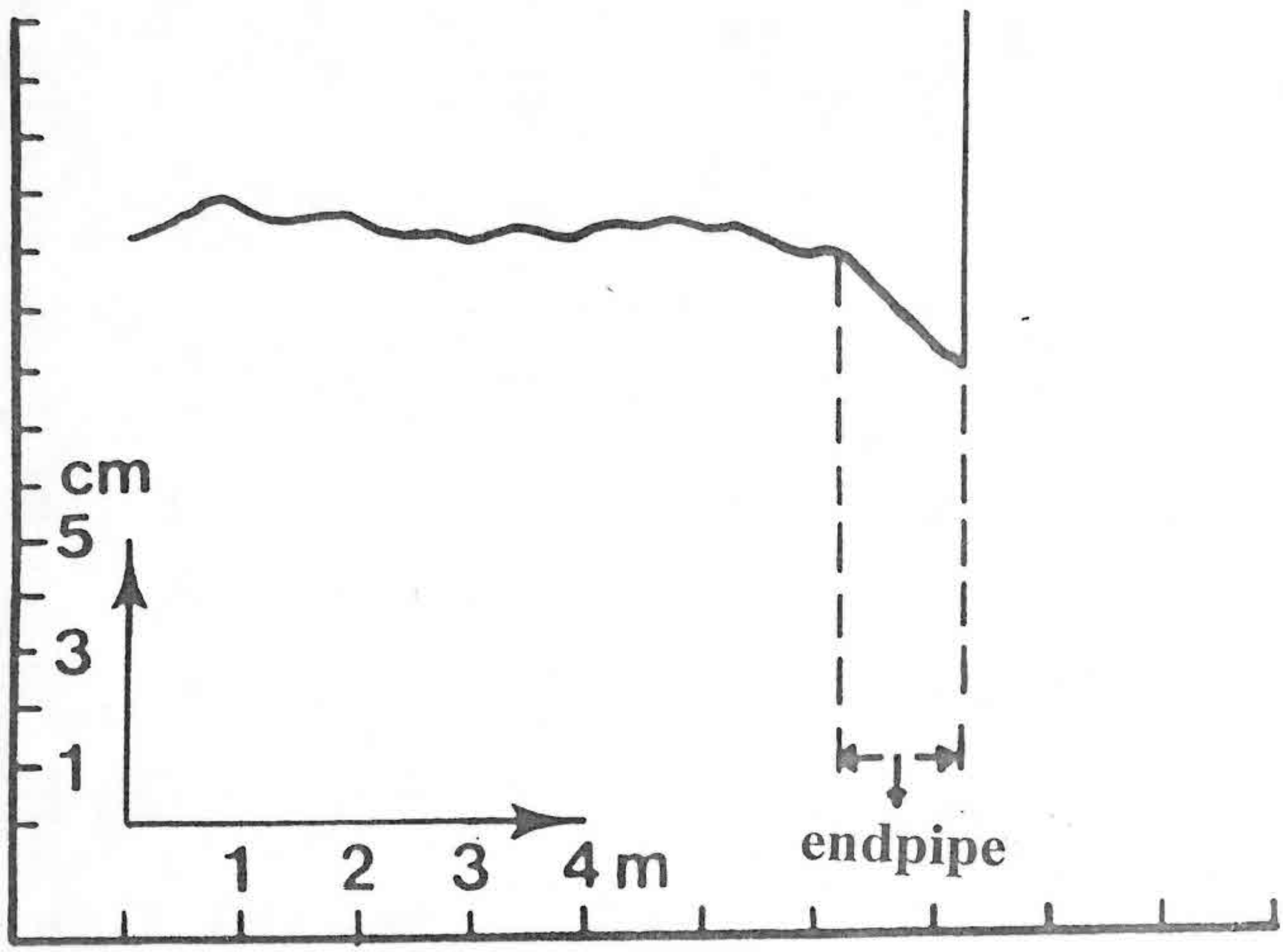
- insufficient pressure in the hydrolic system (see diagram)
- too strong reaction hydrolic system on the laser impuls (viscosity of hydr. oil , temperature)

Human factors

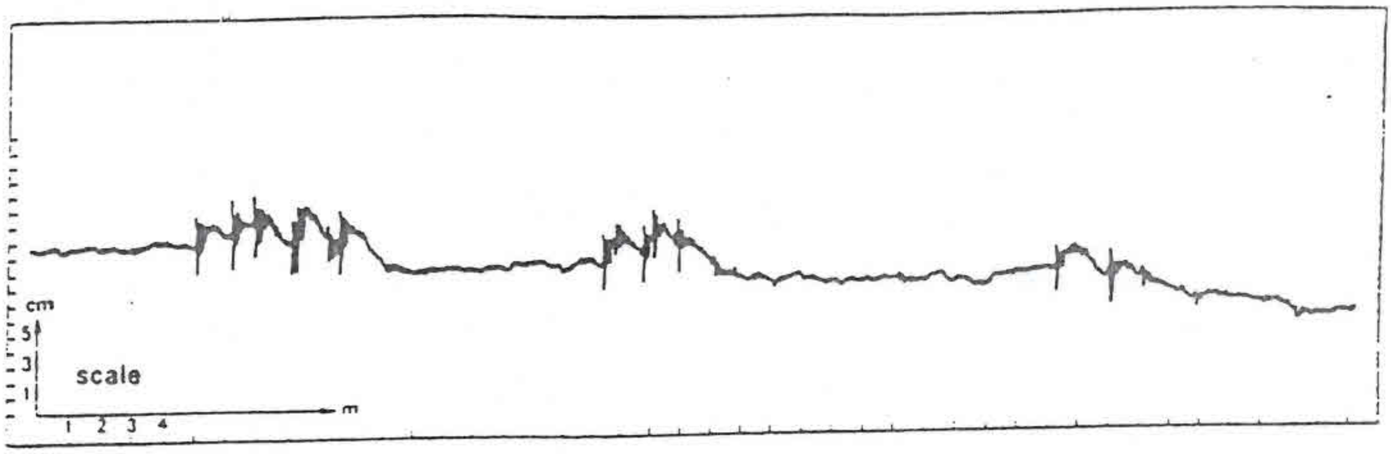
- at the outlet:the bottom of the plough is not horizontal at the start
  : a kink directly after the outlet pipe
  : outlet pipe not attached firmly enough to the drainpipe
- inserting drain too high
- installation speed
- knowledge on the subsoil
- stops of the machine



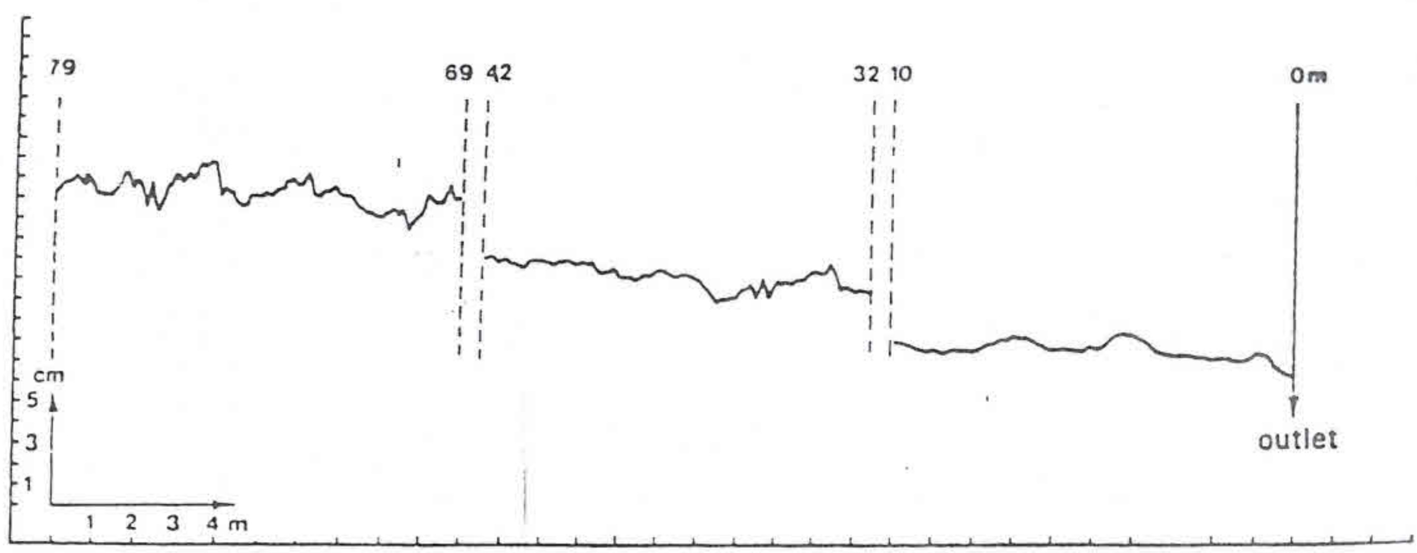
The effect of the incorrectly aimed laser transmitter the grade of the drain.



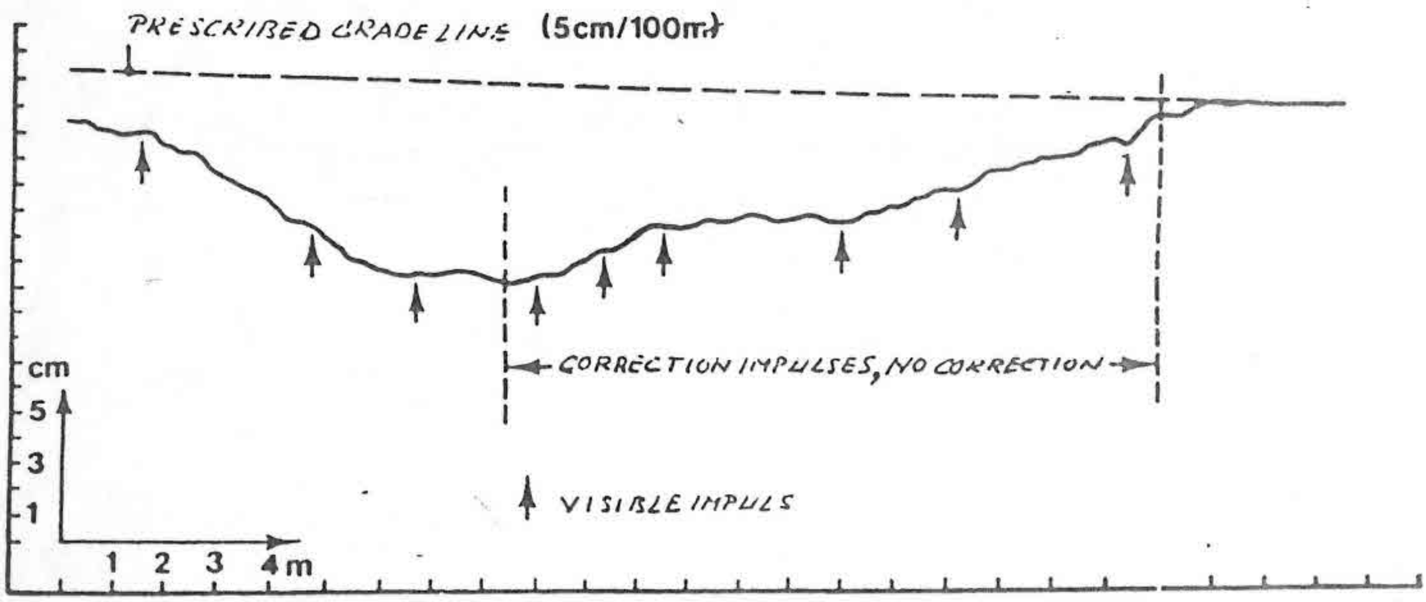
cm
5
3
1
1 2 3 4 m
endpipe

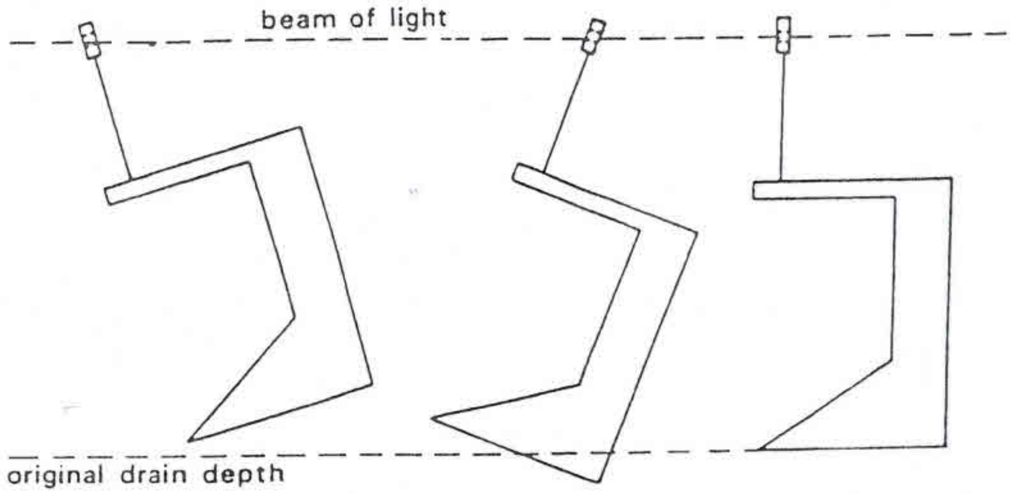


Deviations in the grade of a drain caused by the effect of radar.

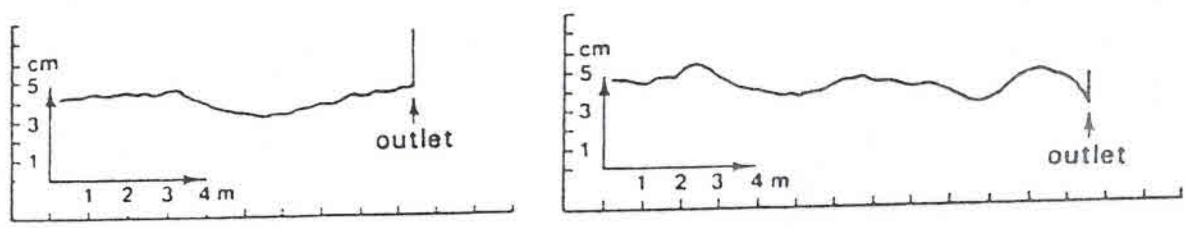


The greater the distance from the laser transmitter, the stronger the effect of the wind (laser transmitter erected near the outlet).

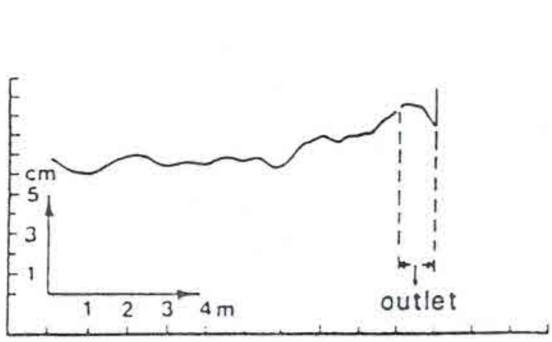

PRESCRIBED GRADE LINE (5cm/100m)
CORRECTION IMPULSES, NO CORRECTION
cm
5
3
1
1 2 3 4 m
VISIBLE IMPULS



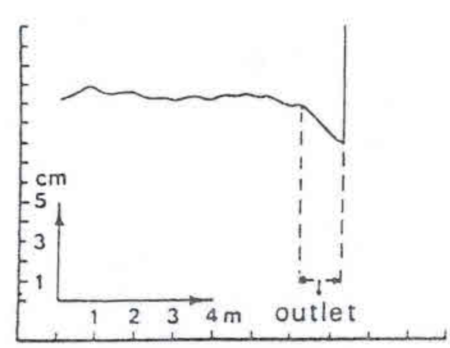
A change in the position of the plow alters the height difference between the laser receiver and the slip shoe.



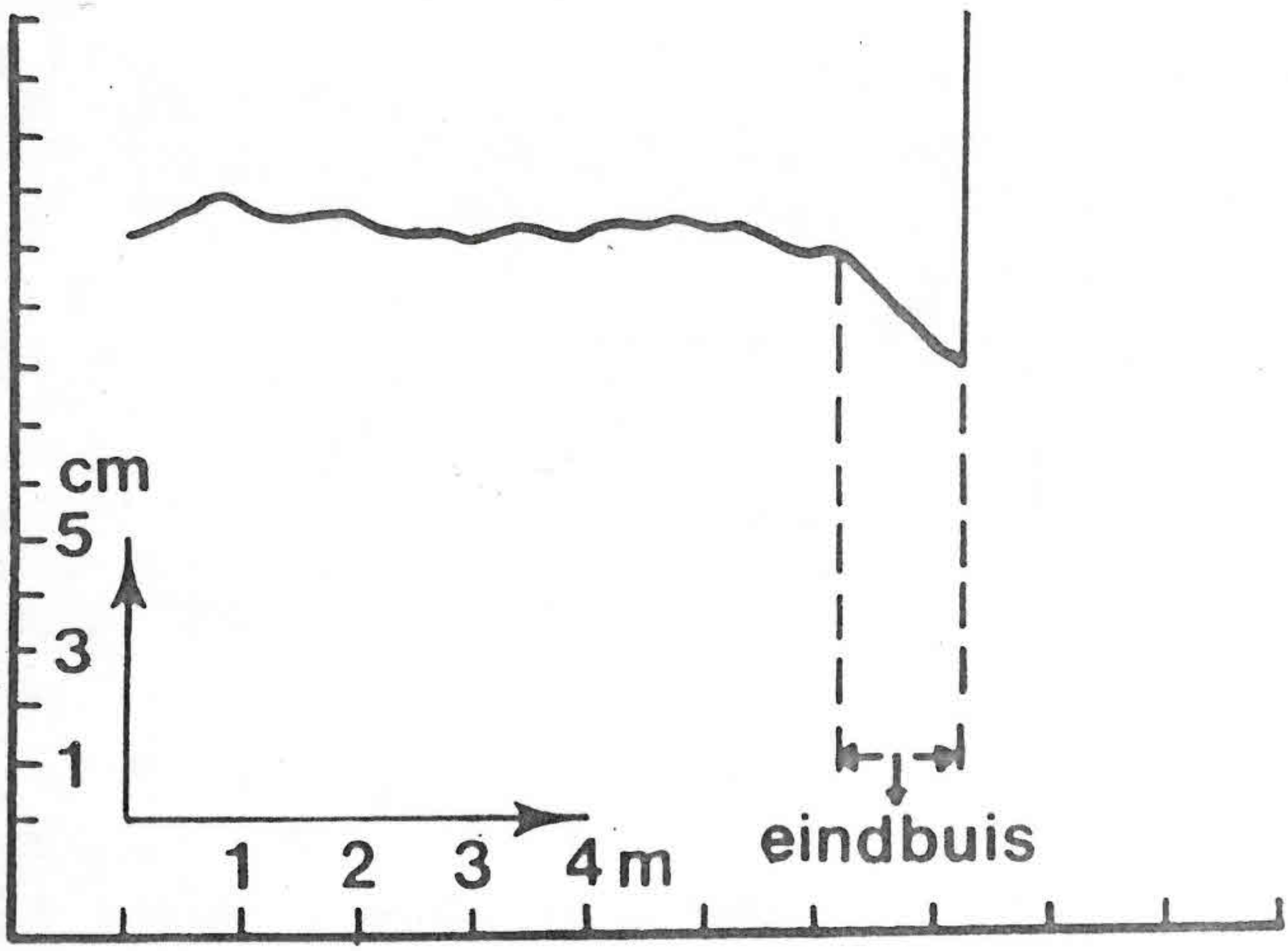
The bottom of the plow is not horizontal at the start.



Inserted too high and plow bottom not horizontal.



Example of inserting slightly deeper.



cm
5
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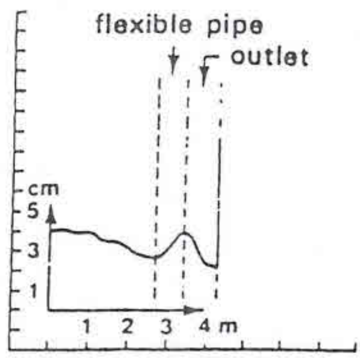
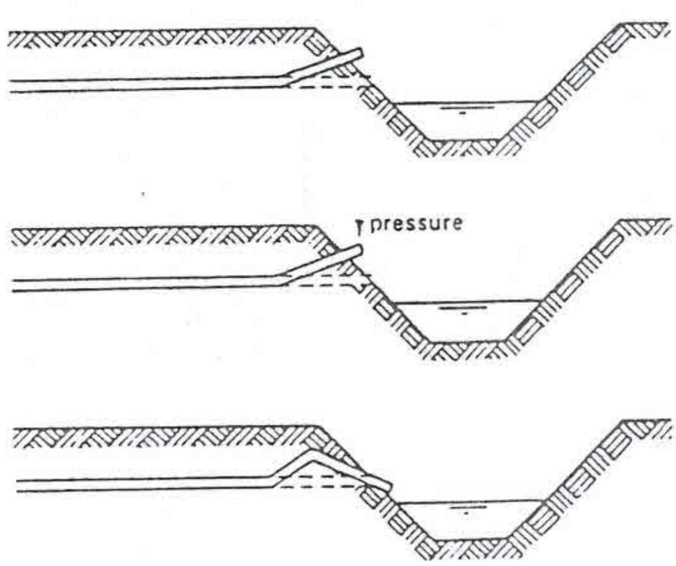


The outlet pipe is brought into the "correct" position by foot.

A kink immediately after the final drain



The removal of the visually disruptive effect results in a situation which is even worse.

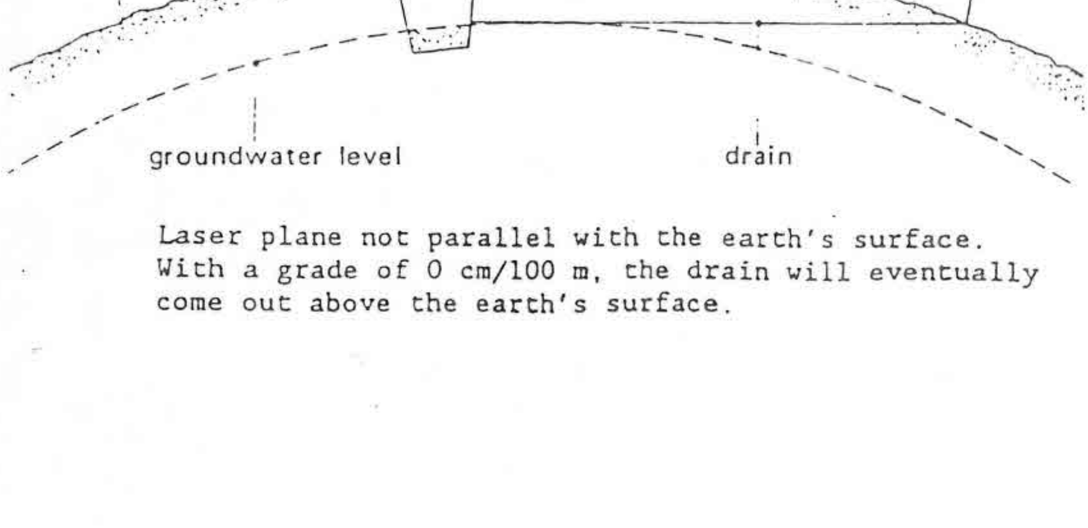
EFFECT OF THE DISTANCE BETWEEN THE LASER TRANSMITTER AND THE LASER RECEIVER

In good weather conditions, the maximum permitted distance from the laser transmitter is 300 m. With larger distances between transmitter and receiver, the effect of the curvature of the earth is relatively large. This can be calculated using the following formula.

$$\text{Curvature of the earth} = \frac{(\text{distance})^2}{\text{diameter of the earth}} = \frac{(\text{distance})^2}{12\ 765\ 300} \text{ (M1)}$$

Filling in this formula gives the following results:

distance	curvature of the earth
100 m	0.78 mm
200 m	3.1 mm
300 m	7 mm
500 m	19.6 mm
1000 m	78.5 mm



Laser plane not parallel with the earth's surface. With a grade of 0 cm/100 m, the drain will eventually come out above the earth's surface.

LASER CONTROL IS VERY USEFUL ,

BUT IT IS NO GUARANTEE

FOR GOOD GRADE CONTROL

EXECUTION
Planning and Organisation of Drainage works

CONTENTS Page

1. INTRODUCTION

Planning and organisation of drainage works are important in order to achieve a high work output before and during execution and maintenance.
To increase the effect of planning and organisation operational research is often applied.

Objectives of operational research are: a more clear idea of the required amount and type of equipment for the execution of activities, and a more efficient use of labour and materials/equipment in *work processes* and organizations.
Important herewith is to attain the set objectives of the work processes with a minimum of human efforts, and costs of labour, machines and materials, operating within certain limits of *tolerance*, considering the *ergonomic* aspects. For this purpose study is made of special work processes and organizations. This research leads to specific work and organisation methods, including *work and time norms* for manual and mechanized labour.

In this paper operational research results obtained during the reclamation and exploitation of the state farm in the Lake IJssel Polders are used as examples.

Explanation of some technical terms used above:

1 a **work process** is a coherent set of different activities leading towards a result or product.
For instance, for the work process of laying drain pipes, subsequent activities are:
- Loading drainpipes up the machine;
- Lowering the shoe into the ditch;
- Laying and fixing outfall pipes;
- Laying the pipes:
  - driving the machine
  - loading pipes up the machine
  - displacing sighting boards
  - checking the depth of lines of pipes
- Lifting the shoe
- Removing the machine backwards to the ditch for the next run.

etcetera..

A description of the work process of laying drain pipes as applied in the IJsselmeer polders (open collectors) is presented in Annex 1.

2 **tolerance** includes the permitted deviations in the quality of the product, whereby a preset limit is not exceeded. For instance in drainage execution: the maximum difference in thickness of the filter envelope materials which will be used, the maximum deviation in the gradient of the drainage pipe line, etc.

3 **ergonomy** deals with the adaptation of a machine to the operator driving it in order to create optimum working conditions for him. Nowadays machinery industry pays much attention to comfortable operating conditions for machine drivers through practical adaptations of driver's seats (two or more positions), cabins (climatic protection) or more effective positions of steering wheels, clutches and handles etc.

4 a **work norm** is the standard production rate of a machine (in ha, litres, metres, pieces, tons) per unit of time (hour, minute, centiminute).

5 a **time norm** (the inverse of the work norm) is the standard time (h, min, cmin) per unit of production (ha, litre, metre, piece, ton etc.).

In fact both (4) and (5) are parameters, which are characteristic for every kind of machine working under certain kind of conditions, as is shown in the following example.

Example: drainage execution

material:	plastic pipe
Length:	drainpipe of 210 m long
Diameters:	135 m x Ø 135 mm and Ø75 m x 60 mm
Spacing:	24 m
Envelope:	20 cm topsoil
Machine:	Draientie type D20
WORK NORM:	529 metres of drain/hour
TIME NORM:	1.89 hours/km drain

To obtain a good view on a work process, it is necessary to consider the following five points (in the same order):

- Volume of work;
- factors of influence on work time;
- periods during which works must be executed;
- effects of climate on work time;
- detailed time scheduling.

These points will be discussed in the next chapters.

2. VOLUME OF WORK

The volume of work is a specification of the work to be executed or produced, expressed in measurable quantities, e.g. area (ha, m^2), length (m, km), weight (kg, ton) or volume (litres, m^3)
Also the conditions under which the work has to be carried out are to be clearly described, as e.g.

- dimensions of the field (m x m);
- type of drains: open, subsurface, irrigation canals;
- type of vegetation (crops, grass) condition of the soil surface

Moreover, it should be indicated which type of machines and/or implements/tools are available for the execution of the work. A simple example of an inventory of conditions for a farm is presented in Annex 2.

3. FACTORS OF INFLUENCE ON WORK TIME

Within a certain period of for instance 24 hours, certain factors may affect the execution of the works in such a way, that the time is not used efficiently. Such a day of 24 hours consists of real working time and time during which there is no work, e.g. evening and night hours. Once the duration of the working time is known, other items can be distinguished which may reduce or increase the actual working time. The operation time of a machine is the period in which the actual work is performed. The rest of the time is not used in a productive way: *non-effective time*. It is important to check whether non-effective time could be transformed into effective time and thus be added to the operation time of the machine.

As is shown in figure 1, a fixed period of 24 hours can be divided into units of time and sub-units of time:

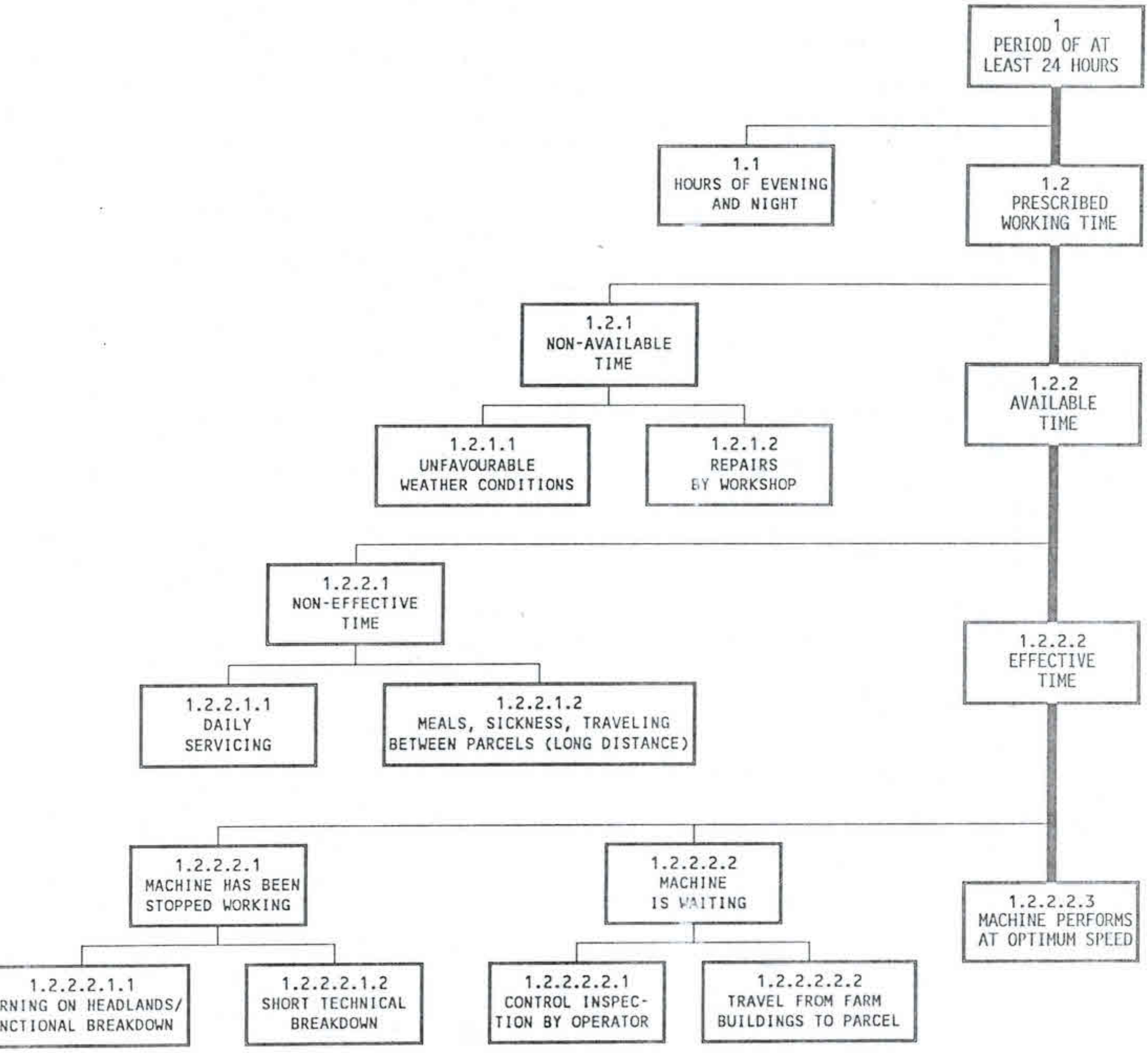


Figure 1. Relations between the factors which influence working time

Using this figure the time in which the machine is operating at its optimum (1.2.2.2.3) can be calculated by subtracting all the measured time periods which are not directly productive (1.1, 1.2.1 etc.) from the *period of at least 24 hours* (1). This step-by-step operation is further explained in chapter 8.

4. PERIODS DURING WHICH WORKS ARE TO BE EXECUTED

In order to obtain a maximum output at farm-level or in the project, it is essential to investigate which period(s) are most suitable for executing the work. This should be done in the most accurate way, taking into account all available information, e.g. cropping activities, climatic restrictions, costs of machinery and personnel etc.

In Annex 3 a summary is presented of the optimum periods in which the cultivation works of rape seed (*colza*) should be executed, from soil preparation up to harvesting.

5. EFFECTS OF CLIMATE ON WORK TIME

One of the factors which may influence working time is the climate. In fact it is possible that because of rainfall and its effects (such as wet soil and wet crops) works cannot be executed in the field. It is therefore important to collect statistical data, from which *available time* and *non-available time* can be determined in minutes and percents (see Fig. 1: respectively nos. 1.2.2 and 1.2.1).
For this purpose a special form may be used (Annex 4), in which daily and for each hour, can be indicated (by drawing a horizontal bar) when and why the work can or cannot be executed because of the weather. It is recommended to have this registration performed by personnel in charge with supervision on or execution of the work. From the obtained data the *weather working time* and the *no-weather working time* can be computed. Annex 5 gives a summary of these percentages for the windrowing of rape seed.

6. DETAILED TIME SCHEDULING

When during a certain period works are to be executed in the field, it is necessary to know the time schedule of all activities. Or, in other words, one should know how much time is spent on the different factors (as listed in Figure 1), in order to be able to organize the work more efficiently.

In Annex 6 a time schedule is presented for the windrowing of rape seed.

The *effective (machinery) time* can be computed by using Figure 1.

From this time (415 minutes) can then be subtracted:

- the machine-has-been-stopped-working time (1.2.2.2.1) and
- the machine-is-waiting time (1.2.2.2.2).

The result will be the time during which the machine operates at optimum speed (1.2.2.2.3) or the effective machinery time.

Annex 7 presents an example of how to calculate the work and time norms for windrowing rape seed.

7. PREPARATION AND EXECUTION OF FIELD DRAINAGE (case example)

For the planning of complicated projects in which many activities take place simultaneously, sometimes use is made of *network planning* techniques. Characteristics of this method:

- the total project is divided into separate actions;
- all these actions are arranged into a network diagram;
- the actions which primarily determine the progress of the project are identified and investigated.

To build up a network schedule, three questions must be answered for each action:

- which action(s) precede(s)?
- which action(s) come(s) next?
- which action(s) can be performed simultaneously?

Figure 2 illustrates the basic principles or setup of a network schedule.

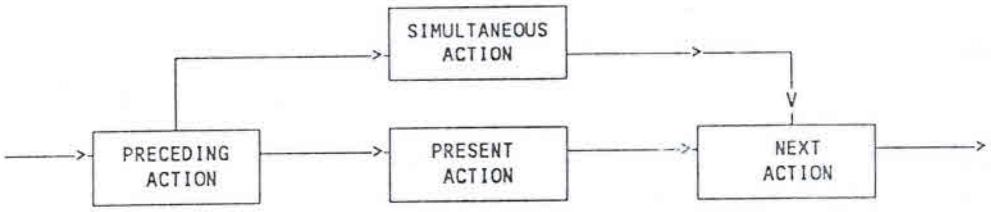


Figure 2. Setup of a network schedule

In Figure 3 the first two questions are elaborated for a drainage execution case example. The network schedule gives a comprehensive idea of the actions that have to be performed to complete a sub-surface drainage system for any agricultural parcel. Also the relations between the actions are indicated.

The network schedule is based on the following assumptions:

a) the parcel is chosen at random, having an indefinite size and an indefinite soil type and vegetation;
b) the most common actions are all included. It may, however, occur that one or more actions do not need to be performed. In this case the network should be modified and adapted.

A narrative description of all the actions in the network schedule can be found in Annex 8.

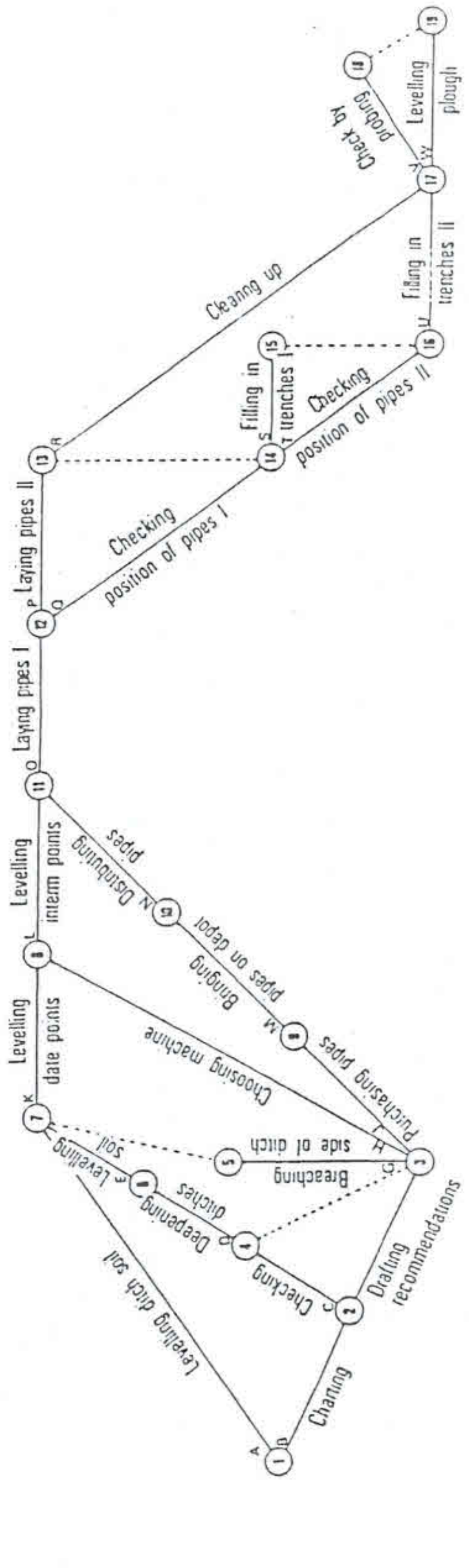


Figure 3. Network schedule for a drainage execution work process

8. WORK AND TIME NORMS, TIME STUDY

After a work process is analyzed in detail, work and time norms can be determined through a time study. Time and work studies can be considered as research on the time required for manual and mechanized work or jobs. Time and work studies lead to well defined figures for output per unit of time, or durations per unit of output, and finally to time and work standards.

Results of the time study, the time and work norms, can be used for:
- comparing working methods;
- appraisal of efficiency;
- planning;
- coordinating different types of work;
- budgeting etc.

In a time study different terms and parameters are being used, which are explained below:

- element	:	clearly defined part of an activity;
- construction time	:	standard duration(s) of (an) element(s) out of which work and time norms are determined;
- layout and routing schedule	:	a spatial plan of a farm, division or working place, including a working or processing route;
- process schedule	:	schedule representing the elements and the coherence between them.

In Annex 9 a comparison of output and cost between caterpillar and wheel tractors, as an example of how collected data can be used.

Before doing a time study, it is important to be well prepared.
First, one must be aware, that time periods measured by human beings depend on different factors, which can vary slightly or considerably. It is difficult to predict or estimate these factors in advance. Therefore, it is recommended to describe all prevailing factors, in order to check which ones are relevant.

Second, all tools for the study should be made available:

- a simple **stopwatch**, for measuring time periods per activity or action. To make calculations more easy time is normally expressed in *centiminutes* (cmin = 0.01 minute);.
- special **data sheets**, on which all measurements are written down.

The different data sheets are discussed below, taking the execution of drainage work as a case example.

1 **Survey sheet:**
in this form all actions related to the work are noted, including the corresponding time periods. An example for laying drainpipes in agricultural soil is shown in Annexis shown in Annex 10. Normally measurements are repeated and elaborated on different survey sheets;

2 **Summary sheet:**
On this sheet the totals of different survey sheets (for the same working process) are summarized. See the example of Annex 11a. Then, actions and total time periods are put into a table and average time periods are computed (Annex 11b).

3 **Overall sheet:**
On this sheet the average time periods and factors per element or activity are arranged in such a way, that research on the relation between the time periods and the factors becomes possible. All time study data are sorted into a logical order, per action or activity. The above mentioned "average time periods" are the so called "construction time" used for the computation of the time or work norm for a complete process. A time or work norm is only related to the "effective time". This effective time is only a part o the day. A specification for the total time period of a working day for drainage of 9 hours (540 minutes) is represented in Annex 12a. It shows, that the effective time was 308 minutes or 57%. A more detailed specification of the time is shown in Annex 12b. This table clearly shows, that out of a working day of 308 minutes only 155 minutes or 50% are really spent on laying the drain pipes.....

4 **Composition form:**

As soon as sufficient time periods of all relevant actions within a process are recorded on the overall sheets, averages and possible allowances (in %) can be calculated, followed by composing the norms (Annex 12c)

9. COORDINATION OF ACTIVITIES

Next step is to determine the required number and type of machines (including if possible the staffing), making use of data on volume of work, time period, work and time standards (effective time). See as an example Annex 13, which gives a comparison between different ploughing methods to be applied during the year 1989).
With these data a "machinery requirement schedule" can be composed, for those activities that need to be executed by equipment. Such a schedule represents per activity and per week how many machines of a certain type are required. See Annex 14 for a practical example.

10. SOLVING BOTTLENECKS

When all activity plans and schedules are completed it may appear that they differ on some points from the actual situation. For certain periods there can be a shortage of equipment or too much personnel etc. To solve technical or organizational bottlenecks in the execution phase it is necessary to follow a structured and logical apporach. The following steps can be distinguished:

1. **Problem definition**

   To be done in consultation with all concerned. Formulate briefly and clear. Objective oriented. Omit irrelevant matters.

2. **Problem analysis**

   Discussions with direct supervisors and executive staff. Measuring, observing of data. Retrieve data from administration

3. **Alternative solutions**

   Make a list with different methods leading towards the same goal

4. **Select the best alternative solution**

   Choose, in cooperation with executive management, the most suitable alternative.

5. **Introduce the solution**

   In cooperation with the executive management the chosen solution is put into practice

6. **Monitoring**

   Checking whether the chosen solution is practical, effective and efficient, by using observation data and administrative data.

7. **Adjustment**

   Apply corrections if necessary, in cooperation with the executive management.

ANNEXES

Annex 1. Execution of subsurface field drainage in Eastern Flevoland

The following factors, which are usually variable, are considered to be fixed factors in the given description of the method of draining with plastic pipes.

area of parcel	:	30 ha (approx. 300 m x 1,000 m) Eastern Flevoland
	:	60 ha (approx. 500 m x 1,200 m) Southern Flevoland
land	:	not yet drained
machine	:	fitted with chain excavator
type of pipe	:	corrugated plastic pipe, 60 mm outside diameter
covering material	:	none
spacing	:	24 metres
flow	:	two-sided

Only the operations most closely connected with the actual drainage are described. The network diagram (Figure 1) gives a rough idea the order in which the various operations are carried out when a drainage system is installed under different circumstances.

1 Preparatory work

Marking

On receipt of the drainage recommendations the division responsible for carrying out the work will detail two or three men to fix the main points of reference.
Instruments: level, markers and stakes.

Sighting-in intermediate stakes

This is done by two or three men.
Instruments: a number of sighting boards, mallet and stakes.
Sighting boards are not necessary when a laser-plane equipped drainage-machine is used.

Annex 1. Execution of subsurface field drainage in Eastern Flevoland (continued)

Distributing pipes

The pipes are stored in a depot on the road verge, alongside the land or nearby.
Men required: 2 men for loading and unloading, 1 tractor driver.
Vehicles, etc., required: 1 wheeled tractor, about 3 wagons.
One wagon can carry 12 coils of corrugated plastic pipes.
Each coil has a length of 150 m.

Distributing outfall pipes and makeshifts

One man will be required for this.
Vehicle: tractor and wagon.
One outfall pipe; a plug and some makeshifts are deposited near the end of each line of pipes to be laid.
The outfall of pipes are made of plastic and 120 cm in length; 80 cm may be telescoped to enable the side of the ditch to be mown.

2 Laying drain pipes

General remark

The laying of pipes starts at the ditch and proceeds towards the middle of the parcel. Then the machine is driven backwards to the ditch again. The pipe-laying machine is manned in the following manner:
2 operators; one to drive, the other to move the sights;
2 men to place the coils of pipes on the machine and to connect them;
1 man to install the outfall pipe, and to close the opening in the side of the ditch.
A foreman is in charge of the five-man gang.
The men can switch jobs at regular intervals. The laying of pipes can be effectuated in the three recurrent stages: preparing the machine in the field at the beginning of each run; laying the pipes; removing the machine at the end of each run and moving the machine on for the next run.

Annex 1. Execution of subsurface field drainage in Eastern Flevoland (continued)

Preparing the machine in the field at the beginning of each run.

- Placing first coils of pipes on machine;
- Lowering shoe and excavating mechanism into ditch;
- Setting and connecting outfall pipe;
- Depositing surplus material left behind during the previous run on the side of the ditch.

Laying pipes

Each member of the gang now takes up his appointed station and the machine is set in motion, the men discharge the duties described in 2.1. One of the operators drives the machine, carefully controlling the direction and the depth at which the pipes are being laid. The other operator walks ahead of the machine and moves the sighting boards and the stakes to the next line of pipes to be laid, placing them at the correct height[1]. The two men handling the pipes check them to see whether they are cracked or damaged. The man who sets the outfall pipe carefully restores the side of the ditch to its former condition. The foreman sees to it that enough natured soil reaches the bottom of the trench.

Removing the machine at the end of each run

The pipe setter places a concrete blank on the last section of pipe at the end of each line to prevent soil from being washed into it. The driver drives the machine a few yards further to finish laying soil in the trench, then raises the excavating mechanism and the shoe above groundlevel and removes the machine backwards to the ditch for the next run. The entire gang, except the driver, of course, walk back to the ditch.

3 Final operations

Inspection

A foreman and two assistants check the depth of the lines of pipes.

Instruments: a level, 2 steel probes, 2 markers. Each line is probed every 10 metres. The findings are entered in a drainage-levelling form. Any defects discovered are usually corrected by hand.

---

[1] Control of the depth is not necessary when a laser-plane equipped drainage machine is used.

Annex 1. Execution of subsurface field drainage in Eastern Flevoland (continued)

Clearing up

A driver and one or two assistants clear up the unused, broken and rejected pipes, etc.

Vehicles: tractor and wagon.

As everything that needs clearing up is already at the side of the ditch, the driver and his assistants only have to drive once round the perimeter of the drained parcel.

Filling in the trench

The trench is filled by driving a wheeled tractor with scraper board down each trench once to return to the latter the soil lying alongside it and deposited there when excavating the same. This may also be done with a crawler tractor with scraper board.

Connected up with farmyard drainage system

If a ditch is dug after drains have been laid in a parcel land, the lines of pipes disturbed by the operation must be provided with outfall pipes by hand.

When the work of laying drain pipes has been completed, the division carrying out the work will fill in a drainage system form giving particulars of the system, the materials used, the nature of the soil and other information.

The position of the lines of pipes is checked by probing during the first winter after they have been laid. The outcome is entered in a drainage inspection and maintenance form.

The ultimate state of the parcel as regards type of drainage, gross and net area available for cultivation, size of fields, etc., is entered in a surveyor's chart.

Annex 2. Worksupply per kind of crop on Farm I.Z. I

Number of the parcel	kind[1] of drainage	Gross area in ha	Net area in ha	winter wheat	spring wheat	winter barley	spring barley	oats	winter rape seed	grass	flax	potatoes	peas	beans	grass seed	sugar beets	onions	unsown
KZ 31	G	80.25	72.23						2) R.73.23									
32	G	86.45	77.95					2) T.5.38										
33	T	17.46	16.86				2) T.15.16										3) Pv.1.70	
34	T	23.00	22.21				T.22.21											
35	T	27.70	26.77				T.26.77											
36	T	29.28	28.32				T.28.32											
37	T	30.23	29.25				T.29.25											
38	T	31.28	30.27				T.30.27											
39	T	21.00	20.18				T.20.18											
LZ 3	G	83.75	76.49						J.75.49									1.00
4	G	83.40	76.12						J.74.14									1.98
5	G	82.20	75.00						R.66.25									8.75
6	G	82.05	74.84						G.69.64									5.20
7	G	82.90	75.62						R.66.84									8.78
8	G	68.77	62.20						G.57.70									4.50
11	G	88.65	80.85						J.77.28									3.37
12	G	91.15	83.19						J.78.52									4.67
13	G	90.40	82.32	2) A.74.48														7.84
14	G	90.25	82.13	N.73.77													Pv.0.52	7.84
15	G	89.43	81.40	Ar73.58														7.82
16	G	86.90	78.27					T.69.39										8.88
17	T	22.23	21.04						R.21.04									
18	T	34.18	33.07						R.33.07									
19	T	35.35	34.22					T.34.22										
20	T	36.55	35.37				G.35.37											
21	T	37.05	35.87				G.35.37											
22	T	37.00	35.82					T.35.82										
23	T	34.48	33.39				A.33.39											

Total

1) Kind of drainage: G = open drain
T = open and covered drains

2) Letter in front of the area = variety of crop

Annex 3. Important activity periods during the crop cycle of rape seed

Activity	periods	required number of days
1. Rape seed		
1.1. Cultivating of soil		
1.1.1. Reclaimed land	[1]) [2])	
(sprayed with herbicide)	1/6 - 1/9	
1.1.2. Stubble field (barley and	5/8 - 1/9	
wheat)		
1.2. Sowing		
	15/8 - 1/9	
1.3. Spraying	1/9 - 1/10	
- insecticides	1/9 - 1/10	
- herbicides		
1.4. Spreading fertilizer	5/3 - 15/4	
(Nitrogen on the whole area)		
1.5. Harvesting	6/7 - 24/7	10 - 8 days
- windrowing	14/7 - 9/8	8 days
- threshing the swath and transport of seed		

[1]) Number of the day

[2]) Number of the month

Annex 4. Sheet for data on (no) weather-working time during windrowing of rape seed

Date:______________________________ Number of the farm:________________

Type of soil:____

Hour of the day	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Weather-working														
No weather-working induced by:														
- Precipitation														
- Wet soil														
- Wet crop														
- Strong wind														

1) Kind of precipitation: rain - drizzling rain - heavy shower - hail - snow

Quantity of precipitation: ____________ mm

Note down weather-working or no weather-working time by ticking off.

The period of the observation runs from 1 till 20 july 1980

1) Delete as applicable.

Annex 5. Weather-working/no-weather-working time at windrowing rape seed

Research period: 1966-1973

Period of observation: 1 July - 20 July

	% weather-working hours from:			% no weather-working average hours (06.00 - 20.00 hrs.), as a result of:				
	7.00-17.00 hrs.	6.00-7.00 and 17.00-20.00 hrs.	6.00-20.00 hrs	rain	wet soil	strong wind	wet crop	rainfall in mm
July 1st decade 2nd decade	 91.2 86.3	 91.0 87.0	 91.1 86.6	 4.4 10.7	 4.3 2.4	 0.1 0	 0 0.3	 25.3 29.5
Over the whole period	88.9	89.5	89.1	7.6	3.3	0.1	0.2	54.9

Annex 6. Activities during one day of windrowing rape seed

Elements	Percent %	Minutes (incl. overtime)
1.2.1. Non-available time of the machine		
1.2.1.1. No weather-working time	11.8[1])	85
1.2.1.2. Repair by workshop	6.9[2])	50
Total 1.2.1.	18.7	135
1.2.2. Available time of the machine	12.9	92
1.2.2.1.1. Daily servicing	2.5	18
1.2.2.1.2. Travel between parcels	8.3	60
1.2.2.1.2. Meals		
Total 1.2.2.1	23.7	170
1.2.2.2. Effective time of the machine	57.6	415
Total 1.2.2.	81.3	585
Total general	100.0	720

[1]) Average percentage of no weather-working time for windrowing between 6.00 and 20.00 hrs. from 1966 till 1975.

[2]) Results trom report by workshop "Repairing windrowers"

Annex 7. Effective time of a (rape seed) windrowing machine (one day period)

Elements		Working width 20 feet		
		Percent %	Time (min.)	Worknorm (ares[1]/hr)
1.2.2.2.3.	Machine is performing at optimum speed - Windrowing	68.6	285	
	Total 1.2.2.2.3.	68.6	285	416
1.2.2.2.1.	Machine has been stopped working			
	1.2.2.2.1.1. Turning on headlands	6.3	26	
	1.2.2.2.1.1. Short break down	11.4	47	
	1.2.2.2.1.1. Rest	5.1	21	
	Total 1.2.2.2.1.	22.8	94	
	Total	91.4	379	313
1.2.2.2.2.	Machine is waiting 1.2.2.2.2.2. Organization inside 1.2.2.2.2.1. the farmborder	8.6	36	
	Total	8.6	36	
	Total 1.2.2.2. Effective time	100.0	415	286

[1] 1 are (Dutch unit of area) = 0.01 hectare = 100 m^2

Annex 8. Actions during the drainage execution process (figure 3)

Reference is made to figure 3 (page 12).

Action	From	To	Description
B	1	2	Mapping ("charting") of section profiles of ditches up to 1.5 m depth. Mapping on the parcel can be done at a later stage.
A	1	7	Levelling of soil excavated from the ditches
F	2	3	Drafting and issuing recommendations on drainage, highlighting trenching, drainage grid, depth and spacing of tile drains etc.
C	2	4	Checking ditch bottom depth and depth of water table below surface level
-	3	4	extra arrow or *dummy*: this arrow does not denote any activity or time, but it is used for computer processing when two or more activities have the same starting and finishing points
G	3	5	Making breaches in the bank of the ditch to be linked with the drainage lines (only required if the soil excavated from the ditches has not yet been levelled)
H	3	8	Deciding on the type of drain-laying machine to be used
J	3	9	Purchasing drain pipes and filter material
D	4	6	Deepening of the ditches
-	5	7	*Dummy*
E	6	7	Levelling of soil excavated from the ditches
K	7	8	Surveying with a level instrument between the main points (benchmarks)
L	8	11	Putting the intermediate points in the line (not required in case laser equipment is used)
M	9	10	Transport of drain pipes and filter material to the depot
N	10	11	Transport of pipe and filter material to the parcel (at one side, divided at regular distance)
O	11	12	Laying the drain pipes (including end pipes, first part of the drain, until the middle of the parcel)
P	12	13	Laying the drain pipes (including end pipes, second part of the drain)

Annex 8. Actions during the drainage execution process (continued)

Action	From	To	Description
Q	12	14	Checking of grade, position of lines of pipes (first part of the drain)
-	13	14	*Dummy*
R	13	17	Clearing the area, removing bits of broken pipe, wire etc.
S	14	15	Fill up drain pipe trenches, first part of the drain
T	14	16	Checking of grade, position of lines of pipes (second part of the drain)
-	15	16	*Dummy*
U	16	17	Fill up drain pipe trenches, second part of the drain
V	17	18	Second checking of position of pipes (also called "winter checking") by rodding
W	17	19	Ploughing and levelling of the parcel
-	18	19	*Dummy*

Annex 9. Work and time norms and cost for different types of tractors

Activity	Tractor	Implement	Cost per hour in guilders				Norm		Cost per ha or km in guilders	Number of ratio, wheel tractor 80 kw = 100
			Tractor	Implement	Driver	Total	ha or km/hours	hours per ha/km		
Preparation soil for spring crops	Crawler tractor	discharrow 6 m	45	14	24	83	2.78	0.36	29.90	128
	Wheel tractor 80 kw	discharrow 6 m	40	14	24	78	3.33	0.30	23.40	100
	Wheel tractor 160 kw	discharrow 10,5 m	60	24	24	108	6.66	0.15	16.20	69
	Wheel tractor 80 kw	fieldcultivator 6 m	40	18	24	82	3.41	0.29	23.80	100
	Wheel tractor 160 kw	fieldcultivator 10,5 m	60	22	24	106	7.89	0.13	13.80	58
Preparation soil for rape seed	Crawler tractor	discharrow 6 m	45	14	24	83	2.78	0.36	29.90	128
	Wheel tractor 80 kw	discharrow 6 m	40	14	24	78	3.33	0.30	23.40	100
	Wheel tractor 160 kw	discharrow 10,5 m	60	24	24	108	7.69	0.13	14.04	42
Cultivation of stubbles	Crawler tractor	discharrow 6 m	45	14	24	83	1.88	0.53	44.00	123
	Wheel tractor 80 kw	discharrow 6 m	40	14	24	78	2.17	0.46	35.90	100
	Wheel tractor 160 kw	discharrow 10,5 m	60	24	24	108	7.14	0.14	15.10	42
Cleaning open drains	Wheel tractor 80 kw	ditchcleaner	40	17	24	81	2.4	0.41	23.20	100
	Wheel tractor 160 kw	ditchcleaner	60	23	24	107	4.4	0.23	24.60	74
Digging open drains + levelling soil	Crawler tractor (3)	ditch plow	45	15	24	223	3.33	0.30		
	Crawler tractor	bulldozer	50		24	74	1.32	0.76		
	Wheel tractor 80 kw	discharrow (small)	40	12	24	76	2.78	0.36	206.10	100
	Wheel tractor 80 kw	discharrow	40	14	24	78	4.34	0.23		
	Wheel tractor 80 kw	grader	40	18	24	82	2.17	0.46		
	Wheel tractor 160 kw	ditchcleaner	60	23	24	107	1.03	0.97	103.80	50

Annex 10. Laying drain pipes: Survey sheet

Laying drainpipes in agricultural soils			laying pipes	lowering shoe	lifting shoe	driving back	loading	fixing						
0000	lowering shoe	42		42										
42	laying pipes 1.	32	32											
74	fixing outfall pipe	119					119							
193	laying pipes cont.	677	677											
870	fixing pipe Ø80mm to 60mm	10						10						
880	laying pipes cont.	402	402											
1282	lifting shoe	20			20									
1302	driving back	373				373								
1675	refuelling	579							579					
2254	driving back cont.	71				71								
2325	lowering shoe	30		30										
2355	laying pipes 2.	53	53											
2408	loading pipes and fixing outfall pipe	97					97							
2505	laying pipes cont.	643	643											
148	fixing pipe Ø80mm to 60mm	36						36						
184	laying pipes cont.	128	128											
312	removing string	30								30				
342	laying pipes cont.	300	300											
642	lifting shoe	13			13									
655	driving back	274				274								
929	arranging materials	31									31			
960	driving back cont.	165				165								
1125	lowering shoe	35		35										
1160	laying pipes 3.	28	28											
1188	loading pipes and fixing outfall pipe	60					60							
1248	laying pipes cont.	22	22											
1270	fixing outfall pipe	183					183							
1453	laying pipes cont.	617	617											
2070	fixing pipes Ø80mm to 60mm	370						370						
2240	displacing sighting boards	12										12		
2452	laying pipes cont.	61	61											
2513	lifting shoe	17			17									
2530	driving back	388				388								
2918	lowering shoe													
	total	5918	2963	107	40	1271	459	416	579	30	31	12		
	frequency		3	3	3	3	3	3	1	1	1	1		

Annex 11a. Laying drainpipes: Summary/workout sheet (part 1)

IJSSELMEERPOLDERS DEVELOPMENT AUTHORITY — TIMESTUDY — Workout sheet

Sheet no	Total	Laying pipes	Lowering shoe	Lifting shoe	Driving back	Loading pipes and fixing outfall pipes	Fixing pipe Ø 60 mm to 60 mm	Removing string	Arranging materials	Displacing sighting boards	Personal care taking	Displacing laser	Rest	Refuelling
1	5918	2963	107	40	1271	459	416	30	31	12	-	-	-	579
2	11400	4324	154	69	1598	575	18	35	-	-	850	1155	2632	-
Total	17318	7287	261	109	2869	1034	434	65	31	12	850	1155	2632	579
Frequency														
1		3	3	3	3	3	3	1	1	1	-	-	-	1
2		4	4	4	4	4	1	1	-	-	1	1	1	-
Total		7	7	7	7	7	4	2	1	1	1	1	1	1

Sheet 2

Activity: Laying pipes	Devision: Reclamation	Observation no 76-182 sheet 1 up to 2
Implement: Draiëntie drainagemachine type D 20	Time of: up to:	Observer: K.v.d.Linde Date: 27-9-1976

Description[1]	Time in mm	Frequency	Time / freq	Unit in m'	Time per 100 m'	m' per hour
1 Machine is performing at uptimum speed						
- Laying pipes	7287	7.	1041	1470	496	1210
2 Machine has been stopped working						
- Lowering shoe	261	7	37			
- Lifting shoe	109	7	149			
- Driving back	2869	7	16			
- Loading and fixing outfall	1014	7	411			
- Pipes						
- Fixing pipe Ø 80 mm to 60 mm	434	4	109			
- Removing string	65	2	34			
- Arranging materials	31	1	31			
- Displacing sighting boards	12	1	12			
- Personal care taking	850	1	850			
- Displacing laser	1155		1155[2]			
Total 2.	6820					
Total 1 + 2	14107					
3 Machine is waiting						
- rest after meal time	632	1	612			
Total 1 + 2 + 3	14917					
Non. effective time						
- refuelling	579	1	579			
Total general	15110					

1) See appendix 6 too

2) This displacing counts for 40 drains. For one drain $\frac{1155}{40}$ = 29 cmin.

DETAILS Sheet 3

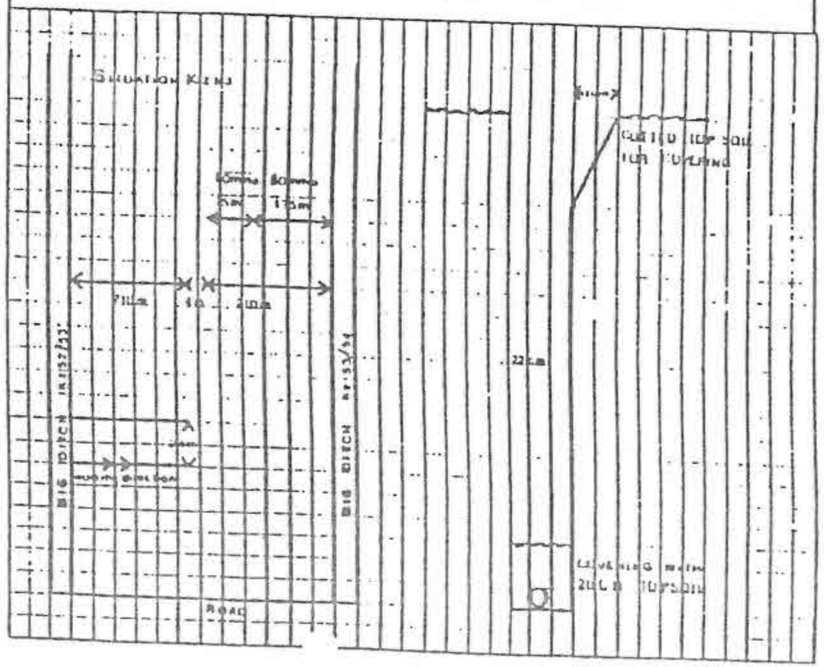
Machine:
Draiëntie drainage machine type D 20; 160 Kw; chain excavator.

Object:
Parcel KZ 53 1200x424 m; dry, well aerated, cracked clay soil, sown with rape seed; open fielddrains, space 12 m, depth 60 cm.

Weather conditions:
Semi clouded, weak eastern wind, 20° C.

Activety:
Laying corrugated plastic pipes from both sides of the parcel at a space of 24 m in an existing trench (open field drain); length of half a drain 210 m', of which 135 m' with 80 mm Ø and 75 m' with 60 mm Ø; plastic pipes present on the headland at distances of 24 m'; slope of the lateral 4 cm/100 m'; total slope 8,4 cm on 210 m'; depth of the lateral: 20 m out of the drain ditch 1,38 m and at the end 1,26 m; pipes covered with 20 cm top soil laying alongside the trench; carried out with knife on the shoe; around the knife some blocking occurs by old straw; cleaning of the knife by one man necessary during execution.

Other remarks:
Operating: 2 operators, 1 for installing outfall pipe and reconstructing slope of the main ditch, 3 men loading plastic pipes and joining 80 mm Ø pipe to 60 mm Ø pipe; one of these 3 is also foreman; depth control with Laserplane and sender on headland; laser has a reach of 500 m; this means that during execution displacing is necessary.



Annex 12a. Time specification for one day of laying drainpipes

Element	Percentage	Minutes/day
1.2.1. Non available time - unfavourable weather conditions - repair by workshop	 6 13	 30 70
Total 1.2.1.	19	100
1.2.2. Available time 1.2.2.1. non effective time - daily servicing - travel parcel to parcel (over a long distance) - meal time	 11 2 11	 60 12 60
Total 1.2.2.1.	24	132
1.2.2.2. Effective time	57	308
Total 1.2.2.	81	440
Total general	100	540 = 9 hours

Annex 12b. Effective time during one day of laying drainpipes

Elements	Percentage	Time in (min)	Production (m/hr)
1. Machine is performing at optimum speed - draining	50	155	
Total 1	50	155	1210
2. Machine has been stopped working - turning on headlands including lifting and lowering shoe - loading and fixing pipes (draining and outfall pipes) - displacing sighting boards and laser - rest	 23 11 1 6	 70 34 3 18	
Total 2	41	125	677
Total 1 + 2	91	280	
3. Machine is waiting - onprescripted time for mealtime - bonus for organization inside the farmboards	 5 4	 15 13	
Total	9	28	
Total 1 + 2 + 3	100	308	614

Annex 12c. Time and work norms for laying drainpipes

Example (February 1980)

Composed

Method

Laying plastic pipes from both sides of the parcel at a spacing of 24 m in an existing trench (open field drain). Length of the drain 210 m'.

Machine : Draintie type D 20.

Draining materials : Plastic pipes of which 135 m' with 80 mm ϕ and 75 m' with 60 mm ϕ per drain.

Material of covering : 20 cm topsoil.

Number of men : 6.

Construction elements	Minutes per km' drain
1. Laying pipes	49.6
2. Turning and driving back	22.0
- laying outfall pipes + fixing pipes of different diameter	10.4
- loading pipes on the machine	2.1
- displacing sighting boards and laser	1.4
Total 1 + 2	85.5
3. Short breakdown 15% of 1, 2	12.8
Total 1 + 2 + 3	98.3
4. Organisational losses during the work 10% of 1, 2, 3	9.8
Total 1 + 2 + 3 + 4	108.1
5. Personal care taking 5% of 1, 2, 3, 4	5.4
Total 1 + 2 + 3 + 4 + 5	113.5
Hours per km of drain	1.89
m of drain per hour	529

Annex 13. A comparison between ploughing methods

	Period (week no)	Quantity of work (ha)	Speeding time, or effective time (hrs)	Production (ha/hr)	Available capacity per tractor (ha)	Number of required tractors	Area per kind of tractor in (ha)
- discharrow)	24 up to 32	1300					
- crawler tractor			159+108¹)	2.78	742		
- wheel tractor (four wheel driven) 80 kw			165+111¹)	3.33	919		
- wheel tractor (two wheel driven) 80 kw			165+111¹)	3.13	863		
- wheel tractor (four wheel driven) 160 kw			165+111¹)	6.52	1800	1	1300
- Plowing land for rape seed (after barley or wheet)	33 up to 36	5700					
- crawler tractor			144	0.90	130	15	1950
- wheel tractor (four wheel driven) 80 kw			148	1.14	169	3	507
- wheel tractor (two wheel driven) 80 kw			148	0.83	123		
- wheel tractor (four wheel driven) 160 kw			148	1.80	266	12	3243
- Plowing land for forest	37 up to 39	120					
- crawler tractor			102	0.50	51		
- wheel tractor (four wheel driven) 80 kw			105	0.54	57	1	120
- wheel tractor (two wheel driven) 80 kw			105	-	-		
- wheel tractor (four wheel driven) 160 kw			105	-	-		
- Plowing land for winter wheat	39 up to 43	7280					
- crawler tractor			120	0.71	85	10	850
- wheel tractor (four wheel driven) 80 kw			125	1.14	143	12	1716
- wheel tractor (two wheel driven) 80 kw			125	0.83	104		
- wheel tractor (four wheel driven) 160 kw			125	1.80	225	21	4717
- Plowing land for forest	44 up to 48	280					
- crawler tractor			115	0.34	39		
- wheel tractor (four wheel driven) 80 kw			120	0.54	65	43	280
- wheel tractor (two wheel driven) 80 kw			-	-	-		
- wheel tractor (four wheel driven) 160 kw			-	-	-		
- Plowing land for springcrop	44 up to 48	6830					
- crawler tractor			112	0.50	56	14.4	806
- whee tractor (four wheel driven) 80 kw			117	0.87	102	51	5120
- wheel tractor (two wheel driven) 80 kw			-	-	-		
- wheel tractor (four wheel driven) 160 kw			77	1.45	112	8	896
- Plowing land for sowing grass	32 up to 38	475					
- crawler tractor			240	0.71	170		
- wheel tractor (four wheel driven) 80 kw			240	1.14	274	1.7	475
- wheel tractor (two wheel driven) 80 kw			240	0.83	199		
- wheel tractor (four wheel driven) 160 kw			240	1.80	432		

Annex 14. Activity planning of machinery (example)

No	Activities (Kind of tractor 1) / Week no)	1						2						3						4					
		1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
1	Destroying reed																								
2	Discharrowing reedland																								
3	Digging trenches																								
4	Leveling trenchsoil																								
5	Laying outfall pipes																								
6	Destroying reeds and straw	2	1					2	1					2	1					2	1				
7	Cleaning land of obstacles			3		2				3		2				3		2				3		2	
8	Transport for drainage	2						2						2						2					
9	Transport of draining materials																			2	4			4	
10	Transport of fertilizer																								
11	Spreading fertilizer																								
12	Preparation soil for seedbed																								
13	Transport of sowing seed																								
14	Sowing crop																								
15	Destroying weed and vermin																								
16	Mowing grass	3						3						3						3					
17	Transporting seed (harvest)																								
18	Filling up trenches																								
19	Cultivating stubble																								
20	Cleaning trenches																								
21	Cleaning big ditches	1						1						1						1					
22	Leveling ditchsoil after cleaning																								
23	Leveling tracks																								
24	Cleaning covered drains	2						2						2						2					
25	Plowing etc.																								
26	Subsoil mixing																								
27	Harvesting forest	2						2						2						2					
28	Harvesting willowshoots	2						2						2						2					
29	Transporting willowshoots	3	4	1				3	4	1				3	4	1				3	4	1			
30	Transporting forest plants	12		2		1		12		2		1		12		2		1		12		2		1	
31	Planting forest	1		7				1		7				1		7				1		7			
32	Digging plant holes																								
33	Destroying forest		2						2						2						2				
34	Transporting sand		7						7						7						7				
35	Leveling soil by wheel tractor																								
36	Leveling soil by bulldozer						22						22						22						22
37	Preventing soilerosion			10						10						10						10			
38	General transport	8	2	1				8	2	1				8	2	1				8	2	1			
39	Various work	4	2	2				4	2	2				4	2	2				4	2	2			
40	Farm A 93	1	2					1	2					1	2					1	2				
41	Farm Y 66	3						3						3						3					
42	Farm N 78	10	1					10	1					10	1					10	1				
43	Central store	4						4						4						4					
44	Work shop	2						2						2						2					
45	Training centre																								
	Repair by work shop	7	6	6	1	4	2	7	6	6	1	4	2	7	6	6	1	4	2	7	6	6	1	4	2
	Total	69	27	32	1	7	24	69	27	32	1	7	24	69	27	32	1	7	24	69	30	32	1	11	24
1	Wheel tractor 50 Kw	+22						+22						+22						+22					
2	Wheel tractor 80 Kw		+23						+23						+23						+23				
3	Wheel tractor four wheel driven 80 Kw			+36						+36						+36						+36			
4	Wheel tractor four wheel driven 160 Kw				+4						+4						+4						+4		
5	Crawler tractor					+37						+37						+37						+37	
6	Bulldozer						+1						+1						+1						+1
	Number of tractor who are present	91	50	68	5	44	25	91	50	68	5	44	25	91	50	68	5	44	25	91	50	68	5	44	25

QUALITY ASPECTS OF DRAINAGE

QUALITY: WHAT MEANS QUALITY ?

* GOOD WORKING/ FUNCTION
* SUSTAINABLE (=> MAINTENANCE)

(RELATION TO THE COSTS)

QUALITY OF THE DRAINAGE SYSTEM AS A WHOLE

DESIGN

ASPECTS:

* FIELD RESEARCH
* CLIMATOLOGIC DATA
* CROPS / CROPPING PATTERN
* CHOICE OF MATERIALS
* MAINTAINABLE
*
*

INSTALLATION

PROPER INSTALLATION IS INSTALLATION ACCORDING TO THE DESIGN

ASPECTS OF QUALITY OF INSTALLATION
(FOLLOWING THE ORDER OF WORKING)

* TRANSPORTS OF MATERIALS
  FACTORY TO WORKSITE

* STORAGE OF MATERIALS

* TRANSPORT STORING SITE TO FIELD

* FIELD CONDITIONS

* INSTALLATION:
  - RIGHT DEPTH
  - RIGHT GRADES
  - CONNECTIONS
  - NO DAMAGED MATERIALS
  - TIMELY FINISHING OF THE ENTIRE SYSTEM (SPECIAL IN CASE OF COMPOSITE SYSTEMS)

HOW TO CHECK ?

GENERAL DEVICE : PREVENTION IS BETTER THAN CURE !!

1. VISUAL CHECKING
2. LABORATORY TESTS
3. REVIEW DURING/ AFTER INSTALLATION

1. VISUAL CHECKS :

- QUALITY OF MATERIALS (TRANSPORT DAMAGES BY ROUGHLY HANDLING)

- STORING - ROUGHLY HANDLING
  - U.V. PROTECTION

- FIELD CONDITIONS

2. LABORATORY TESTS:

- QUALITY OF MATERIALS

3. REVIEW DURING INSTALLATION PROCESS

4. REVIEW AFTER INSTALLATION:

LEVELLING - (RIGHT) DEPTH
- (RIGHT) GRADES

RODDING - DAMAGED DRAINS
- CONNECTION FAILURES
- MISALIGNMENT

REQUIREMENTS TO THE POSITION OF A DRAIN :

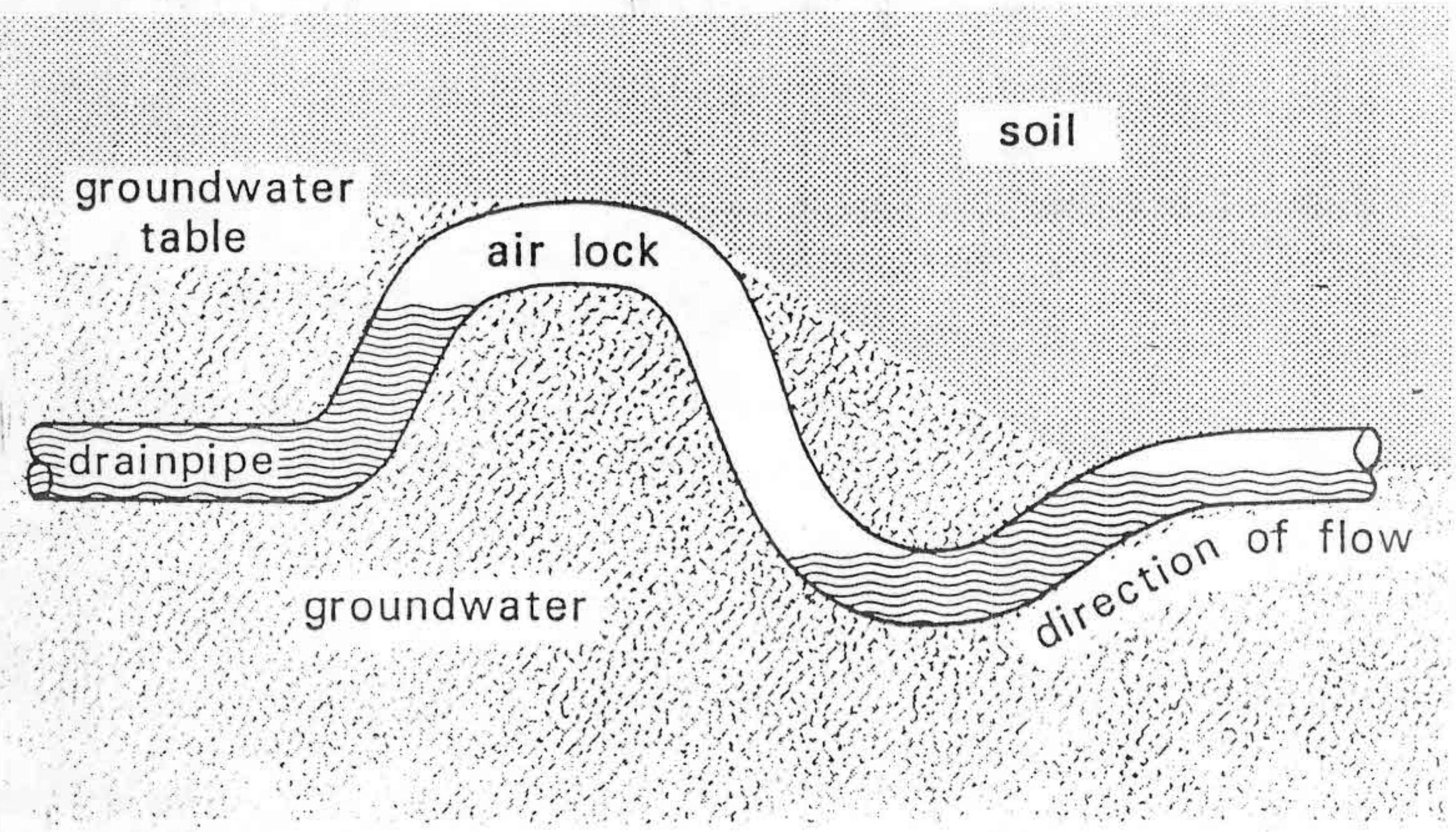
* RIGHT DEPTH

* STRAIGHT GRADE LINE

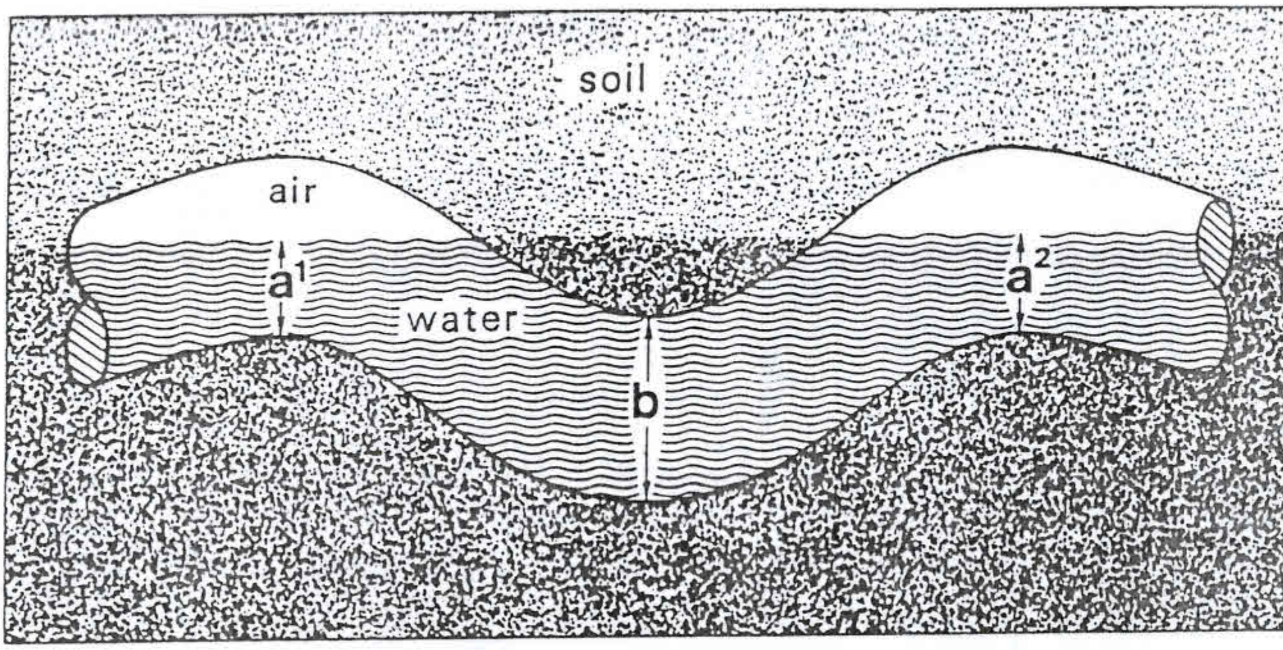
If the deviations from the straight line are too big, the flow resistance in the drain as the results of air locks in the higher parts and silt deposits in the lower parts can be inadmissibly high.

How to check : 1. By levelling

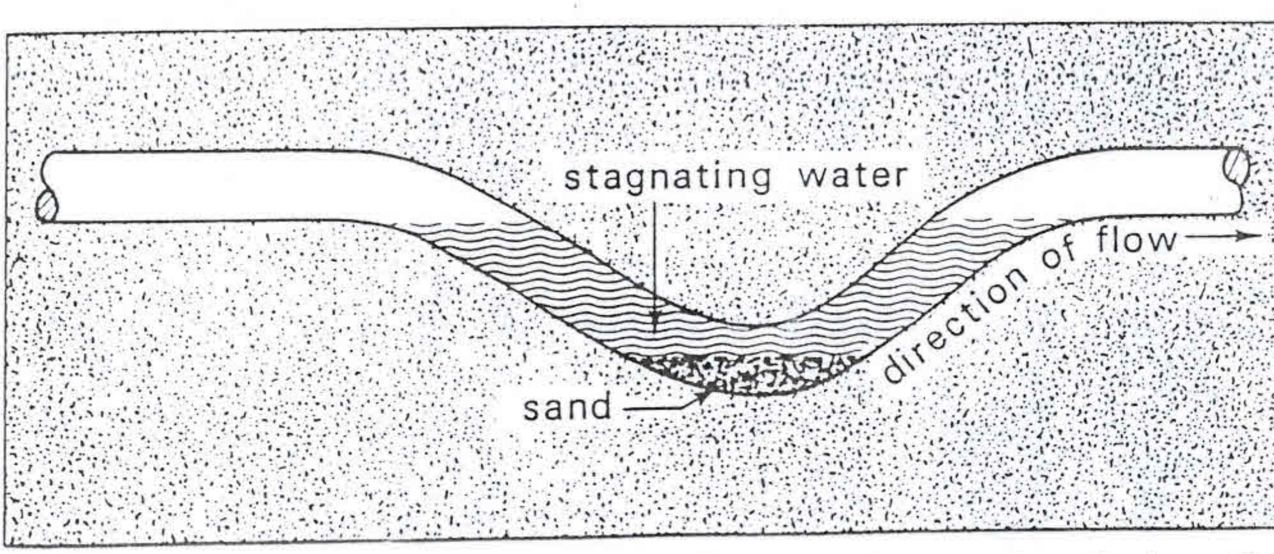
2. By special developed apparatus (based on the principles of hydrostatic pressure)
Continuous registration



An air lock prevents smooth discharge, resulting in a rise of the groundwater table.

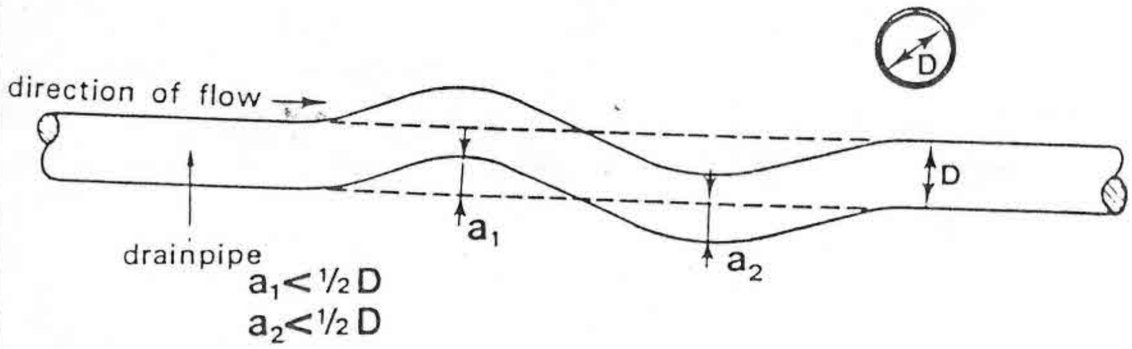


With constant discharge, the rate of flow at a1 and a2 will be higher than at b as the result of a smaller wetted area. Therefore, soil particles will be able to sink at b.



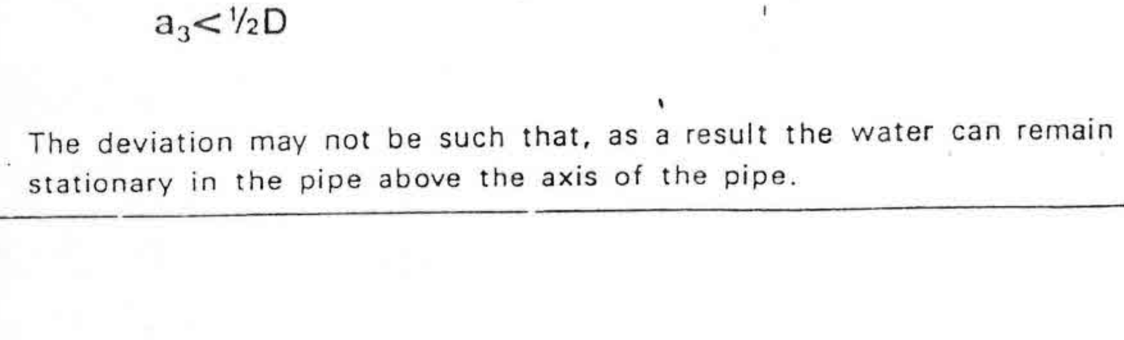
Narrowing of the flow profile as the result of the siltation in the closed-in dip.

requirement 1

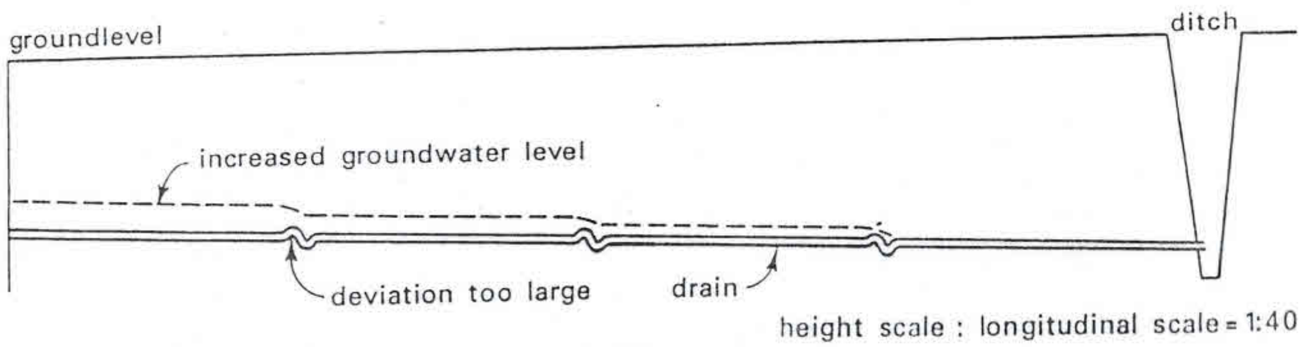


The deviation (al and a2) of the pipe in relation to the prescribed line may not be more than half of the internal diameter (0,5D).

requirement 2

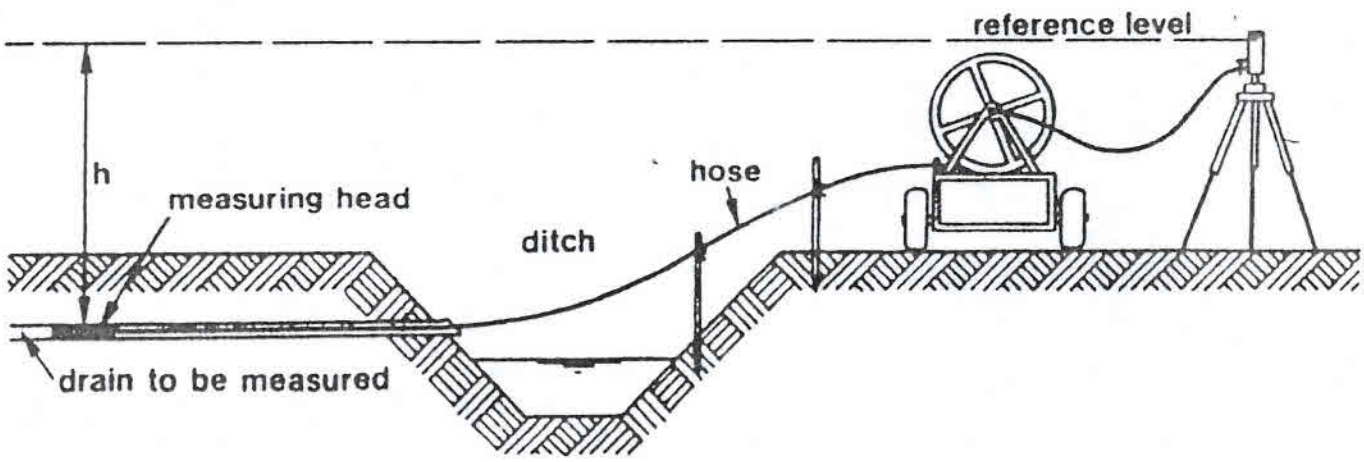


The deviation may not be such that, as a result the water can remain stationary in the pipe above the axis of the pipe.

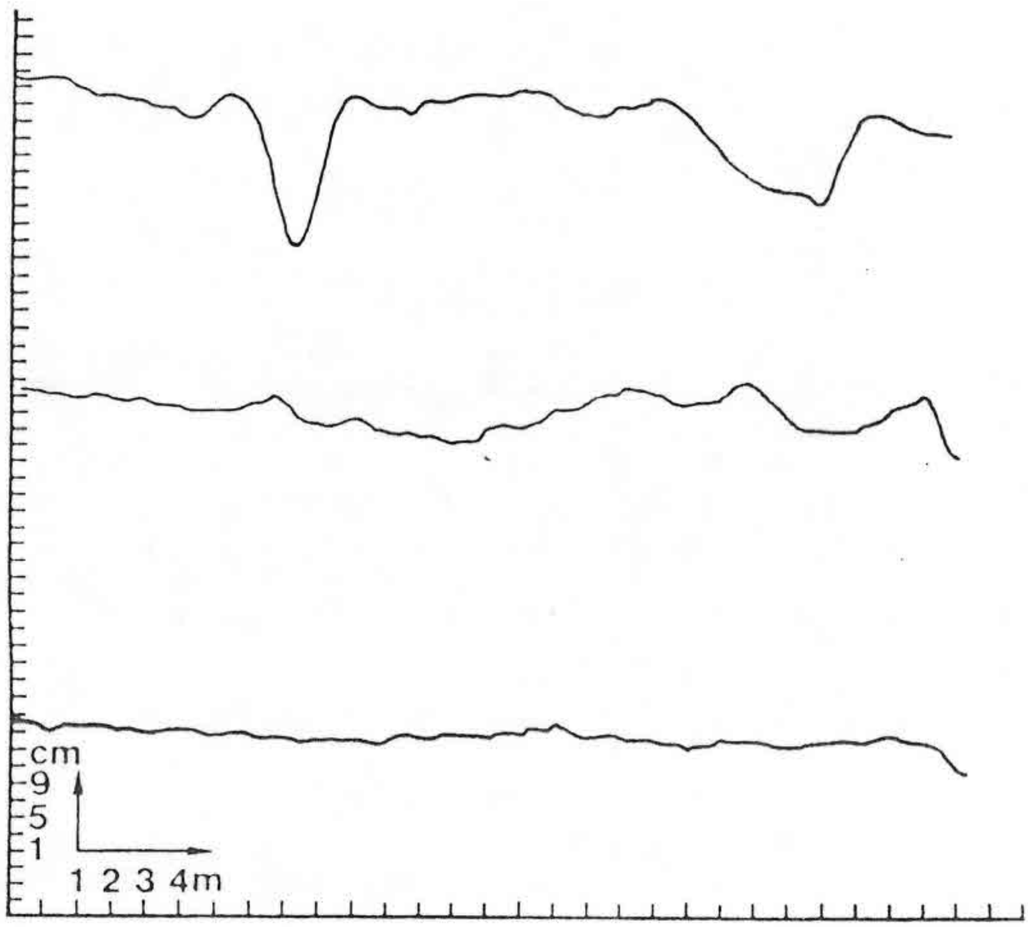


Longitudinal cross-section of the drain. The three deviations which are too large have led to a rise in the groundwater level.

READING	LEVELING : OBSERVATION SHEET				DRAIN NR.
PEG	NAME :				-------
--------	DATE :		DISTANCE IN METERS.		
DISTANCE	READING	DISTANCE	READING	DISTANCE	READING



Diagrammatic representation of the measuring instrument for continuous depth recording.

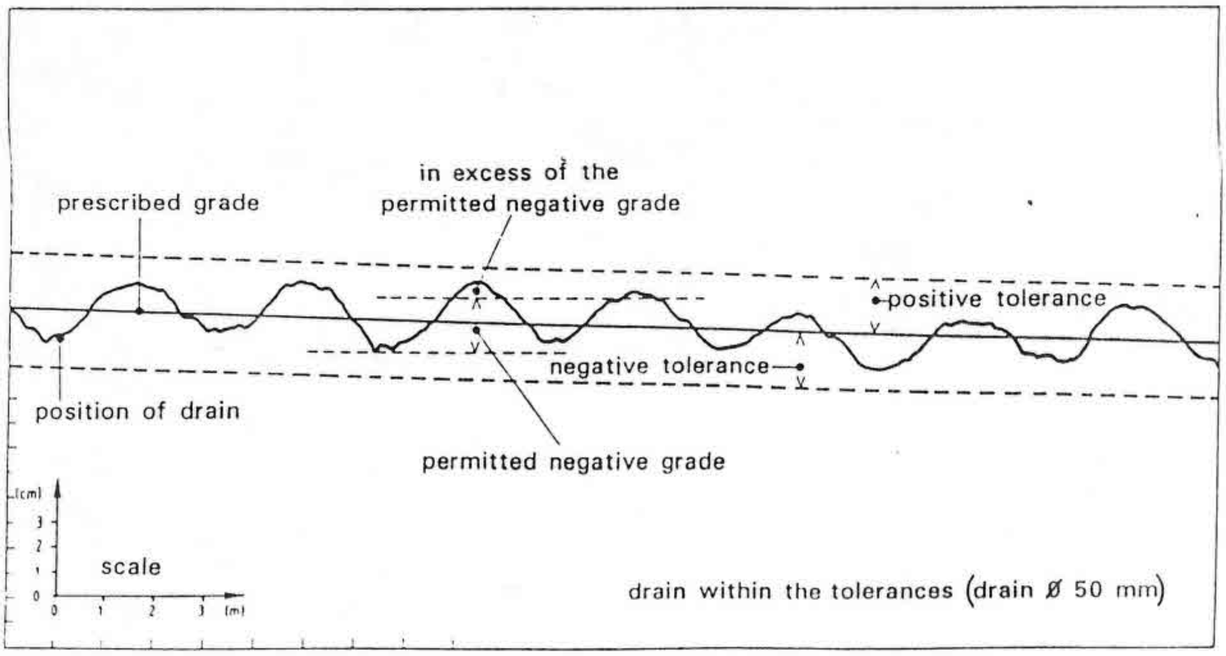


The elevation of drains as given by the Collins and Schaffer equipment. Only the drain from the bottom graph complies with the requirements.

Table 2. The chance of rejection using levelling at various intervals compared with the Collins and Schaffer method of measuring.

Interval	Number rejected	Chance of discovery compared with "Collins"
20 m	17	27%
15 m	25	40%
10 m	29	46%
5 m	40	63%
2.5 m	51	81%

With levelling using the smallest interval, 12 drains (19%) are incorrectly approved.



The position of the drain remains within the tolerances but the drain must be rejected because of a negative grade which is too large (see section 3.5.).

RODDING

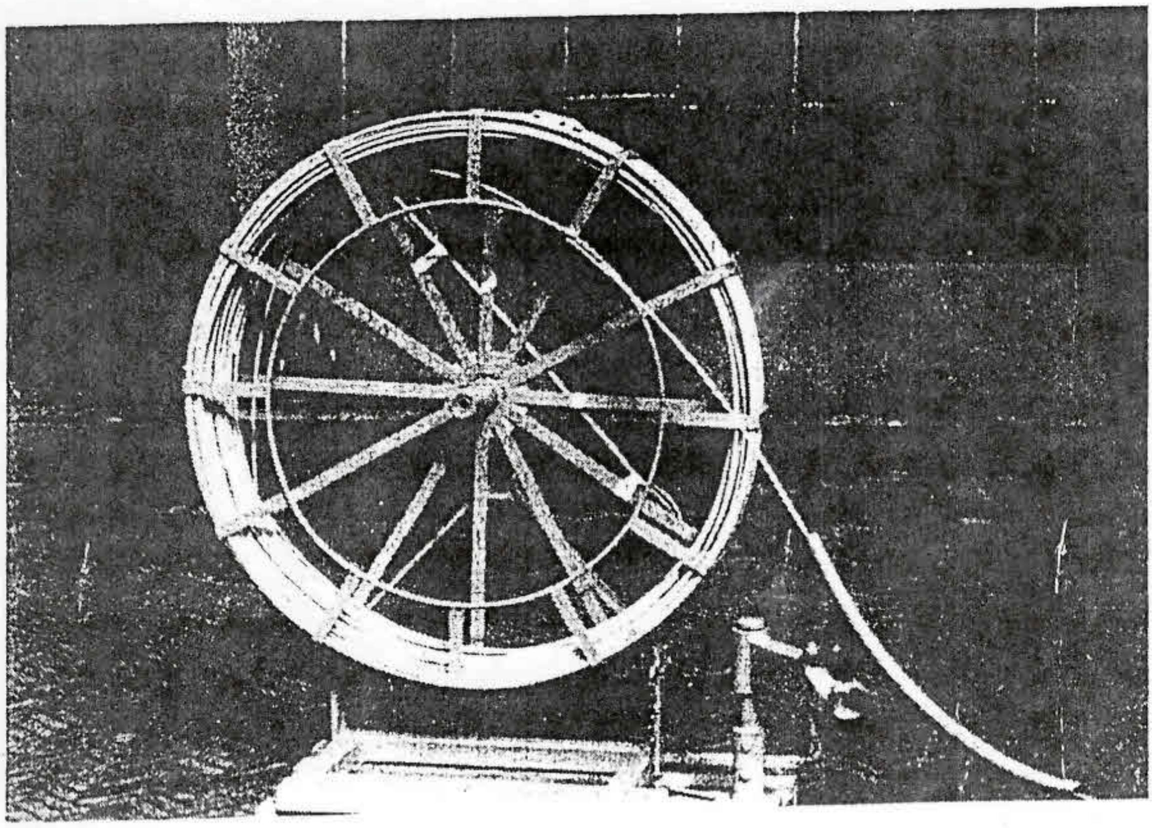
DAMAGED DRAINS : KINKS
DENTS
TWISTED

UNCOUPLED CONNECTIONS: MUFFS
`OUTLET DEVICE

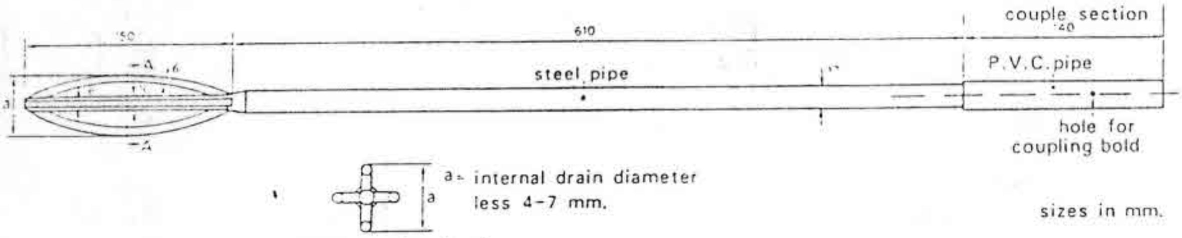
MISALIGNMENT

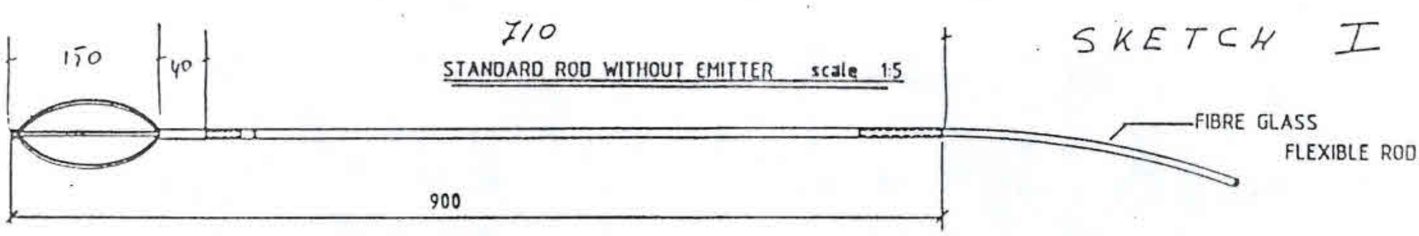
RODDING EQUIPMENT

The glassfibre rod coiled against the inside of a cage

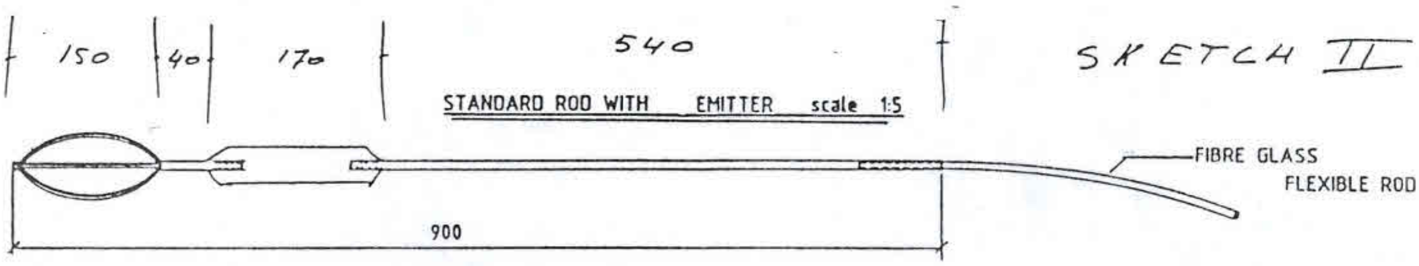


Rodding head with “go- gauge”

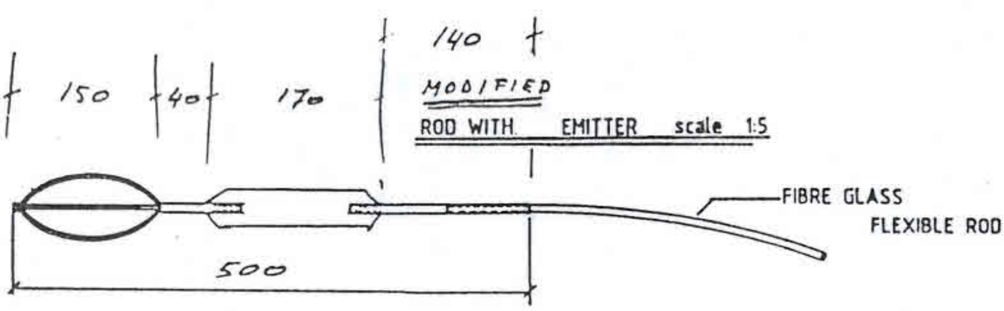




SKETCH I

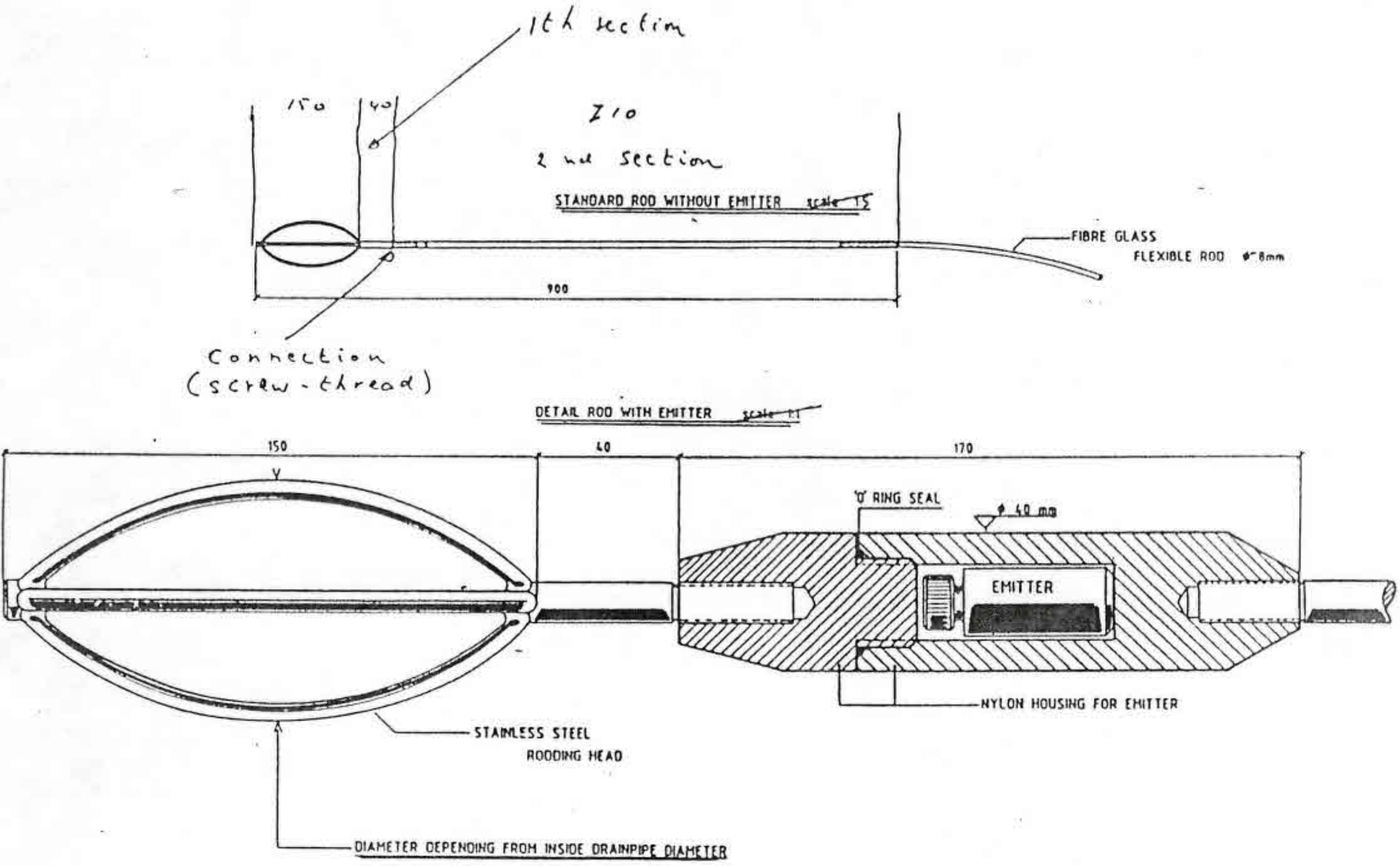


SKETCH II



SKETCH III

STEENBERGEN HOLLANDDRAIN RODHEAD WITH EMITTER 34.2.0653.01



MISALIGNMENT

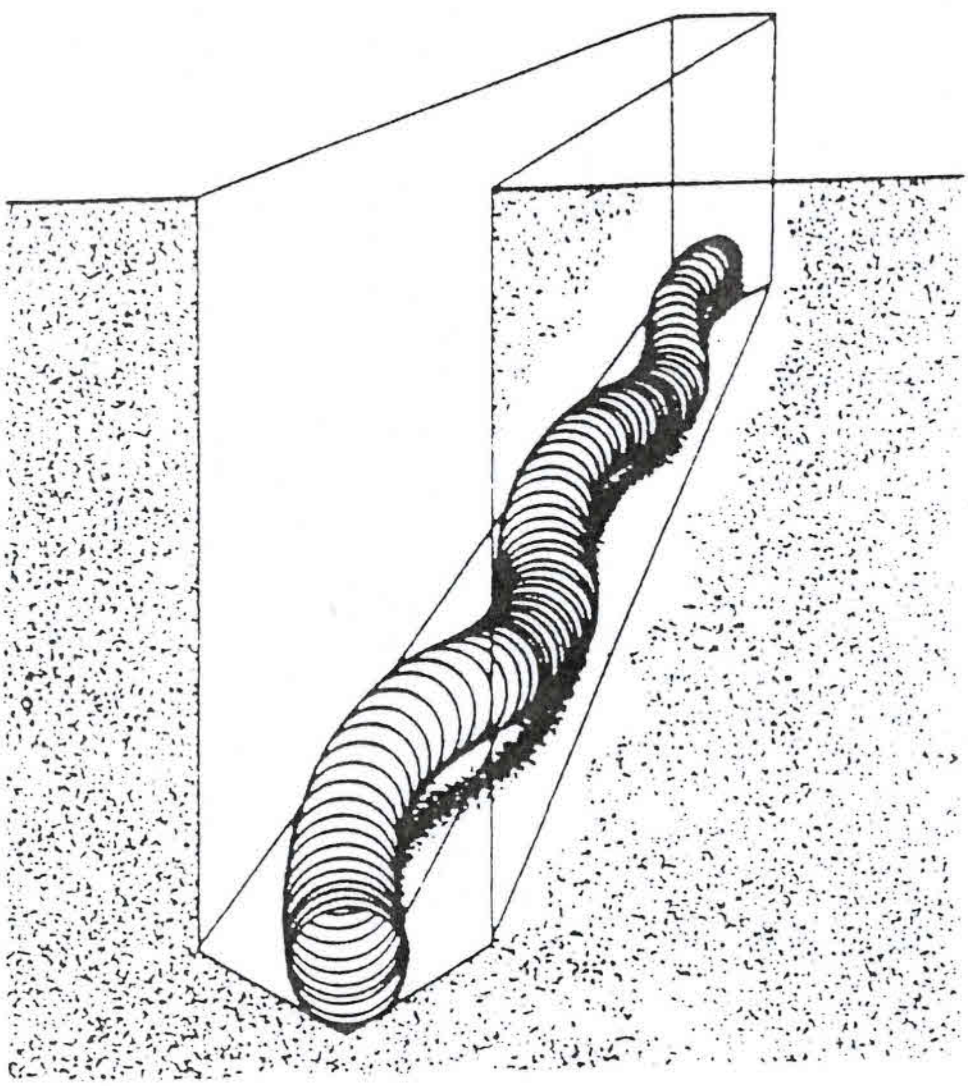


Table 1. Maximum permissible forces/resistances for drain diameters of 50 - 65 mm

Distance from outlet	Visible drain discharge	No drain discharge
from 0 to 100 m	from 20 to 30 N	from 20 to 40 N
from 100 to 200 m	from 30 to 60 N	from 40 to 80 N
from 200 to 300 m	from 60 to 90 N	---------------
from 300 to 400 m	from 90 to 120 N	---------------

The resistance encountered during rodding is measured with a simple measuring tool (figure 5) which is clamped around the glassfibre rod when a measurement is required. Measurements should only be done when the rod does not encounter any resistance from the drum in which it is coiled or from any guides.

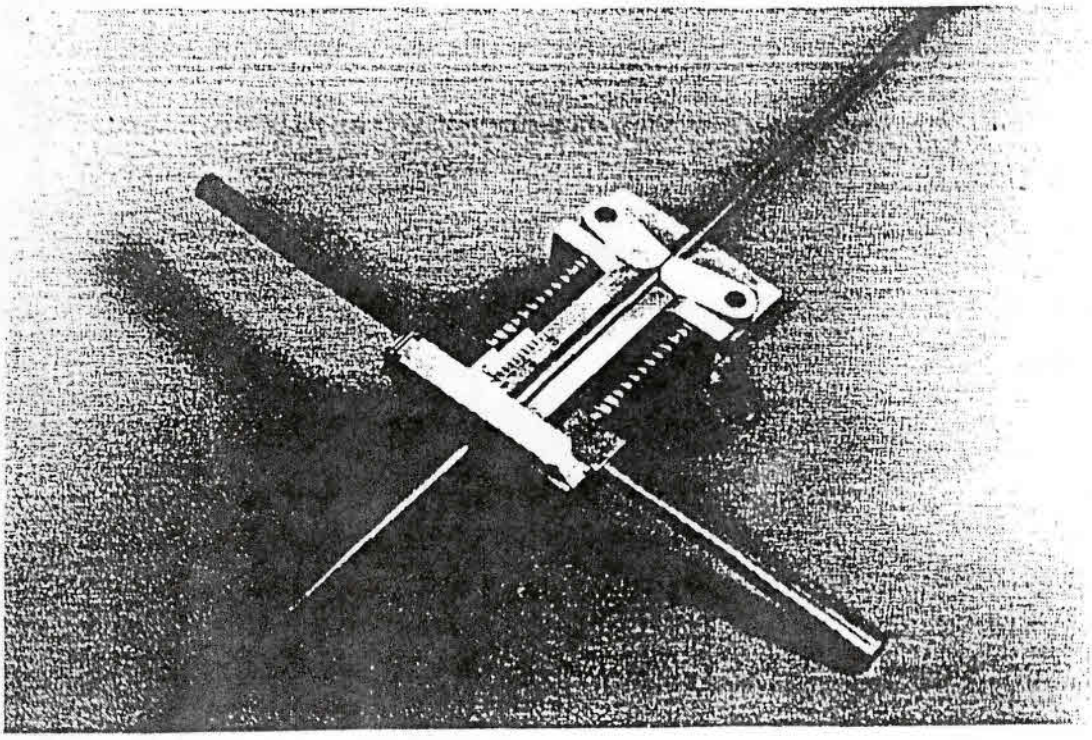
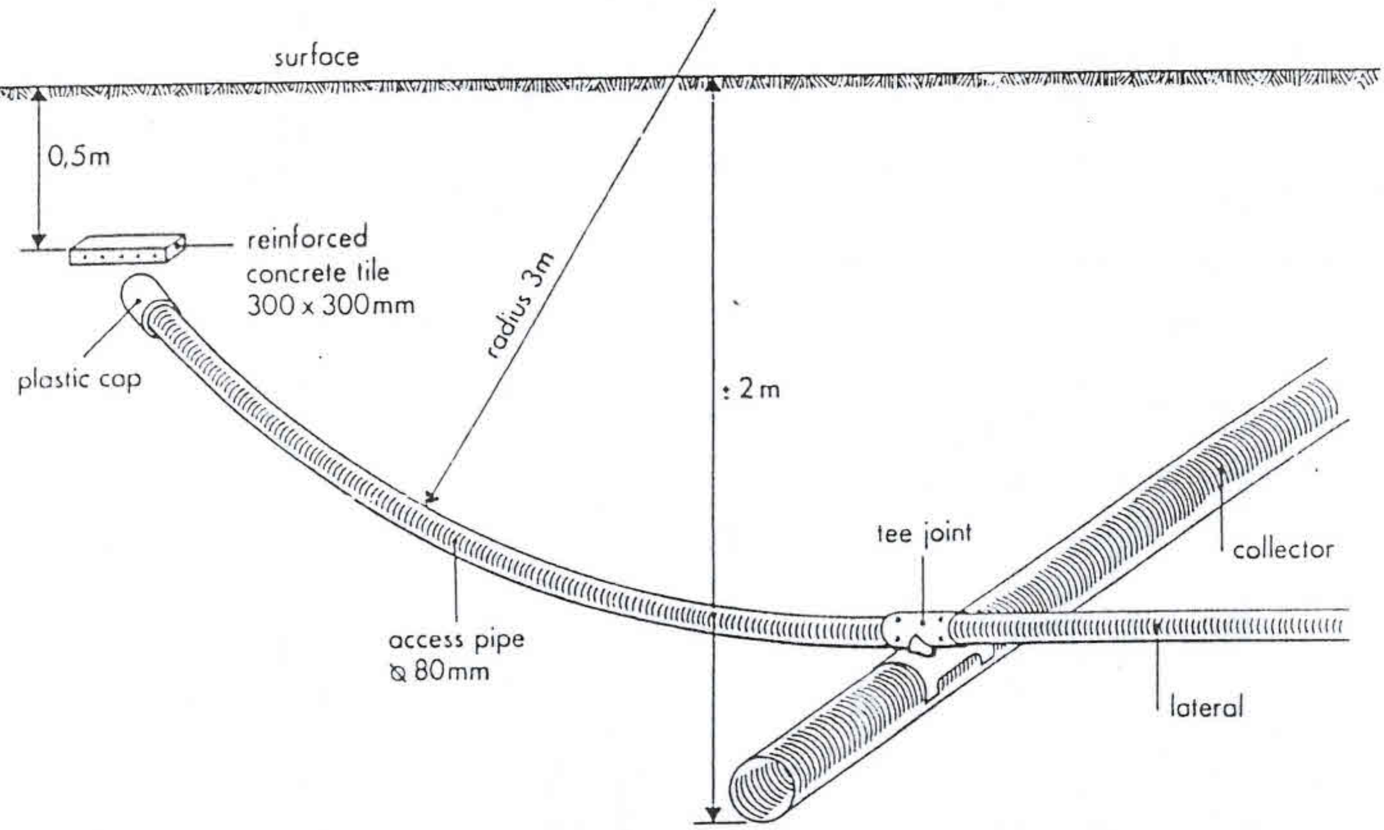


Figure 5. The resistance met during rodding is measured with an apparatus clamped around the glassfibre rod



Connection of lateral drain to collector drain with access pipe to allow entry of jetting equipment for cleaning the lateral, which also allows entry for the rodding equipment.

EFFECTS OF JET FLUSHING ON DRAIN PERFORMANCE AND SUSTAINABILITY

EFFECTS OF JET FLUSHING ON DRAIN PERFORMANCE AND SUSTAINABILITY

LES EFFETS DU NETTOYAGE A PRESSION SUR LE FONCTIONNEMENT ET LA LONGEVITE DU SYSTEME DE DRAINAGE

Toni van Zeijts[1] and Arie Bons[2]

ABSTRACT

Cleaning of pipe drains can increase their performance and sustainability. In The Netherlands this is often done by jet flushing. Also in other countries there is a keen interest for this method. Jet flushing cleans the sub surface drain pipes internally by water. Water jets loosen the pollution, which subsequently is carried with the discharging water to the drain outlet.

It is known that by this method the internal part of the drain pipe can be cleaned effectively from fine particles, such as clay and iron deposits. Although coarser material, such as sand, can be dislodged by the water jets, it may be too heavy to be carried with the water all the way to the drain outlet. Up till now it has not been established clearly whether the perforations in the wall of the drain pipe and in the drain envelope are cleaned satisfactorily by this method. The degree of success is therefore strongly related to the kind of pollution.

Jet flushing may temporarily increase the water pressure in the drain pipe and in the surrounding soil. This may effect the stability of the soil around the drain pipe. In particular for weak or non-cohesive soil there is a substantial risk that temporarily a condition of quicksand develops. This can deteriorate the soil structure around the drain pipe, which consequently can reduce the hydraulic conductivity. The temporary instability may lead also to severe sedimentation of soil particles in the drain pipe.

The authors develop in this paper preliminary guidelines, by weighing the advantages and disadvantages of jet flushing, to select the appropriate equipment for local conditions and to answer the question whether jet flushing is effective. As research results are sparse, the processes and factors which influence the effect of jet flushing are analysed and presented for discussion for the benefit of future research.

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RESUME ET CONCLUSIONS

Le nettoyage interne des drains peut augmenter l'efficacité et la longévité du système de drainage. Aux Pays-Bas le nettoyage à pression est une technique fréquemment appliquée pour laquelle d'autres pays ont également manifesté leur intérêt. En vue du transfert de cette technique, les auteurs présentent une synthèse des connaissances et expériences acquises, en s'étendant notamment sur les possibilités d'application dans d'autres parties du monde et sur la nécessité d'études plus approfondies. Le colmatage des matériaux d'enrobage, des perforations et de la section mouillée du drain peut être d'origine minérale, racinaire, biochimique (p.e. hydro-oxydes de fer) et physico-chimique (composés sulfurés). Le colmatage entrave le fonctionnement des drains.

Le nettoyage à pression consiste à introduire un tuyau sur toute la longueur du drain et à le retirer ensuite. Une extrémité du tuyau est reliée à une pompe d'aspiration qui refoule l'eau dans le tuyau, l'autre extrémité est munie d'une buse à 5 à 13 orifices. Par la force des jets d'eau, les dépôts sont enlevés et entraînés par l'eau courante vers l'extrémité du drain. Peu de recherches ont été effectuées sur le nettoyage à pression et leurs résultats sont peu concluants. Il a été mis en évidence que la méthode permet de bien nettoyer la section mouillée en éliminant les fines particules et les dépôts biochimiques. Les gros dépôts - tels que les particules de sable - sont bien enlevés, mais ne sont pas suffisamment entraînés par l'eau courante pour être éliminés du drain. Il n'a pas encore été établi si les matériaux d'enrobage et les perforations sont également nettoyés.

Le nettoyage à pression peut augmenter temporairement la pression d'eau dans le drain et le sol qui l'entoure. Ce dernier phénomène est de nature à compromettre la stabilité du sol. Notamment pour les sols à faible cohésion, le nettoyage à pression risque d'induire le phénomène passager de sables mouvants. L'instabilité de la structure peut diminuer la perméabilité du sol et entraîner également le colmatage minéral du drain. Pour cette raison, les appareils à haute pression ne sont plus utilisés aux Pays-Bas pour les travaux d'entretien, contrairement à la pratique dans d'autres pays.

Si le nettoyage à pression est envisagé, il convient d'étudier d'abord les avantages et les inconvénients. Le présent document décrit un modèle-conseil provisoire permettant de connaître et d'évaluer ces avantages et inconvénients. Tenant compte des conditions locales, ce modèle permet de choisir le type d'équipement approprié et de donner une réponse globale à la question de savoir si le nettoyage à pression est en principe efficace.

Il s'agit d'une technique fréquemment appliquée dans la pratique qui, jusqu'ici, n'a pas encore fait l'objet de beaucoup d'études. Pour un transfert efficace de technologie, il y a encore trop d'éléments inconnus. Comme première démarche vers des études plus approfondies, les auteurs analysent les processus et les facteurs qui influent sur les effets du nettoyage à pression.

1. INTRODUCTION

Jet flushing is a method to clean sub surface drainage pipes. The aim is to improve the performance and to extend the period of operation. Due to the good results, this method has gained wide acceptance in The Netherlands and interest is rising in other countries too for this method of maintenance. Equipment is being exported, but there is hardly any transfer of knowledge so far. To fill this gap an inventory was made of the knowledge on this subject. Uptill now hardly any research has been done on jet flushing. This lack of research results is the main reason for the slow progress of knowledge transfer. The inventory (Bons and van Zeijts, 1991) leads to practical guidelines for flushing, both for humid and arid areas.

Beside advantages there are also risks associated with jet flushing. In this paper both are being weighed - in connection with the different distinguished types of equipment. Also an attempt is made to develop an outline of decision criteria for the use of jet flushing. Finally - for the planning of future research - an analysis is made of the factors which influence the results of jet flushing.

2. CLOGGING

Drain performance and sustainability can deteriorate due to blockages of the drain envelope, the perforations in the drain pipe wall or the drain pipe itself. The blockages or clogging consist of bio-chemical compounds (biochemical clogging) or soil particles (mineral clogging).

2.1 Biochemical clogging

Biochemical clogging occurs when soluble chemicals of the inflowing groundwater convert to non soluble compounds which deposit consequently near or in the drain pipe. In many temperate areas this process occurs with iron-oxygen compounds; in saline areas with sulphur-oxygen compounds. These deposits can harden and block off the perforations. Bacteria do often play a role in these chemical conversions, leading to jelly-like substances which can block the drain envelope and the drain pipe. Biochemical clogging is often associated with upward inflow of ground water, which makes it a permanent process.

2.2 Mineral clogging

Mineral clogging can occur by soil which is pressed through the perforations into the drain pipe (Stuyt, 1992) or soil which is carried by the drag force of inflowing groundwater. Chances for mineral clogging are small for stable soil profiles and large for unstable profiles. The risk is most severe during or directly after the laying of the drain pipes. In principle no mineral clogging will occur after the drain trench has stabilised itself. However, mineral clogging can re-occur if by jet flushing a new unstable condition is created.

3. JET FLUSHING

3.1 Principle of jet flushing

Jet flushing is a technique used to dislodge the pollution (clogging) of drain pipes by the impact of water jets. The loosened material is subsequently conveyed by the outflowing water towards the outfall end of the drain. The water jets eject from a nozzle as shown in figure 1. The nozzle is connected by a hose with a pump that delivers a certain yield, at a certain pressure.

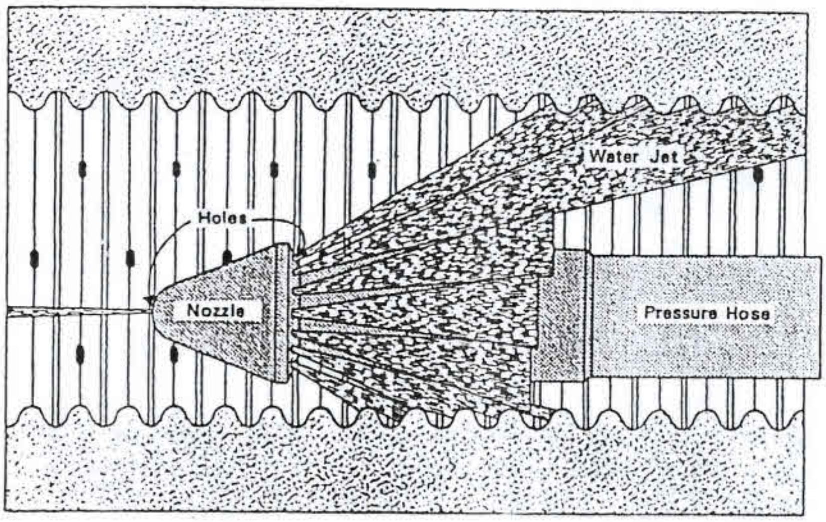

Figure 1 Schematic representation of the nozzle during jet flushing. The 3 middle water jets are interrupted in the figure to show the pressure hose. (Représentation schématique de la buse pendant le nettoyage à pression. Sur la figure, les trois jets d'eau au milieu sont interrompus pour pouvoir bien montrer le tuyau de nettoyage)

Powerful water jets are formed by water that is pressed through very small holes in the nozzle. The water charge that carries the loose material is a combination of the discharge of the jet flusher and the normal drain discharge. During the flushing process the nozzle is inserted as fast as possible into the drain pipe starting from the outfall end. After that the nozzle is withdrawn with a rate of approximately 20 m per minute.

The presently available commercial jet flushing equipment is usually divided into three groups:

. high pressure equipment	(>60 bar at the pump)
. medium pressure equipment	(20-35 bar at the pump)
. low pressure equipment	(<20 bar at the pump)

3.2 High pressure equipment

Characteristic for this type of equipment is that the forward movement of the nozzle originates from the reaction force of the water jets. The nozzle "pulls" the hose further into the drain. The forward movement of the hose is assisted by the pulsing action of the piston pump. The flexible hose usually consists of canvassed rubber, or nylon which is more resistant to wear, lighter but more expensive.

The rate of advance depends on the pressure applied, the length of hose and the friction and can therefore not be controlled very well. The withdrawal of the hose is done by reeling. Pump and reel are built on a small trailer and are driven by the Power Take Off of an agricultural tractor.

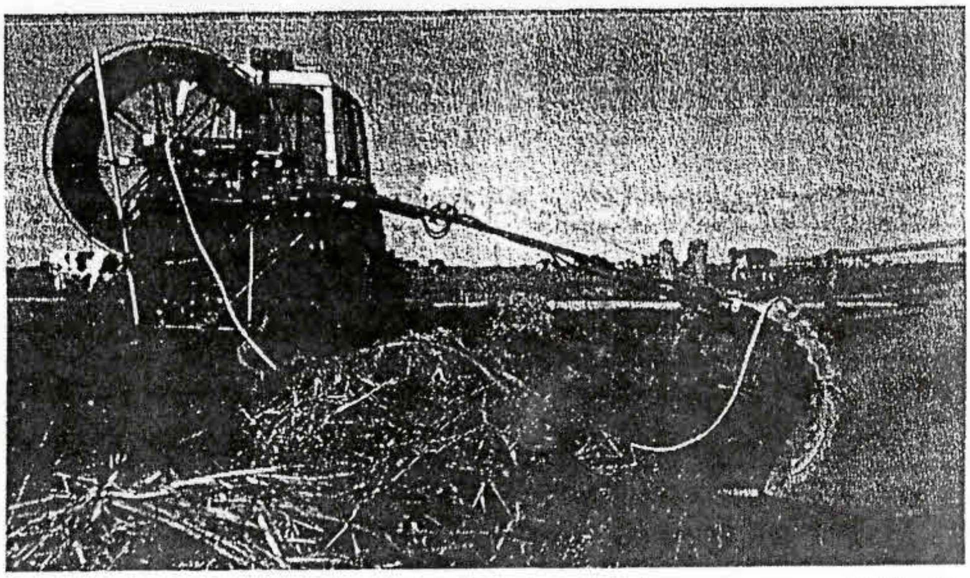

Figure 2 Jet flushing a lateral drain at a singular system. With this modern medium pressure equipment the operator can position the nozzle hydraulically in front of the pipe (Le nettoyage à pression d'un drain latéral en cas d'un système débouchant dans un fossé)

3.3 Medium pressure and low pressure

With these types of equipment the reaction force of the water jets is not sufficient to pull the hose into the drain. The entry and withdrawal is mainly achieved by a configuration of driving wheels, which pushes or pulls the hose. The rate of entry and withdrawal can be regulated accurately. The hose needs to be rather stiff as it is pushed into the drain pipe. Hard Poly Ethylene (HPE) is the commonly used material. Nylon is more resistant to wear but a more expensive alternative. With the use of a special guide, such as the roller guide (see Fig 2) attached to an adjustable arm, the nozzle can be positioned in front of the drain pipe outlet hydraulically. The equipment is hitched to the three link system of an agricultural tractor and driven by the Power Take Off. Low pressure equipment, as opposed to medium pressure, is rarely used nowadays, due to insufficient yield and pressure at the nozzle at greater hose lengths.

4. RESULTS

The research of jet flushing has been overshadowed by research into drain pipes and drain envelopes. Jet flushing has often been applied on trial fields as a necessary measure. However it has hardly been subject of research itself and consequently research results are scarce.

4.1 Biochemical clogging

Ven (1986) reported about a trial field in The Netherlands with an excess of biochemical clogging resulting from a strong iron rich upward seepage (approx 20-25 mm/day): jet flushing improved the drain performance dramatically. Figure 3 shows the results based on a large number of observations on lateral drains of 100 m length. The piezometers in the drain pipe were positioned 75 m from the outfall end. The figure shows the development of the hydraulic head in the drain pipe and the drain discharge. It is clear that both are adversely effected by the upward seepage of iron rich groundwater, but also that after jet flushing both return to approximately the original value. The groundwater level in between the drains was closely related to the hydraulic head in the drain pipe due to the low entrance resistance, narrow drain spacing (8 m) and the good permeability of the subsoil (approx. 1 m/day) (Scholten, 1992). The trial field met the drainage requirements as long as jet flushing was done periodically, but suffered from waterlogging after jet flushing was not carried out any longer (Scholten, 1992).

Huinink (1991) experienced however, on another Dutch trial field prone to strong upward seepage, no drainage improvement after jet flushing. Von Scheffer (1982) gives a qualitative description of the effects of jet flushing. He states for a trial field in NW Germany, that flushing with medium pressure had a high cleaning effect on the inside of the drain pipe. However, pipe perforations that were clogged by encrusted iron ochre could not be opened. Drains polluted with iron ochre could be cleaned as long as the iron deposits were not encrusted. Von Scheffer recommends frequent flushing with medium pressure to prevent crust formation.

Van Hoorn (1978) and others noted large improvements of drain performance in heavy clay soils after jet flushing of drains that were regularly under water for long periods and without maintenance for a decade. The drains were effected by both biochemical and mineral clogging.

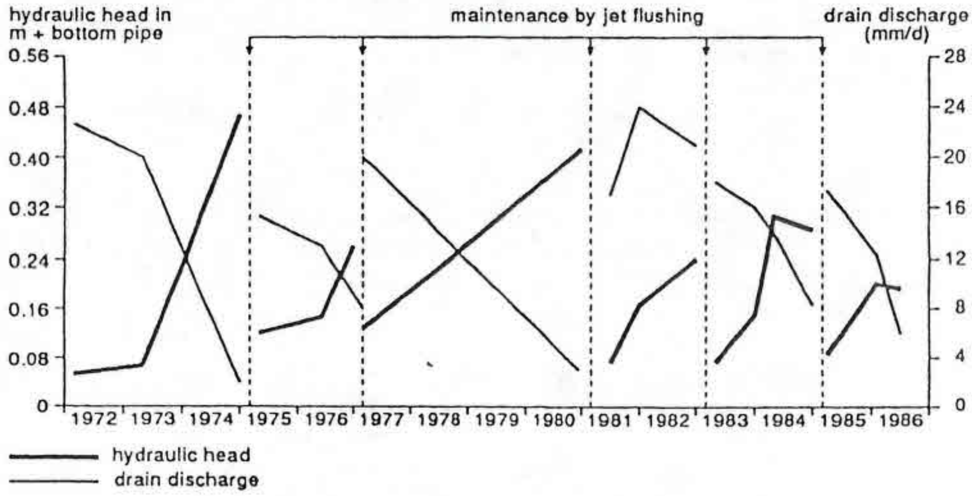

Figure 3 The effect of flushing on the discharge rate and the hydraulic head (after Ven). Heavy upward seepage of iron rich water causes serious biochemical clogging (L'effet du nettoyage à pression sur le débit et la hauteur de pression hydraulique (d'après VEN). Le suintement d'eau ferreuse cause un grave colmage biochimique)

Although not all research results support each other it can be stated that in case of biochemical clogging jet flushing contributes towards the improvement of drain performance and extension of the service life (sustainability). Cleaning of the drainpipe has been demonstrated, but cleaning of the pipe perforations and envelopes has not been established with certainty.

4.2 Mineral clogging

El-Atfy a.o. (1992) report on jet flushing with high pressure equipment of large diameter collector drains in the Nile Delta: a positive effect on the hydraulic performance of plastic pipes and a negative effect on concrete pipes. The negative effects are explained by the severe sedimentation in the pipes after flushing. The powerful water jets induce instability of the soil which enters the concrete pipe through the gaps between the pipes. Use of high pressure is dissuaded.

For non-cohesive soils in The Netherlands Brinkhorst a.o. (1983) describe that with some envelope materials jet flushing with high pressure led to considerable sedimentation in the drain pipe, while jet flushing with medium or low pressure did not. Some landusers however, claim that also jet flushing with medium pressure led to sedimentation of the drains in non or weakly cohesive soils.

The generally accepted ideas are that mineral particles larger than 0.05 mm - 0.1 mm can not be removed by flushing (Brusser, 1978). Further more that the risk of sedimentation induced by jet flushing is small for cohesive soil profiles, sound pipe material and good envelopes. Risk of sedimentation is high at:

a) application of high pressure equipment
b) jet flushing shortly after drain installation (trench not yet stabilised)
c) damaged pipes and envelopes
d) non-cohesive soils and possibly weak cohesive soils
e) low entrance and withdrawal rate

The cited research results do not give reason to change these ideas.

5. APPLICATION OF JET FLUSHING

The decision whether the drains need to be cleaned or not is a matter of cost and benefit. The benefits arrive from improved drain performance and durability of the system. The aim of jet flushing is to improve drain performance but it can lead to worsening of the situation by inducing sedimentation as discussed earlier. For each individual project both effects have to be considered seriously beforehand. Figure 4 is an outline of the present understanding of flushing with medium pressure, which can be helpful in the assessment.

The outline is still rather abstract as the boundaries between the various classes are not defined. In absence of other factors (like ripening and salinity) on soil stability the boundary between "strong" and "weak" is taken at 25% clay content and between "weak" and "absent" at approx. 10% clay content. The limits between classes for biochemical charge (such as ochre) can not be determined yet. Although there are methods to determine the degree of biochemical substances in the soil and groundwater, it is not possible yet to relate and quantify the (negative) effect on the drainage system.

For the moment the outline serves as a guideline to the user, who can incorporate his own experiences to make it more precise.

6 FUTURE INVESTIGATION : ANALYSIS AND DISCUSSION

It is clear from chapter 4 that jet flushing is not really well understood. Before a sound recommendation can be given further research is needed. Jet flushing is governed by a number of processes and many factors do influence each other. Prior to determine which research is relevant, these processes and factors need to be analysed. This chapter is to make a start.

Figure 4 Outline for advice on use of jet flushing, based on biochemical charge and soil stability (Modèle-conseil sur l'application du nettoyage à pression sur la base de la charge biochimique et la stabilité du sol)

biochemical charge	soil stability			advice
	strong	weak	no	
none	1.1	2.1	3.1	good performance and sustainability possible without any jet flushing 1.1 and 2.1 jet flushing one time within 1-3 years after installation might be useful
light	1.2	2.2	3.2	1.2 and 2.2 good performance and sustainability possible with some periodic jet flushing (once in 2-5 years) 3.2 comparable with 1.2 and 2.2 however high risk of sedimentation
medium	1.3	2.3	3.3	1.3 frequent jet flushing (once in 1-3 year) contribute to performance and sustainability 2.3 comparable with 1.3 however some risk of sedimentation 3.3 comparable with 1.3 however high risk of sedimentation
heavy	1.4	2.4	3.4	installation of pipe drainage is not recommended. for existing systems: jet flushing not feasible.

6.1 The cleaning effect of water jets

The pollution in envelope, perforations and drain pipe is dislodged by the jet force of the nozzle. The effectiveness depends on resistance to removal and the applied energy per surface unit. The resistance to removal relates among others to the kind of material and moisture condition. Severely dried up bio-chemical deposits and clay deposits are very difficult to move: wet clay and sand are easy to move. The available energy depends on the pressure at the nozzle, the discharge, the number of holes in the nozzle, the diameter of the holes, the angle of attack, the drain pipe diameter and the rate of entry and withdrawal.

Discussion point number 1. The cleaning effect on the inside wall of the drain pipe has been clearly demonstrated: this is not the case for the perforations and envelopes. The expected improvement of the cleaning process is so small that it does not justify the use of high pressure.

6.2 Risk of sedimentation as a result of jet flushing

The analysis in the paragraphs 6.2 and 6.3 is done with reference to Figure 5. The figure indicates the hypothetical changes in pressure and velocity during jet flushing. The most critical situation, when the nozzle is moved back towards the outfall end, is presented here (nozzle moving from left to right in the figure).

The broken line shows the imaginary situation of a blind pipe (non perforated): the solid line shows the situation which may occur as a result from the in- and out flowing water from a perforated drain pipe.

Jet flushing creates an overpressure just behind the nozzle (top of figure). This pressure transfers via the perforations and the drain envelope into the soil profile. The increased soil pressure causes a reduction in the cohesive forces between the soil particles. In case of less cohesive soils this can lead to instability (e.g. quicksand). In this unstable condition the soil particles may locally start moving as a result of the water jets. Furthermore, drain envelopes can be damaged by the water jets and soil particles can be carried into the drain by the drag force of the water discharged: these effects reinforce each other.

Due to the "suction power" of the backward tilted water jets (venturi effect), the pressure in front of the nozzle is much lower than just at the back of the nozzle. The withdrawal of the nozzle causes an abrupt pressure difference in the unstable soil conditions described above. The tendency of soil particles to flow towards the drain is aggravated. Also it may be possible that during the period of instability the soil is pushed into the pipe perforations - as shown on the TV images (Stuyt, 1992). These processes will end as soon as the soil profile has reverted to a stable condition. The height of the overpressure at the back side of the nozzle depends on the pressure in the nozzle, the angle of the water jets, the discharge, the capacity to convey the water (through the soil and drain pipe) and

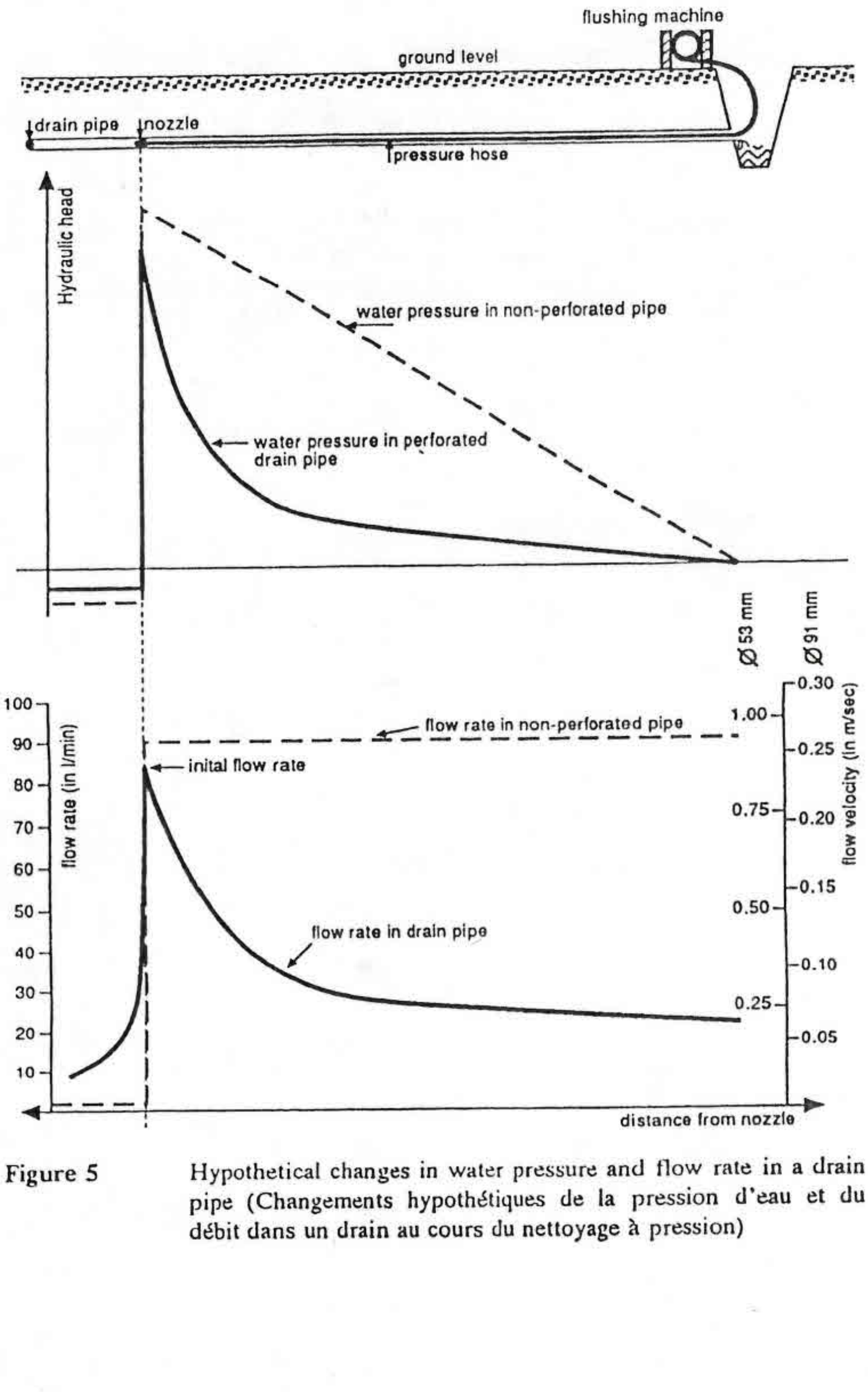

Figure 5 Hypothetical changes in water pressure and flow rate in a drain pipe (Changements hypothétiques de la pression d'eau et du débit dans un drain au cours du nettoyage à pression)

the movement rate of the nozzle. The magnitude of the underpressure at the front of the nozzle depends, among other things, on the venturi action of the nozzle.

6.3 Transport capacity of the flush water

The lower half of Figure 5 shows the hypothetical case of drain discharge during jet flushing. The left vertical axis shows the discharge (in l/min) and the right vertical axis the flow velocity (in m/sec) for corrugated pipes with an internal diameter of 53 mm (common in Europe) and 91 mm (common in North Africa) using a pressure hose of 27 mm external diameter.

Diagram 1. Important factors that influence the transport capacity of the flush water (Facteurs importants qui influent sur l'entraînement des dépôts par l'eau)

1. *Flow velocity in the drain pipe*
 1.1 Discharge
1.1.1 Initial discharge
1.1.1.1 Discharge jet flusher (various factors)
1.1.1.2 Drain discharge (various factors)
1.1.1.3 Rate of advance of nozzle
1.1.2 Flow of water from the pipe into soil
 1.2 Drain pipe
1.2.1 Diameter
1.2.2 Degree of pollution (k_m value, various factors)
 1.3 External diameter pressure hose

2 *Particle size of pollution (or equivalent values for non-granular material)*

The degree of removal of pollution by the flush water depends on many factors as shown in diagram 1. The flow velocity within the drain pipe reduces with the distance to the nozzle. Therefore material loosened by the water jets and transported in suspension can sediment again before the outfall end is reached. Near the approaching nozzle erosion may occur again. It is assumed that this process of erosion and sedimentation is cyclic such that at heavy load, accumulated material near the nozzle can not be carried away in one continuous movement. The sediments left behind in the drain pipe after jet flushing are smoothened and spread out (Stuyt, 1992).

Gradually advancing the nozzle by repeatedly pushing and pulling is not feasible due to the high risk of induced instability and sedimentation (para 6.2).

Discussion point number 2. The transport capacity for sediments depends mainly on the flow velocity. The pressure is not of direct importance. In practical field applications one often does not realise that small diameter drains are cleaned more effectively - given the same discharge - than drains with a large diameter.

Discussion point number 3. The study of jet flushing is complex. A feasibility study is needed beforehand, for parts of the research as well as for the whole research, to weigh the cost and benefit. Furthermore, choices have to be made between thorough investigations into the actual processes that occur, and broad surveys to quantify the flushing effects on drain performance and sustainability.

7 CONCLUSIONS

1. The effects of jet flushing on the drain performance and sustainability can be positive as well as negative. Jet flushing cleans the drain pipe and probably also the pipe perforations and envelope. The flow resistance reduces and the Q/H ratio increases. These positive effects can be expected with biochemical and mineral clogging. The disadvantage of jet flushing (sedimentation of soil particles in the drain pipe) is a result of the destructive action of the water jets on the drain envelope and the soil structure. Weak envelopes and non- or weak cohesive soils are most sensitive to this adverse effect.

2. High pressure equipment, used for regular maintenance jobs, does not clean better than medium and low pressure equipment. The high pressure composes a higher risk for destruction. For this reason this equipment is not recommended for regular maintenance. Only in cases where the deposits in the drain pipe are very encrusted, the additional water pressure can be advantageous.

3. The advantages and disadvantages have beforehand to be weighed for each case. A preliminary outline presented here can be of help and at the same time can serve as a base to structure future research and local experience.

4. The available research results are too few for a sound transfer of knowledge. Analysis show that the effects of jet flushing arrive from an intricate complex of factors. Prior to new research a comparative cost/benefit ratio of a broad study on practical field results as against detailed studies should be determined.

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Case study Hansi

DRAINAGE

From 19 August to 6 December 2002, Wageningen, The Netherlands

ASSESSMENT OF DRAINABLE SURPLUS BY GROUNDWATER BALANCE ANALYSIS
CASE STUDY HANSI FARM

1 INTRODUCTION

Let us consider a rectangular farm, 1600 m long and 860 m wide, that is located in a flat alluvial plain. An irrigation channel crosses the farm approximately in the middle. The crops cultivated on the farm are irrigated with water from this canal. Rice is grown in a strip on both sides of the canal, and cereals and other field crops on the remaining parts of the farm.

The lands surrounding this farm are also cultivated, but because of a shortage of irrigation water, they are not supplied with water from the canal. Some farmers have a shallow hand-dug well and use its water to irrigate small patches of the land.

During the irrigation season, it was found that the watertable in parts of the irrigated farm was rather shallow, and the question arose whether the farm land needed artificial drainage.

Shallow piezometers were placed in a regular grid, and monthly readings were made of the depths to the watertable. This observation network was also surveyed, so the observed watertable depth data could be converted to absolute watertable elevation data. Groundwater samples were taken from the piezometers and their electrical conductivity was determined.

1.1 Processing and Interpretation of Basic Data

The above data were processed to produce depth-to-watertable maps, watertable contour maps, and electical conductivity maps (Chapter 2). Their results and interpretation are briefly summarized below.

Figure 1 shows the depth-to-watertable map on a certain date in the irrigation season.

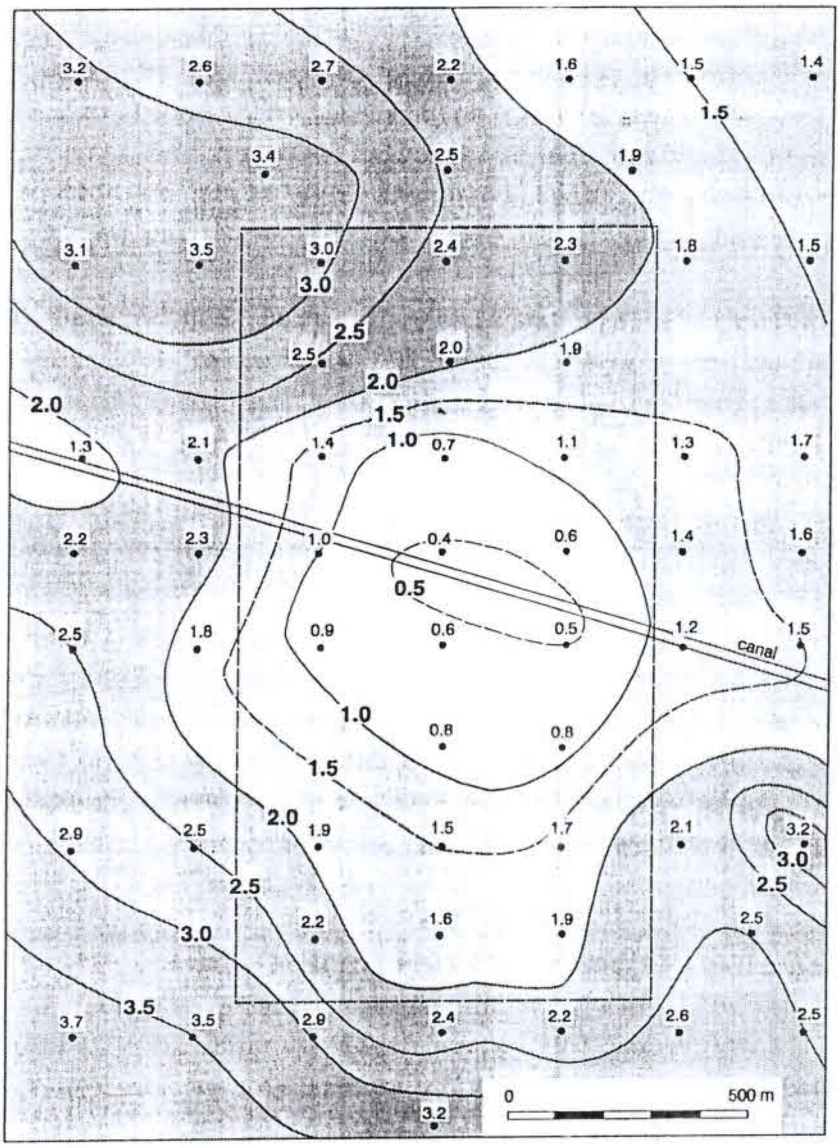

Figure 1. Depth-to-watertable map
1.6 : watertable depth 1.6 m below soil surface

The watertable in the middle of the farm is shallow - less than 1 m below the land surface, and along the canal, even less than 0.5 m. This is caused partly by leakage from the canal, but mainly by the heavy percolation from the rice fields near the canal. In the other parts of the farm, less irrigation water is applied (cereals and field crops), percolation is less, and the watertable deeper: 2 to 3 m.

The direction of groundwater flow can be derived from the watertable contour map (Figure 2).

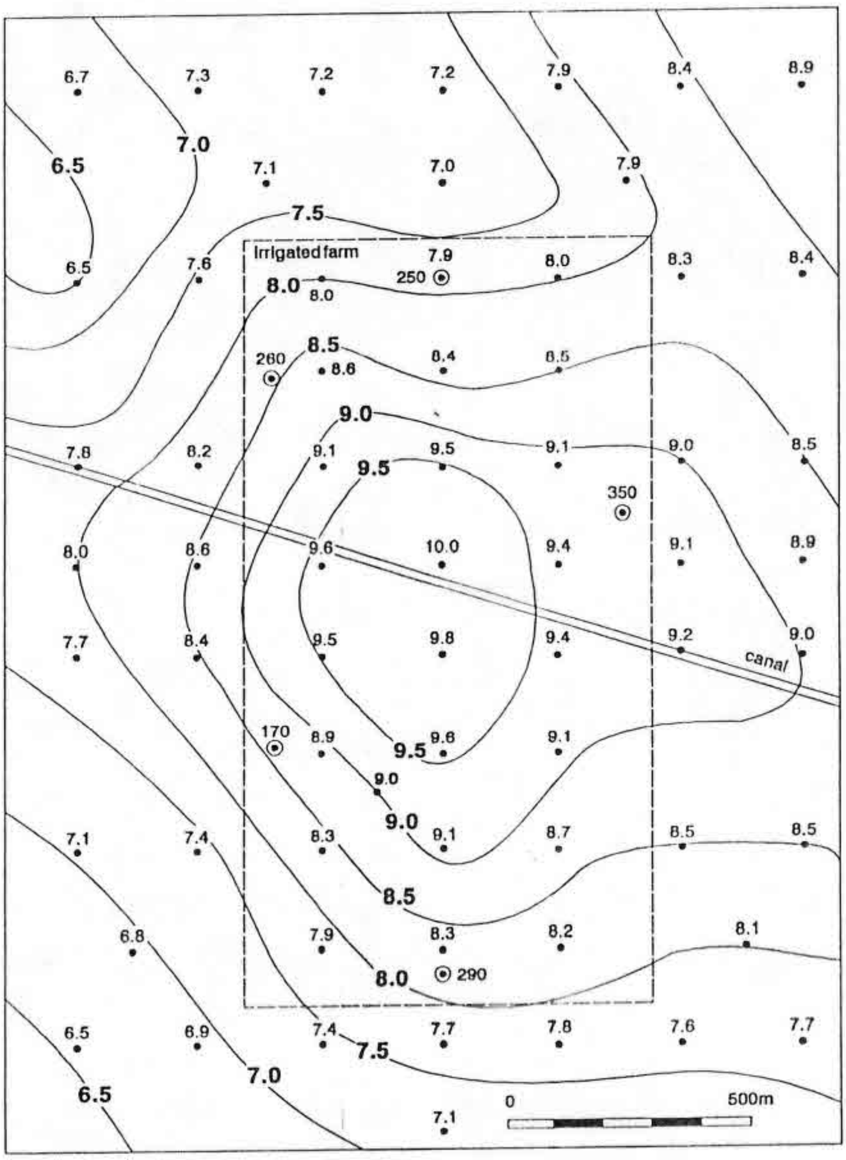

Figure 2. Watertable contour map
8.3 : watertable elevation 8.3 m above sea level
290 : transmissivity KD = 290 m^2/d

The flow direction is perpendicular to the contour lines (equipotential lines). In the middle of the farm, near the canal, a groundwater mound has formed from where water flows in all directions. Everywhere along the farm boundaries groundwater flows out from the farm, except in the north-east and south-east where the boundary is nearly perpendicular to the watertable contour lines. This means that these parts of the boundary are flow lines across which, by definition, no groundwater flows. Along the other parts of the farm boundary, the watertable gradient varies from about 1:200 to 1:400. This indicates that the aquifer system is more or less homogeneous.

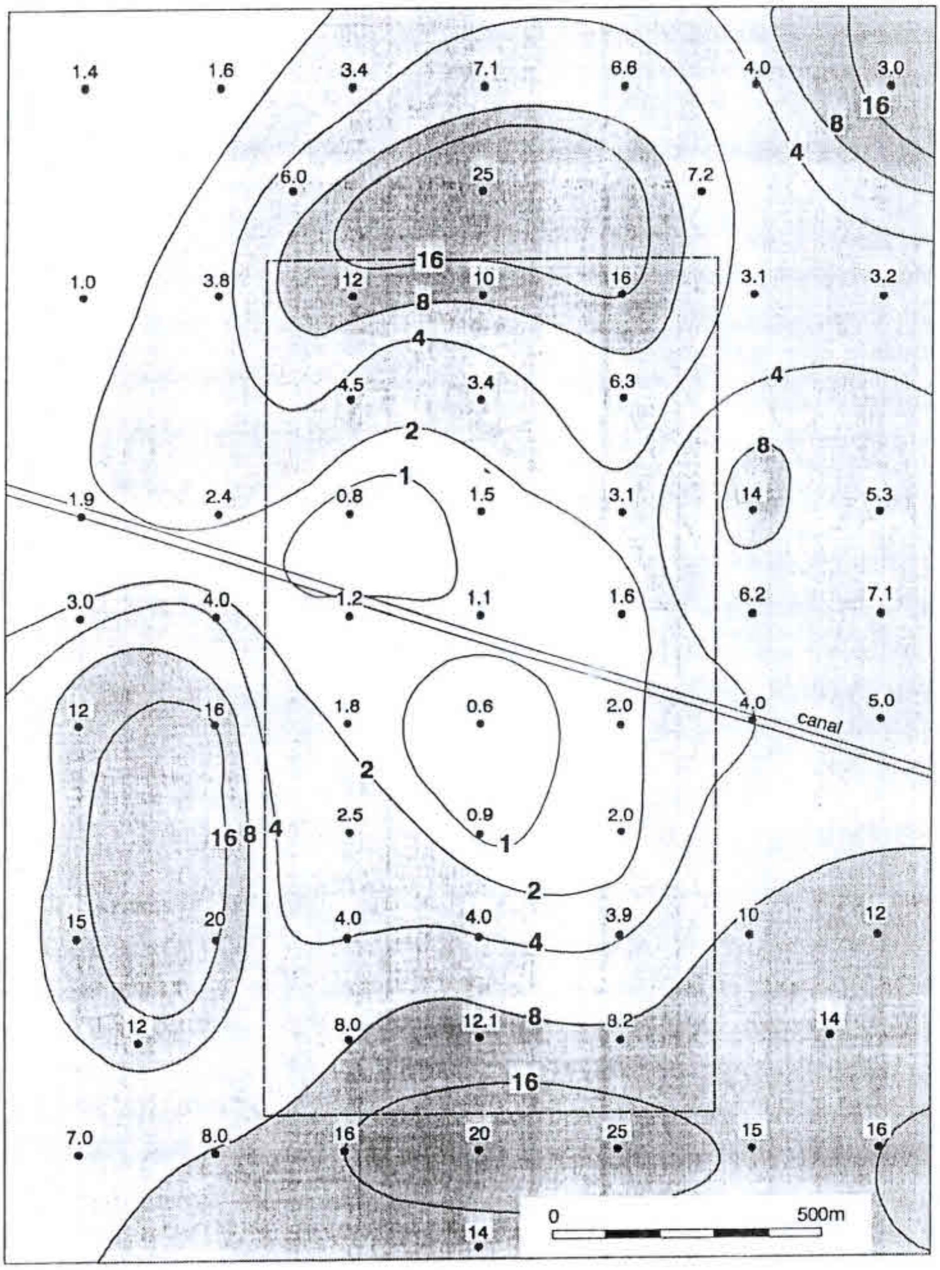

Figure 3. Electrical conductivity of the shallow groundwater in dS/m

Figure 3 shows the electrical conductivity map of the shallow groundwater. The least saline groundwater is found in the middle of the farm, even though the watertable there is at its shallowest. The heavy percolation in this part of the farm apparently prevents capillary rise and since groundwater flows away from this area in all directions, soil and groundwater cannot become salinized. In the direction of flow, however, the salinity increases rapidly, and just beyond the farm boundaries, i.e. in the non-irrigated areas, it reaches its highest values (EC = 20 to 25 dS/m). Farmers in these areas suffer in three ways: they do not receive surface water from the canal for irrigation because it is in short supply, they cannot use groundwater because it has become too saline, and their lands are in danger of becoming salinized because the inflow of groundwater from the irrigated farm causes the watertable in their land to rise to or within critical heights and the capillary rise to become important.

From this information, it is clear that no artificial drainage for salinity control is required for the irrigated farm itself. Even for watertable control no drainage is required because rice is being grown in the area with the shallowest groundwater depths. To protect the surrounding area, it would, however, be advisable to impose certain watertable control measures within the irrigated farm. Changing the cropping pattern (rice should never be cultivated on relatively light soils) will undoubtedly alleviate the problem.

1.2 Water Balance Analysis With Flow Nets

So far, we have discussed how to make a qualitative water balance analysis. Here, and in the next section, we shall discuss how to make a quantitative analysis by setting up groundwater balances.

Let us make a water balance for the irrigated farm. For simplicity, let us assume that the data in Figures 1 - 3 are representative of the irrigation season, i.e. let us assume that the groundwater system is in a steady state during the irrigation season.
To calculate the rate of groundwater flow across the farm boundaries, we need to know the watertable gradient and the aquifer's transmissivity. Because the equipotential lines in Figure 2 do not coincide with the farm boundaries, but cross them obliquely, we must construct a flow net (Figure 4).
This should be done according to the following specifications:

- To construct the first "square", select a pair of equipotential lines that run along both sides of the boundary of the water-balance area. Draw a first flow line at an arbitrarily chosen location; the smoothly-drawn flow line should intersect both equipotential lines at right angles. Draw a second flow line in such a manner that the distance between the two equipotential lines midway between the two flow lines is equal to the distance between the two flow lines midway between the two equipotential lines. So, a square will generally have four slightly curved sides;
- To construct the next square, use the same pair of equipotential lines if these lines still follow the boundary of the water balance area. Draw the next flow line. If the equipotential lines start to deviate from the area boundary, extend the flow line to another pair of equipotential lines that do follow the boundary. The squares should follow the boundaries of the water balance area as closely as possible;

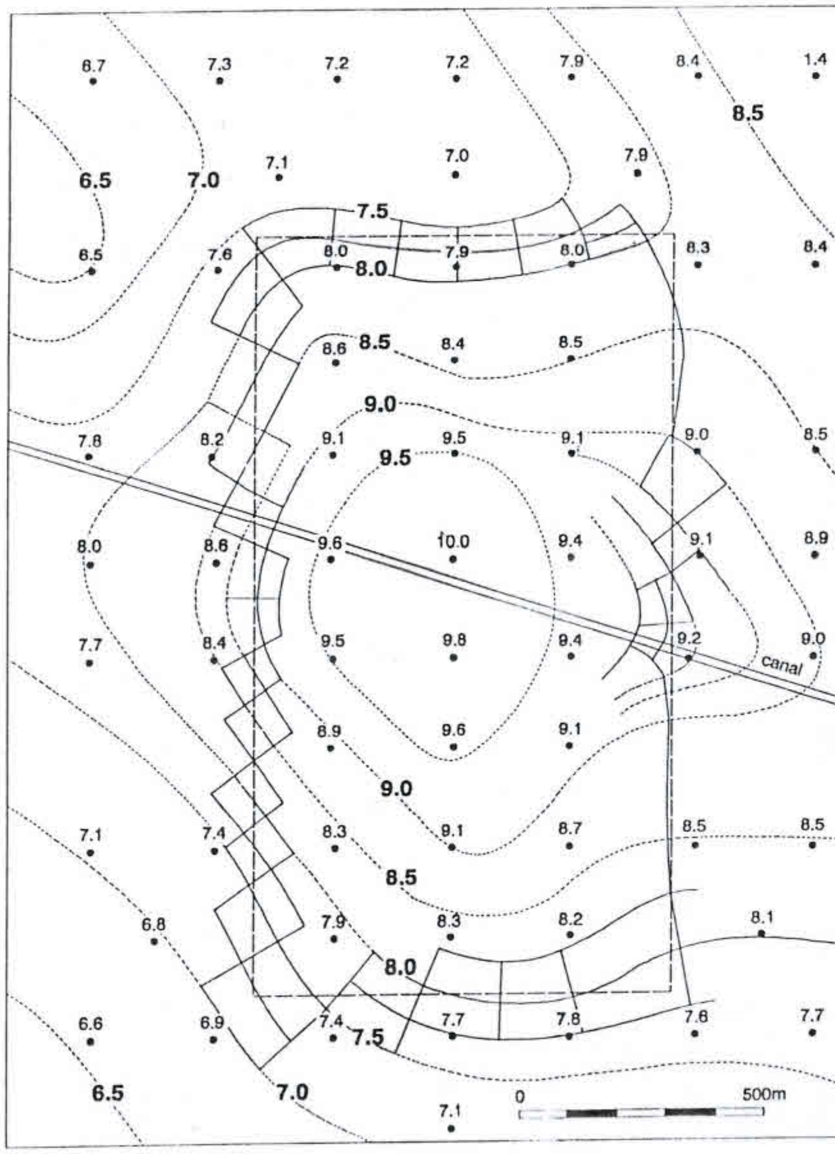

Figure 4. Watertable contour map with a flow net constructed along the farm boundaries

- Continue this process until the last flow line drawn coincides with the first flow line drawn, i.e. until the water balance area is fully enclosed by squares.

Figure 4 shows that to construct a system of squares along the four boundaries of the irrigated farm, it was necessary in some places to reduce the contour interval from 0.50 m to 0.25 m, and even to 0.10 m and 0.05 m in the east of the farm.

Information on the transmissivity of the aquifer was obtained from the analysis of five aquifer test sites. These sites are shown in Figure 2 together with their transmissivity values. The transmissivity values were attributed to certain sections of the farm boundary.

We can calculate the rate of horizontal groundwater flow through each square using Darcy's equation

$$Q = KH\ s\ \Delta y = KH \frac{\Delta h}{\Delta x} \Delta y \qquad (1)$$

with

KH	=	transmissivity of the aquifer (m^2/d)
s	=	hydraulic gradient (-)
Δy	=	width over which groundwater flow occurs, i.e. the perpendicular distance between two flow lines (m)
Δh	=	difference in hydraulic head between two contour lines (m)
Δx	=	distance between two contour lines, as measured in the direction of flow (m)

Because the squares were constructed in such a way that Δx equals Δy, the total groundwater flow across the boundaries of the water balance area reduces to $Q = n\ KH\ \Delta h$, where n is the number of squares provided the proper KH and Δh values are attributed to each square.

For the flow net in Figure 4, this procedure yielded the following results: starting in the north-east and moving anti-clockwise

$$Q = (1 \times 250 \times 0.25) + (5 \times 250 \times 0.50) + (3 \times 260 \times 0.50) + (7 \times 170 \times 0.50) + (6 \times 290 \times 0.50) + (1 \times 350 \times 0.05) + (3 \times 350 \times 0.10) = 2665\ m^3/d$$

The groundwater balance can generally be expressed as follows (see Figure 5)

$$R - G + 1000 \frac{Q_{gi} - Q_{go}}{A} = S_y \frac{\Delta h}{\Delta t} \qquad (2)$$

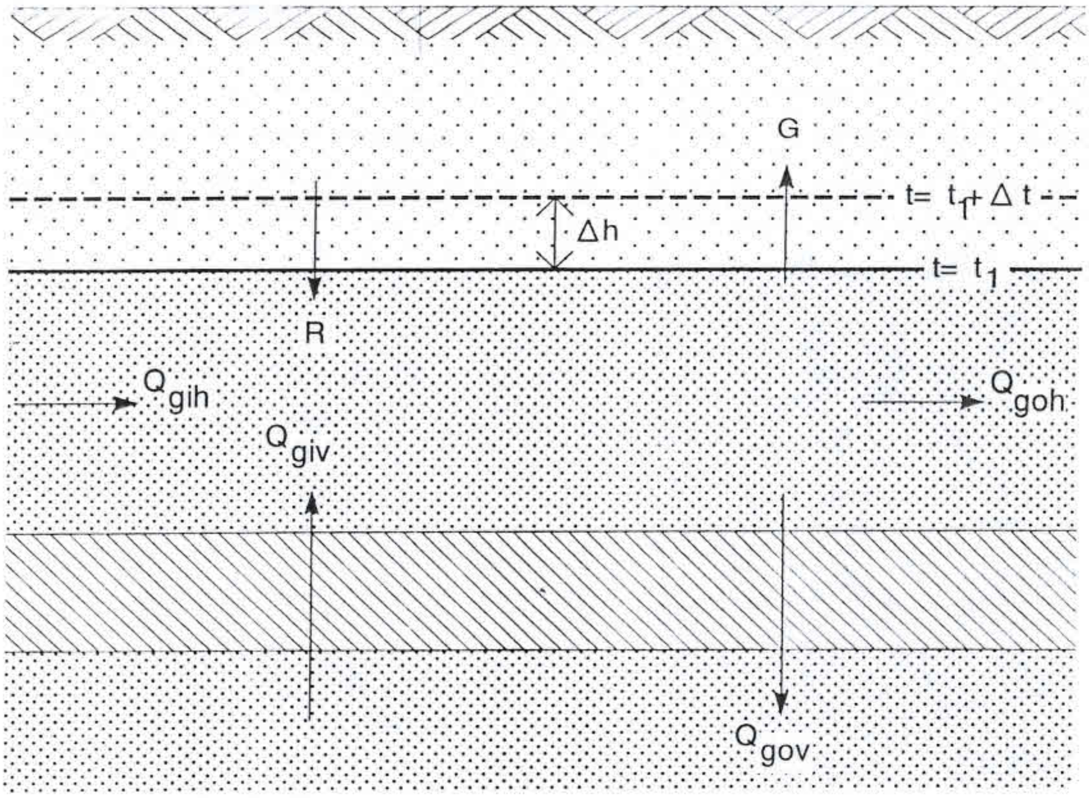

Figure 5. Water balance components of the saturated zone

where

R	=	rate of percolation to the saturated zone (mm/d)
G	=	rate of capillary rise from the saturated zone (mm/d)
Q_{gi}	=	Q_{gih} + Q_{giv} = the total rate of groundwater inflow into the shallow unconfined aquifer (m^3/d)
Q_{go}	=	Q_{goh} + Q_{gov} = the total rate of groundwater outflow from the shallow unconfined aquifer (m^3/d)
Q_{gih}	=	the rate of horizontal groundwater inflow into the shallow unconfined aquifer (m^3/d)
Q_{goh}	=	the rate of horizontal groundwater outflow from the shallow unconfined aquifer (m^3/d)
Q_{giv}	=	the rate of vertical groundwater inflow from the deep confined aquifer into the shallow unconfined aquifer (m^3/d)
Q_{gov}	=	the rate of vertical groundwater outflow from the shallow unconfined aquifer into the deep confined aquifer (m^3/d)
A	=	the water balance area (m^2)
S_y	=	the specific yield or effective porosity, as a fraction of the volume of soil (-)
Δh	=	the rise or fall of the watertable during the computation interval (mm)

For the irrigated farm, Equation 2 reduces to

$$R - G - 1000 \frac{Q_{go}}{A} = 0 \qquad (3)$$

in which Q_{go} is the horizontal outflow of groundwater. This is so because:

- We assumed the aquifer could be treated as an unconfined aquifer (no vertical inflow from or outflow to a deeper aquifer, i.e. $Q_{giv} = Q_{gov} = 0$);
- We observed no horizontal groundwater inflow anywhere along the boundaries of the irrigated farm, so $Q_{gi} = 0$;
- We assumed the groundwater system was in a steady state during the irrigation season, so $\mu \, \Delta h/\Delta t = 0$.

If we assume that $Q_{go} = 2665$ m³/d and that $A = 1600 \times 860 = 1\ 376\ 000$ m², then Equation 3 yields

$$R - G = 1000 \frac{2665}{1\ 376\ 000} = 1.9 \text{ mm/d}$$

And if we assume that steady-state conditions prevail in the unsaturated zone, Equation 3 then yields I - E = 1.9 mm/d. This is the net infiltration rate, and it represents an average taken over the total area of the irrigated farm. We can expect the net recharge to be substantially higher in the middle of the farm and lower along the fringes.

We have used a groundwater balance to estimate the natural drainage (some 2 mm/d). This value does not, however, represent the drainable surplus, as we shall see below.

A groundwater model was introduced to get information on the required drainable surplus. In this study, an updated version of the groundwater model SGMP was used (Boonstra and De Ridder 1990). The area of the irrigated farm was discretized into 24 rectangles. Figure 6 shows this nodal network.
Most of the nodes coincide with the locations of the observation wells shown in Figure 1. Note that the observation well network is slightly irregular. The nodal network defines the geometry of the aquifer in horizontal space.

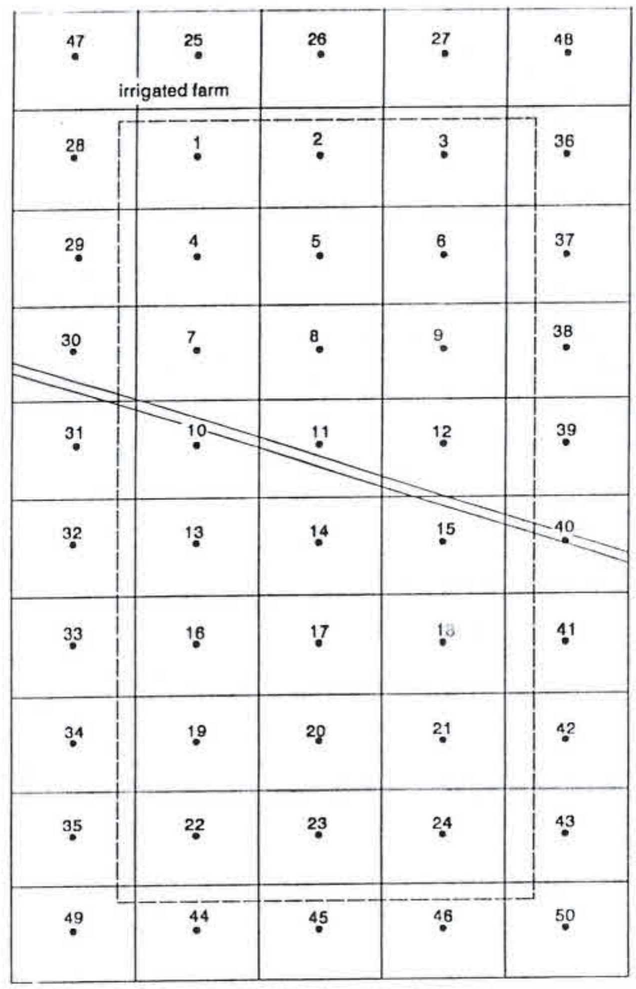

Figure 6. Lay-out of nodal network with nodal areas of 250 x 200 m^2

The discretization in vertical direction was done as follows. The surface elevation of each nodal area was estimated by adding to the observed watertable depth as given in Figure 1, the absolute watertable elevation as given in Figure 2. This value, which actually represent the surface elevation at the location of each observation well, was regarded to be representative for the particular nodal area as well. The elevation of the impermeable base, defining the thickness of the underlying aquifer, was not known. Assuming for the aquifer thickness a constant value of 100 m, the bottom elevation could be calculated.

The reported transmissivity values from the five aquifer test sites (see Figure 2 for their location) were used to make a map that showed lines of equal transmissivity. The nodal network map was superimposed on this transmissivity map, and the actual transmissivity value read for each nodal area side. Because SGMP requires aquifer thickness and hydraulic conductivity values in stead of transmissivity values, the hydraulic conductivity value for each nodal area side was calculated by dividing its transmissivity value by 100, the assumed aquifer thickness. Note that for the calculations by SGMP the assumption of the aquifer thickness value is not important; taking a different value will result in different values for the hydraulic conductivity, but their algebraic products being the transmissivity values remain the same.

Since the groundwater system was assumed to be in a steady-state condition, the specific yield of the aquifer did not matter. This condition is being simulated in SGMP by assigning a zero value to this parameter.

The absolute watertable elevations as observed in the observation wells (see Figure 2) were regarded to be representative for the initial watertable elevations at the nodes of the nodal network. Because of the irregularity, the watertable elevations for those nodes that did not coincide with observation wells, were interpolated from the watertable contour map.

Since the groundwater system was assumed to be in a steady-state condition, the time-dependent watertable elevations were made equal to the initial watertable elevations. In SGMP, the watertable elevations at the nodes of the so-called boundary nodal areas actually represent the time-dependent boundary conditions.

For the unit of volume and time, MCM (LSW1=1) and year (TMBAS) were respectively selected. The time step size (DELTA) was set to 10 and the total number of time steps (LISTxMAJORxMINOR) was set to 5. So, SGMP will run for a time span of 50 years; at the end of this time span, one can expect that steady-state conditions will occur with respect to the groundwater regime.

All the above mentioned data were entered in the input data files HANSIINV.

3 RUNNING SGMP

The following steps should be made.

Step 1:

- Start the program by typing SGMP;
- Go to 'Do the calculations' and use 'Retrieve a file with input';
- Select the file HANSIINV;
- Go to 'Do the calculations' and make a simulation run with SGMP;
- Go to output menu, Select output data, Space-related data: waterbalance components, select 10^6 per year and time step 5;
- Write the values under the heading 'Artificial flow', which in inverse mode represent the nodal net recharge values required to reproduce the observed watertable elevations, in enclosed table.

Step 2:

- Go back to 'input menu' and use 'Retrieve a file with input';
- Select the file HANSIINV;
- Select 'Title of data' and change the second line into 'Nodal net recharge from inverse modelling (steady state)' for identification purposes;
- Go to 'General data for calculation process' and make LSW6 equal to 0 (normal mode);
- Go to 'Time dependent data' and enter the nodal net recharge values in MCM/year which you noted down in the enclosed table under Step 1 from the inverse modelling results;
- Save these data in another file using the name HANSINOR;
- Go to 'Do the calculations', and use 'Retrieve a file with input';
- Select the file HANSINOR;
- Go to 'Do the calculations' and make a simulation run with SGMP;
- Go to output menu, Select output data, Time-related data: watertable data and evaluate the results for all the nodes; the watertable data calculated for time steps 1 to 5 should in principle be identical to the initial observed ones (time step 0).

Step 3:

- Go back to 'input menu' and use 'Retrieve a file with input';
- Select the file HANSINOR;
- Select 'Title of data' and change the second line into 'Nodal net recharge from inverse modelling (de-watering depth > 1 m)';
- Go to 'General Data' and make LSW2 equal to 1 (UL and LL levels to be prescribed);
- Go to 'Geometry system' and adjust the UL values for all the nodes so that they become equal to SL values minus 1 (de-watering depth);
- Save these data in another file using the name HANSIND1;
- Go to 'Do the calculations', and use 'Retrieve a file with input';
- Select the file HANSIND1;
- Go to 'Do the calculations' and make a simulation run with SGMP;
- Go to output menu, Select output data, Space-related data: waterbalance components, select mm/d and time step 5;
- Write the values under the heading 'Artificial flow', which now represent drainage volumes expressed as depth values, in enclosed table.

Step 4:

- Go back to 'input menu' and use 'Retrieve a file with input';
- Select the file HANSIND1;
- Select 'Title of data' and change the second line into 'Nodal net recharge from inverse modelling (de-watering depth > 1.5 m)';
- Go to 'Geometry system' and adjust the UL values for all the nodes so that they become equal to SL values minus 1.50 (de-watering depth);
- Save these data in another file using the name HANSIND2;
- Go to 'Do the calculations', and use 'Retrieve a file with input';
- Select the file HANSIND2;
- Go to 'Do the calculations' and make a simulation run with SGMP;
- Go to output menu, Select output data, Space-related data: waterbalance components, select mm/d and time step 5;
- Write the values under the heading 'Artificial flow', which again represent drainage volumes expressed as depth values, in enclosed table.

Table to be used to note down the various results

Nodal area	Nodal net recharges		Drainage rates	
	HANSIINV		HANSIND1	HANSIND2
	MCM/yr	mm/d	mm/d	mm/d
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
17				
18				
19				
20				
21				
22				
23				
24				
Total				

4 RESULTS

4.1 Results Inverse Modelling

The model yielded a set of nodal net recharge values in the inverse mode. Table 1 shows these values according to this run.

Table 1 Nodal net recharge values from inverse modelling run

Nodal area	Net recharge value	
	MCM/yr	mm/d
1	0.06	3.3
2	0.02	1.1
3	-0.02	-1.1
4	0.07	3.8
5	-0.10	-5.5
6	-0.02	-1.1
7	0.03	1.6
8	0.14	7.7
9	0.02	1.1
10	0.10	5.5
11	0.17	9.3
12	0.02	1.1
13	0.08	4.4
14	0.06	3.3
15	0.03	1.6
16	0.00	0.0
17	0.13	7.1
18	0.00	0.0
19	-0.02	-1.1
20	0.13	7.1
21	0.00	0.0
22	0.02	1.1
23	0.02	1.1
24	-0.02	-1.1
Total	0.92	50.3/24=2.1

Table 1 shows that the nodal recharge values substantially differ in space. They range from 9.3 mm/d in the middle of the farm to - 1.1 mm/d in certain areas. In these areas, the percolation losses from irrigation are apparently so small that the capillary rise rate exceeds them. The high negative value in nodal area 5 is probably due to a measuring error. Figure 2 shows that due to the reported value of 8.4 m the watertable contour line of 8.5 m exhibits an odd curvature.

The last line in Table 1 shows the overall water balance of the irrigated farm according to this inverse model run. The total net horizontal groundwater outflow rate, Q_{go}, equals 0.92 10^6 m^3 / yr = 2521 m^3/d. This latter value corresponds reasonably well with the total groundwater outflow as calculated from the flow net analysis.
Note that the boundaries of the farm do not coincide exactly with the sides of the nodal areas.
The similarity proves that SGMP run in inverse mode can give information on the spatial distribution of nodal net recharge values.

4.2 Results simulating Horizontal Drainage System

A horizontal drainage system can be simulated in SGMP in the following way. It is assumed that such a system will maintain a certain minimum watertable depth that can be regarded to be a horizontal plane within a particular nodal area. In SGMP, certain maximum watertable elevations - the natural surface elevation minus a particular de-watering depth - can be prescribed for each nodal area separately. If the watertable elevations calculated by SGMP exceed these levels during a simulation run, the model will introduce artifical negative flow rates. These negative flow rates will then yield calculated watertable elevations equal to the prescribed maximum watertable elevations within a certain range.

Two situations were simulated: one with a minimum watertable depth of 1 m and one with a minimum watertable depth of 1.5 m. Table 2 shows the results of these simulation runs.

Table 2 Water-balance components of the irrigated farm according to the model runs, in m^3/d

Actual and simulated watertable elevations	Net recharge	Groundwater outflow	Drain discharge
Actual situation	2466	2473	-
Watertable depth 1.0 m	2466	1728	740
Watertable depth 1.5 m	2466	606	1863

The data in Table 2 were taken from the files HANSIINV.OU3, HANSIND1.OU3, and HANSIND2.OU3 and converted to m^3/d. Table 2 shows that the total subsurface horizontal groundwater outflow decreases and the drain discharge increases with increasing de-watering depth, as was to be expected.

Note in this respect that when a tubewell-drainage system is considered instead of a subsurface drainage system, such a system can cause a substantial increase in the required drainable surplus if the watertable depth inside the farm drops below the levels in the area surrounding the farm; groundwater will then be 'attracted' from the surrounding areas to the farm.

Table 3 shows for the two simulation runs the values of the drainable surplus only for those nodal nodal areas where the calculated watertable elevations would have exceeded the prescribed maximum watertable elevations, i.e. where SGMP introduced watertable control by maintaining the prescribed minimum watertable depth. The data were taken from the files HANSIND1 and HANSIND2.

Table 3 Nodal drainable surplus calculated by SGMP, in mm/d

Nodal area	Minimum watertable depth	
	1.0 m	1.5 m
8	-	3.8
11	6.0	6.6
12	2.2	6.6
13	-	1.6
14	-	1.1
15	6.6	9.3
17	-	2.2
18	-	4.4

Table 3 shows that the actual required drainable surplus depends on the average watertable depth to be maintained. This table also shows that the area in need of drainage increases with increasing de-watering depth, as was to be expected.

It should be noted that according to Table 3 the areas in need of drainage are somewhat smaller than according to the watertable depth values presented in Figure 1. This difference can be explained by the fact that implementing a horizontal subsurface drainage system in the middle of the irrigated farm will automatically result in a greater watertable depth in the surrounding area, especially within the farm.

By providing this kind of information, groundwater simulation models can help the drainage engineer to design subsurface drainage systems. The great advantage of these models is their ability to illustrate the consequences of man-made interference in the natural flow system without the need for actual implementation.

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