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AGRICULTURAL CRITERIA FOR SUBSURFACE DRAINAGE: A SYSTEMS ANALYSIS

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ABSTRACT

The effects of subsurface drainage on agriculture are analysed in relation to drain discharge, control of the watertable and salt evacuation. The drain discharge depends mainly on external factors (the water balance), whereas the level of the watertable can be influenced by the design of the drainage system. Agricultural drainage criteria must therefore be sought in the required degree of watertable control, given a certain water balance. To this end, relationships between watertable depth and crop production or production factors need to be determined, and critical depth values need to be derived. As the watertable fluctuates, a suitable indicator has to be found for it from the depth-duration-frequency relationship. The variable that gives the highest degree of statistical explanation is the most suitable. It can be a long-term, average depth, or an extreme, short-term, shallow depth. The corresponding agricultural drainage criteria are called long-term and short-term criteria. The first are associated with steady-state drain-spacing equations, the second with either steady-state or unstead-state equations, depending on the ratio of storage to recharge or discharge.

INTRODUCTION

Van Schilfgaarde (1979) claims that 'drainage criteria need to be better defined and the data base for crop response as well as for trafficability needs to be expanded'. He also says: 'Drainage projects are more often than not based on guides derived from experience rather than on analytical formulations'.

Found et al., (1976) conclude from a survey of drainage projects in Canada that 'a significant minority of drainage projects have failed to generate enough agricultural benefits to justify their construction'. Further, they consider that 'despite the significance of drainage, little analysis of the full effects has been undertaken'.

Zaslavsky (1979) calls for a new engineering approach, 'otherwise the design of drainage projects will often be based on habits, superstition, and prejudices, rather than on really measured and checked experiences'.

In the light of the foregoing statements, this paper will attempt to show that the concept of agricultural drainage criteria can be generalized from the local, empirical level to a more systematic level, thus enhancing:

- the development and applicability of agricultural drainage criteria;
- the methodology of monitoring existing drainage schemes to evaluate their effectiveness or to improve the criteria;

- the transferability of the criteria to regions with entirely different drainage conditions;
- the methodology of predicting the economic results of proposed drainage projects, including the side effects;
- the design of drainage systems, to avoid over-design and thus save funds for drainage in regions that could also benefit from drainage systems, but that would otherwise not be eligible.

EFFECTS OF SUBSURFACE DRAINAGE ON AGRICULTURE

The objectives of agricultural land drainage are to reclaim and conserve land for agriculture, to increase crop yields, to permit the cultivation of more valuable crops, to allow the cultivation of more than one crop a year and/or to reduce the costs of production. These objectives are obtained through two direct drainage effects and, subsequently, a large number of indirect effects (Fig. 1).

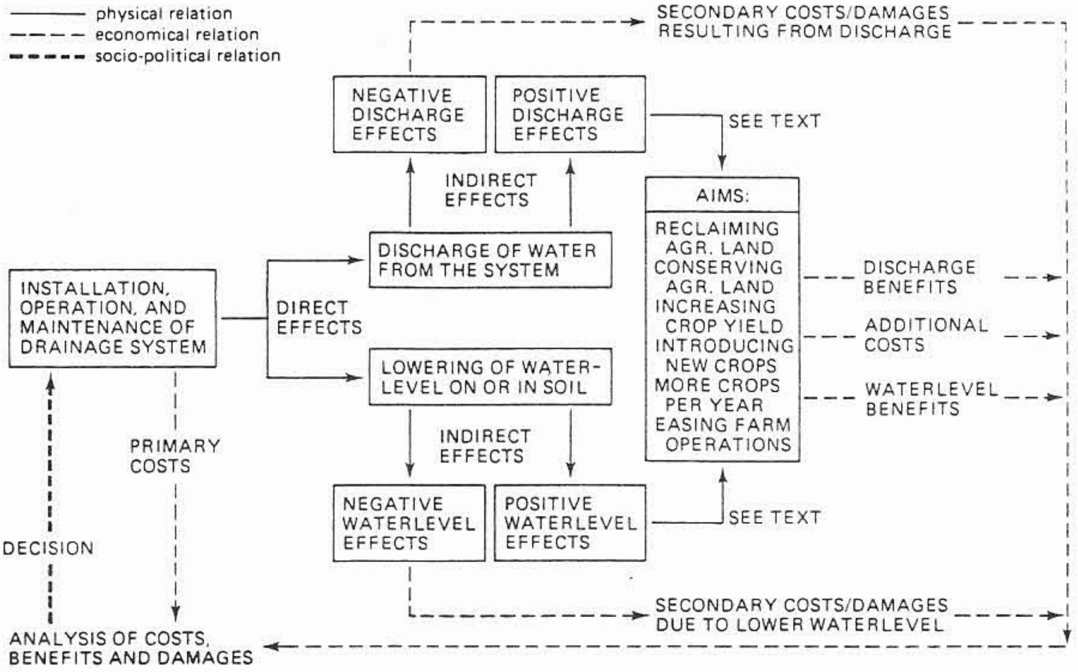

Fig. 1. Generalized diagramn of effects of subsurface drainage on agriculture, and their economic evaluation.

The direct effects of the installation of a subsurface drainage system in waterlogged lands are:
- a lower average water level on or in the soil;
- a discharge of water from the system.

These direct effects are determined mainly by hydrological conditions, hydraulic properties of the soil, and design characteristics of the drainage system.

The indirect effects are, in addition, determined by climate, soil, crop, agricultural practices, and the social or natural environment. The indirect effects can be divided into positive effects (benefits) and negative effects (damages). Some examples of indirect effects are:

- positive effects owing to discharge: removal of salts or other harmful substances from the soil; (re)use of drainage water;
- negative effects due to discharge: downstream environmental damage by salty or otherwise polluted drainage water; the presence of ditches and canals interfering with other infrastructure of the land;
- positive effects owing to lowered water levels: increased aeration of the soil; improved soil structure; better nitrogen balance in the soil; higher or more varied crop production; better workability of the land; earlier planting possibility; reduction of peak discharges by increased storage capacity of the soil;
- negative effects due to lowered water levels: decomposition of peat soils; soil subsidence; acidification of cat clays; increased risk of drought; ecological damage.

The indirect effects of drainage on weeds, pests, and diseases can be both positive and negative: the net result depends on environenmental conditions (Van de Goor, 1982).

KINDS OF VARIABLES USED IN DRAINAGE DESIGN

In drainage design, one deals with four kinds of variables (Fig. 2):

- Engineering variables, which represent the different possible magnitudes and quantities of the technical and material components of the system (e.g. depth, spacing, dimensions of drains); the engineering variables can be subject to certain limitations or constraints, which give the engineering options; the options selected for implementation yield the drainage plan and are reflected in tender documents.
- Environmental variables, which represent the natural or other conditions under which the drainage system has to function; irrigation, rainfall and the soil's hydraulic conductivity are typical environmental variables; they usually vary considerably in time or space; a fixed value chosen to represent th environemental variable in the design procedure is called a parameter.
- Object variables, which represent the different possible degrees to which the aim of drainage is realized; crop production is a much-used object variable, but also the workability of the land or other production factors may be used.
- Criterion variables, which are variables that can be related to the object variables e.g. in the production function, as well as the engineering options e.g. in the drain-spacing equations; in subsurface drainage, one often uses the depth of the watertable as a criterion variable.

The criterion variables can, in principle, be optimized, which means that they can assume an optimum value, which produces the maximum net benefit. However, if they cannot be optimized, they should yield at least a critical or just permissible value. The optimum or critical value is called criterion. It serves to provide instructions to the designer so that he obtains the best engineering options. Further it can be used to estimate the need of drainage in a certain area, and the expected benefits of a proposed drainage project (Nijland and El Guindy, 1984). After implementation of the project, it can be used to evaluate the correctness of the plan or its implementation and operation.

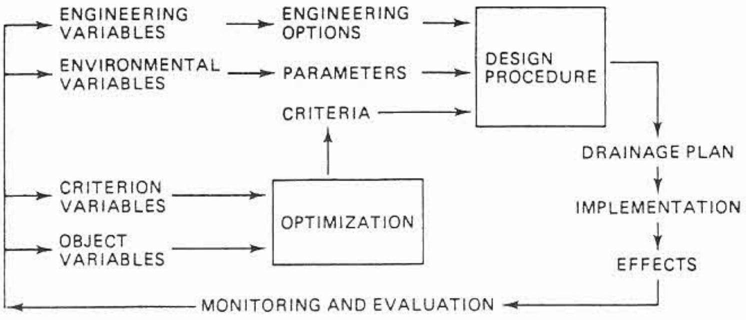

Fig. 2. The role of criteria in the optimization, design, and evaluation of drainage systems. There is a feed-back in the proces.

DEPTH, DURATION, AND FREQUENCY ANALYSIS OF THE WATERTABLE

Because of variations in recharge by irrigation and precipitation, a drainage system cannot ensure a constant groundwater table. Hence, to use the depth of the watertable as a criterion variable, one must select a representative value or indicator, using the characteristics of its frequency dustribution (Fig. 3).

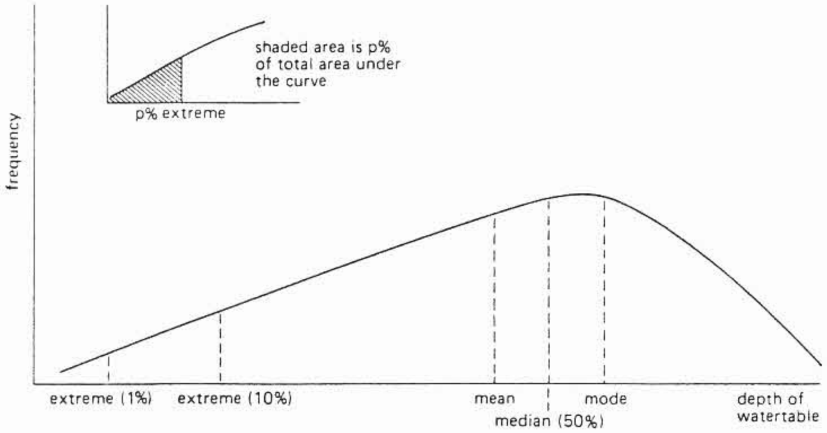

Fig. 3. The frequency distribution of the daily average watertable depths in a certain place over time, some of its characteristic values, and extremes with percentages of non-exceedance.

The choice of a representative value of the watertable from a frequency distribution must be made in relation to the duration or period it

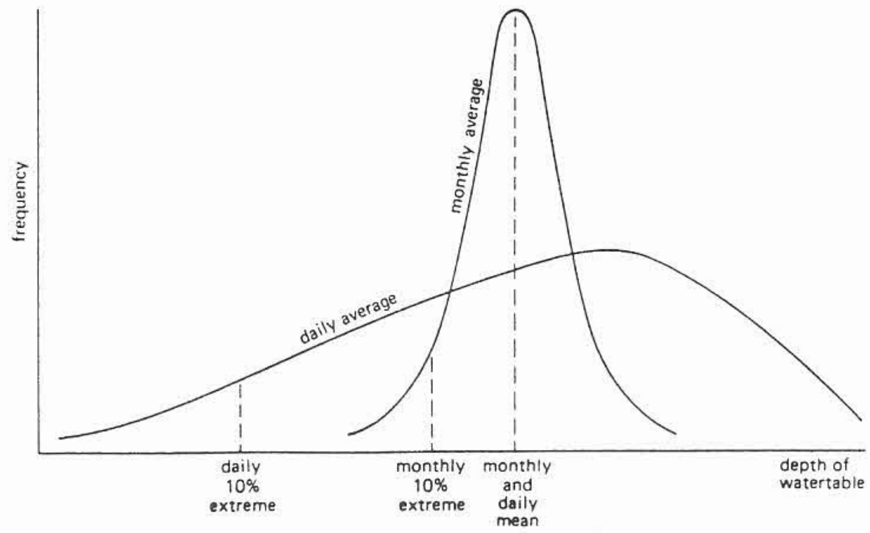

Fig. 4. Differences between the frequency distributions of water levels during short and long periods.

is thought to represent. Fig. 4 illustrates this point, showing frequency distributions of daily watertable depths and their monthly averages. Both distributions have the same mean value, but the extremes of the monthly depths are much closer to the mean value than those of the daily depths. Also, the mean, mode, and median values of the monthly depths practicallly coincide, whereas those of the daily depths do not. In other words, the mean is more representative of the distribution of the monthly depths than of the daily depths. This is in accordance with the central limit theorem in statistics.

Hence, the longer the period can be taken, the more logical it is to use the average watertable depth over that period as the representative value of the watertable regime and as a criterion variable. If the period has to be short, the representative value is rather an extreme with a specified, low, frequency.

PERMISSIBLE LENGTH OF THE PERIOD IN A CRITERION VARIABLE

The permissible length of the period to be used in a criterion variable depends on how accurately the corresponding criterion variable explains variations observed in the object variable, e.g. crop production. Often, the average seasonal conditions are more indicative of production than extremes over short periods as shown by the production functions in Fig. 5 and 6. In Fig. 5, where the extremes are used, there is hardly any relation with crop yield. From Fig. 6, however, it can be concluded that the average depth of the watertable during the summer season should be at least 0.8 to 1.0 m. Under the prevailing farming conditions in the part of the Nile Delta where the data were collected, this is usually the case.

A discussion on the scatter of data, as in Figs. 5 and 6, and on how to determine the critical value of the criterion variable despite the

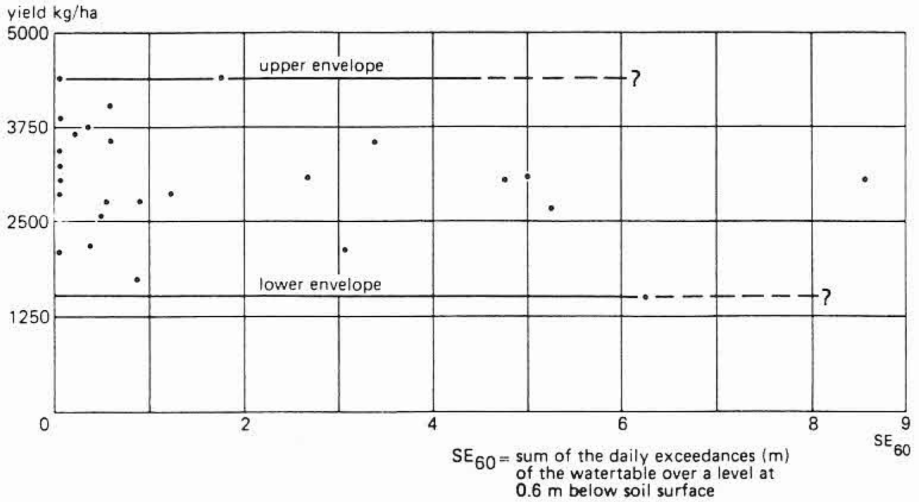

Fig. 5. Cotton yield (lint + seed) and the occurrence of shallow watertable depths, expressed in SE_{60}, in the Nile Delta (after Advisory Panel, 1982).

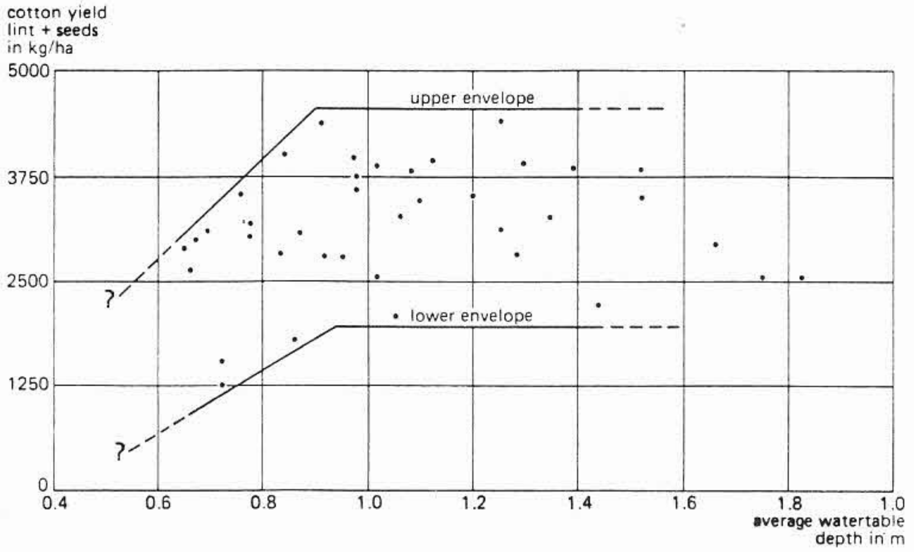

Fig. 6. Cotton yield (lint + seed) and the average depth of the watertable during the summer season in the Nile Delta (after Nijland and El Guindy, 1984).

scatter was given by Oosterbaan (1980), Nijland and El Guindy (1984) and, in statistical terms, by Nijland and El Guindy (1985). These references also discuss the assessment of the extent of drainage problems e.g. as the percentage of the area affected by too shallow watertables, and how a proposed drainage project could benefit not only cotton but also other crops. In addition, the references include data on levels of soil salinity.

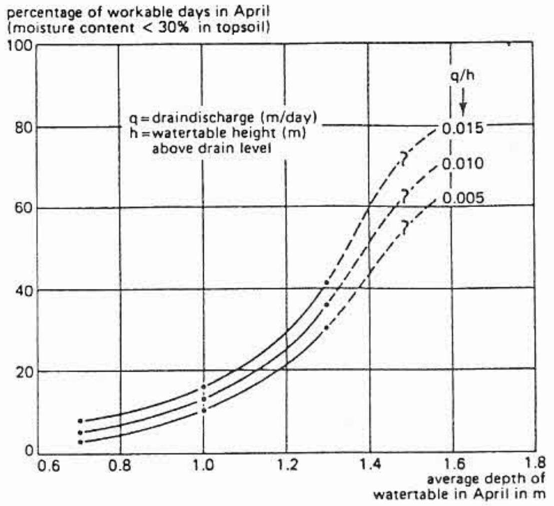

Fig. 7. Drainage and workability of a uniform silt-loam soil under Dutch climatic conditions. (Adapted from Wind and Buitendijk 1979).

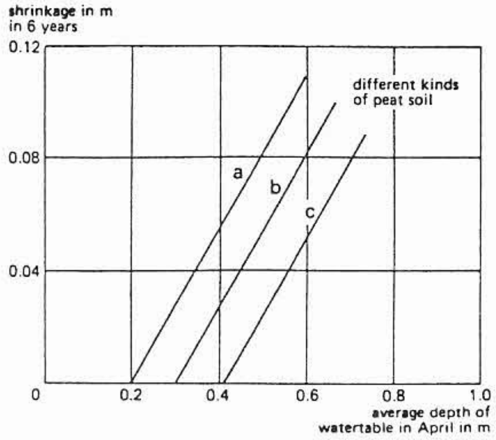

Fig. 8. Shrinkage of peat soils in The Netherlands versus average depth of the watertable (after Schothorst, 1978)

If, as in Fig. 6, the long-term average watertable depth is more indicative of crop production or other object variables than extreme, short-term, shallow depths, the use of long-term average depths as a criterion variable is preferred to the use of exceptional, shallow depths.

The long-term average depth of the watertable can be a significant criterion variable not only for crop production, but also for the workability of the land (Fig. 7) and the subsidence of peat soils (fig. 8).

The permissible length of the period, and the degree to which the variations in the object variable are explained by the corresponding criterion variable, depend not only on the kind of object variable, but also on the ratio of the soil's storage capacity to the volume of recharge and discharge over that period. The smaller the storage capacity and the greater the recharge intensity, the shorter the period that should be taken, and vice versa.

Subsurface drainage systems with pumped wells (vertical drainage), by which the watertable is lowered to a great depth, create a high storage capacity in the soil. For these systems, one can use the seasonal or yearly average water levels as a criterion variable. The water balance over the corresponding period can then be used to determine the design discharge.

Subsurface field-drainage systems with pipes and ditches (horizontal drainage) create a medium storage capacity in the soil. In regions with low rainfall, say less than 100 mm per month, and in irrigated lands in arid regions, one can base the drainage design on average monthly or seasonal water levels and corresponding water balances, taking into account the month or the season with the highest recharges. In regions with high rainfall intensities, it is preferable to work with shorter critical periods of, say, 1 or 2 weeks.

Surface field-drainage systems create a small storage capacity. Hence, design of discharge drains for these systems can be based on periods of 1 to 5 days.

FORMULATION OF AGRICULTURAL DRAINAGE CRITERIA

If one expresses the drainage criterion as the lowest permissible value of the average watertable depth over a long period, it can be called a long-term criterion. An example of such a criterion for subsurface drainage in irrigated land is: the average watertable depth during the irrigation season should be at least 1.0 m. A long-term criterion for rain-fed areas could be: the average watertable depth during the humid season should be at least 0.5 m.

If one expresses the agricultural drainage criterion in terms of a critically-high watertable level, above which the watertable may rise only infrequently and for short periods, it can be called a short-term criterion. An example of such a criterion for subsurface drainage is: the watertable may be higher than 0,3 m below the soil surface for only one day a year. An example of a short-term criterion for a main drainage-system is: the water level in the open drain may rise above the soil surface for only one day in ten years.

It can be deduced from Fig. 9 that, in the area where the data were collected, the drainage conditions do not meet the above long-term criterion. This leads to the conclusion that additional drainage is required. But if the highest permissible average depth of the watertable level were 0.6 m instead of 1.0 m, there would be no need for additional drainage. Similarly, the drainage conditions would not meet the short-term criterion if it specified a permissible 5 per cent extreme watertable depth of 0.5 m. Additional drainage would then be required. If, on the other hand, the 5 per cent extreme depth were put at 0.3 m, there would be no need for additional drainage.

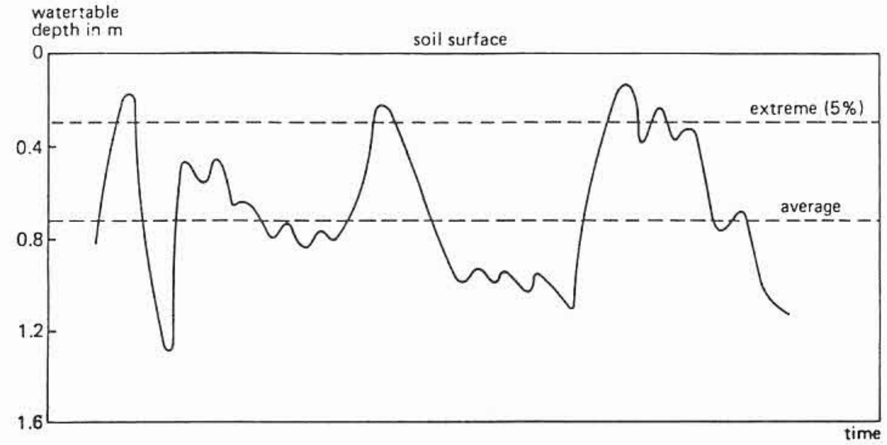

Fig. 9. The difference between mean and extreme water levels in a hydrograph.

There are certain types of criteria that use conditional statements, for example:

- When the watertasble reaches a specified height, h(m), above drain level, the discharge should be q(m/day).
- When, after an sudden recharge, the watertable has reached the soil surface, it should drop to d meters depth within t days, after the recharge has stopped.

These conditional criteria are usually not derived from a relation between an object variable (e..g. crop production) and a corresponding criterion variable. They are not transferable, but are applicable only in the region where they were developed. Elsewhere one runs the risk of applying them to situations which never occur, or which occur much too often.

WATERTABLE DEPTH AND SOIL SALINITY

Sursurface drainage in waterlogged agricultural lands of arid and semi-arid regions is often practised to reduce or prevent high levels of soil salinity. The salt balance of these lands depends greatly on the water balance, in which the amount of irrigation water is a dominant term. If sufficient irrigation water is applied, the effect of drainage on the salt balance is due to the discharge of salts with the drainage water (Van der Molen, 1973). Hence, drainage for salinity control is primarily based on its discharge effect, rather than on its effect related to the lowered watertable. Criteria for salinity control should therefore be sought in the amount of irrigation water needed to provide sufficient leaching instead of in the depth of the watertable. Drainage, then, is only a complementary factor, in which the discharge is an environmental variable and not a criterion variable. The permissible depth of the watertable has still to be determined from productions, as illustrated earlier, rather than from the salt and water balance.

Often, one relates the depth of the watertable to the upward capillary flow in the soil and the resulting salinization. However, when there is a net downward flow in the soil e.g. due to percolation of irrigation water, there can be no net capillary rise. In this context, Van Hoorn (1979) writes: 'The argument for applying deep drainage to reduce capillary flow is often used in cases for which it is not valid'.

A steady relation between depth of watertable, capillary rise, and salt accumulation in the soil can only be found in areas with upward seepage of groundwater and with long dry periods during which the topsoil desiccates. Due to the seepage and subsequent capillary rise, the soil will (re)salinize, especially when the groundwater is salty. Two cases may be distinguished here.

If the following rains or applications of irrigation water are insufficient to effectuate the necessary leaching, the depth of the watertable during the dry spell should indeed be considered a critical factor for salinity control and drainage design. The reason for this is that, by maintaining a deep watertable, the drainge system can intercept the seepage water and reduce the subsequent capillary rise and salinization. Then, deep drainage is necessary, especially in silty soils or fine sandy loams. However, a careful analysis is required to evaluate the feasibility of such a deep drainage system, because in regions with seepage of salty groundwater, scarcity of irrigation water, and much fallow land, the technical and economic effectiveness of the system may be limited.

If the rains or irrigation applications follwing a fallow period are sufficient to provide the necessary leaching and the upper groundwater zone is not saline, then the depth of the watertable is not critical for salinity control. Drainage criteria should then be based on other objectives.

The cotton data of Fig. 6 were not only related to watertable depth, but also to soil salinity expressed in terms of the electric conductivity (EC) of a saturated paste of soil as an average over the top meter. All data but two had EC values below 6 mmho/cm. Since the critical value of EC proved to be higher than 6 mmho/cm, the soil salinity did not explain the variations in yield. Further, there was no relation between watertable depth and soil salinity. Therefore, these data give an example of the situation where the critical watertable depth of 0.9 m as a seasonal average, established on the basis of waterlogging needs no adjustment for salinity control.

Hence, the use of the watertable as a criterion variable for salinity control is only necessary in the particular situation described above.

TYPES OF CRITERIA AND DRAIN-SPACING EQUATIONS

One can use steady-state or unsteady-state equations to determine the dimensions of the drainage system e.g. depth and spacing of the drains, given the proper criteria and the correct representative values of the environmental variables (Fig. 2).

In a steady-state situation, the recharge equals the discharge and there is no change in storage. Steady-state equations, however, are also applicable to unsteady-state situations, provided that the change in storage is small compared with the volume of recharge and discharge. For example, when the change in water storage in the soil over a period of a month or more is small compared with the drain discharge over that period, as it often is, the steady-state equations can be applied, even though the drainage process is unsteady. Subsurface drainage systems are therefore often designed with steady-state drain-spacing equations. Long-term criteria can be readily processed with these equations.

Changes in storage can also be relatively small over short periods. If so, one can apply steady-state equations, even though one is using extreme, short-duration discharges that are unsteady. In The Netherlands, for example, steady-state equations are applied in the calculation of drain spacings, under the assumption of an infrequent shallow watertable (at a depth of about 0.5 m or less, which occurs only a few days a year) and a corresponding discharge of 7 mm/day.

When the changes in storage are relatively small, there is probably a good correlation between short-term, and long-term criterion variables, as. e.g. in Fig. 10. Steady-state drainage equations are then applicable with both types of criteria.

If one must reckon with extreme, short-duration, depths of the watertable in systems with a relatively high storage capacity, one must use unsteady-state equations, even though these are more complicated to use than steady-state equations.

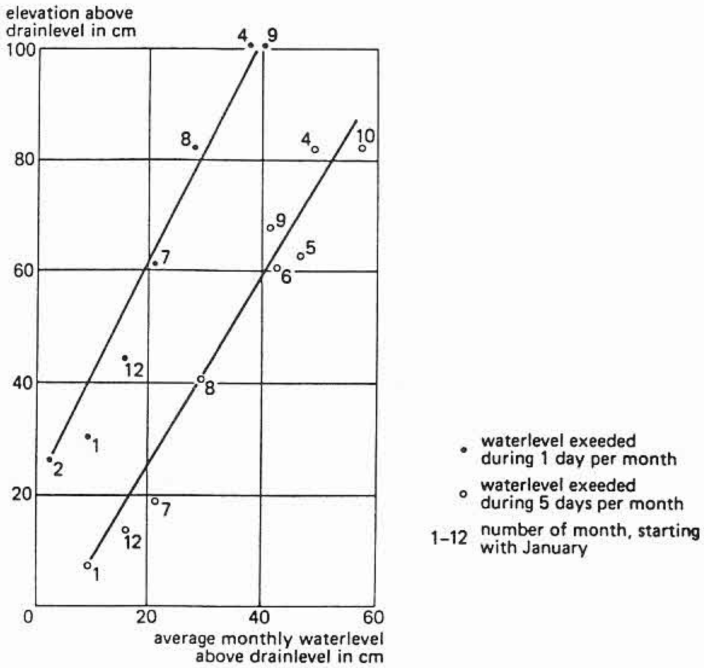

Fig. 10. Relation between daily extreme and monthly average water levels. (after Minderhoud, 1982).

LONG-TERM AGRICULTURAL DRAINAGE CRITERIA IN DRAINAGE DESIGN

The procedure for designing the depth and spacing of a subsurface drainage system according to long-term agricultural drainage criteria can be as follows:

- Determine a long-term drainage criterion, C, dependent on crop, soil, and critical period; if possible, use data obtained from experiments in farmers' fields;
- Determine which fields have an average watertable that is too high during the critical period;
- Set up a water balance for these fields and determine the drain discharge month by month; calculate the average discharge over the critical period;
- Make an assessment of hydraulic conductivity;
- Assume a suitable range of drain depths, D_j and determine the available hydraulic heads ($h = D_j - C$);
- With the above data, calculate the possible combinations of drain depth and spacing, using a steady-state formula for subsurface drainage, and choose the most suitable combination;
- Prepare a layout of the drainage system and adjust depths and spacings where necessary; complete the design with the proper longitudinal sections and cross-sections; check the discharge capacities of the field drains and the collector or disposal drains, using short-term criteria, if necessary in combination with unsteady state equations.

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