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PREFACE

This publication was prepared for the International Seminar on Land Drainage in Helsinki, Finland, 9 - 11 July 1986.

The preparation of the seminar started already in October 1984. The idea to arrange this occasion was first introduced by prof. Glenn Schwab in his letter to undersigned J. Saavalainen. Prof. Schwab proposed a mutual joint seminar in cooperation with USA and Finland and inviting people from other European countries. A quick negotiation with representatives of organizations dealing with drainage in Finland confirmed the intrest and possibilities to start the preparations for the proposed seminar.

Members of the Finnish Organizing Committee have been:

Prof	Matias Torvela, Chairman Agricultural Economic Research Institute
Mr	Risto Andberg Academy of Finland
Prof	Paavo Elonen Agricultural Research Centre
Prof	Osmo Kara State Research Institute of Engineering in Agriculture and Forestry
Mrs	Paula Kariola Finnish Field Drainage Centre
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Prof	Pertti Vakkilainen Helsinki University of Technology
Mr	Jussi Saavalainen, Secretary Finnish Field Drainage Centre

Members of the USA Organizing Committee have been:
Prof Byron Nolte
Ohio State University
Prof Melville Palmer
Ohio State University
Prof Glenn Schwab
Ohio State University

The seminar was made possible by financial support from
Academy of Finland
Ministry of Agriculture and Forestry
Finnish Drainage Foundation

Almost all the experts, who have been invited to present a paper, have had the possibility to attend the seminar. The organizers are very happy that we have representatives from Belgium, Canada, Denmark, England, Hungary, The Netherlands, Norway, Poland and Sweden in addition to those from Finland and USA.

We are convinced that this seminar will benefit drainage research and in the future help the fight against famine. We know from experience that this kind of meeting has effects on different levels. The personal contacts can be more important than the official program.

Acknowledgements: The organizers are deeply indebted to Mr Heikki Perho, Mrs Mirja Suurnäkki and Mr Reino Uronen for their efforts in finding the financial support and to Mr Pekka Saavalainen for practical arrangements.

Helsinki, June 24th 1986

ISLD Organising Committee

M. Torvela
Chairman

J. Saavalainen
Secretary

AGRICULTURE AND DRAINAGE PRACTICES IN FINLAND

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Abstract

The climate and soil conditions are not favourable for agriculture in Finland. In spite of harsh conditions Finland is able to produce all its foodstuffs, even having some overproduction. Drainage is a prerequisite for agriculture. Drainage works are constructed for 33 000 hectares annually. Drainage practices are described.

1. Finland as an agricultural country

1.1 Introduction

Finland is situated in northern Europe between 60° and 70°N latitude. The total land area of Finland is about 337 000 sq.km. Three quarters of this area is forest or peat. Productive forests are some 60 % of the surface area, covering some 20 million hectares. Finland is famous for its 60 000 lakes. These and waterways account for about 10 % of surface area. Only 8 % of the total surface area is arable land, covering about 2.4 million hectares. However, this accounts for fifty per cent of the world's arable land as far north, e.g. in other Scandinavian countries (figure 1).

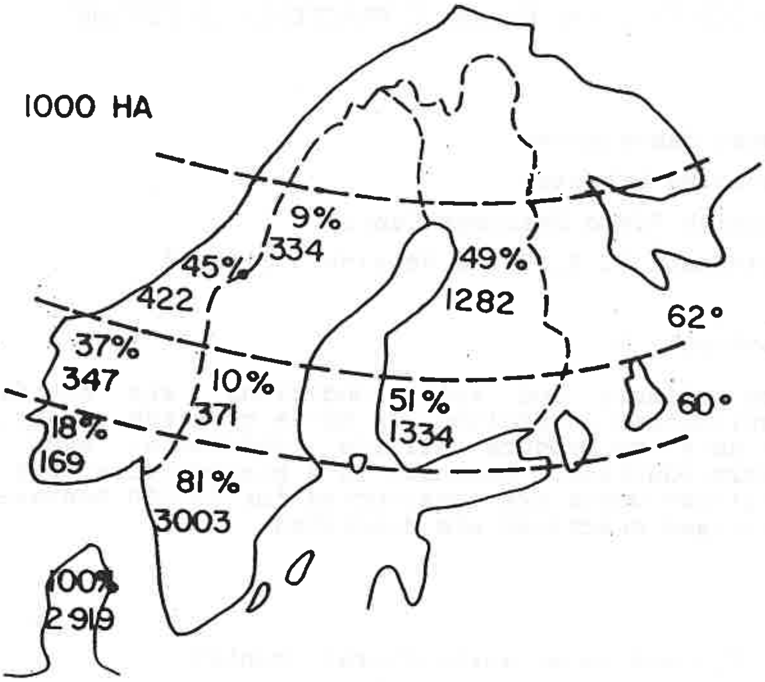

Figure 1. Location of arable land in Scandinavia.

Finland is the northernmost country in which agriculture is practised. This is possible because of numerous highly favourable environmental factors like the low lie of the land, relatively fertile soil, long summer days and the mildness of the climate due to the Gulf Stream. Finnish agriculture has over the years developed a diversified production based on farming, livestock and forestry. Recently, farms with no livestock have been increasing in number in the south and south-west. Also other kinds of specialisation are now becoming more common.

1.2 Climate and soil conditions

Climate

The average annual temperatur in Finland varies between -1 and +5 °C. The temperature may exceed +20 °C in the warmest summer months, being between +13 and +17 °C for July on the average. The long-term mean in February is between -3 and -4 °C. Due to the effect of oceans and the Gulf Stream the average temperature is about 6 °C higher compared with other countries as far north.

Precipitation exceeds evaporation. The mean annual precipitation is 500 - 700 mm, with precipitation highest in the south and east. Half of the precipitation comes during the growing season, and more at the end of the season than the beginning. However, shortage of water occurs in southern and south-western Finland during May, June and July. The rainfall is then only about half of the amount plants lose through evapotranspiration. Part of the annual precipitation falls in the form of snow. The snow cover is thickest in the central, eastern and northern parts of the country.

Soil conditions

The arable land in Finland can be divided into broad regional groupings on the basis of the dominant soil type (figure 2):

- clay areas in south and south-west Finland (1)
- till (moraine) areas in south-east Finland (2)
- silt, peat and till areas in the Lakes Region and south Kainuu (3)
- fine sand areas in Ostrobothnia and north Lapland (4)
- peat areas in Lapland (5).

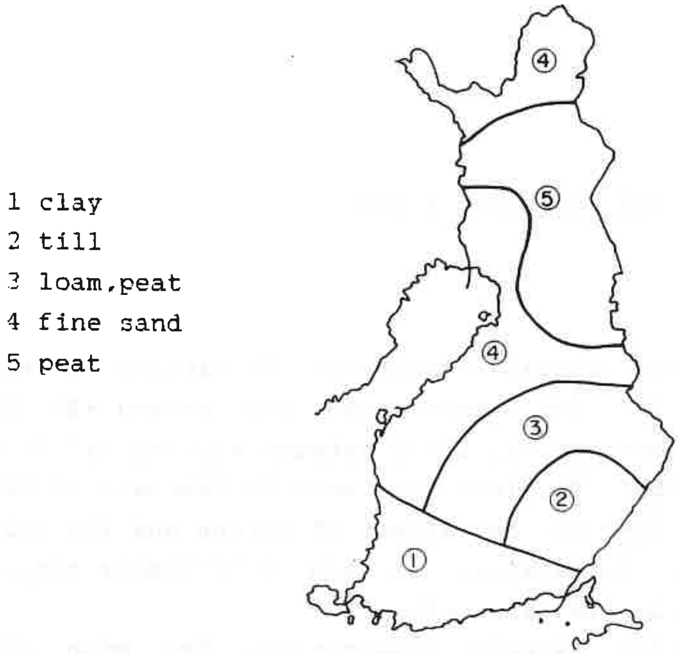

Figure 2. Soil types in arable land in Finland.

The natural humus content of mineral soils is low usually being under 3 %. The humus content of tilled soils is usually 4 - 8 %, lowest in coarse soils and highest in heavy clay.

1.3 Farms

Family farms are typical of Finnish agriculture. There are now about 208 000 farms, their average size being 12 hectares of arable land. Distribution of farms of different size is shown in figure 3. The average farm comprices 35 ha of forest land. The amount of arable land per farm is greater in the south than in the north but farms in the north have more forest. As we move northwards also the emphasis in production changes from cereal cultivation to dairying.

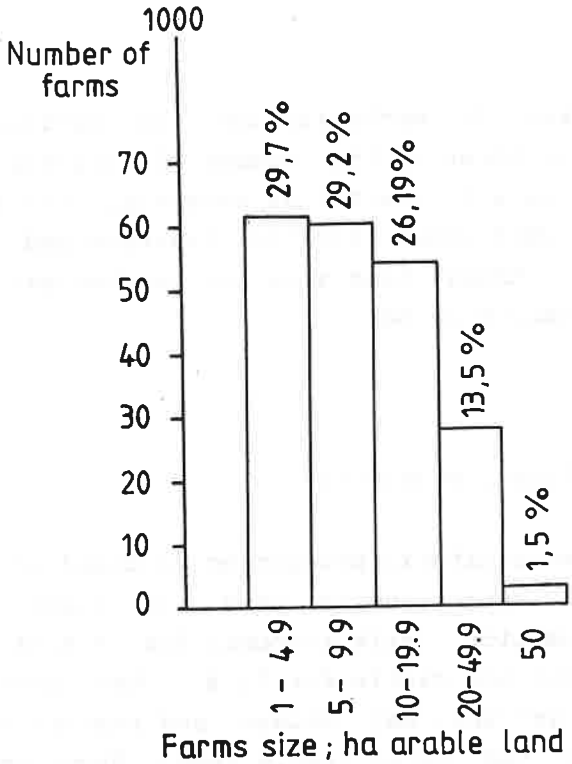

Figure 3. The size and distribution of farms (over 1 ha of arable land)

About 49 % of the farms is owned by full-time farmers. Other farm owners are part-time farmers. Farm population is only 7 % of the total national population (4.9 million in 1985).

A hundred years ago 90 % of the Finnish population lived in the rural areas. The agricultural population peaked at the end of 1920's. The sharp decline in the size of the farm population began only in the post-war period.

Farm machinery

Mechanisation of agriculture has been rapid during the last decades, resulting significant savings in human labour and quicker and more effective farming methods. Some current practices, like drill placement of fertilizer require machinery.

The degree of mechanisation in agriculture is often expressed in terms of the number of tractors and combines because these are regarded as essential field machines. In 1985 there were about 240 000 tractors and 47 000 combines in Finland. Arable land area per tractor was 10 ha and grain area per combine 28 ha.

1.4 Agricultural production

Finnish agricultural production is based on livestock. Only 15 % of the arable land is used for plant production for human consumption. Milk accounts for 38 % of the total value of production and cattle for 53 %, when beef production is taken into account. Hay, silage and pasture constitute about one third of the total arable land. About one third of feed grain is fed to cattle. Figure 4 shows the use of cultivated land.

The specialisation of farming happened in the 1960's and 1970's. Milk used to be produced on almost all farms, compared to only on about 64 500 farms today. About one half of the farms have no livestock. In 1983 there were about 23 000 cereal farms having 10 hectares or more of arable land.

Crop production

About forty different crops are cultivated in Finland. Wheat and rye are the main food grains in Finland. Winter wheat can be cultivated only in the clay soil areas of the south and south-west. Spring wheat also grows best in clay soils in southern Finland. At present it is the most important food grain in south Finland. Rye grows best in light mineral soils. It is cultivated as far north as northern Karelia, central Finland and the central parts of southern Ostrobothnia. Barley is today significant in Finnish agriculture as livestock feed.

In figure 5 yield statistics are presented.

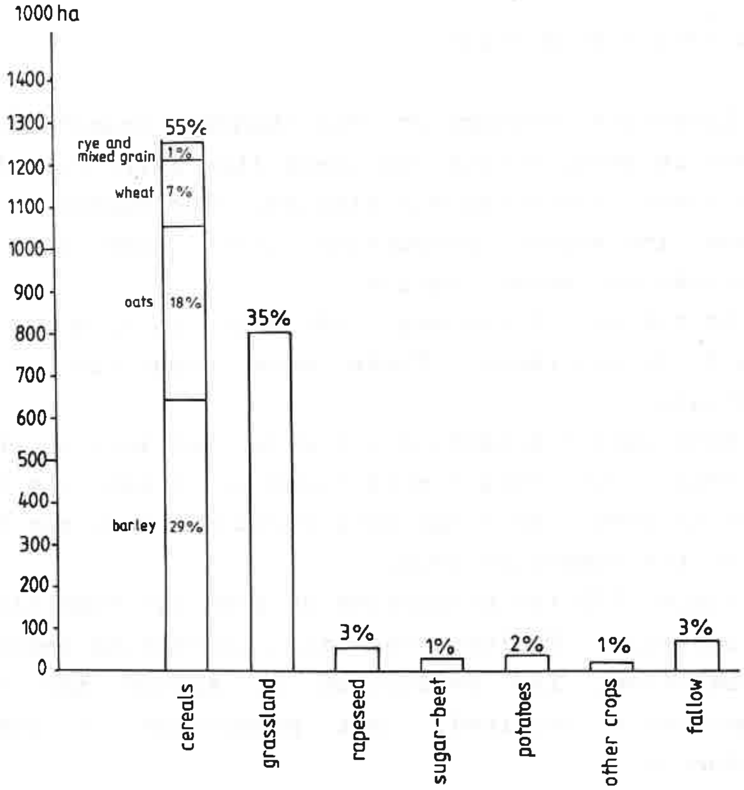

Figure 4. Use of cultivated land in 1985 in Finland.

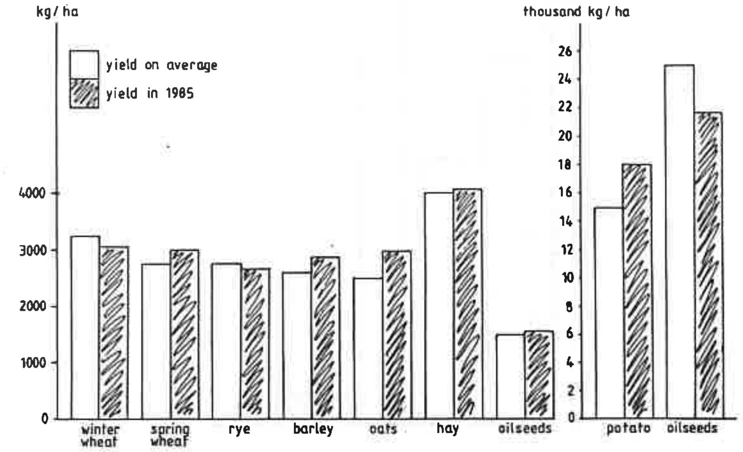

Figure 5. Yields on average and in 1985 of main cereals in Finland.

Livestock production

Livestock production has changed dramatically during the last decades. Horses and sheep like dairy cows have decreased in number since the mid-sixties. The number of hens and pigs have increased. Production units have also grown with increasing specialisation.

At the end of the year 1985 dairy farms accounted for about 30 % of all farms. There were about 628 000 dairy cows in Finland.

With improved feeding and wider reliance on high yielding breeds, the average milk yield has risen to 4 800 litres per cow in 1985. The total milk yield has thus not fallen in pace with the number of cows.

Since 1970 the production of pork has been higher than beef production. Poultry has also increasing importance in meat production. The production of mutton and horsemeat has constantly declined. Meat production in 1985 is shown in figure 6.

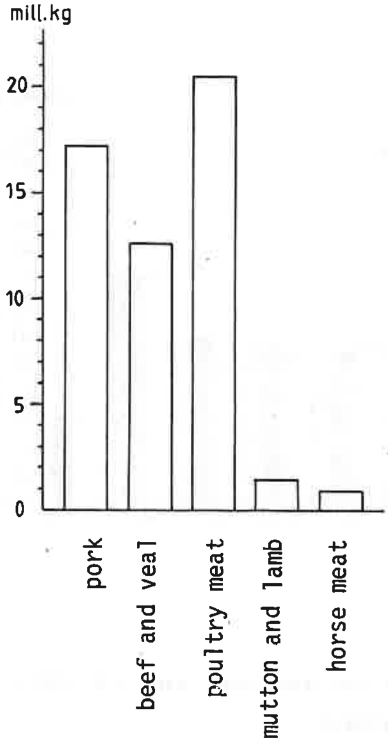

Figure 6. Meat production in 1985.

Self-sufficiency

Self-sufficiency in final products in Finland has been over 100% for a long period. Self-sufficiency in some foodstuffs and vegetables only is below 100% due to the severe climate. Self-sufficiency in milk, eggs and meat has for a long time been over 100%, being greatest in eggs. Also the self-sufficiency in wheat, barley and oats has been over 100% and in rye less than 100%. Annual self-sufficiency is, of course, highly dependant on the annual yield.

2. Draining of arable land

2.1 Main drainage systems

Main drainage systems are mainly constructed with government funding by loans and subsidies, annual amounting to about 20 million FIM, half being loans and the other half subsidies. Since 1960 the construction of main drainage systems has decreased significantly due to funding being now on the level shown in figure 7. At the end of the 1970's only about 5 million FIM was used for the area covered by main drainage, being then only 1600 hectares.

The National Board of Waters and the National Board of Agriculture are involved in this branch of activity, the first board involved in constructing the systems and the latter in financing them.

2.2 Subdrainage

Background

Artificial drainage of arable land is a necessity in Finland because of our climatic and soil conditions. Rapid drying of fields in the spring and during the harvest time is important in order to fully exploit the short growing season. Only 10 per cent of our fields can be cultivated without any drainage because they are located on slopes or the soil is highly permeable and thus self-draining.

Over 1.1 million hectares are still drained by open ditches. At the end of 1985 about 41 % or one million hectares of Finland's arable land were already subdrained. The national target is to get about 800 000 hectares subdrained by the year 2000

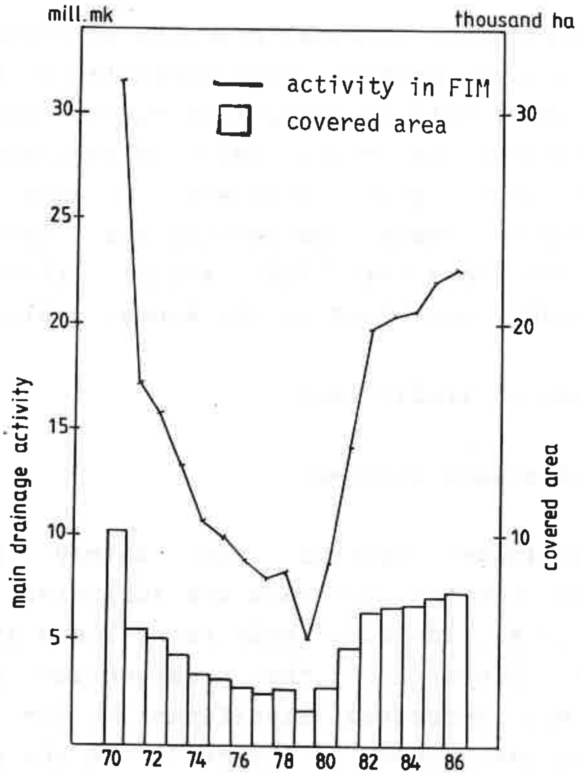

Figure 7. Main drainage activity and investment during 1971 - 85.

The Finnish Field Drainage Centre and drainage planning

Almost 100 per cent of subdrainage in Finland is today based on detailed field surveying and plans drawn up by the Finnish Field Drainage Centre. A plan prepared by the Finnish Field Drainage Centre or the Water District Office is a qualification for government subsidy for subdrainage projects.

The Finnish Field Drainage Centre is an association-form, quasi non-governmental organization that works to promote drainage operations. It works nationwide and has 130 employees of which about 100 are drainage technicians. The association was founded in 1918. Since then subdrainage systems have been constructed according to systematically drafted plans though subdrainage was known in Finland as early as the middle of the 19th century.

Today 33 000 hectares on the average are planned for subdrainage annually. This accounts for about 6 000 plans, their average size being 5 - 6 hectares. The number of plans has been on this level since the 1970's. The number of plans for redrainage or alteration has currently been 1 500 - 2 600 hectares annually.

Subdrainage operations and costs

Mechanisation of subdrainage construction took place in Finland in the 1960's. This was the first step towards more extensive construction of subdrainage systems and is clearly demonstrated by figure 8. Later the invention of plastic pipe and the automatic pipe laying method have also been factors affecting the increase in subsurface drainage construction. Today subdrainage is annually constructed on 33 000 hectares of field area on the average.

Subdrainage costs were 8 000 FIM/hectare on the average in 1985. Of this 40 % is composed of drainage materials, 36 % of construction, 13 % of farm work, 6 % of planning and 5 % of miscellaneous. In recent years drainage costs have increased more than e.g. other building costs in agriculture because of decreased drain spacing. This in turn is a result of the many rainy years in the beginning of the 1980's and the soil compaction that occurred then.

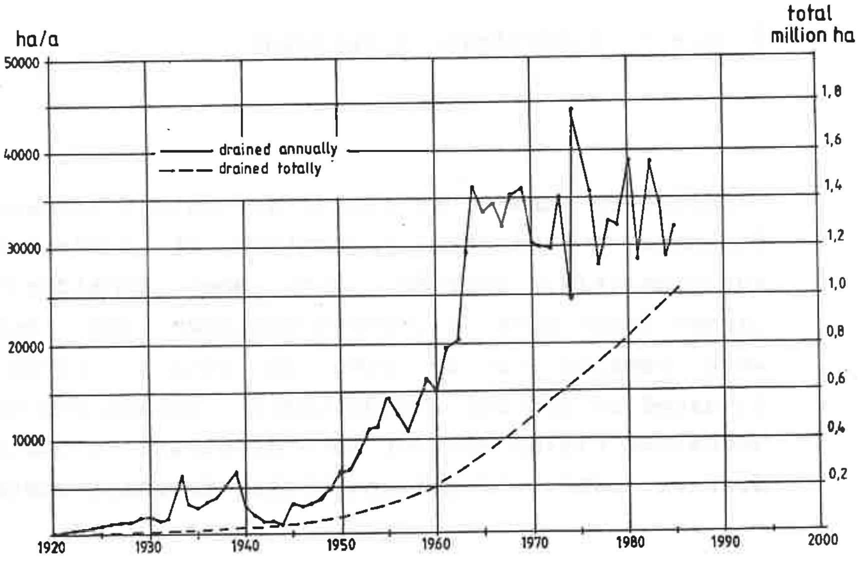

Figure 8. Annually constructed subdrainage systems in hectares

The total investment in subdrainage was about 260 million FIM in 1985 (figure 9). Government loans and subsidies has recently accounted for about 15 - 18 % of total investment. Most municipalities also support drainage mainly by paying drainage planning costs entirely or partly.

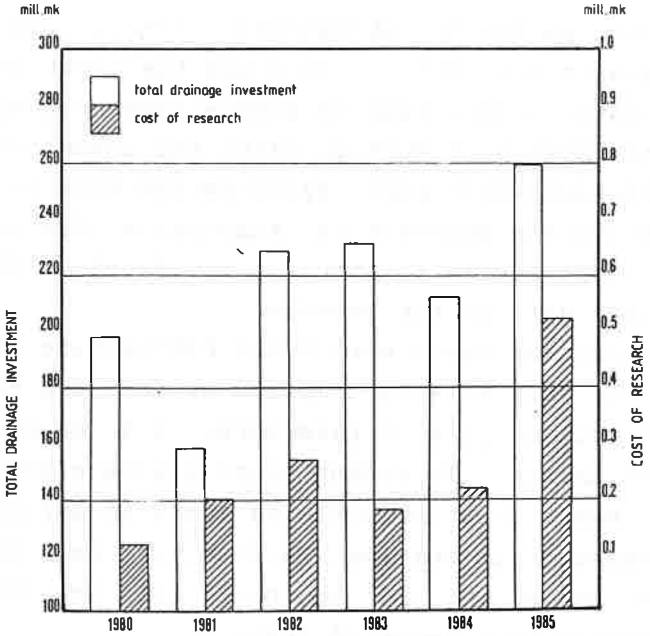

Figure 9. Subdrainage investment.

Completed subdrained fields are mainly situated in southern Finland, where the percentage of subdrainage in some municipalities exceeds 70 %. When considering farm size, larger farms have pioneered drainage and thus subdrainage work remains to be done on smaller farms than before. Situated in central and northern Finland and on small farms, undrained fields present more difficult conditions than the average today, which means higher drainage costs in future.

3. Subdrainage practices

3.1 Planning principles

Finnish Field Drainage Centre has since 1918 provided Finnish farmers with necessary subdrainage plans. During this long time of planning activity a lot of experience has been collected. At the same time a number of drainage experimental fields were constructed.

The reason for the long life-time of subdrainage in this country can be evaluated to be a benefit of following principles:

- Land and soil survey and mapping are allways done before planning
- Drainage plans are stored for later use in the Finnish Field Drainage Centre
- The laterals are placed perpendicularly to sloping
- Gravel is allways used as envelope material
- The gradient design so, that the water velocity is increasing downwards with the current. If the velocity decreases a sludge manhole is placed to the point, where the gradient is changed.
- The high quality of construction work. The bottom of the trench is not allowed to deviate more than 1 cm from marked level. No sludge is allowed in the trench.
- Small diameters of pipes in laterals. These pipes flow water-filled every spring. The sludge will be flushed away because of the high velocity of the water.
- The set up and supervision work done by educated drainage technicians.
- Blind inlets made of gravel are used on heavy clay soils in order to promote the entry of surface water into the drains.
- The minimum gradient by 40 mm pipe is 0.30 %, minimum gradient by 160 mm pipe 0.05 %.
- Drain depth 1.0 - 1.2 meters in mineral soil, 1.2 - 1.5 meters in peat soil.

Table 1. Drain spacings.

	m	m/ha	feet/acre
Heavy clay and loam (silt)	14 - 16	630-700	840-930
Light fine sand	20 - 26	400-500	530-660
Light coarse sand	30 - 40	250-330	330-440
Muddy clay and loam	30 - 60	170-330	230-440
Peat soils	16 - 20	500-630	660-840

Table 2. Runoff values in different soils.

	l/s ha	mm/day	inch/day
Compact soils - level areas	1.0	9	0.35
Peat soil (carex) - level areas	0.8-0.9	7-8	0.28-0.32
Other peat soils	1.0	9	0.35
Loose fine sand	0.8-0.9	7-8	0.28-0.32
Mud and fissured muddy clay	0.6	5	0.20
Compact soils - slopes	0.5-0.8	4-7	0.16-0.28
Slopes - artesian ground water	2.4-4.0	17-35	0.67-1.38

3.2 Construction

Subdrainage systems are constructed in Finland by private contractors. There are now about 280 contractors having drainage as their main occupation and about 130 as a secondary occupation. Drainage machinery in their use is composed of 235 chain-type trenchers, 80 wheel-type trenchers, 345 back-acters, 6 trenchless machines and 4 machines of other type. Chain- and wheel-type machines are almost entirely manufactured in Finland. In addition to these they have about 250 gravelling trailers. About thirty drainage machines are equipped with a laser depth control system.

3.3 Drainage materials

Pipe drainage using clay pipes was introduced in Finland in the 1850's. Since then clay has been the main pipe material though wooden box drains were constructed on organic soils in the first half of this century. Today the share of plastic pipes is 58%, the rest being clay pipes.

Envelope material is always used over the pipes. The dominant envelope material is gravel that fullfills grain size requirements shown in figure 10. Gravel is found in abundance in Finland though its price has recently risen and the availability of good quality gravel has decreased. If gravel is not available it can be substituted by sawdust laid in a 20 - 30 cm layer over the pipe. Pipes prewrapped with polypropylene or coconut fiber material are also available in Finland, but not in common use.

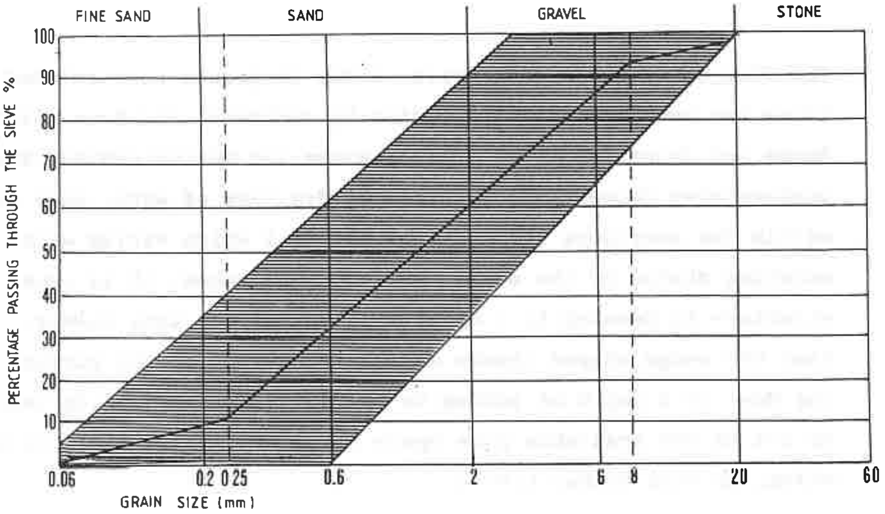

Figure 10. Grain size requirements for gravel for subdrainage systems.

THE MOVEMENT OF WATER IN CLAY SOILS UNDER FLOOD IRRIGATION

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Abstract

Studies of water movement in flood irrigated vertisols showed that although the major soil cracks were important in initial water distribution, their rapid rate of closure made them ineffective for leaching. The small amount of leaching water that does move through the soil profile moves through a few interconnected old root channels.

Introduction

The flow of water in clay soils under temperate zone rainfed conditions has been extensively studied by Anderson and Bouma (1973), Bouma and Jongerius et al (1977), Bouma and Wösten (1979). These workers have shown that, in essence, drainage of water only occurs within the macropore structure of the soil which varies with the moisture status of the soil. In temperate zones, it is usual for the structure to develop to a maximum extent by the late summer. At this time the wedge shaped cracks may be 100mm wide at the surface extending down to a depth of 1000mm to 1500mm. Such large voids represent up to 10% of the available pore space corresponding to a volume of 500 m^3/ha, or more Zrubec (1976).

The pores within clay soils form two populations of different size ranges. The largest group of pores exist within the matrix of the soil between the soil particles. These vary in size but in clay soils are chiefly characterised by their small size, and negligible hydraulic conductivity, <0.0003 m/day, Germann and Beven, (1981). Most of the soil water is held within such pores and is only available to plants which are able to generate the very high suctions needed. The remaining 'macropores' dominate the process of gravitational drainage within the soil.

The nature of the structure governs the pattern of water movement into the soil from either rainfall or irrigation. Under rainfall or sprinkling irrigation, areas on the surface become saturated allowing water to spill over the edges of peds at localised low spots. The water trickles down sections of the walls of the macropores without filling them, in a process termed bypassing. The water negotiates tortuous pathways and is only delayed by the presence of pore necks or by the end of the crack. The water level begins to rise within the cracks resulting in horizontal redistribution throughout the network of cracks and infiltration into the clay peds. The swelling soil initiates progressive closure of the structure.

Unfortunately, the relevance of much of this work to water movement in saline clays under flood irrigation has not been investigated. McIntyre et al (1982) investigated infiltration rates in saline sodic cracking clays in Australia. Their experiments showed initial high infiltration rates into cracks but infiltration rapidly declined over 90 minutes. Farbrother (1972) found similar results in the sodic Gezira clays of the Sudan.

The experiments described were designed to evaluate the situation encountered under flood irrigated conditions.

They were conducted on saline montmorillonite clay to investigate.

a. The pattern of water movement into dry saline clay soils in the field under flood irrigation.

b. The rate of closure of the macropore system in the field as a result of flood irrigation.

c. The pattern of water movement in saturated clay soil in the field.

Soils

The fieldwork was conducted on a site in the 130,000 Ha Lower Seyhan Project near Tarsus in Southern Turkey.

The soils in the area range from silts in the upper regions of the plain to montmorillonitic clays near to the Mediterranean coast. Traditionally, the area was used for dryland farming utilising the 400 - 600 mm of annual rainfall, but yields were often unreliable and poor. Salinity problems were also encountered near the coast where high watertables and high summer temperatures (40°C) resulted in the development of saline, and often sodic, clay soils.

The site selected for the experiments was near Tarsus where there was difficulty from the point of view of salinity control. The field chosen had a heavy clay subsoil, was highly saline, EC 10dSm^{-1} but was not sodic. It had drains installed 1.75 m deep at 40 m intervals.

At the time of the studies (June 1985) the field had been harvested and only the wheat straw and stubble remained on the surface of the field.

The soil which had a clay content of 60% was extensively cracked at the surface into the characteristic hexagonal pattern. The cracks ranged from 10mm - 100mm in width at the surface narrowing with depth until they ended some 800mm below the surface. The top 150 - 200mm of the soil was loose, dry and granular in complete contrast to the massive sub-angular-blocky structure of the subsoil.

The highly structured upper subsoil was mottled indicating periodic water logging whilst the lower subsoil (below 800mm) was rather uniform grey in colour without visible structure.

Method

Experiment 1. Water movement into dry clay under flood irrigation.

A large area within the field was cleared of straw and stubble by burning. A small area was then selected and earthen bunds formed to create a square with sides of length 2.5m.

600 litres of water, with a salinity EC of 2.3 d Sm^{-1} and containing 0.5% by weight of methylene blue dye, was supplied to the bunded area at the rate of 20 litres/minute. The area was then left to allow the water to move into the soil.

After 24 hours a trench was excavated to a depth of 800mm across the middle of the plot. The faces of the trench were then examined for traces of dye after which the soil was cut back in layers 50mm thick to allow the dye patterns to be studied in detail. Individual peds were split apart to determine whether dye had entered them.

Experiment 2. A study of the rate of closure of the soils structure upon irrigation.

A similar 2.5m square bunded area was prepared and three major cracks identified near to the centre of the plot. Pegs were installed into the ground adjacent to and either side of the cracks. The area was then flood irrigated very rapidly and the distance between the pegs measured as the soil swelled. The rise in level of the plot was also recorded.

Three further plots, each of length 1m x 1m were also prepared and the experiment repeated to substantiate the very rapid rate of closure noted in the larger plot.

Experiment 3. Field study of water movement into saturated clay soils.

A 2.5m square area was bunded off as previously described. The area was then irrigated and kept flooded for 48 hours. Methylene blue dye was then introduced into the remaining ponded water, roughly on a 0.3% w/w basis. Flooding was maintained for a further 6 hours during which time the infiltration rate was measured using infiltration rings. After a further 48 hour period of drainage the penetration of dye was investigated by excavating a shallow profile pit. Unfortunately the top 200mm of loose topsoil had absorbed all the dye and none had penetrated below this depth.

The topsoil was immediately removed to a depth of 200mm, and an infiltration ring was placed on the soil in the middle of the plot and filled with dye solution. This was allowed to infiltrate for 24 hours. After a further 24 hours of drainage the soil was excavated by exposing successive horizontal layers at 50mm vertical intervals. The patterns formed by the dye were recorded at each level.

Results

Water movement in dry soil

As water was applied the surface soil around the point of application rapidly became saturated so that runoff spilled over into the large inter-ped cracks. There was considerable lateral re-distribution within the cracks with water rising simultaneously within them up to one metre away from the point of application. As the water level rose to the surface ponding occurred across the whole of the bunded off area. In total 100 mm depth of water was used.

Plate 1 illustrates the pattern of dye movement within the soil with the dye coating the large inter-ped surfaces. The dye coincides with the main pathways of water entry into the soil. Infiltration occurs from these areas into the main body of the peds through micro-pores leaving the methylene blue dye adsorbed on the infiltration surfaces.

The dye had penetrated to the bottom of the visible structure at a depth of 0.8m. Dye was also observed on horizontal surfaces linking the vertical cracks. When the soil was destructively sampled the distribution of dye showed that the massive ped structure within the top 400mm had restructured into much smaller blocky units of between 25mm and 100mm size. These were well coated with dye indicating that the wetting up process was much more uniform throughout the soil than had first been thought likely. Water also entered the soil along insect burrows and root channels. Some of these continued across peds providing a degree of hydraulic continuity.

Rate of closure of the Soil Structure

Altogether twelve cracks were located at the surface and their width measured as they closed with irrigation. Three of the measurements were made in the centre of a 2.5m square plot whilst the remainder were made within 1m square plots. Despite problems of accuracy the experiment achieved the objective of demonstrating the rapidity of closure. The data presented in the Table 1 and Figure 1 details the rate of closure of three cracks in the larger plots.

Time Minutes	Width of 3 cracks, (mm) in large basins			Average
0	24	17	15	18.7
1	21	12	13	15.3
3	12	12	6	10.0
17	9	8	3	6.7
22	4	4	3	3.2
33	2	2	2	2.0
45	1	1	2	1.3
57	0	1	2	1.0
65	-1	1	2	0.7
135	0	1	2	1.0

Table 1 Rate of closure of soil cracks upon soil flooding

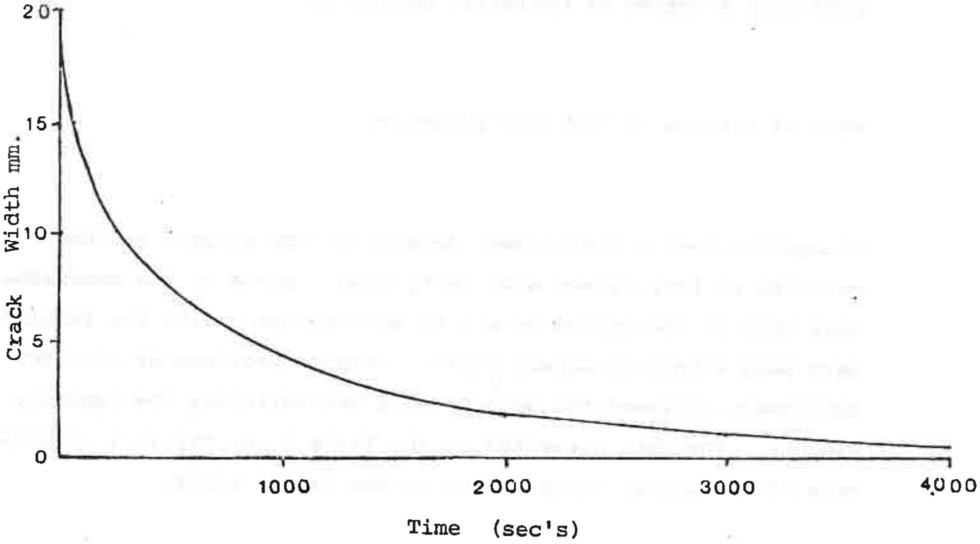

Figure 1 Rate of closure of cracks upon flood irrigation

Visually the cracks appeared to have shut completely after 30 – 40 minutes, any residual gap as is shown on Figure 1 being the result of experimental error. Originally it had been planned to measure the rate of closure at different depths within the soil. In the event this proved impracticable though there is no reason to believe that closure would have been any less rapid. This has serious implications for the drainage and leaching of saline clays.

During flood irrigation it was noted that substantial amounts of loose surface soil were washed down the cracks. The material accumulated within the structure where it formed a band of possibly more permeable soil within the otherwise poorly permeable clay. This debris could also account for the residual gap which remained after the cracks had visibly closed.

The clay also swelled vertically although as Table 2 shows, this was a slower process than the horizontal swelling.

Table 2 Rate of Vertical Swelling of Soil

Time Minutes	Rise in Level (mm) Position 1	Position 2
0	0	0
17	3	5
65	7	9
120	12	19
300	24	31
1440	28	30

Discussion

It is clear that flood irrigation enters the structured clay soil by flowing down and along the major cracks. Initially the cracks are linked allowing substantial lateral flow to occur but as the soil rapidly swells the links are reduced to the few remaining continuous smaller pores formed by insects, roots, voids or loose uncompacted soil 'bridging' between the peds. The process of wetting up creates swelling pressures which the soil is unable to resist, and the cracks formed function as point sources supplying water to the soil under high matric suction forces. Root and insect channels also fulfil a similar function. The mechanism of wetting observed is of considerable importance in revealing that water does not saturate peds by uniform flow through the soil matrix, but moves into the ped through a system of macro pores from where it is absorbed into the surrounding clay micropores. Such a process would be expected to wet up the peds with little if any redistribution of salt within the soil matrix. Secondly, this process explains the very rapid swelling process observed in the field where cracks close within 30-60 minutes and it is clear that the much slower swelling under rainfed conditions must be water limited. Under irrigation, the closure of cracks is far too rapid a process for the structure to be relied upon in any real sense for leaching by means of drainage.

The results have considerable implications for leaching since they mean that most leaching under saturated conditions occurs from the soil to a series of line sinks and not as originally supposed by leaching radially outwards from the mass of the ped to the fresh water surrounding the soil peds in the cracks after irrigation.

The work was commissioned by Hydraulic Research Limited from funds provided by the British Overseas Development Administration. Practical facilities and logistic and technical help were generously provided by the University of Adana and the Turkish Ministry of Agriculture Research Station, Tarsus, Turkey.

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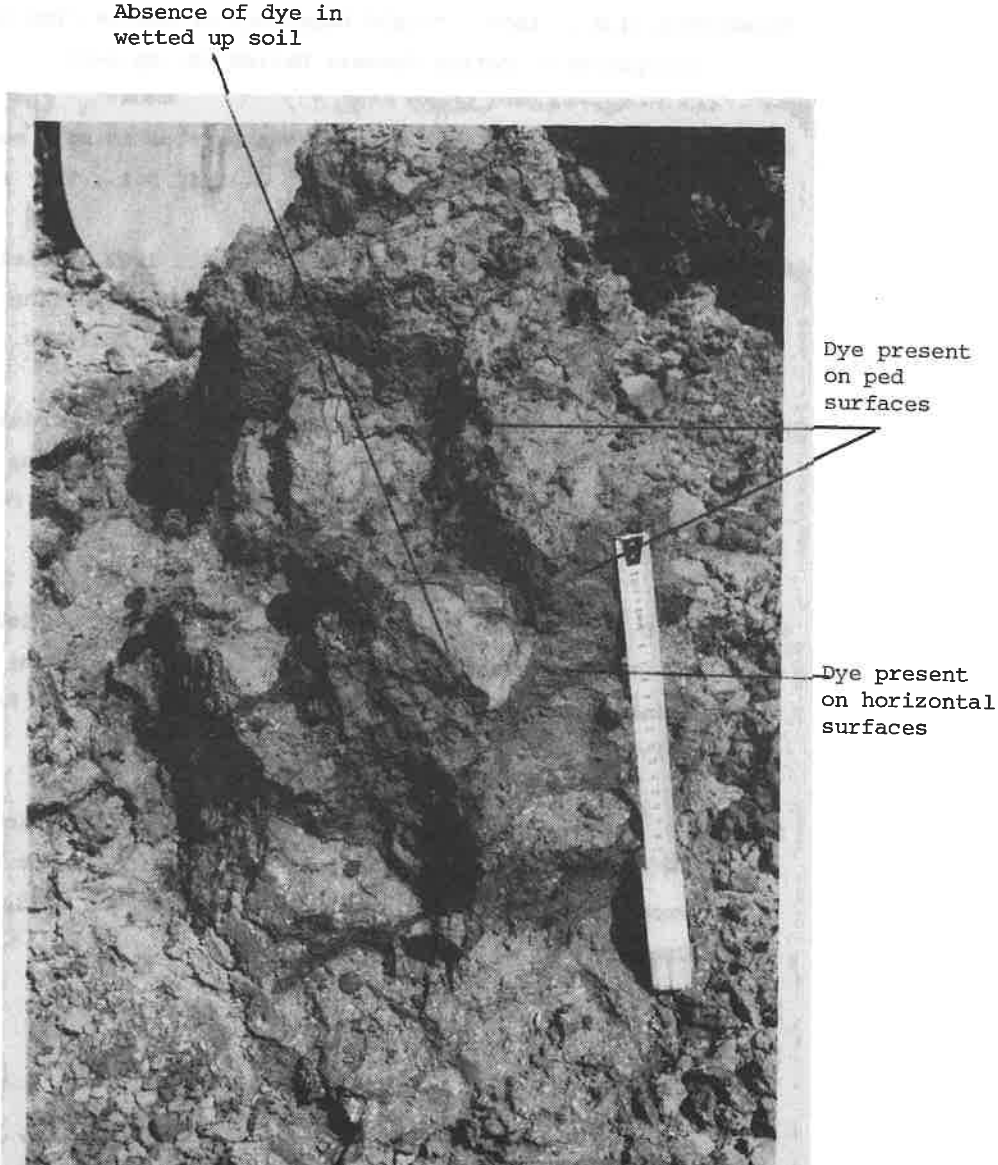

Plate 1 Dye and Water Movement after irrigating dry soil at a depth of 300 - 800mm.

APPLICABILITY OF DRAINAGE DESIGN EQUATIONS TO FINNISH CONDITIONS

Vakkilainen, P.[1] and Virtanen, S.[2]

Abstract

The applicability of some drainage design equations to Finnish conditions was studied. This study encompares the spacings calculated with drainage design equations with spacings in four fields. Both steady state equations and a non-steady state drainage design equation were studied. The soils studied were sandy loam, silty clay, heavy clay and sphagnum peat. The study concluded that the equations are applicable to drainage design in soils where the saturated hydraulic conductivity is moderate to high.

1 Introduction

In Finland the soil and the location of the field determine the drainage design. The common equations for drainage design have not been used in Finland. In order to study the applicability of drainage design equations to Finnish conditions, drain spacings for four fields were calculated. The calculations were compared with the traditional drainage designs.

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2 Experimental fields

The fields represent different types of soil and are located in different areas of Finland. The soils studied and their locations were sandy loam, Muhos (64°3′,25°6′); silty clay, Nurmijärvi (60°3′,24°5′); heavy clay, Loimaa (60°5′,23°5′) and sphagnum peat, Jalasjärvi (62°3′,22°5′). All the fields have subsurface drains. The drainage has functioned satisfactorily in all fields with the exception of the sphagnum peat.

3 Hydraulic conductivity

The saturated hydraulic conductivity of the soils was measured with the Falling Head Permeameter method. The measurements were made of depths of 30, 60 and 90 cm and at 10 to 20 sample places in the fields. Three replications were made at every place and every depth. The results are presented in Table 1.

Table 1. Hydraulic conductivity values and their coefficients of variation.

Field	Soil type	Saturated hydraulic conductivity (cm/h) mean	Saturated hydraulic conductivity (cm/h) geometric mean	Coefficient of variation (%)
Muhos	homogeneous sandy loam	2.9	2.9	15.7
Nurmijärvi	heterogeneous sandy clay	2.8	1.6	88.7
Loimaa	heterogeneous heavy clay	0.53	0.17	124.9
Jalasjärvi	heterog. peat	0.54	0.36	96.5

The distribution of the hydraulic conductivity values was also studied in order to determine the most representative values for the hydraulic conductivity of each field. The saturated hydraulic conductivity of the homogeneous soil was found to be normally distributed and that of the heterogeneous soils log-normally distributed (Fig. 1 and Fig. 2). Consequently both the mean and the geometric mean of the hydraulic conductivity values were used to represent the hydraulic conductivity of the field in the drainage design equations.

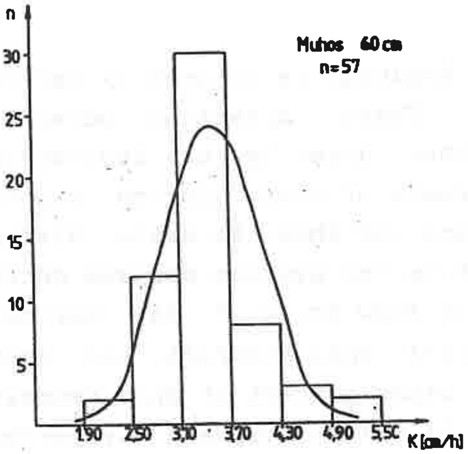

Fig.1. The distribution of saturated hydraulic conductivity in homogeneous soil.

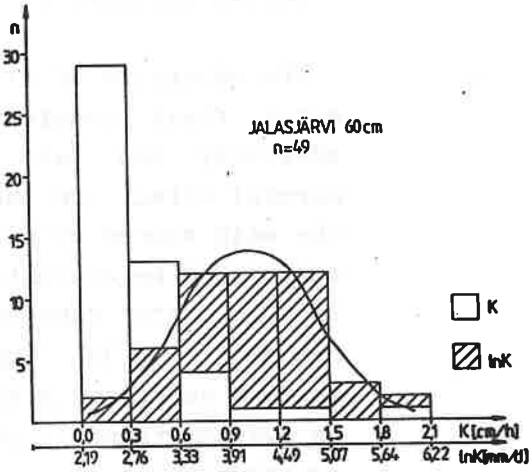

Fig.2. The distribution of saturated hydraulic conductivity in heterogeneous soil.

The variability of the saturated hydraulic conductivity in each field was also studied. The values varied considerably. The coefficient of variation was about 15% in homogeneous soil and 130% at maximum (Table 1) in in heterogeneous soils. Because of the wide variation in the saturated hydraulic conductivity values, the sensitivity of the calculated spacings within these ranges was also studied.

4 Drainage design equation

The applicability of the most common drainage design equations, both steady state equations and non-steady state equation were studied. The steady state equations used in this study were derived by Hooghoudt and by Ernst. The non-steady state equation derived by Kraijenhoff van de Leur and Maasland was used (Wesseling 1973).

5 Design parameters

The objective of field drainage is to prevent excessively moist field conditions. These affecting workability adversely and have -either directly or indirectly- a harmful effect on the growth of crops. Spring runoff is the main source of moisture and thus the drain discharge rate could be evaluated from the avarage maximum decrease in the water content of snow for a 5 day period in Finland (Fig.3). Converted into rainfall, the average maximum decrease in the water content of snow represents an average rainfall of 8.64 mm/day over a 5 day period in southern Finland.

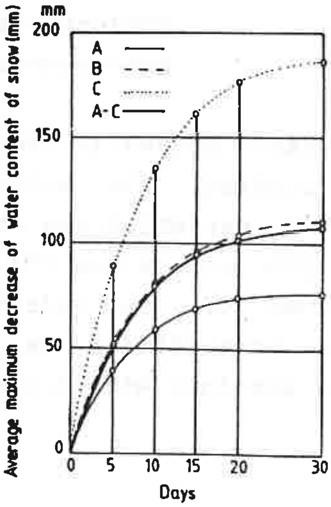

Figure 3. Average maximum decrease in the water content of snow (mm) in different areas of Finland (Kaitera 1939).

Recharge values based on the average maximum decrease in the water content of snow were used calculations made with the drainage design equations. The effects of rainfall during the summer on the depth of water table were also studied (Fig.4).

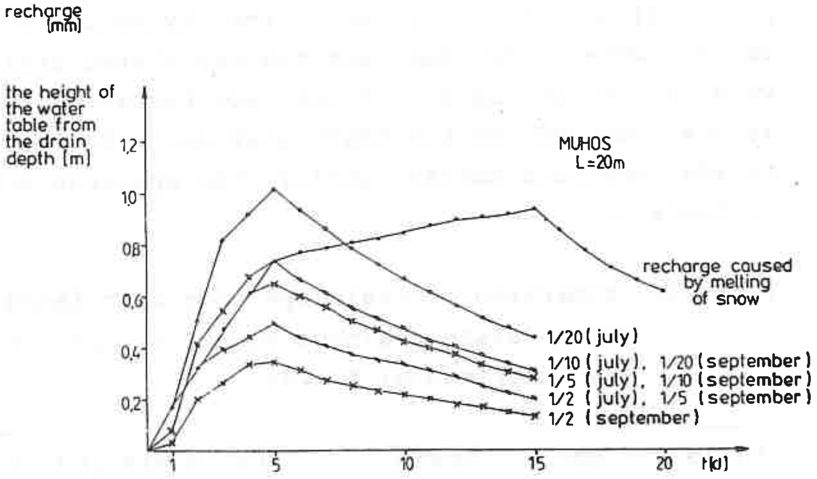

Fig.4. The effect of spring runoff and some summer rainfall on water table fluctuation in the sandy loam field. The non-steady state drainage equation was used in the calculations.

The soil profile of each field was assumed to have uniform structure and hydraulic conductivity down to the impervious soil layer.The mean and the geometric mean of the measured values were used as the hydraulic conductivity values. The drainage depths were the same as those in the experimental fields, i.e. from 1.0 to 1.2 m. The value of 30 cm was used as the permissible depth of the water table. For non-steady state calculations the drainable pore space in soils was determined on the basis of the soil-moisture characteristic curve.

6 Drain spacings with steady state equations

Comparison of the spacings calculated with the steady state drainage equations showed that the calculated drain spacings were almost identical to spacings designed in the traditional Finnish way in soils where the hydraulic conductivity is moderate to high. In sphagnum peat soil the hydraulic conductivity values were low and the calculated drain spacings were only 1/4 or 1/2 of the spacings used in the field. This field has suffered from poor drainage. In clay soil the hydraulic conductivity values were very low and the calculated drain spacings very dense. In spite of the low hydraulic conductivity values measured for the heavy clay soil, drainage in these fields functions satisfactorily. The spacings are compared in Table 2.

Table 2. Comparison of drain spacings calculated with the steady state drainage equations and drainage of the experimental fields.

Field	Soil type	Drain spacing in the field (m)		Drain spacing calculated with equations derived by Hooghoudt (m)	Ernst (m)
Muhos	sandy loam	20		18.2	18.2
Nurmijärvi	sandy clay	20	mean	18.3	17.3
			geom.mean	13.8	12.8
Loimaa	heavy clay	18	mean	9.4	7.2
			geom.mean	4.5	3.2
Jalasjärvi	peat	20	mean	7.8	7.0
			geom.mean	6.6	5.6

7 Drain spacings with non-steady state equations

The drain spacings calculated with the non-steady state equations were found to be similar to the spacings calculated with steady state equations in soils where the hydraulic conductivity values were from moderate to high. With the peat soil data the water table rose very slowly because of the high value of the drainable pore space. This was also the reason for the rate of adjustment in the sinking water table, which was extremely low. When the the drain spacing was 20 m the calculations showed that the water table sank only 1 cm from its maximum height in a 5-day period following after rainfall. The effect of the drain spacing on the water table height in a 20 day period following rainfall calculated with non-steady state equations in peat soil is shown in Figure 5.

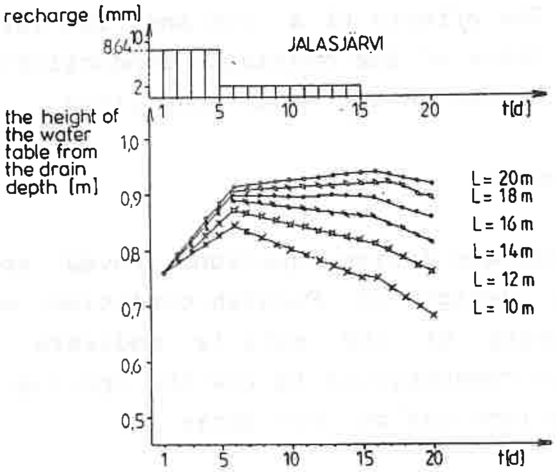

Fig. 5. **Water table height with different drain spacings in peat soil.**

The sensitiveness of the calculated spacings to the variation in the value of the saturated hydraulic conductivity was also studied. In the case of steady state drainage design equations the variation of 20% in the value of the saturated hydraulic conductivity caused a variation in the drain spacings of 1 to 2 meters. A variation of 20% in hydraulic conductivity caused a variation of 20 cm in the water table height when the non-steady state equations were used (Fig. 6).

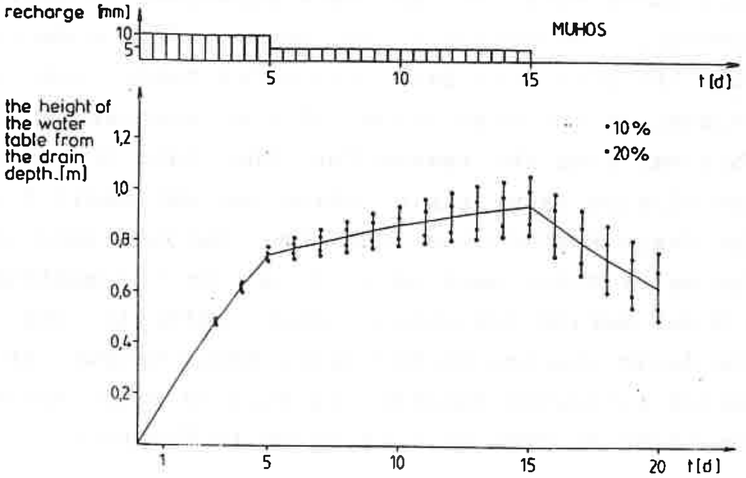

Fig. 6. The effects of a 10% and 20% variation in the value of the hydraulic conductivity on water table height in the sandy loam field.

8 Conclusions

The drainage design equations proved applicable to the drainage design in Finnish conditions when the hydraulic conductivity of the soil is moderate to high. If the hydraulic conductivity is low the spacings calculated with the equations may be too dense.

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INFLUENCE OF COMPACTION ON THE DRAINABILITY OF SOILS

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Abstract

Hydraulic conductivity is the best parameter of soil structure and drainage conditions. A value of 0.1 m/day is shown to be the critical minimum for drainage in Swedish soils. The wide variation in natural permeability of different soil types is illustrated here using 3 examples. Drainage of soils was shown to be reduced by compaction and smearing during tillage.

1 Introduction

The water-holding and water-transporting properties of a soil are, in various ways, dependent on the structure of the layers making up the soil profile. For drainage purposes, the most important relationship is that between soil structure and hydraulic conductivity.

In clay soils, the presence of a macropore system of cracks, worm and root channels determines drainage conditions. A well developed macropore system allows rapid movement of water and air, and permits rapid development of a root system. However, the frequency of cracks and biopores must be relatively high before an effective matrix of macropores is established in the soil. For example, one m^2 of clay soil must have more than 1000 pores with diameter greater than 1mm, including about 100 worm channels, before an effective macropore system is created.

In this paper, quantitative judgements of soil structure and drainage conditions are formed on the basis of hydraulic conductivity data.

2 Measuring hydraulic conductivity

The most commonly used methods of measuring hydraulic conductivity are the cylinder method in the laboratory and the augerhole method in the field.

The cylinder method is used to determine hydraulic conductivity layer for layer in the soil profile, using at least 3 replicate sample cores of approximately 0.5 l volume. This allows an average for vertical and horizontal hydraulic conductivity to be determined fairly accurately for soil layers and typical horizons. The small volume of sample used leads to wide variation in results from aggregated soils, depending on whether or not larger pores and cracks happen to occur in the sample.

The augerhole method is a field method which involves a larger sample volume of 50-200 l. Thus, the influence of all types of macropore on water transport is measured. Measurement is carried out according to the principle shown in Fig. 1, and hydraulic conductivity values are calculated using Beers (1958) formula. Despite the larger sample volume, variation in results is considerable and 3-5 replications are necessary to obtain an accurate value for field hydraulic conductivity.

3 Classification of hydraulic conductivity values

The hydraulic conductivity of a soil, expressed as k-value, is a very important characteristic in determining natural drainage properties and the need for installing a drainage system. Suggestions for classifying hydraulic conductivity values have been presented for English soils by Thomasson (1975) and for German soils by Eggelsmann (1978).

Drainage conditions in the classes shown in Table 1 were found to agree with results from Swedish field drainage trials (Håkansson, Berglund & Eriksson, 1974)

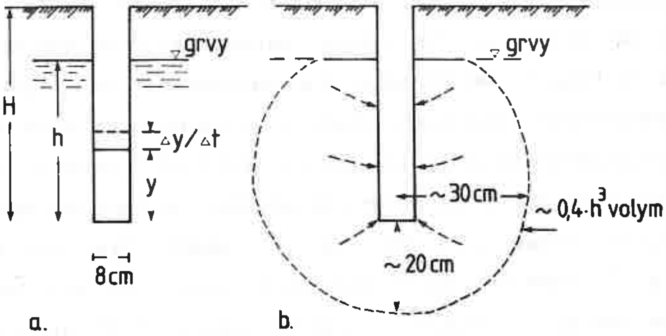

Fig. 1. Measurement of hydraulic conductivity in the field by the augerhole method: a) the principle involved in measurement and b) the soil volume normally included in the measurement, 0.05 - 0.20 m^3 for h = 0.5 - 0.8.

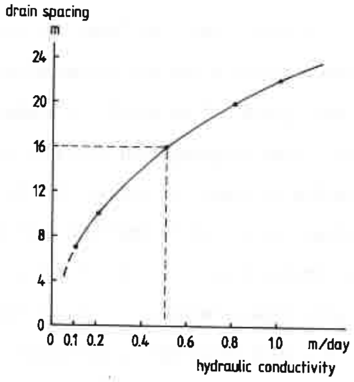

Fig. 2. Theoretical relationship between hydraulic conductivity and drain spacing as calculated from Hooghoudts formula.

In soils with a hydraulic conductivity value of 0.1 - 0.3 m/day or more very good results are obtained from drainage installations. Soils with values of less than 0.1 m/day drain very slowly and at values below 0.01 m/day, movement of water towards drains is critically slow. In such soils, the drainage effect must be assisted by gravelling, liming backfill and moling. Secondary treatments such as surface grading and cutoff drains to prevent inflow of surface water are also necessary.

Permeability of arable soils varies enormously, more than 1000 times if one compares a dense clay to a sand soil. Even within the clay group, the same variation can be seen on comparing a dense, very heavy clay with a fractured gyttja clay. Drainage conditions vary greatly too, in response to variations in the natural permeability of the soil. This is illustrated in Fig. 2, which shows the theoretical relationship between hydraulic conductivity and drain spacing as calculated from Hooghoudts formula. The calculation assumed average rainfall of 7 mm/day for a 5 day period. The soil profile in question was assumed to have uniform structure and hydraulic conductivity down to 1.5 m depth. Drainage depth was set at 1.0 m. Fig. 2 shows the drain spacing necessary to hold the watertable 40 cm below the soil surface. It can be seen that if the hydraulic conductivity value increases from 0.1 to 1.0 m/day, drain spacing can be increased from 7 to 22 m. In reality, drain spacing required is determined by the frequency of the critical 5 day rainfall amount.

Table 1. Classification of hydraulic conductivity values according to the Soil Survey, Rothamstead (Thomasson, 1975)

m/day	classification	drainage
0.01	very low	poor drainage effect
0.01 - 0.1	low	
0.1 - 0.3	moderate	
0.3 - 1.0	high	good drainage effect
1.0 - 10	very high	
10	very high	

4 Variation of hydraulic conductivity with depth and drainage effect

As mentioned previously, hydraulic conductivity varies greatly between soil types. It may also vary considerably with depth in a particular soil due to textural and structural changes in the profile. Due to the size of the variation between soil types, however, some generalisations can be made.

The need for drainage in various Swedish soils was investigated in a large number of field trials carried out on 130 sites during the period 1947 - 1977.(Håkansson 1960, 1961). From the results obtained, optimal economic drainage intensity was calculated by weighing cost of drainage at a particular intensity against profits obtained in the form of improved trafficability and higher yields. The experimental sites chosen represented the main types of arable soil found in Sweden. Soil physical investigations carried out on all sites included measurements of hydraulic conductivity, total porosity, drainable porosity (Håkansson, Berglund & Eriksson, 1974).

As an example, results from a group of drainage trials in Skaraborg District are considered in detail here. Three soil profile types could be distinguished in this group. Results from hydraulic conductivity measurements on these three soil types are shown in Fig. 3, which has a logarithmic horizontal scale to allow for the wide variation in k-values.

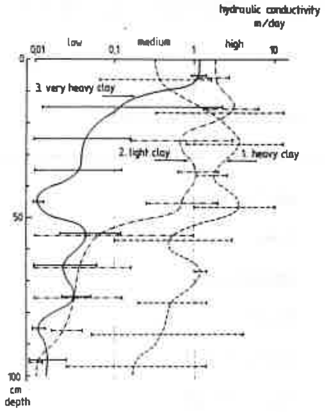

Fig. 3. Laboratory measurements of hydraulic conductivity (m/day) in soils from Skaraborg District. Characteristic variation with depth in a light clay, a heavy clay and a very heavy clay.

Curve 1 represents 5 trials on the Vara plain. These medium and heavy clays have high and uniform hydraulic conductivity throughout the profile of around 1 m/day (laboratory measurements). Drainage systems are thus effective as results from field trials on this type of soil confirm.

Curve 2 represents three trials on the Kåkind plain. The light clay soil of this area has a high hydraulic conductivity, around 1 m/day, in the upper part of the profile. Below 50 cm depth, however, hydraulic conductivity falls to below 0.1 m/day. This is due to layering or stratification of the soil and to the absence of worm channels or cracks. Older cracks which have silted in can be observed in some cases. Drainage effect is reasonably good but because of the profile characteristics described above, a dense drain spacing is necessary.

Curve 3 (Fig. 3) represents two trials on the Vadsbro plain. Hydraulic conductivity is very low, 0.01 - 0.03 m/day, throughout the entire profile. Drainage effect has also proved to be very poor in observations and measurements carried out on these sites during the 30-year duration of the trial. The topsoil is frequently saturated and the soil has poor trafficability at harvest, despite intensive drainage. Spring operations are also delayed because of the poor effect of drainage in these low permeability soils.

5 Influence of soil compaction on drainability

Apart from the 'natural' variations in hydraulic conductivity in a profile as described for three soil types in the previous section, there are also variations in the topsoil and plough pan which have been caused by cultivation. Such effects may be positive, as in mechanical loosening of the topsoil or negative, as in compaction with heavy machinery (Eriksson et al., 1974). Cultivation effects are seen most clearly in clay profiles where a pronounced alteration of structure occurs between 30 and 40 cm depth. Compaction and puddling can reduce the hydraulic conductivity of the topsoil and plough pan to below the critical value for rainfall infiltration of 0.1 m/day. Obstruction of water transport to the lower layers of the profile means, that the effects of drainage are greatly reduced for a shorter or longer period of time.

The effect of compaction on permeability is especially great in profiles which have a high natural permeability (Fig. 4). This diagram shows hydraulic conductivity in clay soils from Ultuna and Valla in the valley around Lake Mälaren. Samples were taken both when the topsoils were in good condition and when they had been compacted by heavy traffic while wet. The subsoil in both these profiles has the good structure typical of many clays in Eastern Sweden, and thus has a high hydraulic conductivity and good drainage. Compaction of the topsoil inhibits vertical flow of water and causes surface puddling.

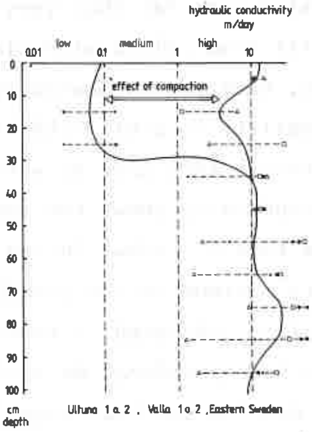

Fig. 4. Hydraulic conductivity in two clay profiles (Ultuna, Valla) in normal and compacted condition.

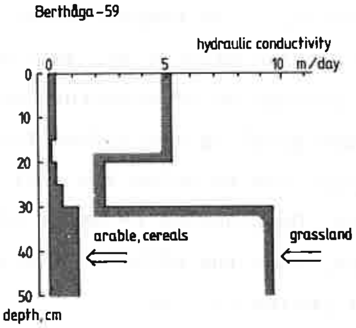

Fig. 5. Hydraulic conductivity in a clay soil under grass and under cultivation. Berthåga, Uppsala District.

Fig. 5 shows another clay soil from Eastern Sweden, namely Berthåga in Uppsala District. The diagram shows differences in hydraulic conductivity between this profile when under grass or in open cultivation for a 10 - year period. Under grass, hydraulic conductivity in the profile is very high, 1 - 10 m/day, while that in the cultivated profile is only a tenth of this. The cultivated plot has thus very poor drainage.

Fig. 6 shows results from trials with winch (tractorless) cultivation on a very heavy clay, Skultorp in Skaraborg District. Differences in the structure and permeability in plots with tractor- and tractorless cultivation are illustrated in this case by variation in air permeability with depth. Hydraulic conductivity shows the same trend. Absolute value of air permeability is less than 0.1 m/day in the subsoil. Heavy traffic produces a marked permeability minimum in the plough pan. Observations on trial sites confirm that plots subjected to tractor traffic had poor drainage and were prone to surface puddling. No surface water was observed on the winched plots and, despite the low natural permeability of the soil, the effects of drainage were high on these plots.

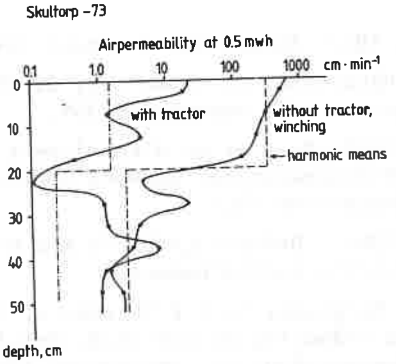

Fig. 6. Air permeability in a clay profile, with tractor and tractorless cultivation. Skultorp, Skaraborg District.

In conclusion, it can be noted that good knowledge of soil structure and function is essential for determining need for drainage, for predicting effects of drainage and for recommending drainage technique. In soils with low permeability (Group 3, Fig. 3), normal drainage is unable to control soil water conditions in periods of extreme rainfall. Worsening of the initial low permeability by soil compaction increases the drainage problem. In Sweden, there are approx. 40,000 ha of these very heavy clays in cultivation.

The second group of clays, medium to heavy clays (Group 2, Fig. 3) have usually a well developed macro-structure and good permeability to drainage depth and below. Installation of drainage systems on these soils can thus achieve good effect, although this effect can be reduced by compaction. This soil type is found in the mosaic clay area of Eastern Sweden and on the plains around Lake Vänern. Moraine clays in Skåne have similar characteristics. Together, this forms an essential and valuable proportion of Swedish arable land.

The third type of soil discussed, light clay, has decreasing hydraulic conductivity with depth above drainage depth. Due to the shallowness of the active profile, light clays require relatively intensive drainage. Soil compaction reduces horizontal flow in the profile further. There are up to 400,000 ha of light clays in Sweden, mainly in central and northern parts of the country.

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MANAGING PERMEABILITY IN FINE TEXTURED SOIL IN COOL CLIMATES

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Abstract

Recently it is frequently reported that the permeability of cool climate fine textured soils has decreased markedly. The intensity of drainage has been increased as an effort to compensate for the loss of permeability, usually by means of closer subsurface drain spacing. Factors such as continuous grain production and large machinery have been indicated as probable causes. The role of cultural practices including tillage, cropping sequence, and machine-traffic-soil relations is discussed and data are presented from an on-going experiment to illustrate the feasibility of managing permeability of these soils.

1 Introduction

When considering land drainage, soil permeability is not usually regarded as a manageable soil property. Most of us think about soil permeability as an inherent, intrinsic soil property that infers some information about the natural drainage condition of the soil and its anticipated response to artificial drainage. We also believe that we can decide the proper choice of surface or subsurface drainage improvements and the optimum spacing of drainage channels and conduits by knowing this soil property.

At the same time, we recognize that soil permeability is regularly managed in the construction of earthworks and impoundments where the objective is to diminish the soil permeability by selective placement and manipulation of the soil material. Detailed procedures and tests have been developed to assure the desired result of lowered permeability. But, very little effort has gone into the development of practices to manage, preserve or enhance the permeability to facilitate water movement in the soil.

Realistically, soil permeability is a dynamic property. It changes seasonally; it changes with cropping sequence; it changes with tillage; it changes with machinery weight. We need to examine these changes and formulate a prescription for maintaining or increasing soil permeability. Drainage system design and performance is dependent on soil permeability and if we manage the soil in a way to preserve permeability we can expect better control of excess water than by increasing the intensity of drainage to compensate for a decrease in permeability.

2 Factors affecting permeability

Soil permeability is largely a function of the size and distribution of soil pores. Therefore, it is important to begin by discussing soil pore space. In general two types of pore space occur in soils. These types are classifed as macro and micro pores. Macro pores characteristically allow the ready movement of air and water into and throughout the soil. These pores are larger than 30 micrometers in diameter. In contrast, in the micro type of pores, air movement is greatly impeded and water movement is restricted largely to slow capillary adjustment or migration. Consequently, as we discuss this topic of permeability management, we are most interested in the macro porosity of the soil. The objective of the management is to increase the fraction of the total porosity that is macro porosity.

Many natural and man induced events and processes may cause a change in the relative proportion of macro pores to total porosity. A partial list includes compaction by high axle loads and|or animal trampling; tillage; land use; drying; burrowing by worms, insects and rodents; drainage; and crop sequence. Some of these events and processes may increase the macro porosity, some may decrease the macro porosity, and some may at one time result in an increase and at another time result in a decrease.

There has been a continuing increase in the size of machines used in agriculture for all operations. Corresponding to this size increase is an increase in axle loads. Heavy axle loads cause high pressures to be transmitted deeper into the soil even though the surface contact pressure is managed at a low level by large tires. These pressures result in soil deformation, increased density and lower porosity. These pressures result in incremental changes that accumulate over time to produce, in conjunction with other processes, lower soil permeability. Deep compaction does not lend itself well to amelioration. Frost heaving does not occur at such depths; deep tillage seems to have only a temporary effect and is very costly; wetness is prolonged within and above the compact zone leading to less root and earthworm activity.

Primary tillage, if done at an appropriate moisture content, can result in an increase in soil volume, therefore, providing lower density and greater porosity, a large proportion of which will likely be macro porosity. Secondary tillage can obviate much of the benefit of primary tillage as the aggregates are broken down and packed close together again. Tillage is especially important in destroying surface crusts of low permeability. Moldboard plowing with improper adjustment can smear or otherwise destroy the continuity of pores and channels at the depth of plowing. This impedes water movement, encourages a temporary perched water table, loss of structure, and formation of a "plow pan" or layer of low soil permeability. Once begun, this is a self generating and self perpetuating condition of diminishing permeability.

Land left in native vegetation of woodland or grassland always has much more organic matter, lower density and higher total and macro porosity than after it is subjected to cultivation. Many reports give evidence of this but one that illustrates the extent of this change with depth comes from the Handbook of Ohio Experiments in Agronomy (OAES, 1957). Here, data are presented for Nappanee silty clay to a depth of 0.9 m showing the difference between virgin woodland and land cultivated for more than 40 years. In the depth increment from 60 cm to 90 cm, the volume weight increased by 19% and the total porosity decreased from 53.5% of total volume to 44.8% under cultivated land compared to virgin land. These measurements were made during the year 1945 and therefore do not represent the effects of large machines, only the natural consolidation of the soil due to loss of organic matter content. We cannot expect to retain or recover this porosity by any subsequent management schemes.

Many of the fine textured soils in cool climates have a sufficient amount of expanding clay minerals so that they shrink and crack upon extensive drying. These cracks, while they exist, serve as macro pores.

Organic residues and surface soil particles tend to fill up these cracks. Plant roots follow the faces of the cracks. Such activities promote the development of soil structure and enhance soil permeability. Similarly the channels formed by earthworms and burrowing insects and animals are large and tend to be structurally stable and persist for many years. These channels and channels left by decayed roots, especially legume tap roots, belong to the macro pore size and are important to maintaining soil permeability.

Drainage lowers the water table level in wet soils and increases the time that the soil is in a favorable moisture condition for root growth and for machinery traffic. These benefits of drainage encourage earlier, deeper and more intensive crop rooting and less opportunity for trafficking on wet soil and thereby causing structural damage or compaction. Collectively the result should be that drainage is helpful in maintaining or even enhancing soil permeability. Realistically, as farm size increases, the pressure to meet planting schedules on many acres within a fixed period of time often results in trafficking too soon on drained land. Rather than being safely trafficable the soil may be optimally compactable.

Within any given soil, the ingredients that favor a stable and acceptable permeability appear to also be those that result in the development of soil structure. Hence the preservation of permeability seems integrally related to the preservation of structure. Stability of structure is fundamentally related to maintenance of organic matter content. Evidence from crop rotation studies in many locations over many years have shown that total porosity, macro porosity and water stable aggregates are all greatest when the cropping sequence includes a grass-legume sod. One year of sod is better than none, but two years seems much more desireable for maintaining macro porosity. The problem for the farmer is, however, that there is no market for the forage. Some farmers have opted to produce high amounts of organic matter by striving for high grain yields.

3 Techniques for enhancing permeability

Presently we know very little about enhacing permeability or for that matter what effect cultural practices and soil management have on any physical properties of the soil. It is frequently suggested, as I have done earlier in this article, that several years of good sod will rehabilitate the soil. Are there other approaches that can be used? Are there other approaches that have a greater appeal to the farmer from an economic viewpoint? It seems well established that a rotation of grain and forage where the sod remains 2 or more years out of every 5 years will be acceptable to maintain soil permeability. But what do we offer to the grain farmer or the vegetable producer as a recommendation for long term maintenance of permeability?

One idea of value it seems is to encourage the use of controlled traffic. Traffic lanes would of course become somewhat compacted, but only the lanes would be affected. The non trafficked areas could be deep tilled when the soil is dry to break up existing dense layers. Proper care to maintain an open surface for infiltration and good surface drainage seem to be necessary components of such a system. Efforts to increase the organic matter content should be made.

4 Ohio Field Studies

We have begun a field experiment in Ohio to examine the recovery of permeability in a Hoytville silty clay soil that has a very low permeability layer created by tillage and traffic. This layer is approximately 20 cm thick and it lies between 30 and 50 cm depth in the profile. We have established 2 cultural practice treatments for study. One treatment is an alfalfa-red clover sod that was seeded in June of 1984. The second treatment is a conservation tillage practice known as ridge tillage on which we have a corn-soybean rotation. The ridges were formed in January 1984 after moldboard plowing. The practice involves removing the top several centimeters of the ridge with a cultivator sweep mounted ahead of the planter units. A cultivation is done in June each year to provide some weed control and to rebuild the ridge. No other tillage is performed and all operations are carried out on controlled traffic lanes. We measure surface runoff and subsurface drain flow to evalute these systems. Some of the subsurface drains also have a gravel backfill that acts as a hydraulic connector between the drain and the formerly cultivated layer of the profile.

Drain flow measurements in 1980 and 1982 indicated peak flow rates of 0.15 m^3|day|m without gravel backfill and 0.52 m^3|day|m with gravel backfill. During 1985, the flow rates from the sodded area were 0.08 m^3|day|m without gravel backfill and 1.02 m^3|day|m with gravel backfill. The flow rates from the controlled traffic-ridge till area were 0.11 m^3|day|m without gravel backfill and 0.49 m^3|day|m with gravel backfill. Peak surface runoff rate was 3.2 mm|hr from the ridge till treatment and 1.8 mm|hr from the sodded treatment. These data are preliminary and represent only 2 crop years and 1 winter for treatment effects to begin to have an influence. The data suggest some positive influence of the sod treatment on reduced surface runoff and enhanced tile discharge where gravel backfill was used. We expect to continue to monitor these systems for 3 to 5 more years to accumulate evidence about any changes in soil permeability with time. Other similar studies are needed to verify the effects of management schemes on soil permeability so that recommendations can be made to farmers regarding techniques to manage soil permeability.

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FIELD EXPERIENCE AND LABORATORY RESEARCH ON DRAINAGE ENVELOPES

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Abstract

Drainage practise and practical experience on drainage envelope materials in Belgium are described. This experience shows that it is very difficult to predict the need of envelopes and the kind of envelopes to use. They are still always based on too subjective criteria. Therefore a model research has been set up, to simulate flow conditions in the vicinity of drain pipes. It allows to predict the need of envelopes and to select the most suitable envelopes.

1 Introduction

Drainage materials have gone through an important evolution, the last twenty years. The formerly frequently applied clay drain pipes are, in Belgium at least, completely replaced by corrugated drain pipes of polyvinyl chloride. Smooth plastic drain pipes were not used in a large extend. Corrugated plastic túbing allows a far-reaching mechanization and lends itself very easily to prewrapping with envelopes. Envelope materials are mainly used to prevent soil particle invasion into drain pipes, although they also contribute to improve the drainage function of drain pipes

In spite of the evolution in drainage materials, the problems of malfunctioning are still existing because the need for drainage envelopes is not clear in some soils. Also the kind of envelope to use is still unsolved ; especially the mechanical function of drainage envelopes to retain soil particles, without blocking and/or clogging, is not well understood.

The soil invasion problem into drain pipes mainly depends on the structural strength of the soil. In cohesionless sandy soils drainage pipes do need an envelope, while in stable structured cohesive clay soils no envelopes are required. Based on the granulometric composition of a soil, it is very risky to predict its structural stability.

Indeed structural stability does not only depend on the physical soil composition, such as the clay content or the clay/silt ratio, but also on the physical soil conditions, such as the initial moisture content before wetting, on the water flow conditions, such as the hydraulic gradient, and on the chemical composition, such as the sodium concentration. Envelopes are required when the acting hydraulic gradient exceeds the critical hydraulic gradient whereby the disruptive forces exerted by the flowing water cause structural destruction (DIERICKX, 1986a).

2 Drainage practise

Nowadays drainage in Belgium is carried out using modern trenching machines with digging chain, and trenchless machines with the ripper or with the V-plough. Depth regulation occurs with laser beam. Exclusively corrugated polyvinyl chloride drain pipes are used. In practically all cases the drain pipes are wrapped with an envelope which was, in the past, only coconut fibre wrapping ; before also flax straw was successfully applied. Glass fibre sheet and glass wool were also used but their susceptibility for blocking and clogging, especially in soils with a high clay and/or silt content, rich in organic dust or where a risk of iron deposits exists, has cancelled their use as a drainage envelope. Other materials have been tried but they are, for one reason or another, never been accepted. Flax straw and coconut fibre are organic materials which deteriorates ; especially coconut fibre can decay very rapidly, whereby the coconut fibre envelope looses its protective function. Therefore, actually, loose synthetic fibre envelopes are recommanded. This envelope material should meet the following preliminary requirements : a mean thickness of at least 6 mm and a minimal thickness of 5 mm ; a mean weight of at least 450 g/m² and a minimum weight of 400 g/m² ; the 90 % pore size diameter, as a mean value of 5 replications, is in between 600 and 1000 µm ; each individual value does not deviate more than 25 % from the mean value.

3 Actual knowledge on drainage materials

Drain pipes are not completely pervious : their perforated area takes only 1 to 2 % of the total pipe surface. Compared to flow towards an ideal drain, commercial drains cause an extra head loss due to flow towards the isolated inlets.

This flow produces an extra resistance, the so-called entrance resistance. Per unit of hydraulic conductivity this entrance resistance depends only on the drain pipe, ignoring the boundary with the soil. Factors determining the entrance resistance are the total inlet area, and the shape and distribution of the openings. For the same inlet area the lowest entrance resistance is obtained at pipes with the smallest openings, having the largest number of openings (DIERICKX, 1980). It is theoretically proved that corrugated plastic drain pipes, in spite of their smaller outside diameter, should function as well as and even better than clay drain pipes, mainly due to the uniform perforation distribution (DIERICKX, 1985).

Envelopes are mainly used to prevent soil particle invasion into drain pipes ; they can also contribute, in an important way, to the decrease of the entrance resistance. Envelopes operate most efficiently at a thickness of at least 5 mm ; their relative hydraulic conductivity, related to the surrounding soil, should be at least 20 (NIEUWENHUIS & WESSELING, 1979 ; DIERICKX, 1980). The use of suitable and sufficiently thick envelopes strongly levels the differences in entrance resistance between drain pipes and, as a result of the lower entrance resistance of the drainage system, a clearly better drainage efficiency is obtained.

The property of envelopes to retain soil particles is called the filter function. Envelopes must be chosen in such a way that, once installed, no important soil particle invasion into drain pipes occurs. The choice of an envelope is determined by the nature of the soil material, which can be cohesive or cohesionless.

Because of arch formation and hook resistance or apparent cohesion, the largest pores of the envelope material need not necessarily correspond with the smallest particle diameter. Also in fine-textured cohesive soils, it is useless to apply envelopes with a pore size corresponding to a certain particle diameter. It may be accepted that no important through-flow of soil particles occurs when the ratio of the 90 % pore size diameter to the 90 % particle size diameter is between 2 to 3 (DIERICKX, 1986b).

Mostly the pure hydraulic conductivity of the envelopes used is very large compared to the one of the soil ; at the interface soil/envelope the hydraulic conductivity normally diminushes, as a result of the blockage of the apertures of the envelope by soil particles. This phenomenon is called the blocking of envelopes, which can cause an additional flow resistance, as an envelope with insufficient hydraulic conductivity does.

Besides blocking, an envelope may be susceptible to clogging. Contrary to blocking, which is observed immediately, the clogging phenomenon arises in the course of time and is due to the deposition of fine soil particles, to organic dust and to chemical deposits. The problem of chemical deposits can hardly be simulated, but the susceptibility of clogging of envelopes by fine soil particles and organic dust can be evaluated in the laboratory.

It is accepted that all envelopes perform well in cohesionless sandy soils with a small clay and/or silt content and little organic dust, if the envelopes used are sufficiently permeable and not too coarse in order to fulfil the filter function.

So much is certain in structured soils, that it has no sense to assert that, from a certain clay content on, drain pipes do not need envelopes. The soil invasion problem mainly depends on the structural strenght of cohesive soil. The need of drain envelopes will largely depend on the ability of the structured soil to withstand the pressure exerted by the flowing water, and does not only depend on the physical composition of the soil, but also on its chemical composition. The initial moisture content before wetting also influences the structural soil stability (DIERICKX & YÜNCÜOĞLU, 1982).

4 Field experience

Some experimental fields were installed to evaluate the treatment of trench backfill with soil conditioners and to compare it with plain drains, drains wrapped with coconut fibres and drains wrapped with tangled synthetic fibres. Drain pipes of these experimental fields were visually inspected by endoscopy, and other installed drain pipes were dug up, to evaluate soil invasion into drain pipes (DIERICKX, 1986a). Experimental fields were installed on grassland and on arable land with, at drain level, a loamy texture (clay content of 10 %), a sandy texture (clay content of 4 %) and a sandy clay loam texture (clay content of 25 %).

From this field experience it follows that stabilisation of the trench backfill does not prevent siltation of drain pipes. Organic envelopes and especially coconut fibre are sensitive to decay, soon or later ; hence siltation hasard of drain pipes still latently exists. Tangled synthetic fibres seem to function well in light textured soils. In fine textured soils a large amount of fines are found in the pipe because of too coarse an envelope ; hence they were not so effective as supposed.

Since the coconut fibres of a mixture with synthetic fibres also decay, the remaining synthetic fibre envelope may become too coarse to prevent soil invasion.

5 Laboratory investigation

Because of the large variability of soil properties, it will be very difficult to assess differences in drainage working in the field. It is also difficult to ascertain what is happening in the vicinity of drain pipes and the phenomena which occur. In order to obtain a better understanding of the drainage problems an hydraulic flow model was developed. The model is shown in fig. 1. It consists of a vertically mounted plexiglass cylinder, which is partly filled with soil aggregates for the particular case of cohesive soil.

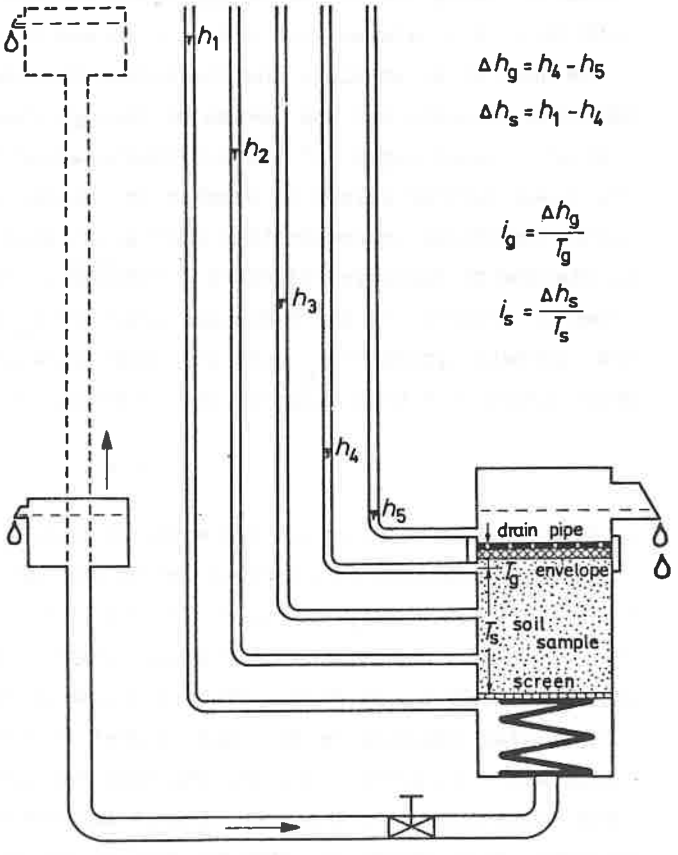

Fig. 1. Scheme of the apparatus for testing the functional properties of envelopes.

Since the soil is subjected to an upward flow, the eventually used envelope and the open-folded and flattened drain pipe are placed above the soil. A spring beneath the soil sample keeps the soil slightly in contact with the envelope or the drain pipe. A movable reservoir with overflow enables the setting of the hydraulic gradient. The plexiglass cylinder is provided with piezometric tubes to measure the hydraulic head at different places in the soil sample and at the soil/envelope interface.

Since conclusions based on one experiment are uncertain, the soil aggregates are prepared in a certain way to obtain comparable replications. The method usually applied consists of passing air-dried soil clods through a 5 mm square hole sieve. These aggregates were brought to a slightly higher moisture content than the desired one by spraying water with a paint gun while mixing. The moist aggregates were sieved again through 4.76, 3.36 and 2.00 mm square hole sieves. Aggregate samples were then prepared, using the following aggregate composition : 40 % between 0 and 2.00 mm ; 40 % between 2.00 and 3.36 mm and 20 % between 3.36 and 4.76 mm.

The need of an envelope and the filter function of an envelope can be observed visually and the degree of through-flow can be quantified from a slight discoloration of the outflowing water to the fatal through-flow. The model further allows to predict the blocking and clogging risk of envelope materials in combination with given soil types or soil conditions by piezometer readings (DIERICKX & YÜNCÜOĞLU, 1982). Blocking can be derived by determining the hydraulic gradient i_s over the soil column and the hydraulic gradient i_g over the drain pipe with or without envelope which includes a thin layer of soil material. If the condition

$$i_g \leq i_s$$

is fulfilled no blocking of the envelope occured.

The susceptibility to clogging can be derived from the ratio of the hydraulic conductivity of the envelope in contact with the soil to the hydraulic conductivity of the soil itself. An increase of this ratio indicates a change in favour while a decrease denotes a clogging.

It is also possible to find out at what flow pressure the cohesive forces will be neutralized, causing soil failure.

For cohesionless soil upward flow is applied because of the more unfavorable flow situation, whereby soil particles are subjected to two antagonistic forces : the flow pressure directed upward and the gravitational force directed downward.

Both forces may neutralize each other, creating an unstable situation at that very moment. Application of downward flow results in two superposing forces, which stabilize the situation by stable arch building. Although not so evident, experiments confirmed that this also holds for cohesive soils (DIERICKX & YÜNCÜOĞLO, 1982).

6 Research findings

From his experimental work on several soil types, WILLARDSON (1984) concluded that there were no differences between the envelope materials ; instead, it was the soils themselves that differed. Our research work partly confirmed this statement. Not only the soils themselves may differ ; within one soil type conditions can be so different that they prevail against the envelope materials. Soil stability depends very much on the initial moisture content and therefore soil will react totally different upon wetting. Air-dried soil aggregates break down in soil particles and much smaller aggregates when saturated, causing an immediate fall of the hydraulic conductivity, which further decreases with increasing hydraulic gradient. After saturation and at lower hydraulic gradients, moist soil aggregates initially show higher hydraulic conductivities, which also decrease with increasing hydraulic gradients. The more stable situation of the moist aggregates when wetted and the larger pores between aggregates explain the higher initial conductivity. The more or less rapid decrease of the hydraulic conductivity with the hydraulic gradient is attributed to the weakness of the aggregates, whereby flow pressure squeezes them together (KABINA & DIERICKX, 1986). Meanwhile soil particles are detaching themselves from the aggregates, causing a slight soil particle movement, up to a given moment at which the cohesive force is neutralized by the flow pressure : the soil fails and the fatal soil particle movement starts.

Envelopes should prevent the wholesale soil particle invasion into drain pipes, but when the soil fails, the whole drainage system fails and hence all envelopes, whatever they may be. So envelopes have to contribute to the prevention of soil failure. Due to the radial flow approach towards drain pipes, high hydraulic gradients may occur in their vicinity. For the same circumstances the hydraulic gradient near drain pipes depends on their entrance resistance (DIERICKX, 1980 ; 1983).

As envelope materials decrease the entrance resistance, the hydraulic gradient will be lowered too and soil failure near the drain pipe, where the gradient is largest, will be avoided. Although the absolute values differ, WILLARDSON (1982) came to the same conclusions.

In the case of soil failure, too fine envelopes will retain all soil particles, creating a quasi-impermable layer surrounding the drainage system ; too coarse envelopes will result in a wholesale soil particle invasion into the drain pipe.

If no soil failure occurs, detached soil particles flow towards the enveloped drain pipe through the active pores. Thin or thick fine textured envelopes will retain fine soil particles, filling up the active pores and reducing the drainage function (fig. 2 a,b). Thin and coarse textured envelopes which are able to retain soil particles by arch building will function quite well, but it will be very difficult to be at the limit of arch formation. Thick coarse textured envelopes, which allow arch formation and even soil particles to penetrate into the envelope (fig. 2 c), keep the active pores functioning as soil particles are distributed in the envelope ; some of them can be washed out, but the more permeable envelope allows water to flow in all directions towards the perforations (KABINA & DIERICKX, 1986).

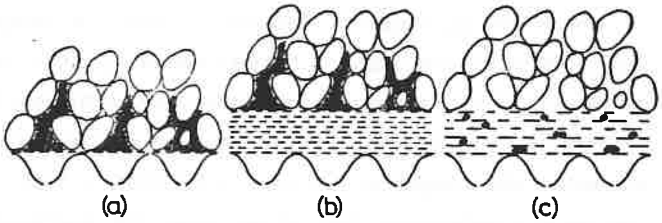

Fig. 2. Drainage envelope functioning
a. Thin and fine textures envelopes
b. Thick and fine textured envelopes
c. Thick and coarser textured envelopes

7 Conclusions

In practically all cases drain pipes are wrapped with envelopes, which were mainly of organic origin, formerly flax straw wrapping, recently coconut fibre wrapping.

Because of their susceptibility to decay, there is a tendency now to replace the coconut fibre wrapping by synthetic fibre wrapping ; this drainage envelope is more expensive than the coconut fibre envelope. Although these synthetic fibres do not decay, it does not mean that this kind of envelope to be the best. The best suited envelope is not yet found. Other trials using soil conditioners to stabilize the trench backfill were not successfull.

Some definite statements on drainage envelope materials may already be made under certain circumstances, such as cohesionless sandy soils. Drain pipes laid in such soils do need an envelope, whereby the kind of envelope is less important, if sufficiently permeable and not too coarse so that the filter function is fulfilled.

In cohesive soils the need of envelope materials depends on the structural stability, which may not only be related to the physical soil composition ; it also depends on the chemical soil composition, on the ability of the cohesive soil to withstand flow pressure and on the physical soil conditions.

Model research, which enables the simulation of field conditions, allows to predict the need of drainage envelopes and the kind of envelope to use. Research findings indicate the importance of the soil itself, which may react differently according to its moisture content before wetting. Dry aggregates immediately break down in smaller onces, while wet aggregates are squeezed together at increasing hydraulic gradient. Detached soil particles are transported through the active pores towards the protective envelope. Too fine envelopes retain fine soil particles in those active pores. Thick and coarser textured envelopes, which enables soil particles to arch or even to penetrate into the envelope, keep the active pores functioning.

Acknowledgement

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SEDIMENT INFLOW INTO PIPE DRAINS THROUGH SYNTHETIC ENVELOPES AND PIN HOLES

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Abstract

Laboratory tests were conducted on synthetic fabrics with square openings and on a plate surface with pin-holes for the purpose of preventing sediment inflow. The fabric was woven nylon screen with precise-sized openings and the pin-holes were drilled in plexiglass. Nearly cohesionless sand was obtained from natural sources in Ohio and North Carolina. For the range of sands tested, sediment movement can be prevented with openings up to about 2 to 4 times the soil particle size at which 60% pass a standard screen.

1 Introduction

With the introduction and widespread use of corrugated plastic drain pipes has come the development of synthetic fabric coverings and commercial production of pin-hole perforated tubing for the protection of these drains against sediment inflow. The synthetic "envelopes" have advantages of low cost and ease of transportation and installation compared to gravel envelopes. Fabrics may be placed directly on the pipe in the factory or they may be placed around the pipe at the time of installation. Such fabrics are also commonly known as geotextiles. Pin-hole perforated plastic tubing can be produced in the factory and installed without additional cost compared to more conventional tubing. It could also be wrapped with synthetic fabrics.

The major factors central to the problem of sediment control are; (a) size and shape of the openings, (b) size and shape of soil particles, (c) cohesion forces in the soil, (d) clogging of the openings with fine particles, (e) deterioration of fabric material by chemical or bacteriological action in the soil and, (f) physical damage to fabric during installation and maintenance operations. Items (a) and (b) were the only factors considered in this study. Fine sands were used in the tests, thus cohesion was not a factor and clogging was not a problem.

The purpose of this paper is to evaluate synthetic fabrics and pin-hole perforated tubing for use in cohesionless fine sands to prevent sediment inflow into subsurface drains. Design recommendations given here are based on limited tests and should be verified under field conditions.

2 Materials and Procedures

Beginning from the premise that there is an opening size which will be too large to restrain a given soil particle size, and one so small that flow will be excessively restricted, it follows that there must exist an optimum opening size, or range of optimum opening sizes between these two extremes. The laboratory experiments were conducted with a 100-mm diameter, 400-mm high plexiglass permeameter, which consisted of two cylinders and a base plate fitted together. The envelope fabric or the pin hole plate was sealed into the permeameter as shown in Fig. 1. The passage of sand through the test specimen was considered as a failure and was determined visually. The susceptibility to failure was evaluated by relating observed failures to the hydraulic failure gradient, as defined by Willardson and Walker (1979). Other criteria evaluated were the volume of sediment flow through the envelope and the water flow rate.

For the fabric tests, the sand was mixed from size fractions of two field samples by sieving the original sand and then recombining to give the desired particle-size distribution curves. Three D_{60} sizes (60% passing) were selected (0.10, 0.14 and 0.20 mm), each with three different uniformity coefficients, which were the same for each of the three different D_{60} sizes. The uniformity coefficient is a measure of the particle size variation (D_{60}/D_{10} in this case). The smaller the uniformity coefficient (i.e. the closer it comes to 1.0), the steeper the grading curve. Sample grading curves are given in Figures 2 and 3. Sample B in Figure 2 is the original field sample, Liberty Center sand, from which samples A and C were fabricated. The remaining samples (D thru I) were fabricated from North Carolina white sand. Soil samples for the pin-hole tests are shown in Figure 3.

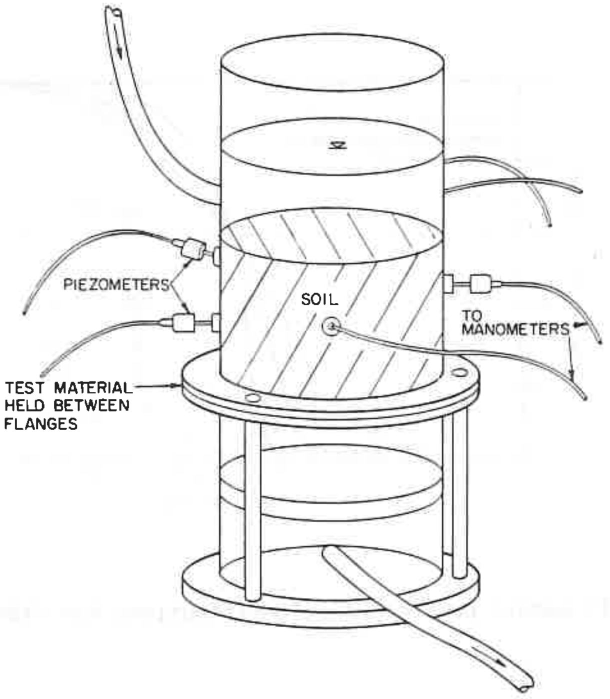

Figure 1. Diagram of the permeameter. Not to scale.

In order to make a qualitative evaluation of the relationship between particle and opening sizes, special woven nylon screen materials, having precise uniform openings were used as the envelopes. They were selected for research purposes only and, because of their high cost, are not intended as envelope material for field use. Square opening sizes were 0.25, 0.30, 0.425, 0.50, 0.60, 0.71, 0.85, and 1.0 mm.

Approximately a 75-mm depth of dry sand was placed on top of the envelope. Water flow was vertically downward through the sand. A fine filter was used to catch and retain soil which fell through the envelope during the test. For the fabric tests, tap water was sterilized with 50 ppm mercuric chloride, filtered and passed through an elevated vacuum flask to remove air from the water before using. Further details are described by Broadhead et al. (1983).

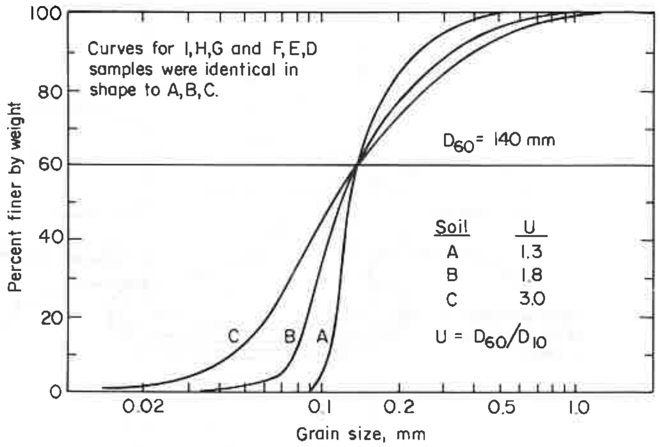

Figure 2. Soil sample particle size distributions for fabric tests.

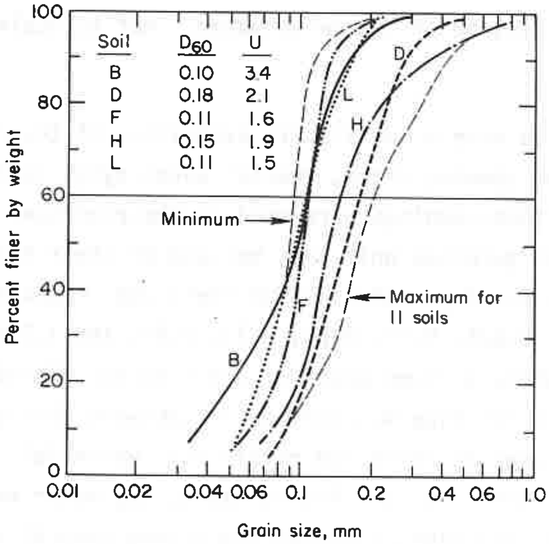

Figure 3. Soil sample particle size distribution for pin-hole tests.

For the pin-hole tests, 21 holes were drilled in a 100-mm diameter plate of plexiglass, 1.6 mm in thickness. This spacing is equivalent to 302 holes per foot length for 114-mm diameter (o.d.)tubing. Holes with 19-mm spacing were uniformly distributed on the plate. Sizes tested ranged from 0.4 to 2.5-mm diameter. Several plates were tested for each soil sample.

The permeameter shown in Figure 1 was modified slightly for the pin-hole tests. As in the fabric tests, piezometers were installed in the soil column. For the pin-hole tests tap water was not sterlizied, but it was filtered and deaerated.

Eleven sand samples of agricultural soil were tested having D_{60} sizes ranging from 0.10 to 0.21 mm and uniformity coefficients all less than 3.6 (D_{60}/D_{10}). Typical gradation curves are shown in Figure 3. Soil samples B, D, and F were original field samples. Sample H was a mixture of two other field sands. All remaining samples were fabricated from other soils by washing out the silt and clay in a cement mixer for 30 minutes. Limits for the 11 soils are shown by the two dashed lines in Figure 3.

3 Synthetic Fabric Tests

The results from 55 permeameter tests on 9 sand samples are summarized from Broadhead et al. (1983). Hydraulic gradients were continually, but slowly increased to ensure that the failure observed was due solely to excessive gradient. For each sand, there was an opening size below which failure did not occur, regardless of the hydraulic gradient. The average square opening size below which failure did not occur is

$$D_s = BD_{60} = 2.3\ D_{60} \qquad (1)$$

where D_s = square opening size in mm,
B = bridging factor, and
D_{60} = sieve opening size in mm at which 60% of sand passes.

The bridging factor defined above was found to range from 1.5 to 3.5. Broadhead et at. (1983) recommended a factor of 2.4 for square openings.

For practical use, the bridging factor for commercial fabrics with randomly placed fibers should probably be reduced to 2.0. Reasoning for such a reduction is given under the discussion heading. Generally, the minimum opening size, which prevented any sand passing, increased with increasing D_{60} size, although it was not completely consistent.

Soil uniformity appeared to play no part in the relationship between the hydraulic failure gradient and the minimum fabric opening size. Although, generally, the more uniform the sand, the less was the range in opening sizes between complete failure and no failure.

There was no significant variation in flow rates with fabric opening size. General trends were an increasing flow rate with increasing D_{60} size and increasing flow with increasing uniformity.

As might be expected, the bridging factor for dry sand would be higher than for wet sand. Willardson (1979) found this factor to be 3.0 for successful bridging of dry sand.

It was obvious that at high gradients the sand samples became increasingly stable. An envelope was more likely to pass sand at a low hydraulic gradient (i.e. less than 1.0) than at high gradients. Even through few gradients higher than four were recorded, the samples were subjected to much higher gradients during the draining of the apparatus, and at no time was failure observed at this stage, if not observed previously. This phenomena is a result of increasing effective stress. The effective stress is the sum of the components of the contact forces normal to a plane passing through the contact points over a unit cross-sectional area of soil. As the hydraulic gradient through the sand increased, the head loss also increased. This, in turn, resulted in an increase in the effective stress.

4 Pin-Hole Tests

In the pin-hole tests, the influence of the hydraulic gradient and the effective stress on sediment inflow was similar to that for fabrics, described by Broadhead et al. (1983). As with the fabric tests, the flow rate did not increase with an increase in hole diameter.

For the limited range of cohesionless sands tested, a bridging factor of about 5.0 or less will prevent sediment inflow. The range for all tests was 4.9 to 9.9. A factor of 4.0 or less is recommended for design. This factor would allow a factor of safety and be more consistent with other recommendations. The U.S. Army (1971) recommended a bridging factor of 1.0 or less and the USBR (1973) a factor of 0.5, using D_{85} size for the filter material. D_{60} is always less than D_{85}. The bridging factor using D_{60} ranged from 13 to 83% more than using D_{85} for the 11 soils tested. The average D_{85} was 41% greater than D_{60}. Bridging over a round hole will occur with a smaller particle diameter than over a square opening of the same area. In a soil with a bridging factor of 1.0, about 40% of individual soil particles would be larger than the hole.

The bridging factor for pin-holes was further evaluated in a small sand tank using (1) 100-mm diameter commercial pin-hole perforated tubing and (2)tubing with 0.635-mm diameter drilled holes. The D_{60} of the sand was 0.11 mm. The commercial pin-hole tubing was perforated at the factory with about 1800 holes per foot, with diameters varying from 0.4 to 1.5 mm. The holes were also indented on the outside surface because they were punched in with sharp needles. The penetration of the needles varied, which accounted for the large range of hole sizes and shapes. The commercial pin hole tubing allowed considerable sand inflow (failure) when the sand was saturated, whereas the tubing with the 0.635 mm diameter drilled holes effectively restrained sediment inflow, even though the bridging factor was 6.0 (0.635/0.11). Visual observations through a plexiglass plate on the sand tank indicated some initial sediment inflow, but the sand would stabilize as the hydraulic gradient increased. Spherical air pockets were observed over the holes inside the tubing which would likely block water inflow. Slight vibration of the tank would instigate sand inflow for a short time and then it would become stable. Possibly, a high water velocity inside the tubing might cause instability of the sand near the openings, but this effect was not investigated. Neither was the effect of air pockets on inflow. For these reasons, and because a limited number of sands was tested, a bridging factor of 4.0 is recommended rather than the measured value of 6.0.

5 Discussion

Commercial synthetic fabrics made of nylon, fiberglass, or polyproplene with randomly placed fibers do not have uniform size openings. They also have openings of varying shapes, usually not circular. The best criteria for fabric opening size is the EOS (Effective Opening Size) test developed by USCE (1955). Many agree that EOS leaves much to be desired, but it is in common use. A fabric could have a reasonable EOS, but if it has a few large openings, sand inflow could be serious. For this reason the bridging factor should be verified for each fabric. Obviously, a torn or damaged fabric or a large hole at any point could result in failure of the entire line.

In commercially perforated pin-hole tubing, the indentation on the outside surface could affect the bridging factor. Some have suggested that holes be punched from the inside out, but this may not be physically possible. As with commercial fabrics, the variation in pin-hole diameter, especially any large holes, may cause serious sediment inflow. Commercial tubing can be easily perforated with a large number of openings, several times as many as used in the permeameter tests.

Although these tests did not show that the inflow of water decreased with decreasing hole sizes, this decrease would be likely for very small openings or for a small number. The entrapment of air might restrict water inflow. Surface tension effects above the water surface in the tubing also could restrict inflow. Finally, the ultimate test is good performance in the field. Because openings in commercial fabrics and tubing vary in size and shape, and because only a limited range and selection of cohesionless sands were tested, these recommendations should be verified under field conditions.

Sands with some clay or other cementing material would tend to be more stable than those tested. The bridging factors recommended here apply to cohesionless sands and are believed to be conservative.

6 Conclusions

The following conclusions may be drawn from this investigation:

1. Below a given fabric envelope opening size, sediment is restrained independently of the hydraulic gradient. For the sands tested, this square opening size (D_s) to prevent sedimentation should be equal to or less than 2.4 times (called the bridging factor) the sand D_{60} size. For

random fabrics, a bridging factor of 2.0 is suggested.

2. Sands with high uniformity coefficients will cause greater sedimentation into a drain than well-graded sands when synthetic envelope openings are too large to support stable bridges of sand particles. Well-graded sands are more stable in the vicinity of large envelope openings than uniform sands.

3. In the case of downward seepage of water towards a drain, sand particles become increasingly stable at high hydraulic gradients, provided that a stable structure exists at the synthetic envelope-sand interface. This stability is a result of increasing effective stresses between sand particles.

4. For uniform size pin holes in tubing, the range for maximum hole diameters was 4.9 to 9.9 times the D_{60} of the soil for all tests. For practical purposes, considering the hole-size variability in commercial perforated tubing and the limited number of sands tested, a bridging factor of 4.0 is recommended. This value is higher than recommendations by U.S. Army (1971) and USBR (1973).

5. The above bridging factors are for cohesionless sands. For sands with clay or other cementing materials, these factors could probably be increased, but this effect and that for small openings on inflow were not investigated.

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ORGANIC AND SYNTHETIC FIBRES AS DRAINAGE FILTERS

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Abstract

In Sweden, there is growing interest in the use of drainage pipes pre-wrapped in a filter envelope. Properties of several such filter materials were tested. Results of laboratory tests, a model experiment and field trials are reported. Effectiveness of filter envelopes in presenting silting up of pipes and in permitting water flow into pipes is discussed.

1 Introduction

In Sweden natural gravel and, to a lesser extent, sawdust have long been the materials used as filters for drainage pipes. These filter materials have many functional advantages but, from a practical point of view, obvious disadvantages. Relatively large labour inputs are required to transport and spread gravel and sawdust. With the intention of reducing labour requirements and increasing efficiency of drain installation, alternatives such as organic or synthetic fibres have been tested. Drainage pipes are pre-wrapped with envelopes made from these materials. To some extent, the increasing use of organic and synthetic envelopes is also a result of unavailability of gravel and sawdust in some parts of Sweden.

In Sweden, as in many other countries, work is going on to develop testing methods for envelopes. The methods can be divided into two types, those for testing the properties of the envelope material and model tests where conditions in the field are simulated. These methods provide a basis for a preliminary selection of an envelope, the functioning of which must then be investigated in the field. In this paper laboratory tests, model experiments in a sand tank and some field experiments are described.

2 Testing the filter envelope

The laboratory method of moisture retention measurement allows particle size distribution of the filter material to be determined. The sample material is placed in a steel cylinder and increasing suction is applied (Fig. 1). Assuming that water is retained in the pore system of the material solely by capillary forces, pore size can be calculated from the expression: $h_t = 0.3/d_v$, where h_t is suction cm w.c. and d_v is pore diameter in cm (Andersson, 1962, Ericson, 1981). This moisture retention method works best for dense material but can be used on all materials. An advantage with the method is that the sample can be compressed, which allows the effects of compaction on pore size distribution to be studied. Fig. 2 shows pore size distribution of materials under 1.5 Kp/cm^2 pressure. This compression value is approx. 10 times greater than the compaction a filter material is subjected to in the field but was considered necessary to compensate for the normal shrinkage of a material under pressure for a long period. From Fig. 2 it can be seen that coco-fibre had a much coarse pore system than the other materials investigated. However, sawdust had the greatest variation in pore size while materials such as the non-woven fiber wraps had a very narrow pore size range.

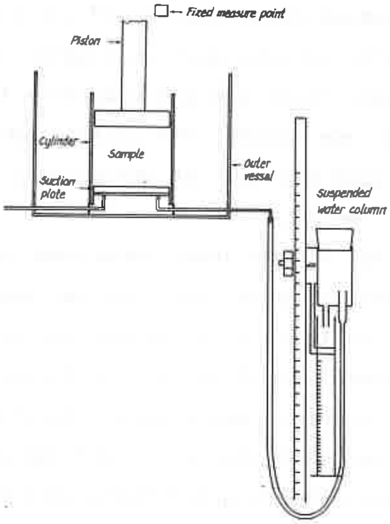

Fig. 1. Apparatus for moisture retention measurement (Ericson, 1981).

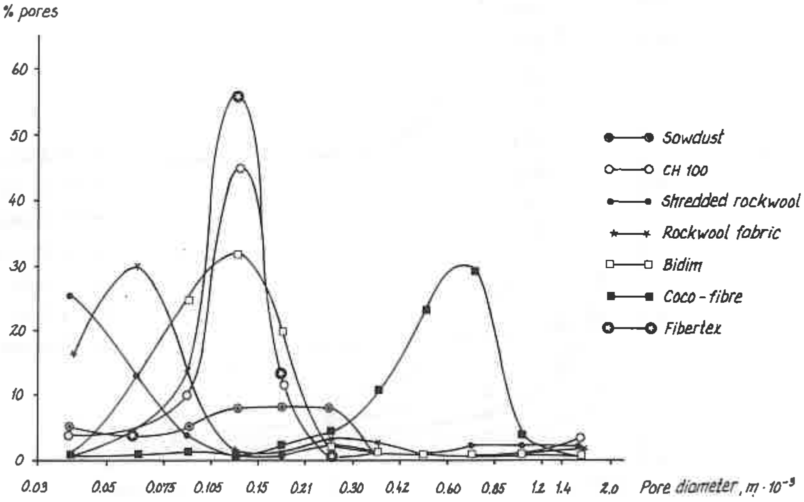

Fig. 2. Pore size distribution o different envelope and filter materials when 1.5 $\mathrm{Kp/cm^2}$ pressure is applied (Ericson, 1981).

Using a method described by Ericson (1981) and shown in Fig. 3, hydraulic conductivity was measured in samples under increasing compression. Results for these measurements are shown in Fig. 4. The coco-fibre material with its coarse pore system has 5 times greater hydraulic conductivity than other materials. The high hydraulic conductivity of the thin, porous filter CH 100 decreases rapidly with increasing compaction. On the other hand hydraulic conductivity of Bidim is scarcely affected by compaction.

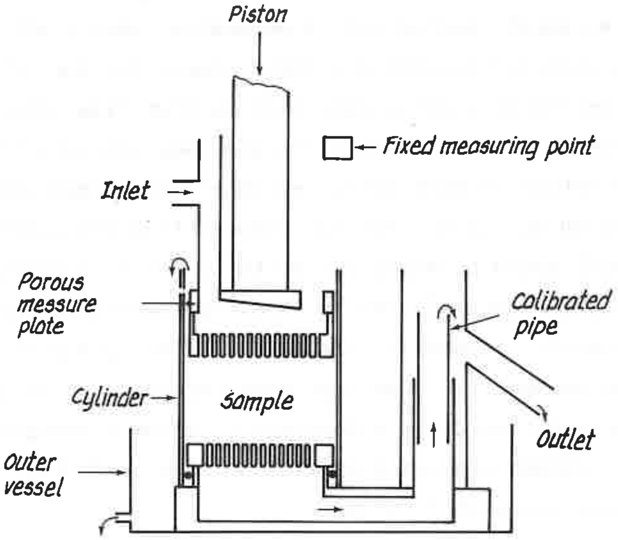

Fig. 3. Apparatus for hydraulic conductivity measurement (Ericson, 1981).

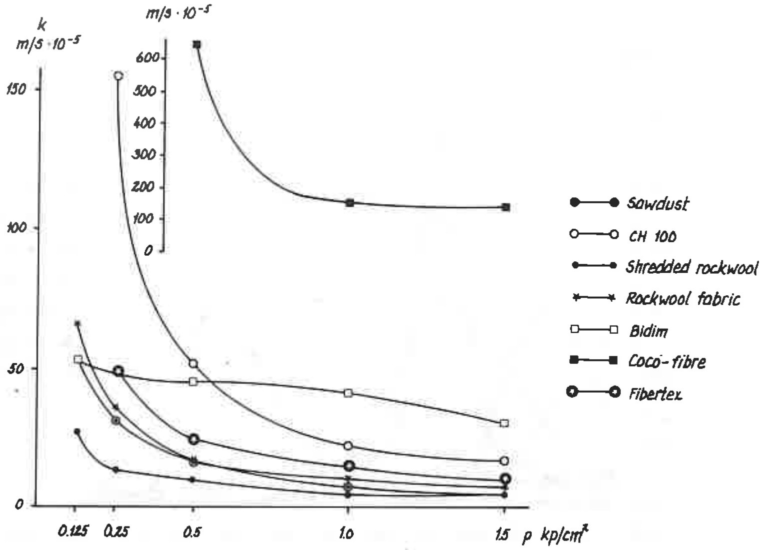

Fig. 4. Influence of different compressions on hydraulic conductivity of different filter materials (Ericson, 1981).

3 Model experiments

Experimental equipment consisted of a sand tank, apparatus for removing air from the water and a number of piezometers connected to waterlevel tubes (Fig. 5). Then sand tank consisted of a U-formed soil reservoir and an outer tank which could be filled to a regulated level with water. The drainage pipe encased in the sample envelope was set in the U-formed container. Since the long sides and base of the U consisted of wiremesh covered with a permeable fibre cloth, a groundwater flow was directed towards the drain pipes. One end of the drainage pipe was connected to a plexiglass disc so that flow into the pipe could be observed. The other end of the pipe was connected to a sandtrap allowing collection of soil particles which had passed into the pipe and been carried out again. Air was removed from all water entering the system.

Soil could be emptied from the inner tank through a pipe in its base. The soil material used in this experimental apparatus had to be easy to handle, permeable, prone to silting-up and be reasonably homogenous. High permeability was important partly to allow sufficient ground water flow into the drain and partly to allow a reasonable run duration. The soil chosen consisted chiefly of fine sand (Fig. 6) and had a hydraulic conductivity of 1.7 m/day.

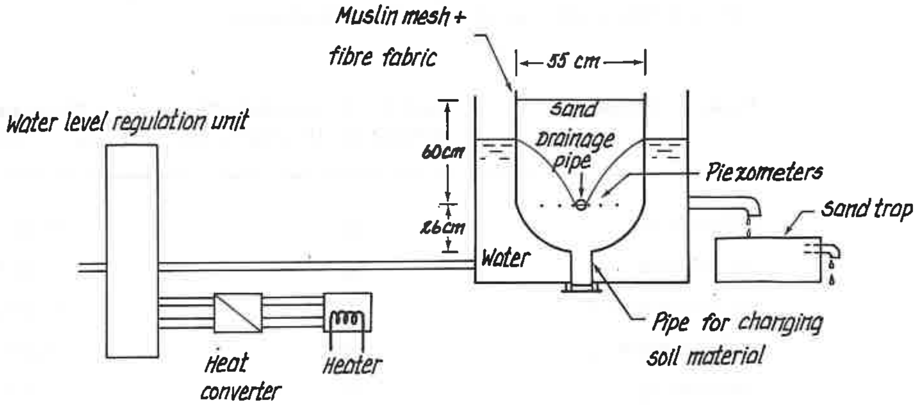

Fig. 5. Laboratory apparatus for testing envelope and filter materials.

Results of experiments using this model are shown in Table 1. The thick envelopes of coco- and polythene fibre were best at reducing entrance resistance but gave less protection against silting up of pipes. The two thick polypropene fibre filters gave good protection against silting-up but their fine pore system increased entrance resistance. The same was true for the thin synthetic "stocking". When no filter was used, silting up of the pipe occurred so rapidly that entrance resistance could not be measured.

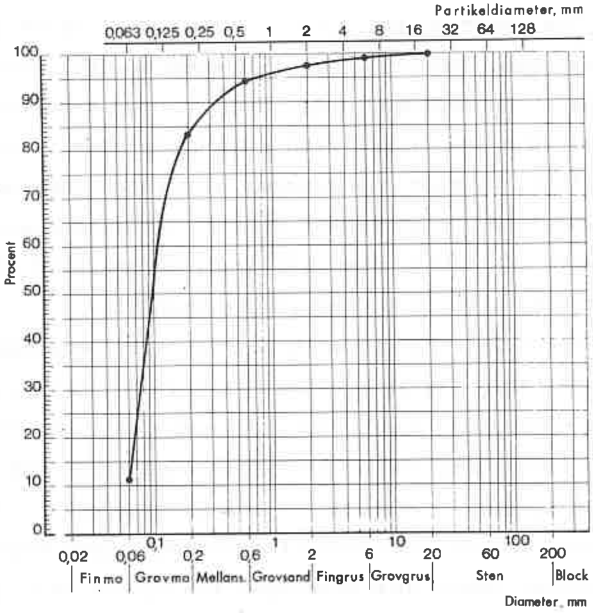

Fig. 6. Particle size distribution curve of the soil material used in the sand tank.

Table 1. Entrance resistance and amount of washed-in soil particles in corrugated pipes with various envelopes.

Pipe + filter	Depth of accumulated material in pipe, mm	Entrance resistance w_e, day/m
coco-fibre	10	0.024
polythene	20	0.025
polypropane 1	6	0.032
polypropane 2	6	0.038
`stocking´	6	0.036
no filter	25	-

4 Field experiments

The first field trials in Sweden on properties of filter envelopes for drainage pipes were set up in 1977 and 1979. The sites are in Värmland and Östergötland Districts. Function of these drainage systems will be investigated for many years, to record longterm effects. Few conclusions can be drawn from these trials as yet.

The experimental site in Värmland District is situated at Larberg, near Karlstad. The trial was laid down in 1977, in conjunction with tile drainage of an embanked area. Fig. 7 shows a sketch of the area. Drain spacing was 18 m and gravel with a particle size of 2-8 mm was used as a drainage filter. A pipe pre-wrapped in a coco-fibre envelope was installed between two of the conventional drains, reducing drain spacing here to 9 m. Drain depth was 1.0 m. The soil profile consisted of a 1 m thick silty sand with approx. 9 % clay, overlying a soap clay.

The first measurements on this site were made in June, 1980, when the watertable lay just below drain depth. Drains with both types of filter were exposed in pits dug at several points. Very little material had washed into pipes and neither filter material had deteriorated.

A similar investigation was carried out in 1982. At this time, a 5mm thick deposit had collected in both pipes with a gravel filter and those with an coco-fibre envelope. The filter envelope was still intact although its fibres had become somewhat brittle.

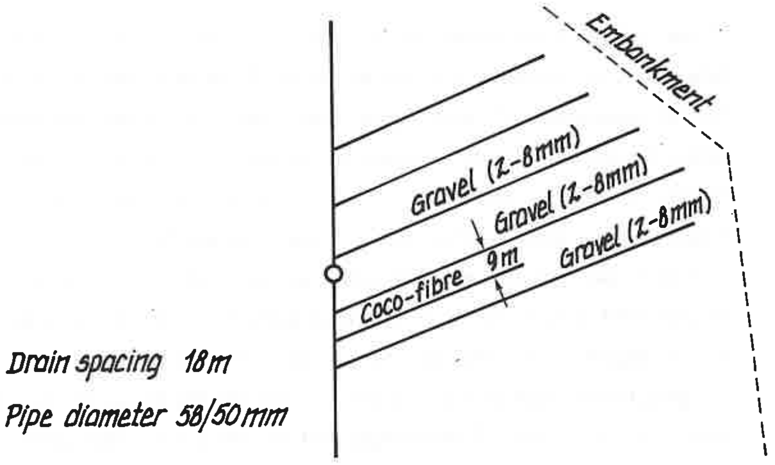

Fig. 7. Field layout of the experimental site at Larberg, Värmland.

The experimental site in Östergötland lies at Täcktö, near Klockrike. The drainage system was installed in June, 1979 and three types of filter envelope and a drain gravel were tested. The envelopes consisted of 1) thick coco-fibre, 2) thick polythene fibre and 3) a thin fibre mat. The drain gravel used has 4-8 mm particles. Drain spacing was 12 m (Fig. 8) and drain depth was just under 1.0 m. The upper part of the soil profile here consists of a silty loam but clay content is not constant, increasing to 10 % towards the centre of the area shown in Fig. 8.

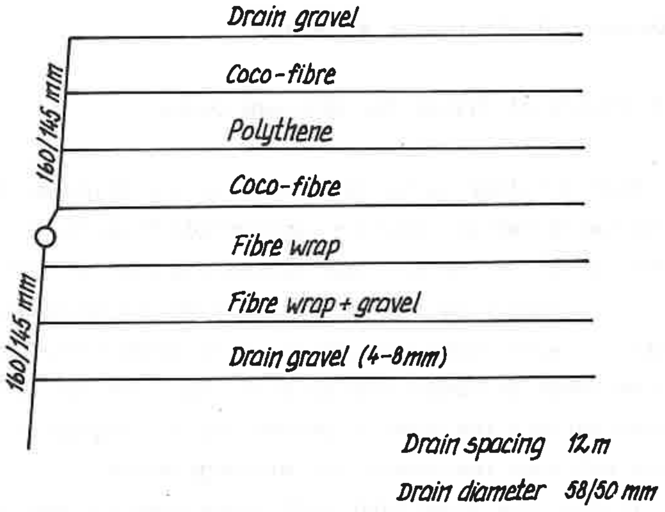

Fig. 8. Field layout of the experimental site at Täcktö, Östergötland.

The first measurements on this site were carried out in November, 1979. Drains were exposed to allow water flow and any silt accumulation in pipes to be measured. It was found that only the pipe surrounded by the drain gravel contained any washed-in material (approx. 5 mm). Water flowed in 4 of the 7 pipes, that is in all but: one in coco-fibre envelope, one in thin fibre mat + gravel and one in drain gravel.

A similar investigation was carried out in 1982. At this time, it was found that pipes with a drain gravel filter had accumulated a 25-40 mm thick deposit. Pipes in coco-fibre envelopes had a 1-4 mm deposit and those in polythene had accumulated a 6-10 mm deposit. Plant roots had penetrated both these types of envelope and there were also obvious iron ochre deposits in the pipes. The pipes in thin fibre mat had not silted up to any measurable extent but the envelope itself was completely blocked up with soil particles. Water could be seen to flow in coco-fibre and polythene wrapped pipes but not in those with thin fibre mat or those with drain gravel.

Tests to date show that cocofibre functions relatively well as a drainage filter although it may allow large amounts of silt to wash into pipes. The structure of this filter was found to be relatively intact after five years in a silty loam with a low humus content.

Thick synthetic envelopes are less effective filters and may allow silting up of pipes with time. The thin synthetic filter tested showed high entrance resistance but gave good protection against soil particles entering the pipe.

Finally, the drain gravel tested proved to be a very poor filter, mainly because of its coarse structure.

5 Choice of filter for drainage pipes

When a filter is to be chosen for a particular drainage situation, the following factors must be considered: Properties of the soil, time of installation of the drainage system and cost of installation.

Soil properties depend on soil type and moisture content and thus vary greatly with place and season. A drainage filter should function under a wide range of conditions to allow for such variations. The filter should also satisfy the aims of preventing silting-up of pipes while not increasing entrance resistance for drainage water.

Trials have shown that both these aims are satisfied by a filter of at least 5-10 mm thickness which has a hydraulic conductivity at least 10 times that of the soil and a wide pore size distribution. A backfill of gravel or sawdust easily satisfies these conditions. Long experience in the use of these materials under different conditions confirms their effectiveness.

The filter envelopes which are commercially available in Sweden at present have not gained wide usage as yet. They have the advantage over gravel of allowing various material compositions, thicknesses and pore size distribution to be used. There are, however, some disadvantages with those available to date.

At present, coco-fibre envelopes assist water flow into pipes but do not provide a barrier to soil particles. No problems have been observed to date with durability of this material.

To judge from present results, thin synthetic envelopes are not effective under Swedish conditions, since most Swedish arable soils have low permeability and require a thick voluminous filter to allow water to flow into drainage pipes. One possible use for these thin filters may be around relatively large diameter pipes, for example collector drains, in sandy soils which do not have ochre problems.

A 1984 comparison of costs of traditional pipe + gravel fill drainage with coco-fibre wrapped pipes showed no appreciable difference between the treatments. Installation of pre-wrapped pipes by trenchless drainage is less labour intensive and may be somewhat cheaper than the conventional alternative, especially in unstable soils. However, the effectiveness of filter envelopes has not proven fully satisfactory at date and in many cases, the extra security of using a traditional gravel backfill may justify the extra cost and labour involved.

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TIMELINESS OF A SILTY CLAY AS RELATED TO DRAINAGE INTENSITY

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Summary.

A higher intensity of artificial draining in a silty clay increaces the sub-surface drain run-off rate in proportion to the length of drain pr. square area drained. A closer grid of drains also makes the soil ready for drilling at an earlier date. The land is prepared for drilling with a higher moisture-content in the surface layer of soil, which is beneficial for agriculture. Better drainage results in better crops and the fields are easier workable. Years with complete crop failure will also become more scarce.

Scope of experiment.

The aim of the experiment is to study the influence of the drainage intensity on the value of agricultural land when used arable for spring-drilles grain production.

Farmers have for years been aware of the importance of an early spring. An old saying is that a day in the spring is equal to a week in the autumn. This may be an exaggeration, but still how important is an eary drilling ?

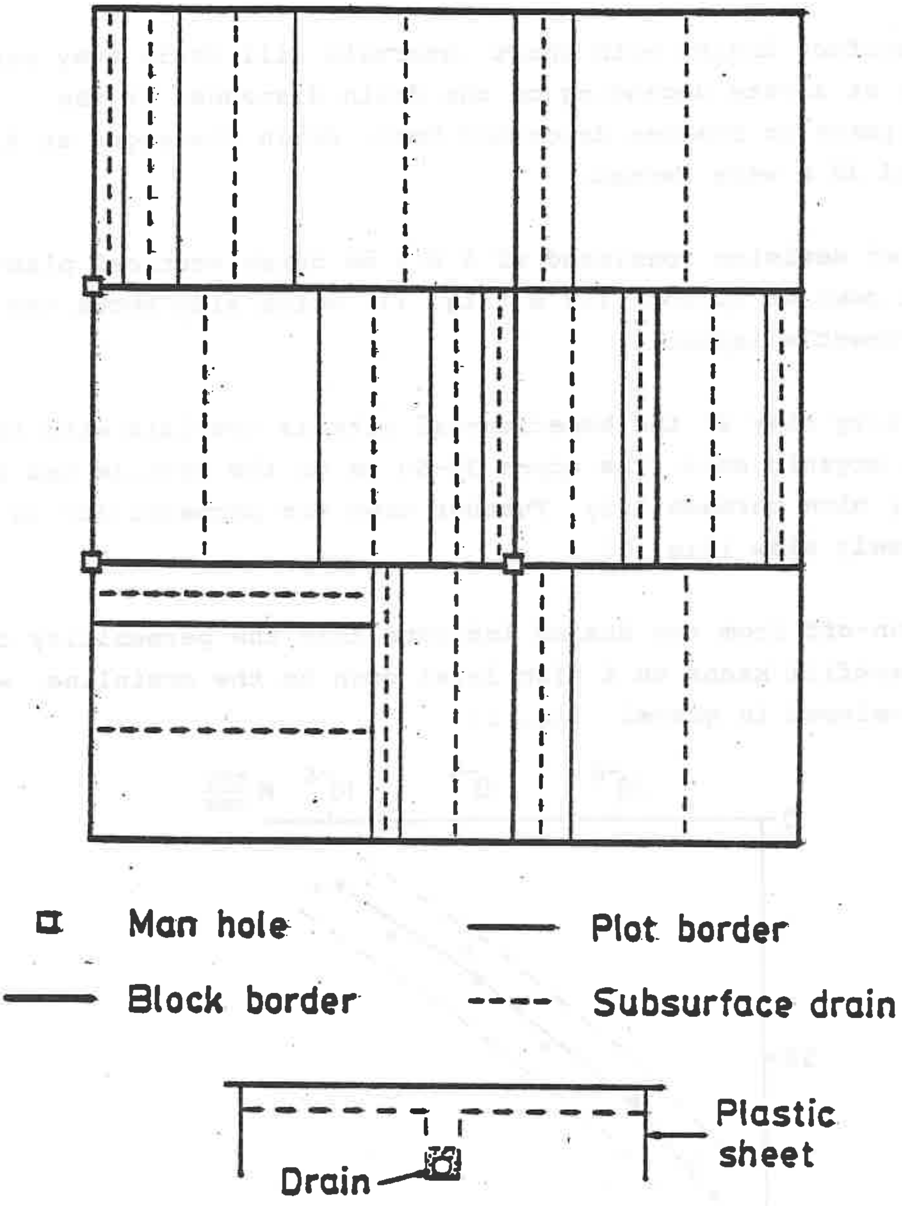

Figure 1. Experimental lay out. End view of drainage plot.

Sub-surface drains with short intervals will drain away surplus water at a rate depending on the drain distance. In the experiment at Støkken described here, drain distances at 4, 8, 16 and 32 m were tested.

A water devision consisted of å 0,4 mm thick vertical plastic sheet down to approx. 1,0 m (fig. 1), which also shows the experiment´s layout.

The silty clay at the experimental site is overlaid with 10-20 cm of organic soil. The upper 30-50 cm of the profile has got a fairly high permeability. Further down the permeability is extremely slow (fig. 2).

The run-off from the drains indicate that the permability of the backfill keeps on i high level down to the drainline, which is enveloped in gravel (fig. 1).

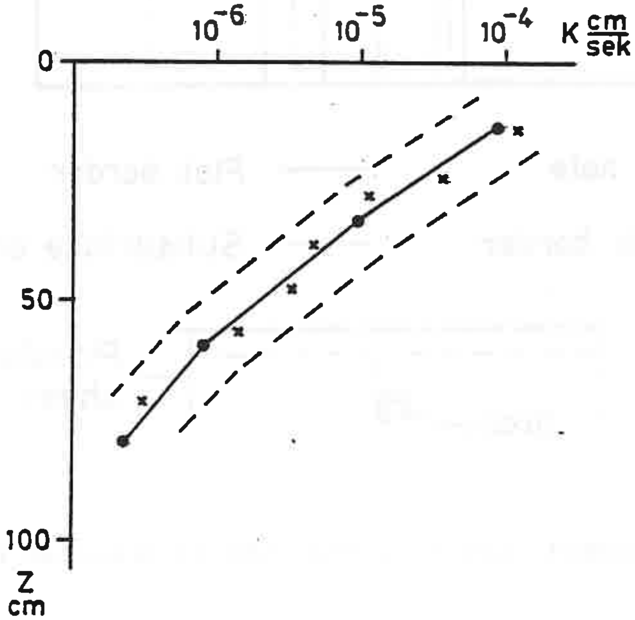

Figure 2. Permeability of various depth´s at the Støkken exp. in 1975 before experiment started. x shows measurement taken in 1982.

The runoff time diagram (durability curve) for the drain system is shown in fig. 3.

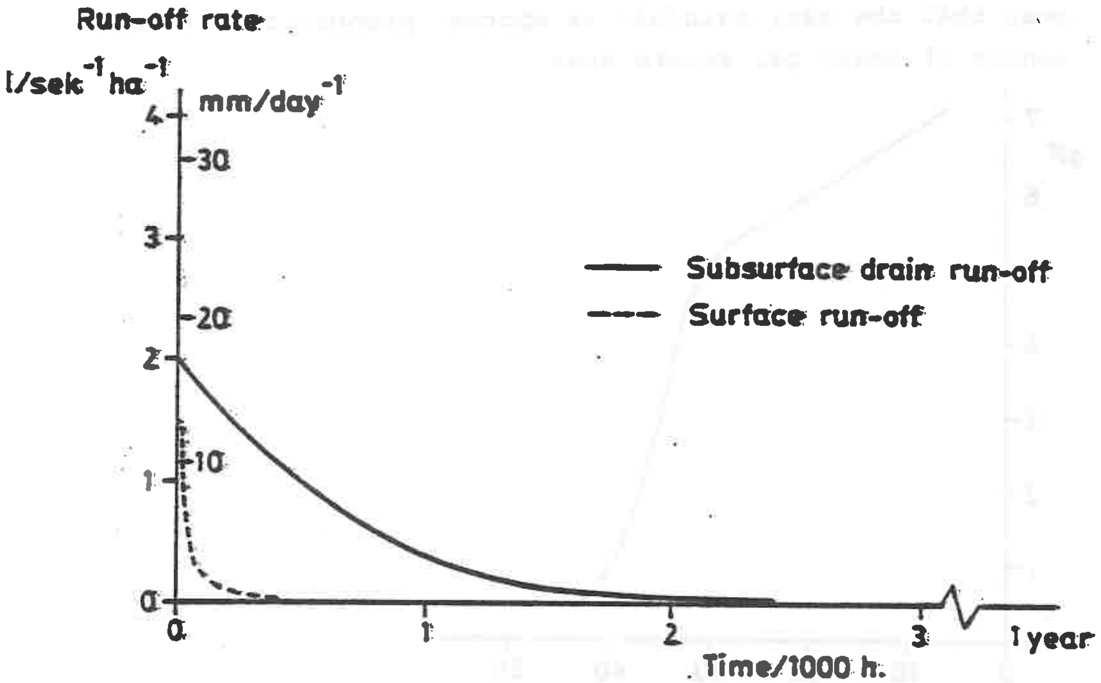

Figure 3. Intensity of run-off time diagraph for subsurface drain run-off water (solid line) and surface water run-off (dotted line) (1983).

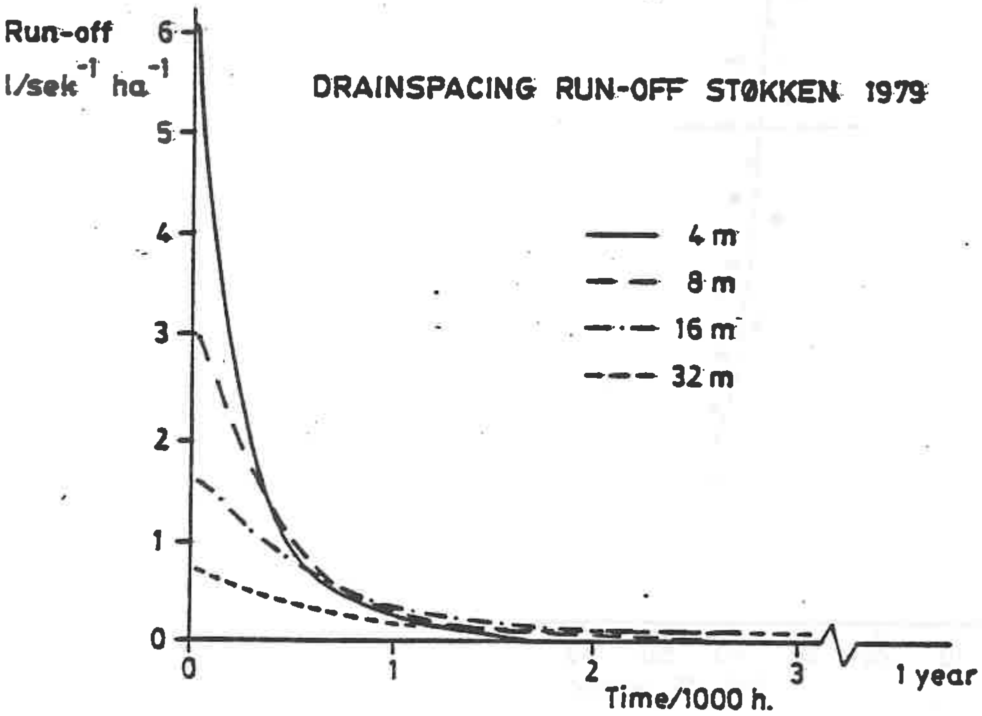

Figure 4. Intensity of run-off - time diagraph for sub surface drains at various distances.

Fig. 4 shows durability curves for various drain spacings. One sees that the max. rainfall is approx. proportional to the length of drain per square area.

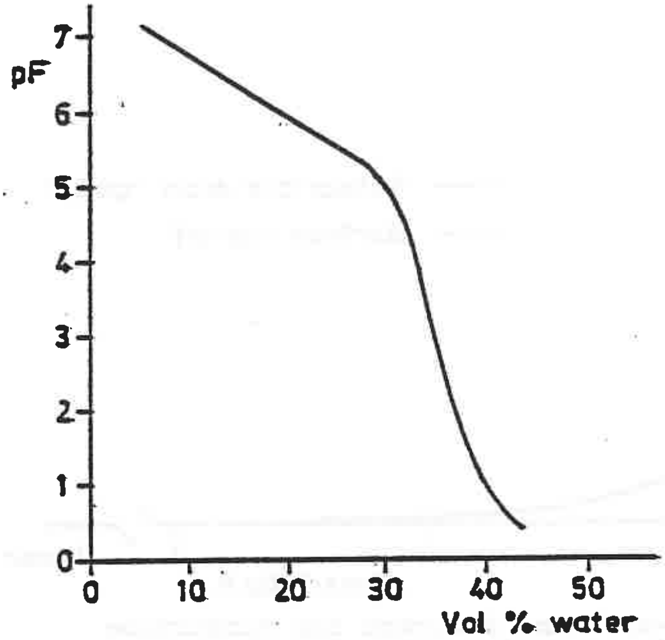

Figure 5. Retention curves for the soil at Støkken.

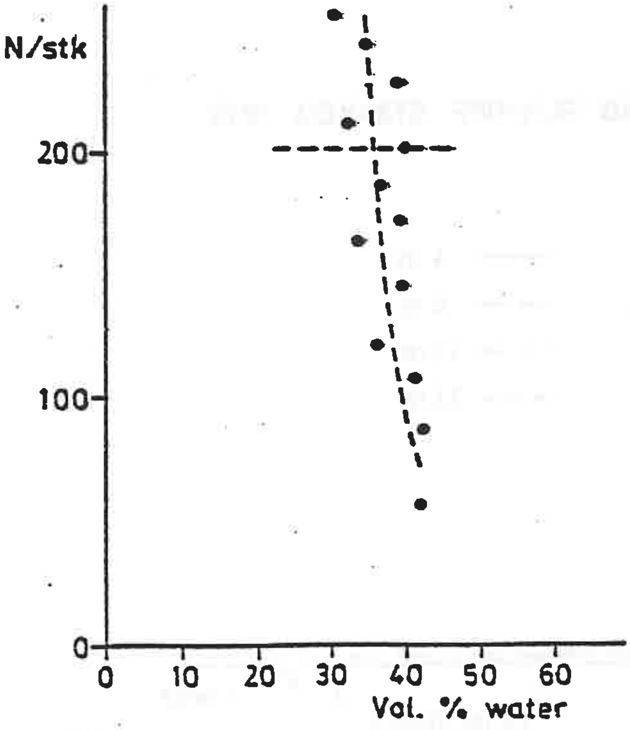

Figure 6. Relation soil strength as measured with a prector meter and water content.

Water regime - strength of soil.

Coulomb´s law states that the strength of a material is porportional to the normal stresses miltiplied by the angle of friction. In the upper layer of the soil the normal stresses mainly depend on the water suction in the soil pores. A volume % moisture - suction diagram of the Støkken soil is given in fig. 5, and in fig. 6 a volume % moisture strength relation diagram is given.

The drying up process.

After snow melting the soil is usually saturated with water. The time it takes to reduce the water content to a level indicated in fig. 7 determines the drilling date.

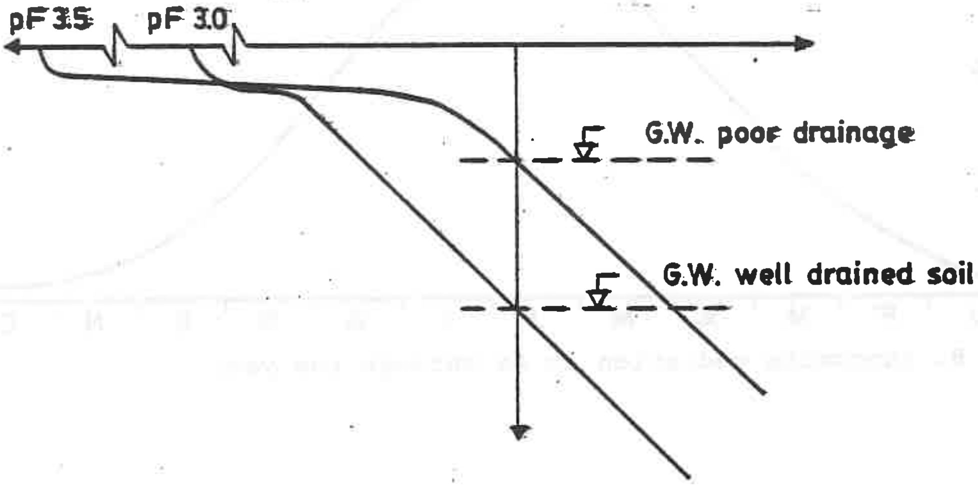

Figure 7. Tension at various depth of soil on well drained and poorly drained ground when the soil is ready for drilling.

Water can be removed by evaporation or by simple gravity drainage. It takes 2,25 MJ/kg to evaporate water (100 °C, at lower temperatures this figure is reduced). The soil at Støkken requires a removal of around 50 mm or 500 m^3/ha. That is the equivalent of over 300 000 kWh of energy, to a large extent can be saved by letting the water drain away under the force of gravity. But that requires a rather close grid of drains in such low permeability soil.

Why the drilling date is of such importance.

The dry matter producing potential of a field depends on how efficient the photosynthesis can function. This again depens on the rate of radiation, and the length of time it goes on, and that there is no bottleneck in the process like draught or lack of fertilization etc. Fig. 8 shows the incoming radiation at Ås,and it is obvious that good timing is essential, especially under these local climatic conditions.

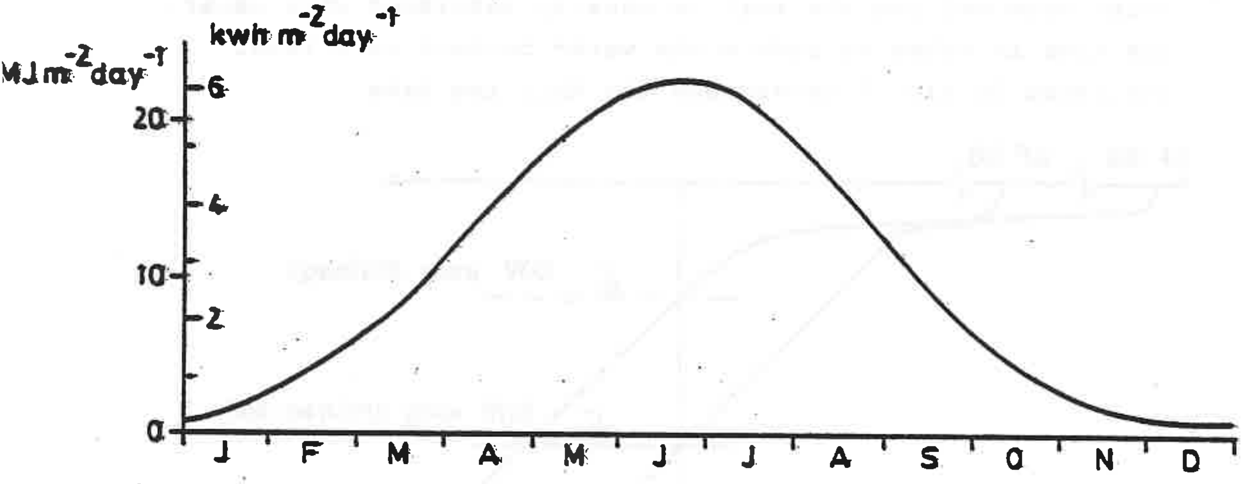

Figure 8. Incomming radiation at Ås through the year.

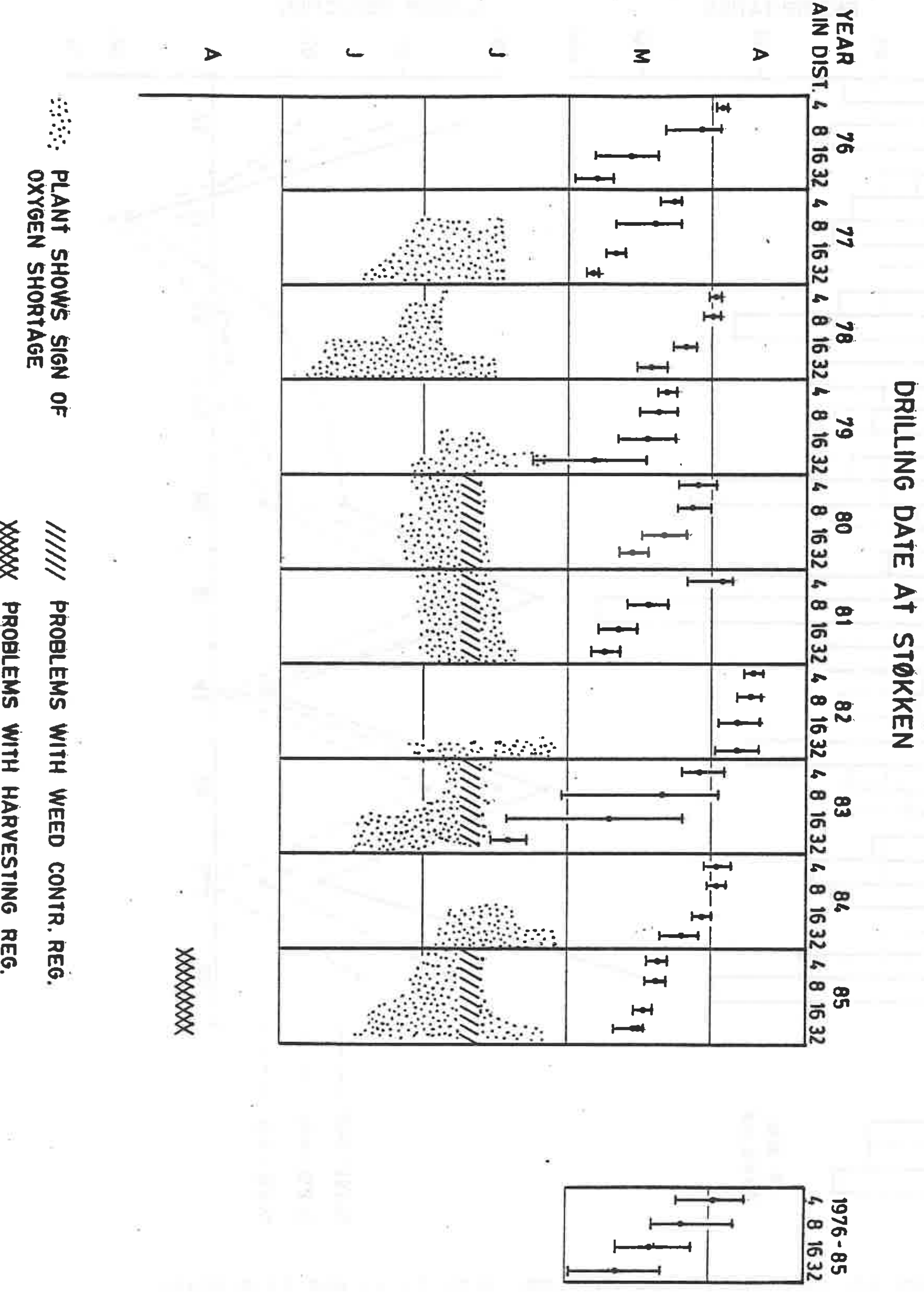

Figure 9. Drilling date on various drain distances through the years 1976-85. Vertical line indicate variation for a drain distance (5 replications).

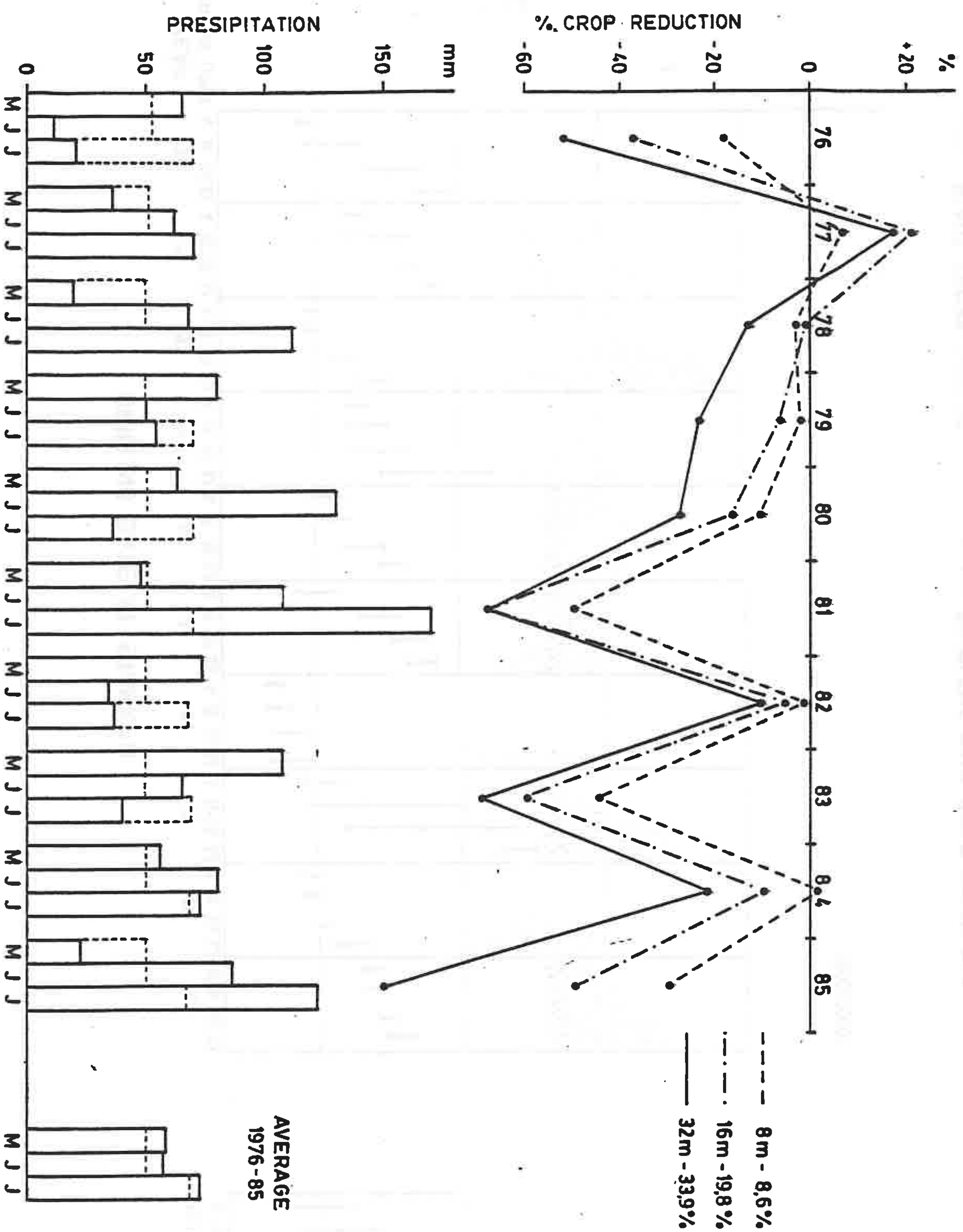

Figure 10. Crop harvested on plots with 8, 16 and 32 m drain spacing measured with the crop on plots with 4 m drain distance. Vertical column shows precipitation in May, Juni and July. Dotted line shows normal precipitation.

Experimental results.

Naturally the effect of drain spacing on the sowing date and the crop varies from year to year. In fig. 9 the sowing date is shown for the various drain distances. On an average over ten years a doubling of the drain distande delays the drilling operations by 6 days. In years with no rain in the drilling season this delay is shorter, approximately 2 days, but in wet years it has been up to three weeks.

Economical importance of drainage.

As fig. 9 indicates, and as shown by the photographs, lack of oxygen may also hamper the crop production. In fig. 9 it is indicated in which years this happened (1977- ....).

Literature.

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A NON-DESTRUCTIVE MORPHOLOGICAL STUDY OF MINERAL CLOGGING OF DRAINS

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Abstract

A research project into mineral clogging of subsurface drains is described. The project aims at the development of criteria for drainage envelopes which guarantee both good hydraulic properties of drains and protection of mineral clogging of drains in unstable soils.

Both laboratory- and field work is incorporated in it in order to guarantee resemblance to field conditions and to allow for minute monitoring of the phenomena under study.

The design of drain envelopes still is in the empirical stage. In this study, various envelope types are subjected to permeameter flow tests with soils from areas where mineral clogging is well-established. Soil sampling is performed in such a way that the structure of the sampled soil is comparable to that of the soil around drains.

Data emerging from ten envelopes tested so far indicate that the sand tightness and the surface area of the envelope, involved in the flow process vary considerably. The hydraulic conductivity of drains wrapped with voluminous envelopes was not significantly higher than that of drains wrapped with thin envelopes, but voluminous envelopes appear to be a better guarantee for favourable hydraulic properties than thin ones. The conductivity figures never reached unacceptably low levels.

An x-ray transmission computed tomography (CT) scanner was used to determine the morphological characteristics of envelope and abutting soil. The CT-scanner appears to be a powerful tool for envelope research. It produces data which are indispensable for our knowledge upon envelope functioning because of its non-destructive nature.

1 Introduction

The design of drain envelopes is still in the empirical stage. Envelopes are usually subjected to field- and permeameter flow tests. Typical variables usually recorded are outflow rates versus time, pore size distributions of envelopes, saturated hydraulic conductivities and mineral clogging rates. In such tests, the variables are considered to be lumped, i.e. their spatial variability is disregarded. Permeameter flow test data however indicate that the spatial variability of relevant parameters of both soil and envelope is often too big to be neglected. The water flow pattern, the hydraulic gradient and the erosive flow rate vary considerably in space.

In the Netherlands, drainage envelope research is prompted by the fact that new drains are installed in Dutch soils for the equivalent of US$ 20 million annually. The majority of these is wrapped with an envelope. The research started in the 1960s (Cavelaars; 1965). However, problems with subsurface drain systems remained. These problems were ascribed to mineral clogging of pipes and to low hydraulic conductivities of drain trenches and -envelopes. In 1980, the Institute for Land and Water Management Research has initiated a new research project (Stuyt; 1983). It was continued in 1985 and is financially supported by eleven Dutch and foreign companies.

In the project, chemical clogging is not considered. This type of clogging occurs in a minority of cases and it is dealt with by other research Institutions in the Netherlands.

2 Procedure

An experimental setup comprising eight permeameters is used for testing envelopes in combination with different types of soils. A permeameter is an acrylic cylinder, 40 cm long and 15 cm in diameter. In fig. 1, a permeameter is shown in vertical position, while a flow test is on. It consists of the following parts: a watertight cap, a spring, a gravel bed diffuser (10 mm thick; not visible), brass piezometers, a soil sample (approx. 100 mm thick), an envelope sample disc, a disc-shaped piece of supporting corrugated pipe, a perforated acrylic template and an upper chamber to collect the soil material which has washed through the envelope and

Fig. 1 A flow permeameter as used in the tests. See text for description

the piece of corrugated pipe. Envelopes are tested in four replicates during a period of 14 days. The soil samples are taken in four pilot areas, located in regions where mineral clogging is well-established; mainly very fine-sandy, unstable marine soils. In the pilot areas, nearly all envelopes have been installed as well. They are monitored while functioning in soil types identical to those which are used in the laboratory setup. Thus, laboratory data can be compared with field data.

In past Dutch envelope research, soil texture was considered to be a dominant parameter for determining the risk of mineral clogging. In the current project it is acknowledged that soil structure is at least as important in this respect. Therefore, soil sampling aims at conserving the actual structure of the soil to the highest possible level. The impact of the structural stability of the soil is assessed by using both disturbed and (nearly) undisturbed soil samples. In doing so, an attempt is made to simulate mineral clogging of drains installed by trenchless machines and by trenchers. Obviously, trenchless installation promotes disturbance of the soil adjacent to the drain to a higher extent than does our sampling with rings.

The undisturbed soil samples are pushed into the permeameters by means of a hand-powered piston system. Filling the permeameters with disturbed samples is done by hand to a bulk density equal to that found in the field. The soil samples are covered with a fine-textured gravel layer. The envelope/ soil samples are securely fastened by springs and water-tight caps. Next, the permeameters are turned upside down in order to get upside flow.

After (partial) saturation, lasting approximately two days, the flow test starts. The setup allows for increasing a hydrostatic water pressure drop over envelopes and soil samples step-wise from 5 to 100 cm in 5 cm increments and from 100 to 200 cm in 25 cm increments. As the soil/envelope combinations are approximately 10 cm high, the hydraulic gradient can be varied from 0.5 to 20 under very low flow conditions. However, if the flow through the samples reaches high figures, the gradient seldomly exceeds 10.

During the flow tests the following data are recorded: flow rate, water head loss as caused by the soil/envelope combination as a whole and amount and distribution of the soil material which has washed through the envelope. The hydrostatic pressure is increased each time after the flow rate has more or less stabilized. Any flow test is completed with the injection of a colouring agent upstream the soil sample, and the recording of the water outflow pattern downstream the envelope sample and the perforated template on video tape. Next, an assessment can be made of the area of the envelope material, effectively involved in the water flow.

During the earlier experiments the water pressure drop was monitored at several heights in the soil column using piezometers. The head loss over the envelope sample was recorded as well. Assuming that one was dealing with Darcyan flow through homogeneous, isotropic media, this is justified. In these tests, structureless soil samples were used so that these assumptions were not conflicting with the actual flow conditions. In the current study where structured soil samples are used and, as a consequence, the flow is restricted to areas having a relatively high hydraulic conductivity (e.g. macropores) water pressure readings taken from randomly placed piezometers would be meaningless. Therefore, monitoring the head loss has been restricted to the total head loss caused by the soil- and the envelope sample together.

Recorded figures are converted into variables relevant for practical assessment of the envelope functioning in various cases. These variables are: i) pipe clogging rate, expressed as layer thickness in a 60 mm corrugated pipe; ii) hydraulic gradient of failure of a soil/envelope combination; iii) area of envelope involved in the flow; iv) mid-drain water table elevation change as caused by a change in hydraulic conductivity of the envelope and the abutting soil.

i) sedimentation rate. After a flow test has been terminated, the soil material which has washed through the envelope is weighed while being wet. Next, this amount of soil is converted into an equivalent sediment layer thickness in a 60 mm corrugated pipe. A 60 mm pipe section having the same area as the pipe sample disc in the permeameter (Ø 15 cm, area = 176.7 cm^2) is $176.7/\pi d = 176.7/6\pi = 9.4$ cm long. In order to estimate the amount of soil, needed to clog such a pipe section completely, a section of the given length was filled with soil while being in a quicksand condition in five

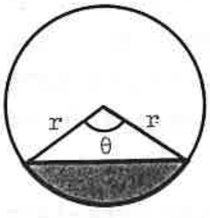

Fig. 2 The cross-sectional segment A of a drain pipe, filled with sediment

replicates. The soil which was used was also used in the flow tests. The amount of soil needed was 520 grams on average, weighed while wet. The cross-sectional area A, filled with sediment as a function of the washed-in soil material W can now be computed from

$$A = \tfrac{1}{2}\, r^2(\theta - \sin\theta) = \pi r^2 W / 520, \text{ where } r = 3 \text{ cm}$$
$$W \leqq 520 \text{ gr.}$$

From the angle θ, the sediment layer thickness is computed, cf. fig. 2.

ii) hydraulic failure gradient. If a hydrostatic water pressure drop is imposed on the upstream- and downstream ends of the soil/envelope combination, a hydraulic gradient will develop in case of water flow. The hydraulic gradient will be linearly correlated to the pressure drop under the assumption of Darcyan flow and a constant value of the hydraulic conductivity of the samples. Regardless the hydrostatic pressure drop, the hyraulic gradient is inversely proportional to changes in hydraulic conductivity in the samples. Due to the varying hydraulic gradients in all permeameters, the hydrodynamic pressure drop in the water supply system of the setup will also vary. The higher the flow rates in the permeameters, the more the hydrodynamic and the hydrostatic pressures in the setup will diverge. Due to the constrained hydraulic capacity of the water supply system the hydrodynamic pressure variations are mutually transmitted between flow permeameters.

An important event in flow tests is soil/envelope failure. This phenomenon was described in detail by Willardson (1983) who proposed the Hydraulic Failure Gradient ('HFG') as the hydraulic gradient at which the drag force of the flowing water causes sudden drastic, upward or downward changes in the hydraulic conductivity whereby i) this gradient decreases or increases respectively, and ii) there is a mass movement of soil particles. As a consequence, monitoring the hydraulic gradient during a flow test will provide relevant information regarding the functioning of soil/envelope combinations.

iii) the area of an envelope involved in the flow. In traditional drainage theory, a drainage envelope and the adjacent soil are assumed to be homogeneous media (Nieuwenhuis; 1979, Widmoser; 1968). As a consequence, head losses over envelopes and soils in trenches can be converted into entrance resistance figures and effective drain radii (Dierickx; 1980).

Results of tracer experiments as well as visual inspection of the spatial distribution of washed-through sediment on the templates of the permeameters, however, indicate that the above assumptions may be erroneous. From a theoretical standpoint, all voluminous envelopes (that is, having a three-dimensional structure, contrary to thin envelopes which may often be considered to be two-dimensional like a sieve) improve the hydraulic flow conditions around drains as they form a highly-conductive layer. In this layer, water will distribute and enter the pipe evenly through the pipe wall perforations. A tracer, injected upstream on top of the gravel bed diffuser would appear downstream of the envelope, evenly distributed over the envelope area. Moreover, soil would wash through the envelope in the same manner. These phenomena were monitored qualitatively during all the flow tests.

iv) mid-drain water table elevation. In a field drainage system, the total head loss is roughly caused by a horizontal and by a radial flow component. The area of radial flow is theoretically confined to 0.7 times the distance from the drainage base to the impermeable layer.

The impact of the hydraulic conductivity around drains is confined to the area of radial flow. The hydraulic conductivities, recorded during the permeameter flow tests can be converted into mean hydraulic conductivities in the area of radial flow if the mean hydraulic conductivity of the undisturbed soil is known (Gustaffson;1946). It is assumed that the head loss, recorded in a permeameter equals the head loss in a drain trench; the sample height in the permeameters is 10 cm on average and the mean trench width in Holland is 20 cm. Using the mean hydraulic conductivity in the area of radial flow, the steady-state drain spacing formula of Ernst can be used to compute the horizontal and the radial flow head loss components. For a typical land drainage system in the Netherlands (drainage coefficient 7 mm/d, spacing 25 m, drain depth 1 m, diameter of drain + envelope 7 cm, K_{soil} 1 m/d) we get

$$h_{total} = h_{hor} + h_{rad} = 0.415 + 0.085 \text{ m} = 0.5 \text{ m},$$

assuming $K_{trench} = 1$ m/d.

For this data, the mean hydraulic conductivity in the area of radial flow, $\overline{K}_r$, can be computed from the conductivity of the trench, K_t, as follows:-

$$\overline{K}_r = 3.0 \;/\; (1.95 + 1.05/K_t) \quad \text{m/d}$$

A decrease in K_t from 1 m/d to 0.1 m/d would result in $\overline{K}_r$ = 0.24 m/d and a radial head loss increase from 8.5 to 35 cm. Consequently, the water table elevation midway between the drains would rise from 50 cm to 23.5 cm below soil surface. Accordingly, an increase in K_t from 1 to 100 m/d would result in a drop from 50 to 55 cm below soil surface under the given conditions.

3 Appraisal criteria

In order to assess the functioning of soil/envelope combinations, processed data are compared with (more or less subjectively defined) threshold levels of the variables concerned. If some variable exceeds a threshold level, the functioning of a soil/envelope combination is regarded to be inadequate for the conditions under which it was examined. The threshold levels are:-

i) sedimentation-rate: 15 mm layer thickness in a 60 mm pipe maximum;
ii) hydraulic gradient: soil/envelope failure below HFG = 3;
iii) area of envelope involved in the flow: data does not

yet allow for setting a threshold level;
iv) mid-drain water table elevation: setting a threshold level is not (yet) relevant; see next.

These levels are justified as follows:-

i) sedimentation-rate. In the Netherlands, the maximum allowed sediment layer thickness in a 60 mm corrugated pipe is 15 mm for reasons of transport capacity of the pipe. This threshold level is indicated in fig. 3 where the weight of the sediment, collected in the permeameter, is plotted against the height of the corresponding sediment layer thickness in the pipe. The curve indicates that a sediment weight exceeding 100 grams is beyond the 15 mm threshold level in the pipe.

ii) hydraulic gradient. The head loss at steady-state design discharge (7 mm/day) for arable land is 50 cm when drains are installed at 1 m depth (Dutch standard). In exceptional cases 60% of the total head loss may be lost in the trench. Therefore, any soil/envelope failure which occurs at a head loss below 30 cm is considered to be unacceptable. In the

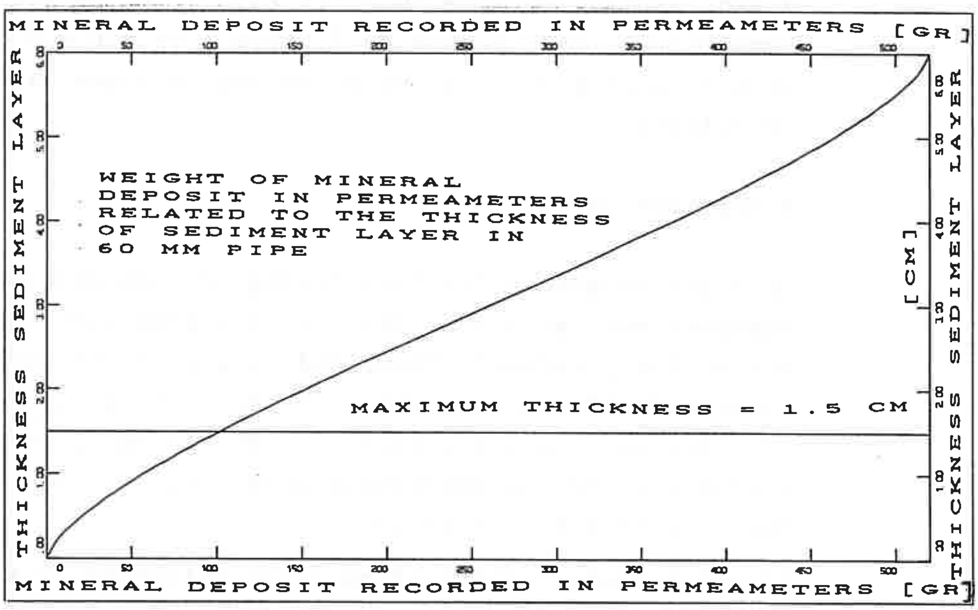

Fig. 3 Relation between deposit weight in permeameter and corresponding thickness of sediment layer in pipe

permeameters used, a head loss of 30 cm is more or less equivalent to a hydraulic gradient 3. The lowest hydraulic failure gradient which still is acceptable is therefore set to 3. It is noted that the radial flow which exists around drains in the field does not exist in our permeameters where the flow pattern is theoretically two-dimensional. Therefore, the acceptable failure gradient should be set at a higher level, e.g. 4.

iii) the area of envelope involved in the flow. The area of the envelope involved in the flow is determined by the structure and the rate of clogging of the envelope and by the structure of the abutting soil. The area is qualitatively assessed by counting the number of perforations through which soil material has washed into the upper chamber of the permeameter and by the tracer experiments described earlier. One may expect that the area involved is positively correlated with the functioning of the drain. The data collected so far however does not yet allow for the definition of an area threshold level.

iv) mid-drain water table elevation. The maximum allowable water table elevation midway between drains is dependent upon a large number of factors, e.g. land use, crop response, soil type and season. It is clear that no single one threshold level can be set. Hydraulic conductivity figures which would lead to an increase in the water table elevation shallower than 20 cm have never been recorded so far. For these reasons a threshold level cannot be defined up to now.

After completion of the project when 30 envelopes will have been examined, it is likely that threshold levels of the latter two variables described above can be set with confidence.

4 Results

Results of the permeameter flow tests are given category-wise analogous to the criteria described above, i.e. sedimentation rate, hydraulic gradient of failure, area of envelope involved in the flow and mid-drain water table elevation.

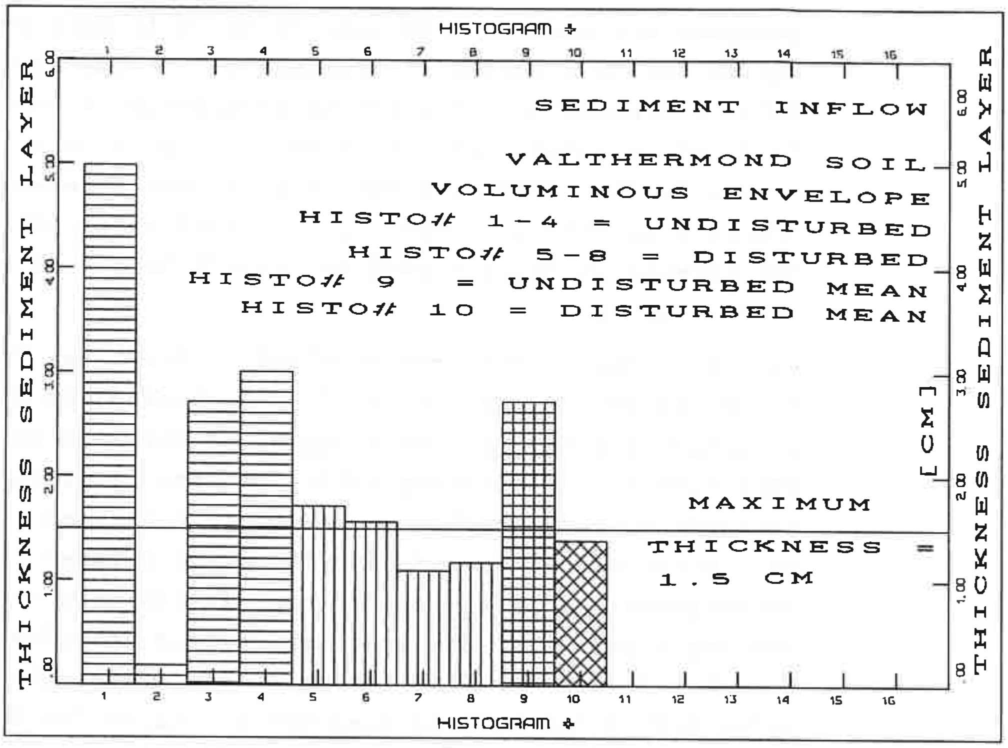

Fig. 4 Soil material washed through a voluminous envelope, expressed as sediment layer thickness in a 60 mm pipe

i) sedimentation-rate. A typical set of converted sedimentation data is depicted in fig. 4. This voluminous envelope could not retain the adjacent, unstable soil material sufficiently in five out of eight cases. In table 1, the number of times is given that the sand-tightness of the envelopes was insufficient. Soil/envelope failure has a positive impact on the hydraulic conductivity of the drain and the abutting soil because it often creates a macro-pore system. The result of this phenomenon is shown in fig. 5, where the thickness of a sediment layer in a drain is plotted against the hydraulic conductivity of a soil/voluminous envelope combination. Obviously, a good envelope controls the sedimentation-rate. Some degree of mineral clogging must be considered to be benificial. Due to the high degree of sand-tightness of thin envelopes, the trend which is easily seen in fig. 5 is virtually absent when using thin

Table 1 Number of times of failure of a soil/envelope combination whereby failure is defined as an amount of soil exceeding a corresponding layer thickness in a 60 mm pipe of 15 mm

		undisturbed soil	disturbed soil
Voluminous envelope	1	3	2
" "	2	1	1
" "	3	1	2
" "	4	1	1
" "	5	0	0
Thin envelope	1	0	0
" "	2	0	0
" "	3	0	0
" "	4	0	0
" "	5	0	0
Plain (no envelope)	1	3	4
" "	2	1	4

envelope materials, cf. fig. 6. A Wilcoxon-test revealed that the sand-tightness of thin envelopes was significantly better than that of thin envelopes for disturbed- as well as undisturbed soil samples.

ii) hydraulic gradient. The hydraulic gradient at which a soil/envelope ensemble fails is easily monitored by sudden changes in the gradient itself and the corresponding transport of soil material. An example is given in fig. 7, where failure occurs twice in one of four repetitions of a test with a voluminous envelope in combination with a disturbed soil. In either case, the hydraulic gradient drops considerably. At the end of this experiment the hydraulic gradient through the samples which failed is approximately 1/10 of that through the other three samples. The amount of soil washed through was beyond the threshold level (15 mm).

In fig. 8, all events where the sedimentation-rate was too high are plotted against the hydraulic gradient at which the failure began. In various cases, failure started at a HFG$\leq$4. However, no significant trend could be distinguished as regards the use of an envelope or not, or the status of the soil (disturbed vs. undisturbed).

iii) area of envelope involved in the flow. The data cannot yet be evaluated since it is insufficient in number. However,

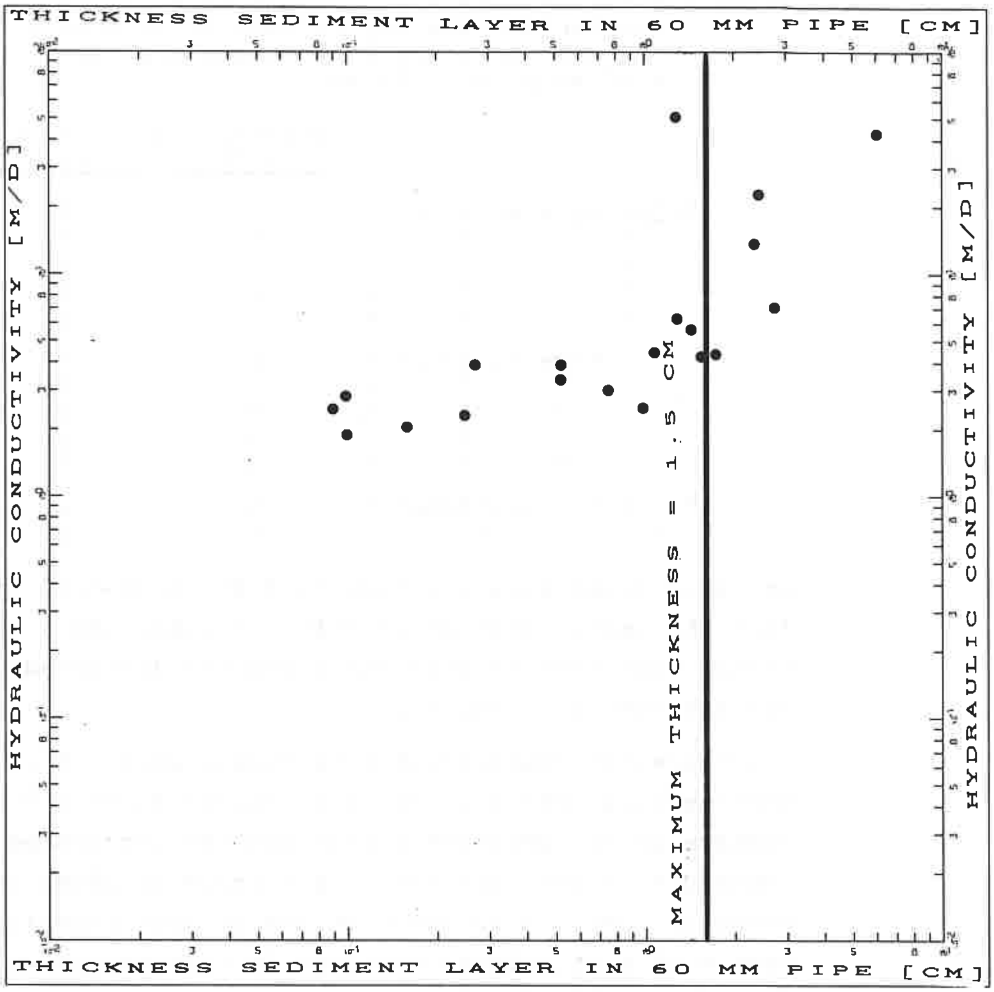

Fig. 5 Hydraulic conductivity of a soil/envelope combination plotted against the equivalent thickness of a sediment layer in a 60 mm pipe. Envelope type: voluminous

according to a Wilcoxon test, the areas of flow through voluminous envelope materials was significantly larger than the areas of flow through thin materials. It is therefore expected that, in the long run, thin envelopes may clog more easily by chemical compounds like iron ochre and manganese as well as by other very fine suspended materials, than voluminous materials.

iv) mid-drain water table elevation. In none of the tests executed so far, the hydraulic conductivity figures give

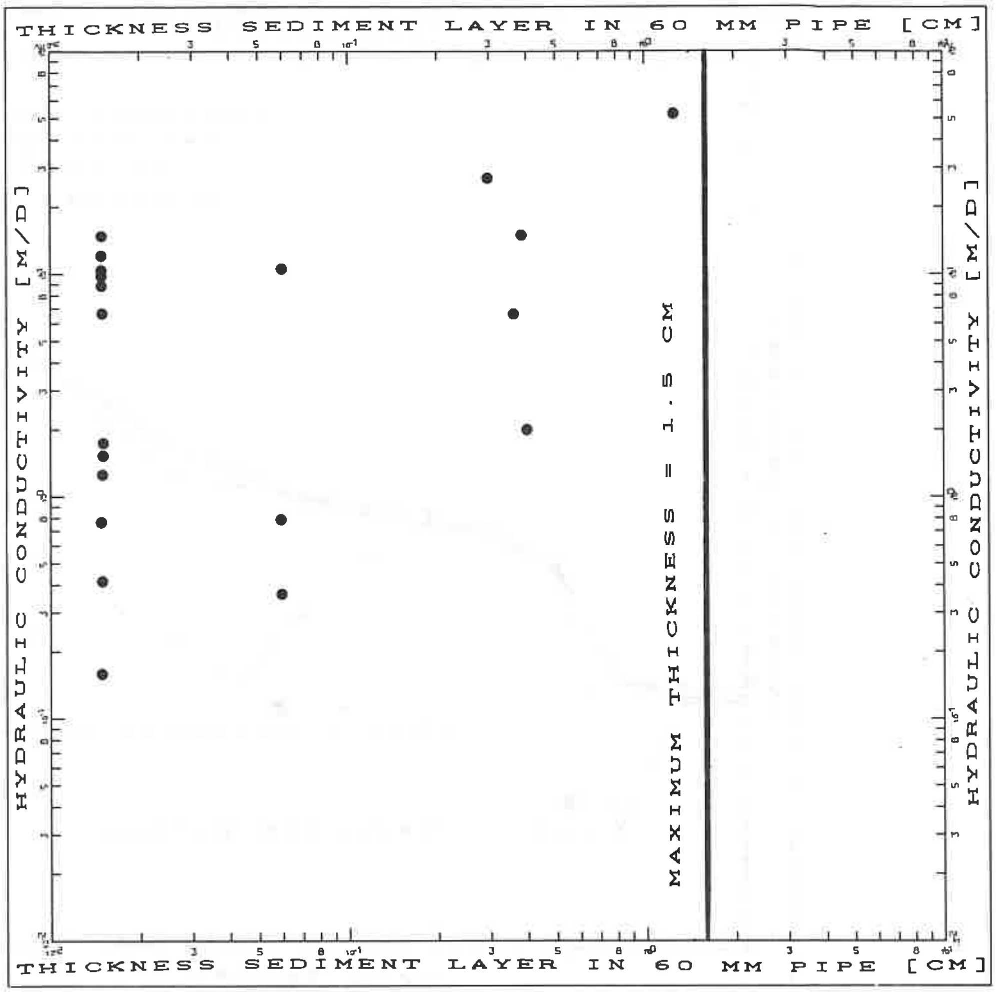

Fig. 6 Hydraulic conductivity of a soil/envelope combination plotted against the equivalent thickness of a sediment layer in a 60 mm pipe. Envelope type: thin

rise to water table elevations shallower than 30 cm below soil surface. The worst case was arrived at with a plain, disturbed soil. A Wilcoxon-test on hydraulic conductivity data revealed that there was a significant difference between the final hydraulic conductivity figures in case of disturbed soil samples on the one hand, and non-disturbed samples on the other hand, both in combination with thin envelopes. This would indicate that voluminous envelopes are a better means to level out the effects of widely different hydraulic conductivities of adjacent soils than do thin envelopes. The

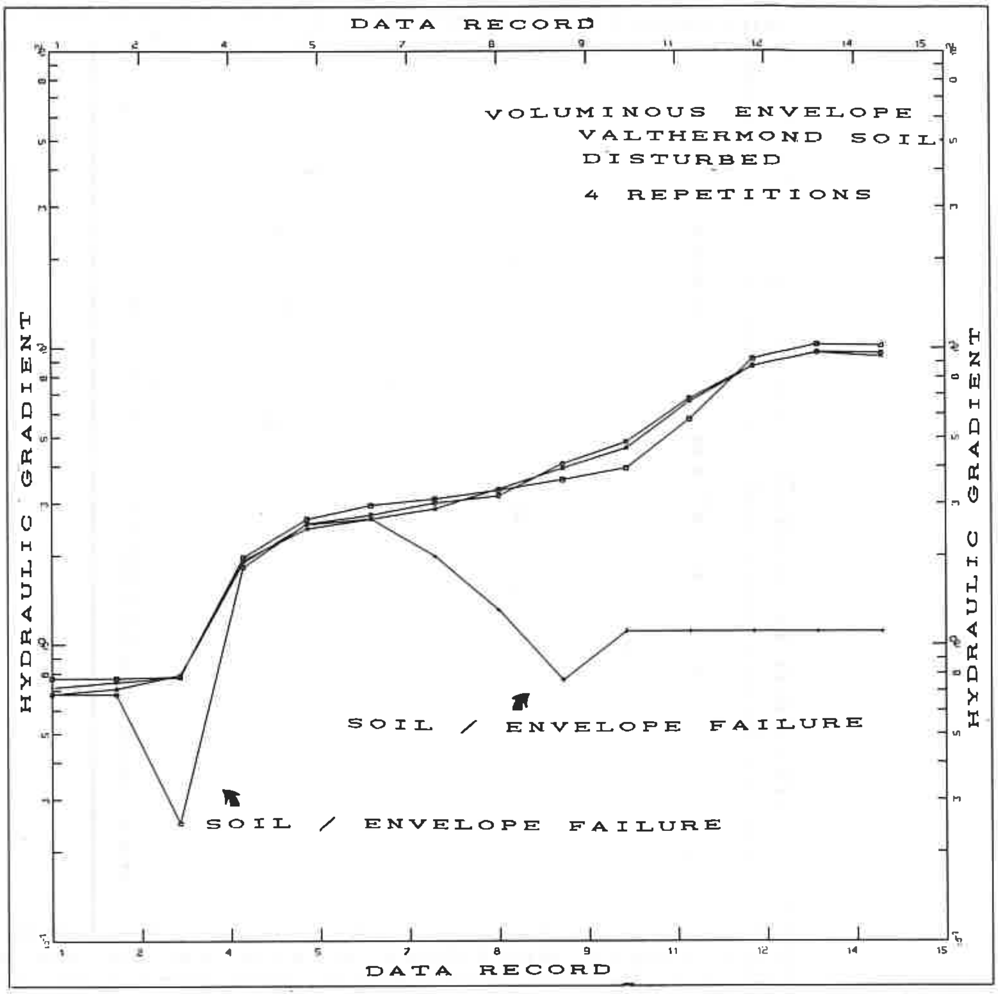

Fig. 7 Soil failure as reflected in a hydraulic gradient decrease

data-spread of hydraulic conductivities, recorded while using thin envelopes is higher than that found for voluminous envelopes, cf. fig. 5 and 6. This fact is important because the status of the soil may have a profound impact on its hydraulic conductivity. All soil samples are subjected to flow tests without an envelope to investigate this. In fig. 9 one of the results is shown. The hydraulic conductivity of the undisturbed sample was very high as a result of the undisturbed macro-pore system existing at drain depth, where the samples were taken. Internal erosion of the macro-pore

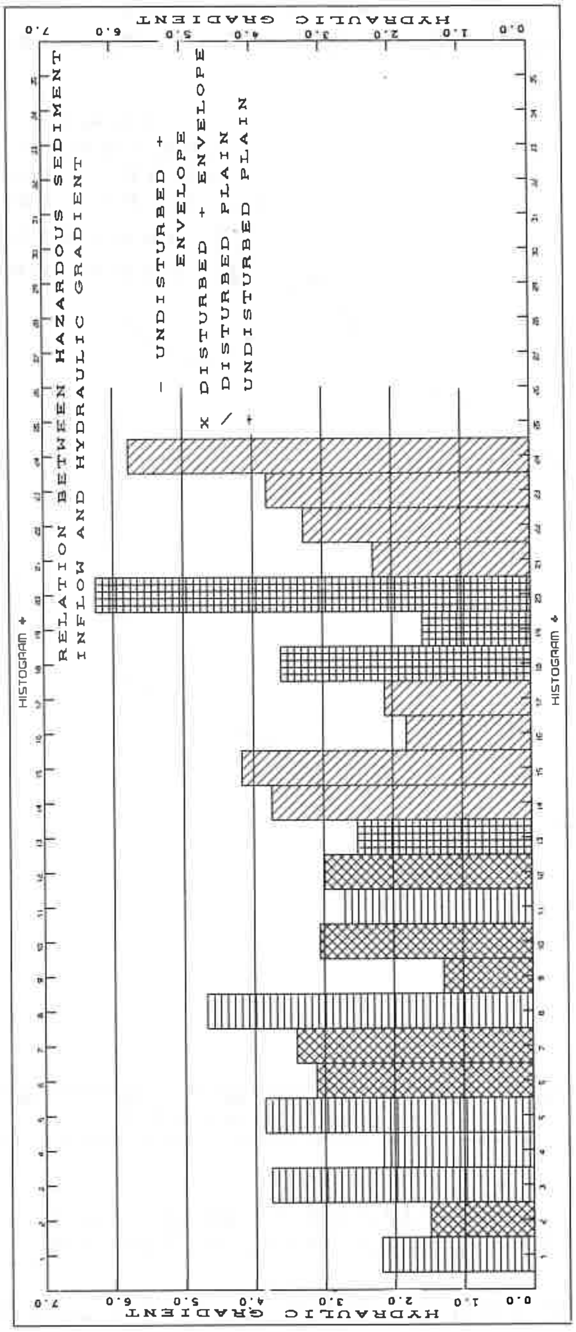

Fig. 8 Relation between hazardous sediment inflow and the hydraulic gradient at which the failure began. No obvious trend can be detected as yet

system caused very high flow-rates and a substantial degree of pipe sedimentation.

Simultaneaously with the laboratory testing programme, field testing programmes are performed. Some preliminary results

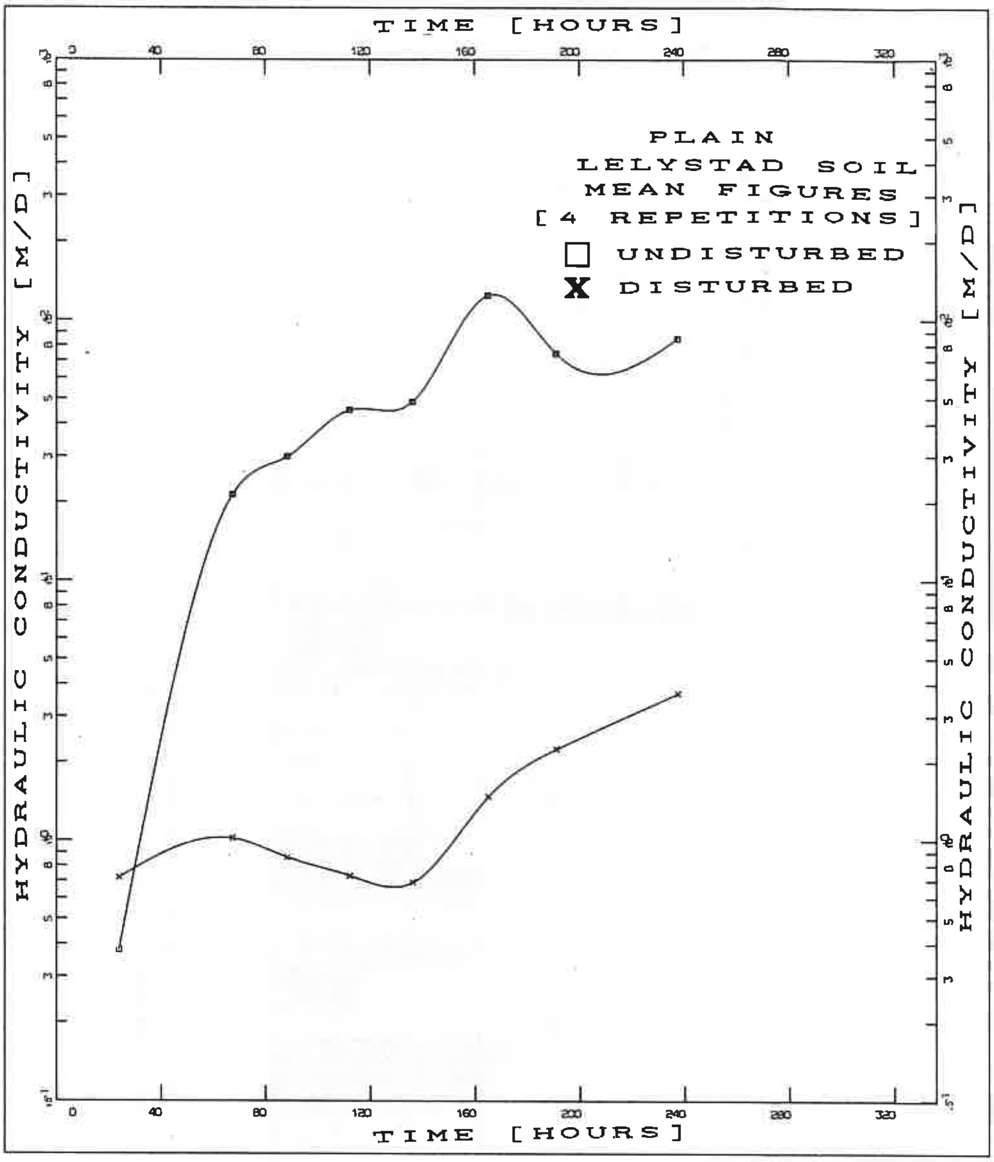

Fig. 9 Hydraulic conductivities of an undisturbed and a disturbed soil sample during a flow test

tend to indicate that, after two years, drainage systems equipped with thin envelopes show a slight efficiency decrease. No firm conclusions can however be made as yet.

5 Discussion

Of the 30 envelope materials scheduled to be tested, 10 were examined so far. Preliminary research outcomes give rise to the following conclusions.

1). Soil texture is an important parameter when it comes to prediction of the likelihood of mineral clogging problems. Soil structure however is at least as important. The structure of a soil however cannot be easily converted into relevant stability figures which can be used for the assessment of clogging under field conditions;

2). A permeameter flow test is an adequate tool for examining and comparing proposed soil/envelope combinations. However, it cannot be used for simulating long-term clogging phenomena;

3). Results of laboratory tests must be compared with data emerging from field trials, especially data which are collected during a prolonged period (years);

4). An obvious heterogeneity of the soil- and envelope samples was detected. As a consequence, variables which are defined for homogeneous media such as entrance resistance and effective drain radius cannot be evaluated. This is not a hindrance when it comes to compare envelope/soil combinations because other data processing techniques are at disposal in this respect;

5). The macro-pore system which develops around a drain is of vital importance for the development of the hydraulic conductivity in this area and, as a consequence, for the functioning of a land drainage system;

6). Thin envelopes may be prone to long-term clogging to a higher extent than voluminous ones due to the smaller surface area which is involved in the flow;

7). The use of voluminous envelopes does not necessarily safeguard higher hydraulic conductivities than the use of thin envelopes.

8). While being accurate, permeameter flow tests do not allow for the monitoring of the relevant processes which occur at the interface and the abutting soil. The test renders data on the functioning of envelope/soil combinations but it does not reveal which physical processes ultimately lead to the phenomena which are being monitored at the outside of the samples. This is a severe drawback.

It is obvious that substantial research progress can only be made if one could dispose of a non-destructive technique, allowing for the physical and morphological changes which are inflicted by the drag force of the flowing water, while the flow test is on. Current soil-morphological techniques aiming at the determination of soil structural characteristics are all disruptive and time-consuming. As a result, little is known so far about three-dimensional changes in soil structure and the macro-pore system which develops at the interface between drain pipes and envelopes.

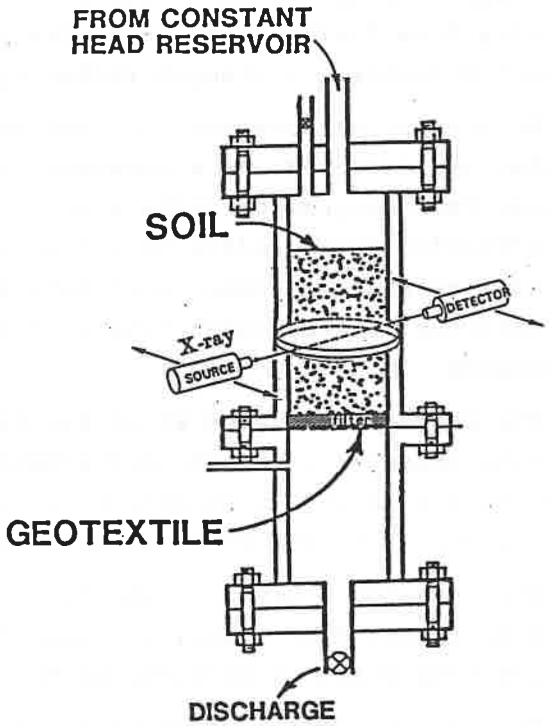

Fig. 10 The principle of a CT-scanner, as applied in this study. An 1.5 mm thick slice of the media is being scanned by a moving x-ray source and a detector

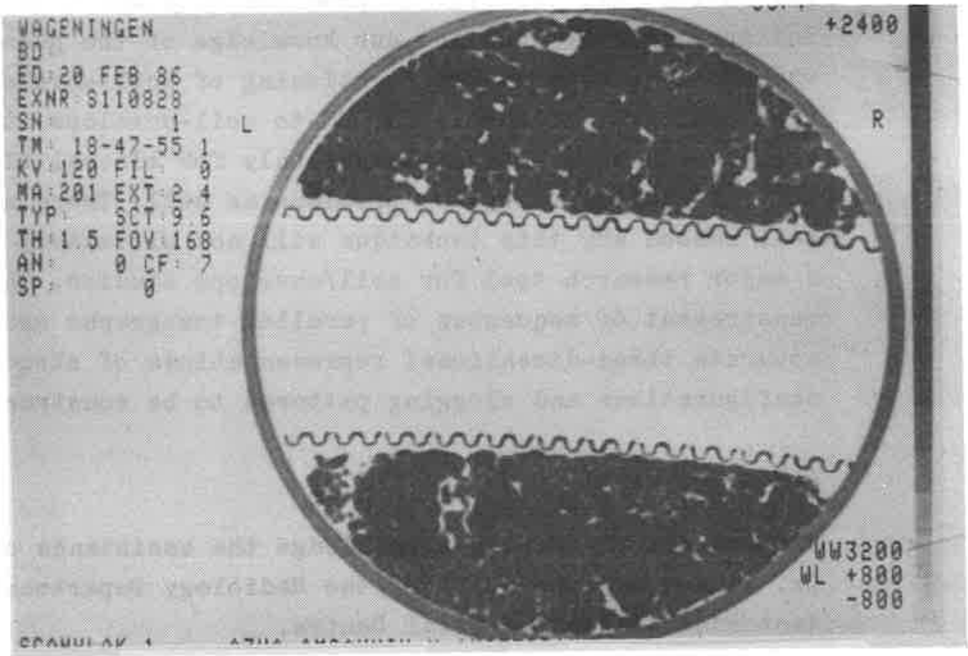

Fig. 11 CT image of an acrylic cylinder cross-section that contains a section of corrugated 60 mm drain pipe, wrapped with a thin envelope and backfilled with loose soil material. The thin envelope is invisible due to the chosen settings of the computer reconstruction algorithm

The field of diagnostic radiology has been faced with the problem how to obtain accurate, non-destructive three-dimensional internal images of the human body. Developments in x-ray physics and computer software enabled the development of the x-ray transmission computed tomographic (CT) scanner by Hounsfield (Hounsfield; 1972). The advantage of a CT scanner over other radiographic processes is that a cross-section of linear attenuation coefficients is obtained with a recordable radiation attenuation difference as low as 0.1% and a two-dimensional resolution of 2 mm^2 or less. The precision, linearity, spatial resolution and limitations of the CT-scanner for determination of soil morphological characteristics like distribution of aggregates and bulk density was evaluated using a Siemens Somatom-DR housed at the Amsterdam Academic Medical Centre (AMC).

It was established that the CT-scanner can be used to determine soil morphological data with good spatial resolution, cf. fig. 10. It produces data which is indispensable to increase our knowledge of the phenomena which play a role in the functioning of soil/envelope combinations. Application of CT to soil-envelope studies possesses a high potential, not only for mineral clogging, but for chemical clogging problems as well. There seems no real reason why this technique will not ultimately become a major research tool for soil/envelope studies. The measurement of sequences of parallel tomographs should enable accurate three-dimensional representations of structural configurations and clogging patterns to be constructed.

Acknowledgement

The authors gratefully acknowledge the assistance of Dr. Venema and the staff of the Radiology Department at the Amsterdam Academic Medical Centre.

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OXIDATION REDUCTION DUE TO A HIGH WATER TABLE 1/

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Abstract

An experiment was conducted in Louisiana, USA to determine the feasibility of using redox potentials (Eh) to indicate the need for subsurface drainage. Sugarcane, wheat, and soybeans in 40m^2 concrete bordered field plots, were subsurface drained and waterlogged for various durations. Eh was measured during the crop's growing season and correlated with crop yields. Relatively good relationships were obtained between the summation of Eh in the oxidized range (332 mV) and yields of cane and sugar. High Eh was associated with high yields. Eh correlations with cane and sugar yields show that redox potentials can be used to indicate drainage needs.

1 Introduction

Excess soil-water is a problem for most crops. Water per se however, is not the problem. It is a symptom of the real problem which is inadequate aeration of the plant's root system. It may be identified as waterlogging, oxygen deficiency, oxidation reduction status, anaerobiosis, carbon dioxide excess, or the existence of other compounds associated with anaerobic conditions that either reduce root functions and growth or kill the root system.

Excess soil-water problems exist throughout the world. During the last half-century thousands of hectares of land in the humid areas of the world have been subsurface drained to reduce the adverse affects of excess soil-water on crops. Even in regions where irrigation is practiced, excess soil-water problems frequently exist due to over-irrigation.

In certain humid areas, like the Eastern United States, there is a need

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to remove excess water from the soil during winter and spring months and a need for irrigation during the summer. To meet this dual need, redesigned subsurface drainage systems have been used. When drainage is needed, the subsurface drain lines are allowed to flow freely into an outlet. When irrigation is needed, the water level in the outlet is raised so water flows back through closely spaced drains to raise the water table into the crop's root zone. The mechanics of such a dual system are simple. The difficult part is managing the system - knowing when to drain or irrigate under erratic and uncertain climatic conditons.

There are many methods and techniques available for determining when to irrigate but only a few techniques for determining when to drain. If impending adverse soil-water conditons could be easily identified, action could be taken at the proper time to alleviate the adverse soil-water excess condition and avoid crop damage. Water table depth and soil moisture percentage are two commonly used techniques to indicate adverse soil conditions. Since these indicate only the symptoms of the real problem, a more basic indicator, such as oxidation-reduction status (redox potential), may be a more direct technique of sensing the true water excess problem if a relationship between the redox measurement and crop response can be established.

The purpose of this paper is to determine the feasibility of using redox potentials to indicate subsurface drainage needs.

2 Background Information on Redox Potential

Redox potential of a soil system is a measure of its tendency to accept or donate electrons and is governed by the nature and proportions of the oxidizing and reducing substances which it contains (Krizek, 1982).

When soil is waterlogged, diffusion of molecular oxygen into the profile is greatly impeded. If the condition persists, normal plant growth can be adversely affected from lack of oxygen or accumulation of CO_2, or other compounds to toxic levels (Kramer, 1951).

After waterlogging, a succession of events occur, beginning with depletion of oxygen trapped in the soil (Patrick and Turner, 1968).

This is followed by a reduction in nitrogen, manganese, iron, and sulphur compounds. If the anaerobic conditions continue, the formation of hydrogen sulphide, hydrogen, and methane occurs in succession (Russell, 1977). These events are closely related to redox potential. Takai and Kamura (1966) published a table showing the relationships between redox potential and the succession of events in a waterlogged soil (Table 1). Note the overlap of redox measurements among the systems. Oxygen disappears in the +600 to +500 mV range while nitrate disappears in the +500 to +300 mV range. The exact point on the redox scale at which there is no free oxygen is uncertain. Researchers have reported several different values below which they estimated no oxygen exists. For example, Turner and Patrick (1968) reported no free oxygen at +332 ± 5 mV while Grable and Siemer (1968) reported no oxygen at +267 mV. Other redox values at which no oxygen exists have been reported

Table 1. Succession of events occuring in a waterlogged soil as related to the redox potential.

Period of Incubation	Stage of Reduction	System	Redox Potential (Millivolts)
		Disapperance of O_2	+600 to +500
		Disapperance of NO_3	+500 to +300
Early	First Stage	Formation of Mn^{2+}	+400 to +200
		Formation of Fe^{2+}	+300 to +100
		Formation of S^{2-}	0 to -150
Later	Second Stage	Formation of H_2	-150 to -220
		Formation of CH_4	-150 to -220

(Bohn, 1971; Pearsall, 1950). In general, one may consider redox potentials ranging from -400 mV (strongly reduced) to +700 mV (well oxidized) with little or no oxygen in the soil at +350 mV or less. Redox potentials are commonly measured with platinum electrodes. (Bohn, 1971). The platinum electrode is not specific to a single redox couple; thus, the measurement generally represents a mixed potential that reflects the weighted average of the potentials contributed by each redox couple in the system (Grambrell and Patrick, 1978). Nevertheless, redox potentials in soils are widely used and are generally well-accepted.

3 Procedure

Twelve concrete-bordered field plots $40m^2$ in size (5.5 by 7.4 m) were installed on silt loam soil at Louisiana State University's Ben Hur research farm near Baton Rouge and equipped with facilities for controlling the water table in each plot at any depth from 0 to 135 cm below the soil surface. This water control facility was achieved by installing in each plot two 10-cm diameter drain lines spaced 2.7 m apart, which passed through the concrete borders after which they were connected by solid pipe to a water level control sump (1 sump/plot) outside the plot area (Figure 1). A water level maintained at a constant elevation in the water control sump provided a similar constant water level in that plot. The effects of waterlogging on yields of three crops - sugarcane, soybeans, and wheat - were determined.

The plots were first planted to sugarcane using conventional practices which included 30-cm high seedbeds spaced 1.8 m apart. The cane plots were exposed to three cyclic and three constant water level treatments in 1972 and again in 1973. The cyclic treatments were imposed by raising the water table to the soil surface (waterlogging) on two plots for 1, 2, and 4 weeks followed by draining (to a 135-cm depth) for 7, 6, and 4 weeks, respectively. The two-month cycles were initiated May 8, July 7, and September 4, 1972, and May 16, July 11, and September 5, 1973, on 2nd and 3rd sugarcane ratoons, respectively. In addition to the high water tables, water was also ponded about 10 cm deep between the rows in 1973. The constant water table treatments were imposed by

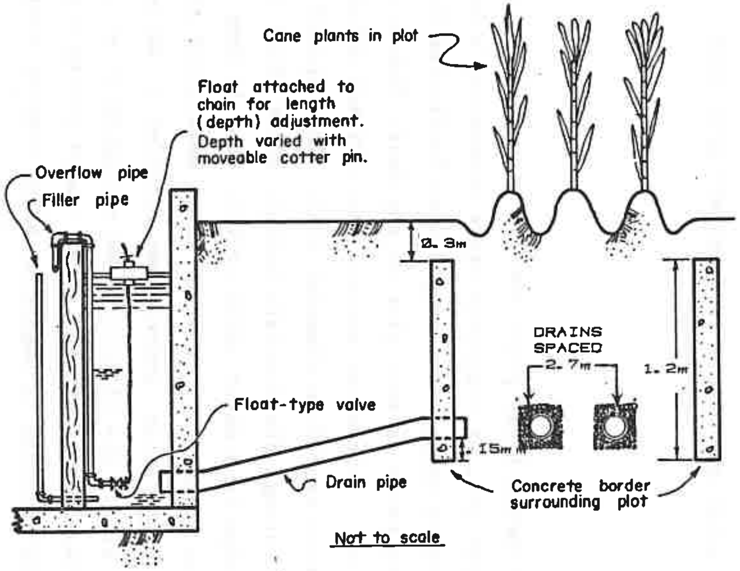

Figure 1. Schematic of the concrete bordered plots used in waterlogging experiment.

maintaining the water table continuously on two plots at 30, 120, and 135 cm below the mean soil surface.

Twelve plots were planted in wheat during November 1984 and in soybeans during May 1985. The crops were flat planted with rows spaced 18 cm apart. After good stands were obtained, the two crops were exposed to three cyclic and two constant waterlogging treatments. The cyclic treatment on two plots each were: a) a high water table (within 30 cm of the soil surface) for two weeks followed by a low water table (drained to 135 cm depth) for two weeks. This high and low cycle was repeated throughout the growing season; b) a high water table for two weeks during the boot stage (for wheat) or bloom stage (for soybeans) with the plots drained to 135 cm at other times; and c) a high water table for two weeks during seed development stages (heading for wheat and pod filling for soybeans) with the plots drained to 135 cm at other times.

The constant water table treatments on two plots each were continuously high (within 30 cm of the soil surface) throughout the growing season and continuously low (drained to 135 cm) throughout the growing season. Two additional plots in the set were available for irrigation if needed. Since no drought occurred, these additional plots were drained to 135 cm continuously throughout the growing season.

The water tables in all treatments were usually checked three times each week and adjusted as needed to the treatment level. Besides the waterlogging treatments imposed during this experiment, other wetting and drying cycles occurred during and after rainfall.

Platinum electrodes were installed 25, 50, and 75 cm below the soil surface (three electrodes at each depth) in the sugarcane experiment. Platinum electrodes were installed (8 to 16 in each plot) 30 cm below the soil surface in both the wheat and soybean plots. Different depths were used in sugarcane because it was planted on high (30 cm) seedbeds and it has a deep root system. Redox potential (Eh) were usually read three times each week using a pH meter with a mV scale, a calomel half cell, and the platinum electrodes. Thermocouples were installed the same depth as platinum electrodes and read at the same time as Eh. The redox potential measurements were adjusted for soil temperature.

In the sugarcane experiment, the entire plot was harvested and weighed in November each year to determine sugarcane yield. A sample of stalks was collected from each plot for determining sucrose content and sugar yield (Legendre, 1976). Wheat and soybeans were harvested with a plot combine in May 1985 and November 1985, respectively. Two passes, the width of the combine (1.3 m) and the length of the plot (7.4 m), were made in each plot at harvest. The seeds from each plot were weighed for yield estimates and sampled for moisture content. Wheat and soybean yields were adjusted to 14% moisture content. Crop yields were correlated with redox potentials.

4 Results and Discussion

Rainfall during the sugarcane experiment was above normal both years with 1585 and 1924 mm measured in 1972 and 1973, respectively (Table 2). Normal annual rainfall in Baton Rouge, Louisiana is 1450 mm. Rainfall during the wheat and soybean experiment was 1531 mm in 1985, 81 mm above normal (Table 2).

Redox potentials (Eh) fluctuated considerably during these experiments as indicated by the data in Figures 2, 3, and 4. The data from electrodes at two depths, shown in Figures 2 and 3 illustrate the relatively high Eh in a drained (oxidized) soil system and relatively

Table 2. Rainfall during waterlogging experiments with sugarcane, wheat, and soybeans.

Year	1972	1973	1985
		(mm)	
Jan	197	90	121
Feb	132	70	141
March	155	299	112
April	24	265	121
May	229	111	67
June	39	76	82
July	113	114	165
August	85	149	144
Sept.	122	282	218
Oct.	106	65	220
Nov.	134	202	28
Dec.	249	201	112
Total	1585	1924	1531

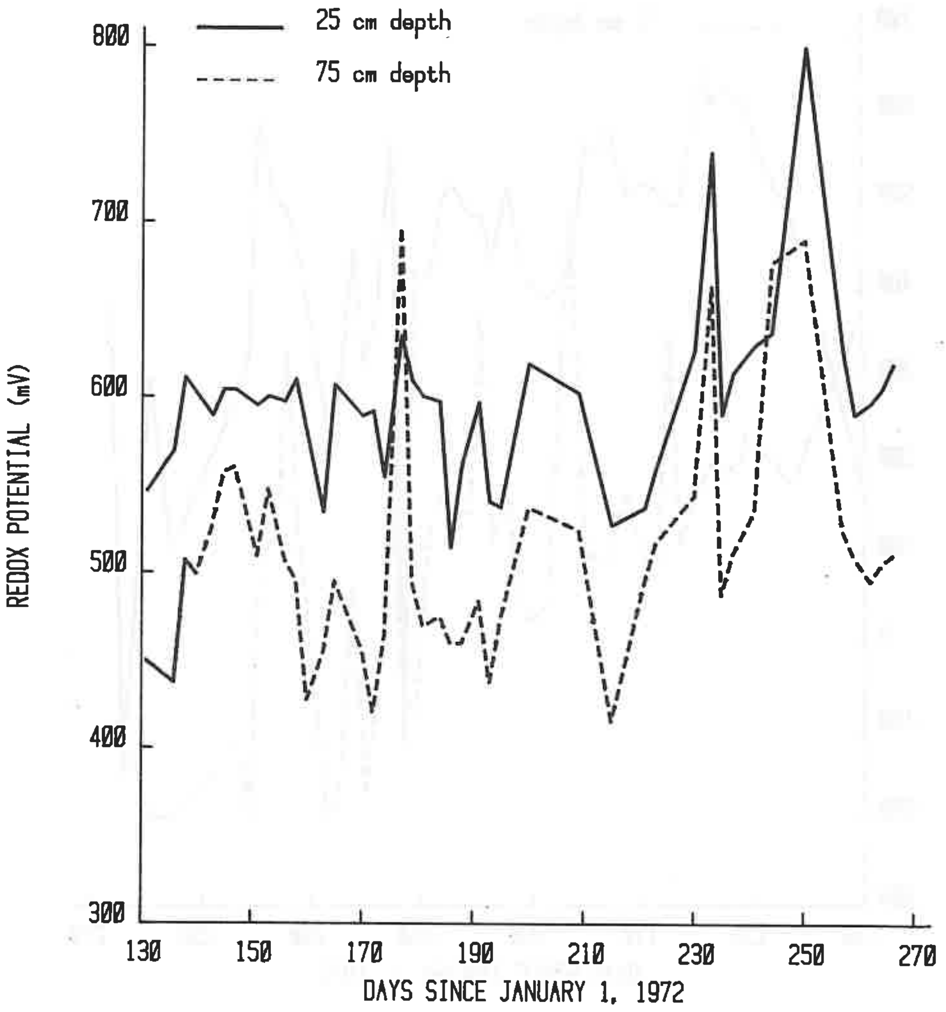

Figure 2. Redox Potentials measured 25 and 75 cm below the soil surface in a drained sugarcane plot in 1972.

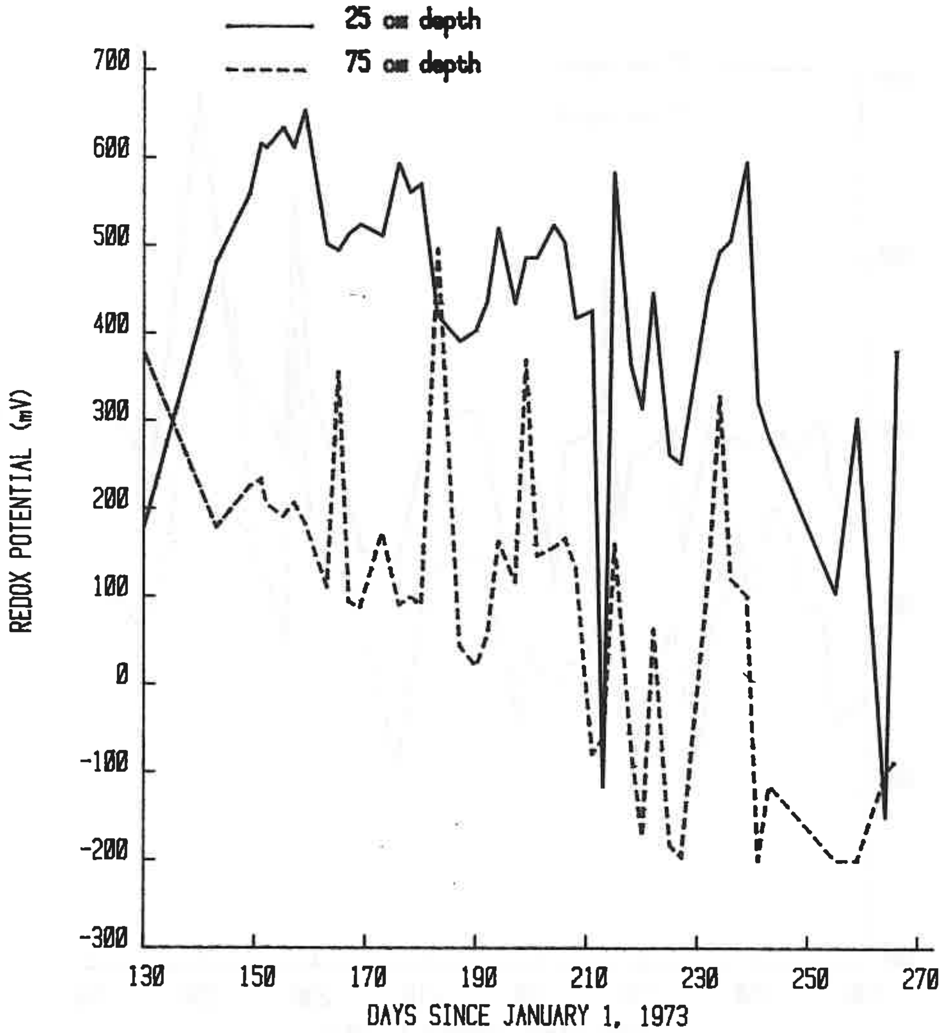

Figure 3. Redox Potentials measured 25 and 75 cm below the soil surface in a waterlogged (to within 30 cm of the soil surface) sugarcane plot in 1973.

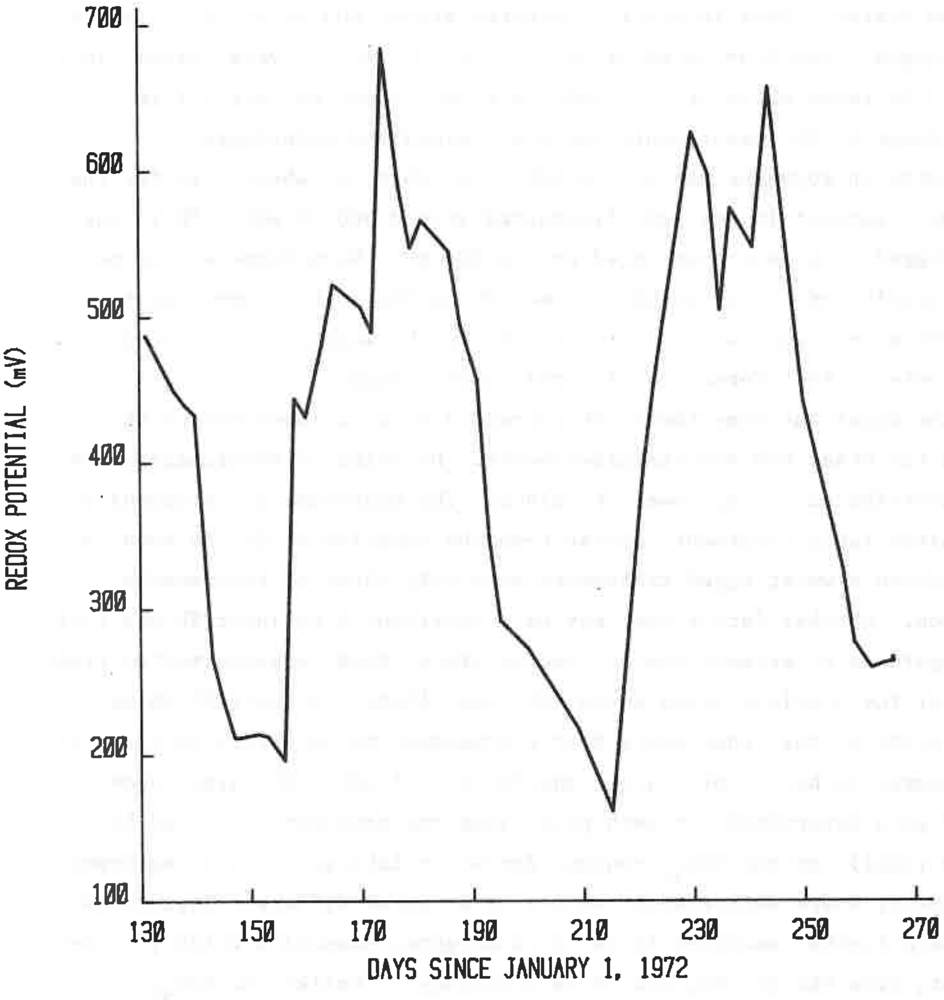

Figure 4. Redox Potentials in a sugarcane plot that was waterlogged for 4-week durations beginning on days 129, 189 and 248, 1972.

low Eh in a waterlogged (reduced) soil system, respectively (See Table 1). Redox values from the 50 cm depth were between those measured at the 25 and 75 cm depth.

Eh for the 4-week waterlogging treatment in 1972 is shown in Figure 4. Eh responded to the waterlogging treatments closely, decreasing during waterlogging, then increasing when the plots were drained. Eh data from the two drained plots in wheat fluctuated around 600 mV while Eh in the waterlogged plots fluctuated around 275 mV. Eh in the waterlogged plots was in the range where iron is reduced from ferrous to ferric form.

The range in Eh measurements for the drained and waterlogged treatments on soybeans was within 100 mV of that for wheat. Eh for the drained treatment in soybeans fluctuated around 500 mV while Eh in the waterlogged treatment fluctuated around 200 mV. Warm temperatures may have contributed to the slightly lower Eh in the soybean experiment. Like the waterlogged wheat plots, the Eh in the waterlogged soybean plots were in the "formation of ferric iron" range.

In the sugarcane experiment, Eh decreased to much lower values than it did in the wheat and soybean experiments. Duration of waterlogging may have contributed to the lower Eh values. The sugarcane's continuously high water table treatment covered 6-months duration while the wheat's and soybean's waterlogged treatments were only three to four months duration. Another factor that may have contributed to lower Eh was that the sugarcane experiment was on stubble crops; thus, organic matter from roots of the previous crops could have contributed to lower Eh values.

The point on the redox scale that corresponds to no oxygen in the soil was assumed to be 332 mV (Turner and Patrick, 1968). Eh values above 332 mV were determined for each plot using the procedure outlined by Sabein (1961) for the SEW_{30} concept for water tables. In the sugarcane experiment, where measurements were made at three different depths, Eh data were further analyzed to obtain a weighted summation which included all data from the 25, 50, and 75 cm electrodes. Unlike the SEW_{30} concept, where large values indicated possible adverse conditions, large values from the summation of Eh > 332 mV (SEh_{332}) represented favorable (oxidized) conditions.

SEh_{332} was correlated linearly with cane, sugar, wheat and soybean yields. Coefficients of determination were 0.639 and 0.687 in 1972 and

1973, respectively. By combining the 1972 and 1973 data, the coefficient of determination increased to 0.727 indicating that 73% of the variation in yield in 1972 and 1973 was attributed to SEh_{332} (Figure 5). Similar analyses were made for sugar yields. The 1972 and 1973 data are shown in Figure 6. Coefficients of determination were 0.269, 0.635, and 0.552 for 1972, 1973, and the combined data, respectively.

The correlation coefficient for sugar in 1972 was very low and may be due to the sucrose content of the cane juice varying inversely proportional with cane yield. The correlation between SEh_{332} and yields of cane and sugar, reported in this paper, was an improvement over the previously reported correlations between number of days redox potential was < 332 and crop yields (Carter, 1980).

The coefficients of determination for SEh_{332} and yields of wheat and soybean were low, 0.371 and 0.232 for wheat and soybeans, respectively. Further analysis of these data showed that the slope of the line which best fit the data for the soybeans was not significantly different from zero. The nature of the waterlogging treatments imposed on these two crops and the nature of the crops themselves probably contributed to these low coefficients. Depth of the electrodes may also have an impact on Eh values.

5 Summary

The data presented in this paper have established that yields of cane and sugar can be linearly correlated with redox potentials. Low redox potentials usually corresponded with low yields and high redox potentials usually corresponded with high yields. Redox potential measurements should not be considered as a replacement for water table measurements but as a supplement to them. Eh measurements can be used to provide further insight into the real problems caused by waterlogging. With further refinements in Eh and crop yield, redox potentials could become a valuable technique in estimating relative crop yield or estimating the consequences of waterlogging if corrective measures are not taken. Further work is needed to establish a better relationship between SEh_{332} and yields of wheat, soybeans, and other crops.

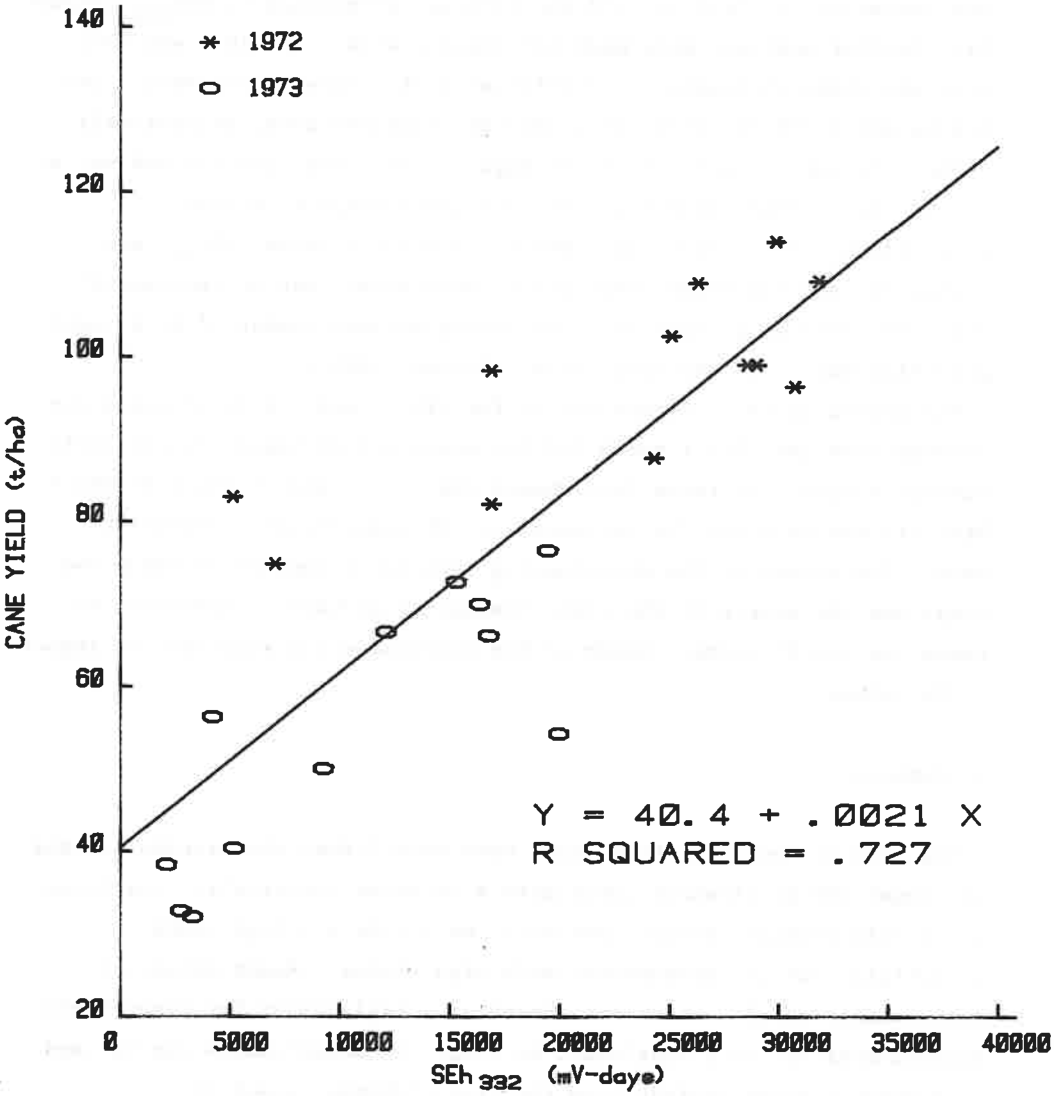

Figure 5. The relationship between cane yield and the summation of redox potentials > 332 mV, 1972 and 1973.

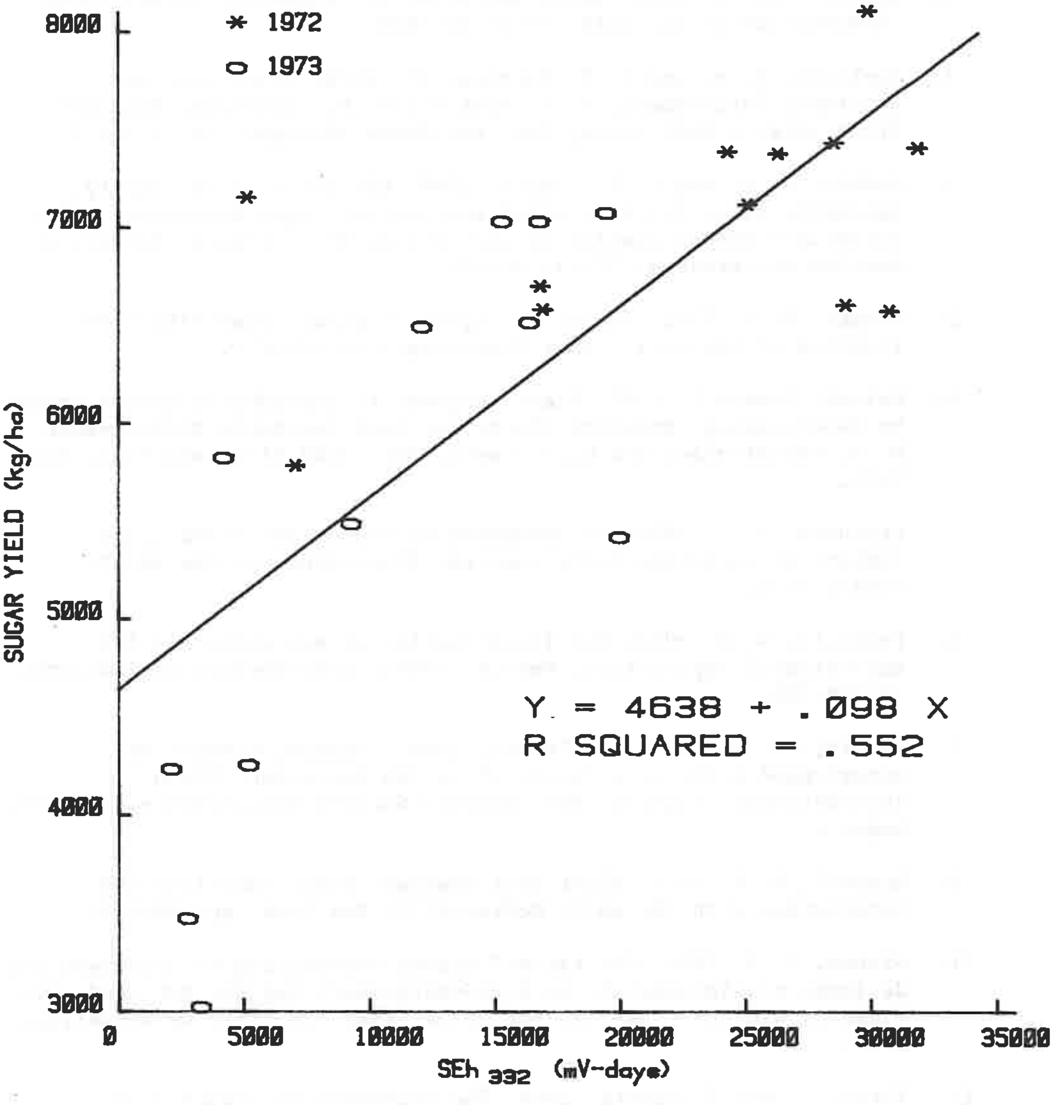

Figure 6. The relationship between sugar yield and the summation of redox potentials > 332 mV, 1972 and 1973.

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SIMULATING EFFECTS OF SOIL TYPE AND DRAINAGE ON ARABLE CROP YIELD

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ABSTRACT

To evaluate effects of drainage on crop yield physical and biological processes occurring in spring, growing season and autumn have been studied in detail. This paper deals with the influence of drainage upon:

- groundwater table depth and waterlogging during winter time;
- number and time of occurrence of workable days for sowing and planting operations;
- duration of germination and time of emergence in dependence on soil water water content and -temperature;
- water uptake, development and growth of crops.

A number of relationships and models have been developed and combined into an integrated model approach that considers all those effects. The model operates on a daily basis using actual weather and soil data. It has been tested for various conditions in the field.

Results of 30 years of model simulation on potatoes grown on two soil types for five different drain depths and three drain intensities are presented.

1. INTRODUCTION

In the Netherlands land development projects are executed over an area of about 35 000 ha yearly. For the economical evaluation of these projects quantitative information is needed on the effects of soil and water management measures upon agricultural crop yield. Up till now these effects are determined in a more or less empirical way.

During the past decade more and more effort has been put into the development of computer models that simulate crop growth and production in dependence of soil and climatic conditions. The advantage of simulation models is that effects of changes in soil/water management can be obtained in a short time over long time periods over which climatic records are available.

During a number of years an integrated model approach that quantifies the effects of water management on crop yield has been developed step by step (see Feddes and Van Wijk, 1977; Van Wijk and Feddes, 1982). The present paper describes the most recent state of the art of this approach. The model predicts effects of changes in water management by drainage on trafficability and workability in spring, sowing/planting time, emergence date, transpiration, growth and dry matter yield of crops, for different types of soils under various meteorological years. To illustrate the capability of the model with respect to the quantification of all these aspects, some examples will be given. These examples include the simulation of drainage effects on the production of a potato crop grown during 30 meteorological years on a sandy loam and on a 40 cm loam on sand soil profile.

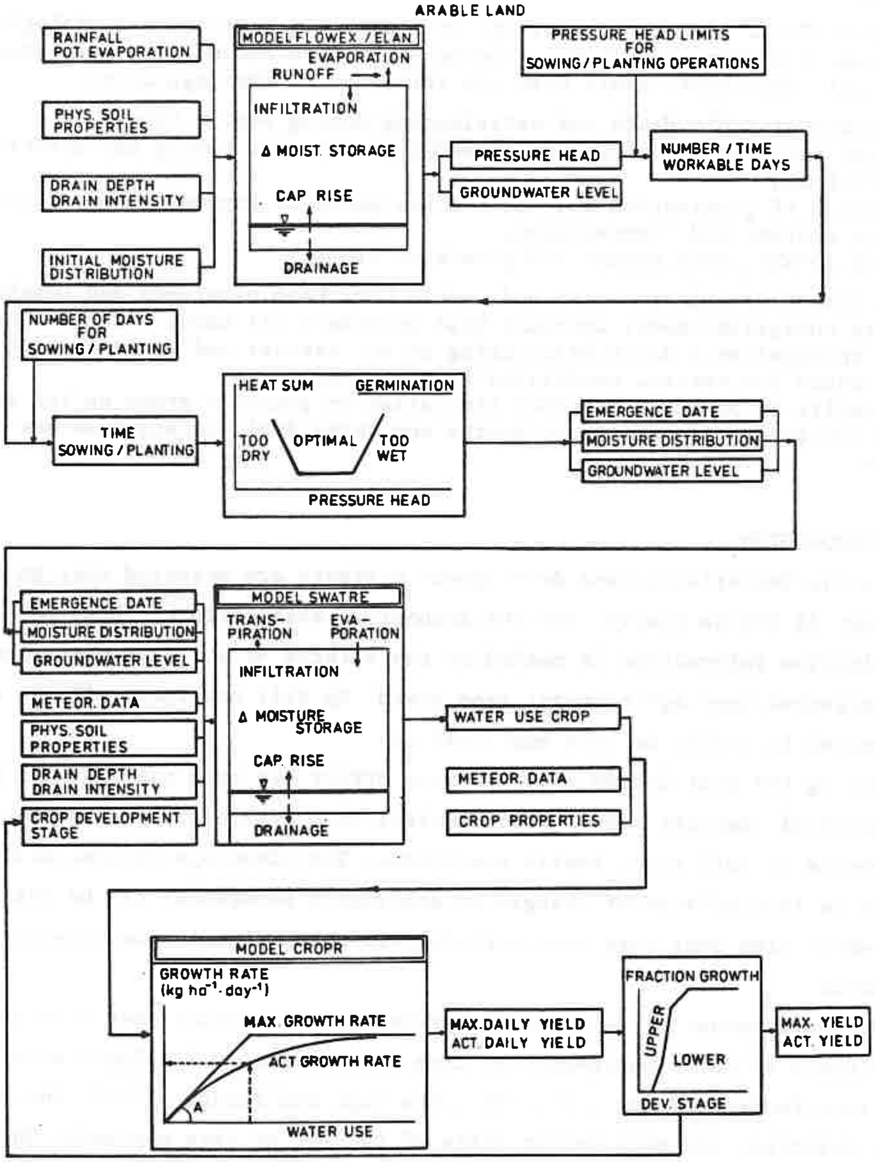

Fig. 1 Flow chart of the integrated model approach for computing the influence of water management on yields of arable land

2. MODELING SOIL WATER MANAGEMENT, CROP GROWTH AND -PRODUCTION

A model that simulates effects of drainage on crop production has to reckon with effects of both 'too wet' and 'too dry' conditions. Such a model must be able to indicate quantitatively how soil water conditions in winter, time of field operations, germination and emergence in spring, crop growth and production in summer and workability in autumn are influenced by drainage conditions. In Figure 1 a flow chart of such an integrated model approach is presented.

2.1. Modeling soil water conditions in winter and spring

The model FLOWEX (Wind and Van Doorne, 1975; Buitendijk, 1984) computes the terms of the soil water balance of a non-cropped soil profile, that may consist of different layers. The model has been developed to consider effects of changes in soil water content on the utilization conditions of the soil, such as workability and trafficability.

FLOWEX is based on an integrated form of the Darcy flow equation assuming an exponential relationship between hydraulic conductivity and soil water pressure head. Combination with the continuity equation results in a description of the non-steady state flow process, layer by layer for consecutive time increments. As boundary condition at the soil surface rainfall/potential soil evaporation is used. As boundary condition at the bottom a flux - groundwater table depth relationship, based on the drainage theories of Hooghoudt (1940) and Ernst (1956) is applied.

Input into FLOWEX is: rainfall and potential soil evaporation on a 24-hour basis, soil water retention and hydraulic conductivity curves for the different soil layers, drain depth and drain intensity and finally the initial soil water profile. Output of the model includes all the terms of the water balance, the distribution of soil water content, pressure head and fluxes with depth. The suitability of the soil for field operations depends on the pressure head in the top layer of the soil. For this purpose the pressure head at 5 cm depth is taken.

2.2. Modeling workability in spring

In two rather different meteorological years measurements of the pressure head at 5 cm depth in spring were regularly carried out on a number of different soils. Simultaneously farmers were asked to give their judgement of the suitability of the soil for field operations in terms of good, moderate and poor. In Figure 2 the result for a number of soils is shown,

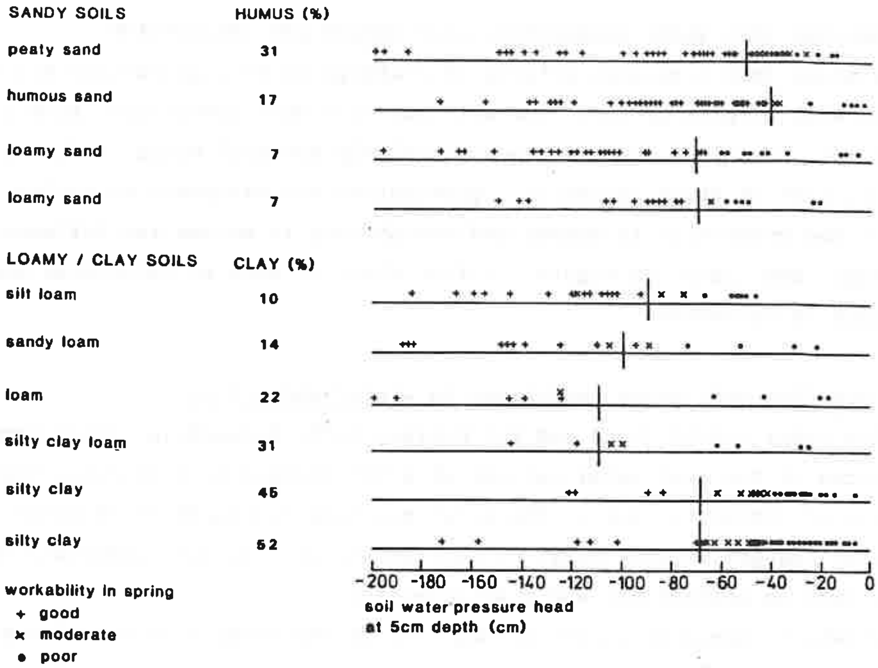

Fig. 2 Farmers' appraisals of workability of a number of different soils for planting potatoes versus the soil water pressure head at 5 cm depth, simultaneously measured in the field

Table 1 Soil water pressure heads at 5 cm depth at which sowing of spring cereals and sugar beets and planting potatoes can be executed without deterioration of soil structure

Soil type	Soil water pressure head (cm)		
	Spring cereals	Sugar beet	Potatoes
Sandy soils	-50	- 70	- 70
Silt/sandy loam (8-20% particles <2 µm)	-80	-100	-100
Loam/silty clay loam (20-40% particles <2 µm)	-60	-100	-120
Silty clay (>40% particles <2 µm)	-40	- 60	- 80

which enables the derivation of pressure head limits that are critical for workability. As a result a summary of pressure head limits for sowing spring cereals, sugar beet and planting potatoes for four main soil groups is presented in Table 1. With the aid of the workability limits in this table, one can derive time and number of days that the soil is workable from a day to day simulated course of the pressure head at 5 cm depth. Knowing the earliest possible sowing/planting date and the number of days required for these operations one can predict the time of sowing/planting.

In the Netherlands the earliest possible sowing date for spring cereals is 1 March. For sowing sugar beets and planting potatoes this date is 20 March. The number of days that are required on an average farm in the Netherlands for sowing and planting is for spring cereals 1, for sugar beets 2 and for potatoes 4 days.

2.3. Modeling germination and emergence

Knowing the sowing/planting date the emergence date can be predicted if one is informed how germination depends on soil water content and temperature in the seed bed. Under optimal conditions of soil moisture time of emergence t can be predicted from the relationship:

$$F = (\overline{T} - T_{min})t \qquad (1)$$

where F = heat sum required for a certain percentage of emergence ($^{o}C \cdot d^{-1}$)

$\overline{T}$ = mean soil temperature

T_{min} = minimum temperature (^{o}C) below which no germination occurs

From sowing - emergence experiments in the field one can derive T_{min} and F through eq. (1), by plotting $\overline{T}$ versus 1/t (see Feddes, 1971). Often soil temperatures are not available, hence one applies in eq. (1) for $\overline{T}$ the average air temperature. As an example Figure 3 is presented for potatoes. Data in this figure are based on 10 years of field experiments.

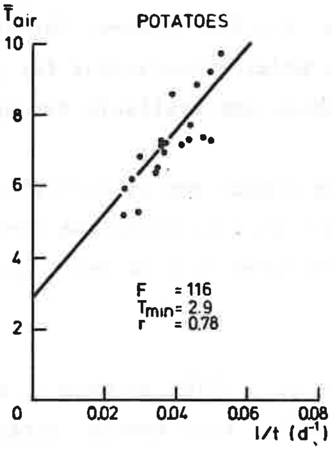

Fig. 3 Mean air temperature $\overline{T}$ plotted versus the reciprocal of time required for emergence of potatoes in order to derive T_{min}.
F = heat sum (^{o}C·days), r = correlation coefficient

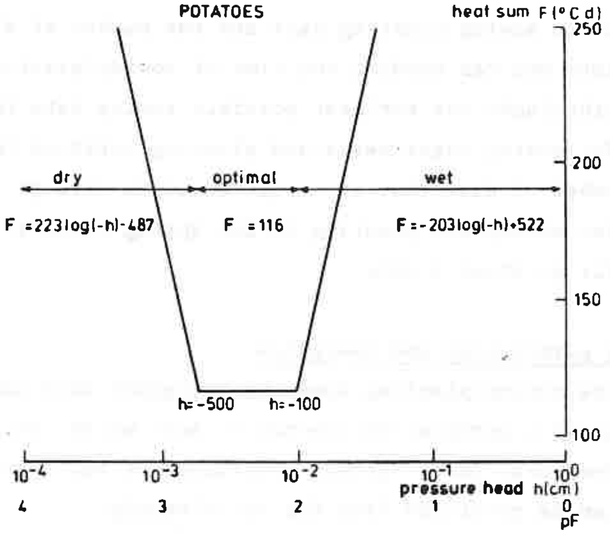

Fig. 4 Relationships between the heat sum required for emergence of potatoes, based on daily mean air temperatures and the soil water pressure head in the seedbed

Under sub-optimal soil water conditions eq. (1) does not apply. Germination is retarded when the seedbed is either 'too dry' or 'too wet'. To model the combined effect of soil temperature and soil water on germination and emergence the effective heat sum can be related to the soil water pressure head of the seedbed. In field experiments Feddes (1971) found for a number of crops a constant sum when the pressure head h ranged between -100 and -500 cm. Outside this range germination was retarded through either abundancy or shortage of soil water. From the same experiments, it appeared that at $h = -20$ cm and at $h = -2000$ cm, $F \approx 250$ °C·days. The relationships thus obtained and finally used in the model calculations for potatoes are depicted in Figure 4. Similar relationships are available for spring cereals and sugar beet.

Starting at the sowing date a heat sum is now calculated day by day according to the relationship in Figure 4, using the 24-hour mean air temperature and the simulated pressure head at 5 cm depth in the seedbed.

2.4. Modeling crop water use

The model SWATRE (Feddes et al., 1978; Belmans et al., 1983) computes water flow in a heterogeneous soil - root system. Water extraction by roots is accounted for by a sink term. The partial differential equation valid for the flow is approached by a finite difference equation. Taking into account the upper and lower boundary conditions the equation is solved implicitly for each separate soil compartment applying the Thomas algoritme.

Input into SWATRE consists of: initial pressure head distribution with depth, 24-hour data on rainfall, potential soil evaporation and potential transpiration, the soil water characteristics and hydraulic conductivity curves for the different soil layers, rooting depth (varying with time), critical pressure head values for water uptake by roots (sink term) and drain depth and -intensity.

Output of the model includes all the terms of the water balance, the distribution of soil water content, pressure head, fluxes and water uptake by roots in dependency of depth. The main output is the transpiration rate, calculated as the integral of the sink term over the depth.

2.5. Modeling crop development, growth and production

Daily actual dry matter growth rate of a crop having optimal nutrient supply q ($kg \cdot ha^{-1} \cdot d^{-1}$) is calculated with the simulation model CROPR (Feddes et al., 1978) as:

$$(1 - \frac{q}{A \frac{T}{\Delta e}})(1 - \frac{q}{q_{pot}}) = \xi \qquad (2)$$

where A is maximum water use efficiency ($kg \cdot ha^{-1} \cdot cm^{-1} \cdot mbar$) determined from field experiments, T is actual transpiration rate ($cm \cdot d^{-1}$) from SWATRE, Δe is vapour pressure deficit of the air (mbar), q_{pot} is potential growth rate ($kg \cdot ha^{-1} \cdot d^{-1}$) computed as a function of among others radiation and leaf area index, ξ is a mathematical parameter ($\xi = 0.01$).

In earlier versions of CROPR, a certain prescribed variation of soil cover with time was assumed. At present the models SWATRE and CROPR are combined into one model, with the development of the crop being generated by the model itself.

The development of a crop with time varies usually from year to year, depending on environmental factors such as temperature, day length, soil water content, etc. To solve this problem time is made dimensionless by introducing the development stage D_s of the crop. If D_s is set 0 at emergence (t_{em}) and 1 at harvest time (t_{ha}) any intermediate development stage is then defined according to:

$$D_s(t) = (t - t_{em})/(t_{ha} - t_{em}) \qquad (3)$$

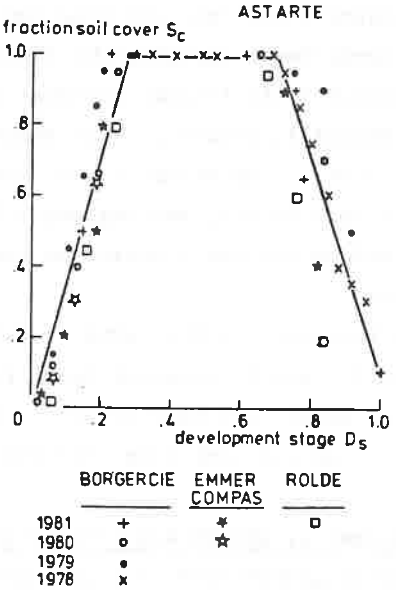

Fig. 5 Variation of S_c with D_s for potatoes (variety Astarte) grown at different locations over a number of years

to obtain information about the parameters in eq. (3) for potatoes used here as an example, long year field experiments were analyzed. This analysis showed that variation of soil cover S_c with D_s is constant over the years (Figure 5). Determination of the parameter t_{em} has been described in Section 2.3. In the Netherlands t_{ha} is about 15 September for the variety Bintje and 15 October for the variety Astarte.

Because there is a fixed relationship between leaf area index I (ha·ha^{-1}) and fraction of soil cover S_c (data of Van Loon, pers. comm.*)

$$I = 2.6S_c + 1.5S_c^2 + 0.9S_c^3 \tag{4}$$

the variation of I with D_s is known also. Hence q_{pot} can be computed and q be solved from eq. (2).

The increase in total dry matter production as a function of development stage D_s is then distributed over shoot and tubers according to the field experimentally based relationship shown in Figure 6.

Having calculated actual growth rates q^i day by day, final yield Q is

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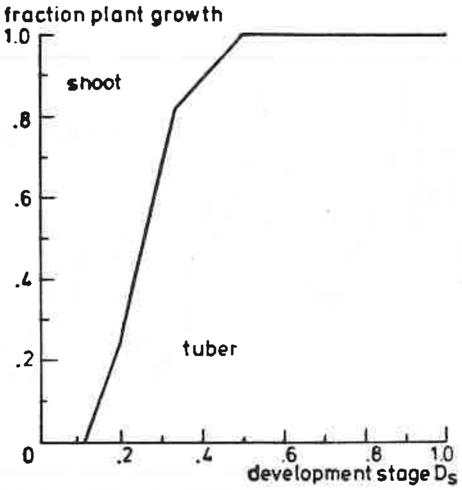

Fig. 6 Distribution of increase in total dry matter production over shoot and tubers of a potato crop

obtained as:

$$Q = \sum_{i=1}^{n} q^i \Delta t \qquad (5)$$

where Δt represents a period of 1 day. In a similar way one can calculate potential yield Q_{pot}.

3. SIMULATION OF THE EFFECTS OF DRAINAGE ON CROP YIELD

The model has been verified with measurements in the field at different points in the scheme given in Figure 1. As an example Figure 7 compares the variation of pressure head at 5 cm depth and the groundwater table depth simulated with FLOWEX with measured data for the sandy loam soil in the spring of 1980. An example of the model behaviour during the growing season is presented in Figure 8. This figure compares the total dry matter and tuber production of potatoes grown in 1981 on a sandy soil simulated with SWATRE/CROPR with measured productions. Both figures show that both soil water and plant growth conditions can be simulated reasonably well.

To illustrate the capabilities of the integrated model approach results of 30 years (1952-1981) of model simulation on potatoes grown on a sandy loam and a 40 cm loam over sand soil profile are used. The soil water characteristic and hydraulic conductivity curve of both soil types have been taken from Beuving (1984). Each soil is thought to have a drainage system installed at depths of 60, 90, 120, 150 and 180 cm. For each drain depth three different drain spacings, expressed as intensities A (d^{-1}) are applied.

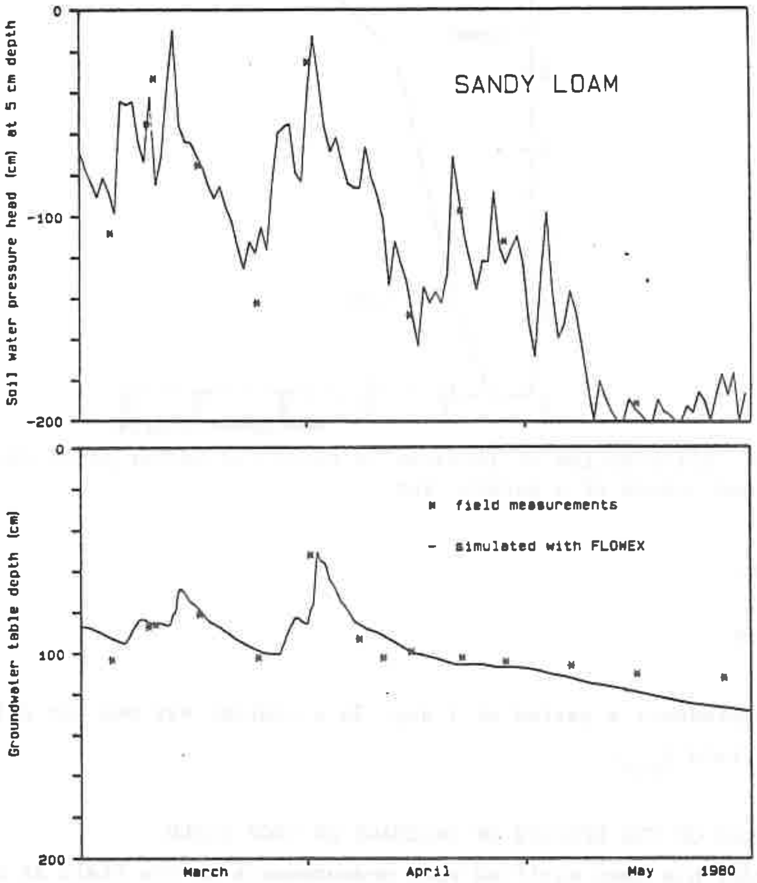

Fig. 7 Comparison of the soil water pressure head at 5 cm depth and groundwater table depth, simulated with FLOWEX with data measured in the sandy loam in spring 1980

The value A in fact gives the relation between discharge and height of water table midway between parallel drains and incorporates the drain spacing L. According to Hooghoudt (1940):

$$A = \frac{8K_s d}{L^2} \qquad (6)$$

where K_s = soil hydraulic conductivity ($cm \cdot d^{-1}$)

d = thickness of the so-called equivalent layer (m)

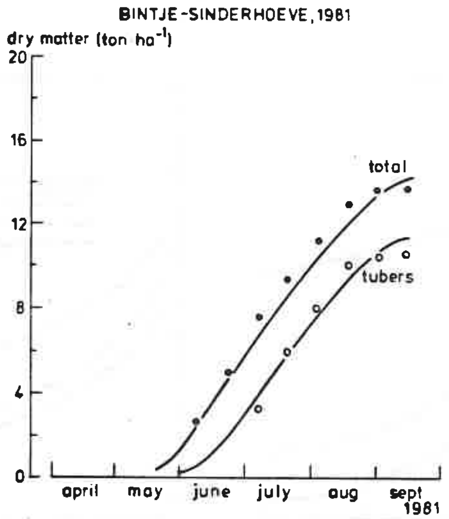

Fig. 8 Comparison of SWATRE/CROPR computed yields (lines) with measured data (points) of potatoes growing in 1981 on a 40 cm humous medium coarse sand overlying very coarse sand

3.1. Influence of drainage on germination and emergence date

In the way described in Sections 2.1 to 2.3 emergence dates were calculated for all combinations mentioned above. Figure 9 shows the emergence date of potatoes grown on the sandy loam soil for each separate year at five different drain depths with comparable drain intensities. It appears to be very effective to increase drain depth. Going from D = 60 cm to D = 90 and

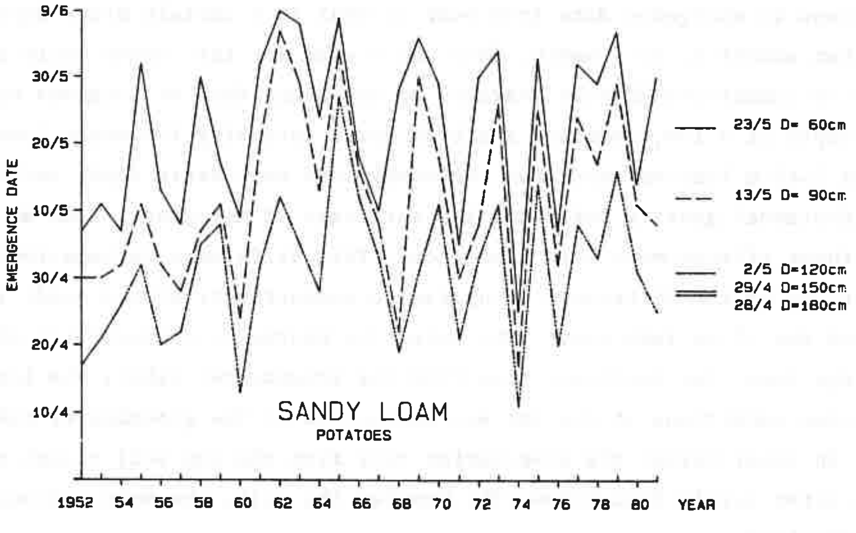

Fig. 9 Yearly emergence dates of potatoes on the sandy loam simulated over a 30-year period at different drain depths

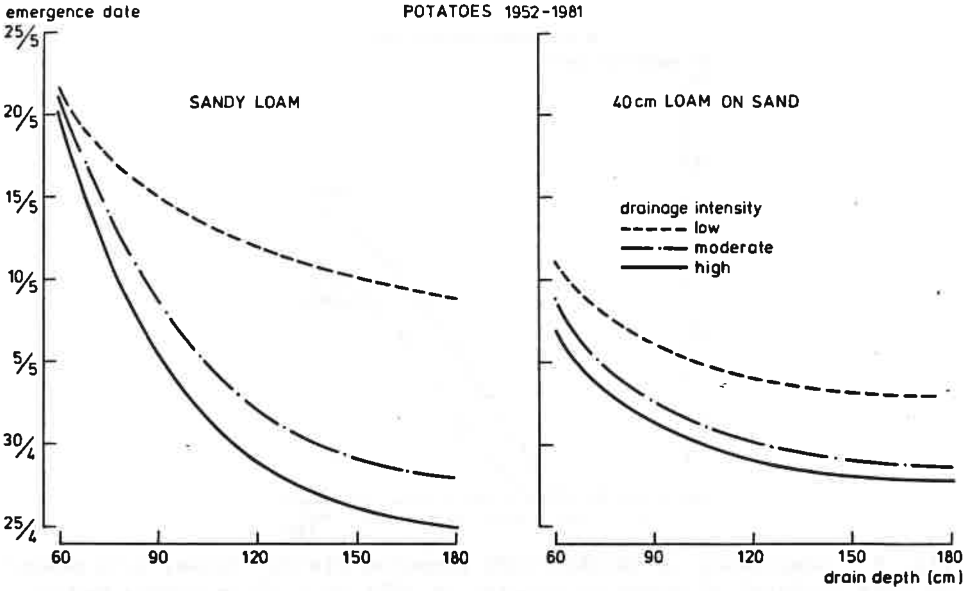

Fig. 10 Influence of drain depth and intensity on the emergence date of potatoes growing on the sandy loam and 40 cm loam on sand soils, based on a simulation over the period 1952-1981

D = 120 cm the 30-year averaged emergence date advances with 10 and 21 days. Increasing drain depth further the advance of emergence date becomes less progressive. Increase of drain depth goes in general together with deeper groundwater tables, hence with less potential for capillary rise from the groundwater and thus more rapid drying of the top soil. Considering the variations in emergence date from year to year at a certain drain depth, these can amount up to 1 month. This holds also for the larger drain depths. Figure 10 summarizes 30-year averages of emergence date of potatoes versus drain depth at a low, moderate and high drain intensity for sandy loam as well as 0.40 m loam on sand. For the sandy loam both drain depth and intensity (distance) greatly influence the earliness of emergence. Loam on sand shows these effects much less pronounced. This difference in behaviour can be ascribed to the difference in hydraulic conductivity of the sandy loam soil and the 40 cm loam cover. The lower the hydraulic conductivity of a soil, the lower the capillary rise from the groundwater table, the less the soil water conditions at the top are influenced by the groundwater table depth. In other words: the evaporation rate from the top soil cannot be met by the water supply from below. The heavier the soil, the more pronounced this behaviour.

3.2. Influence of drainage on crop yield

Crop water use and dry matter production have been calculated for all chosen combinations of soil, drain depth and -intensity for the 30-year period according to the procedures described in Sections 2.4 and 2.5.

In order to account for the drainage effects that occur separately in spring and in summer the following terminology will be introduced:

Q_{max} - maximum possible dry matter yield that can be obtained under the prevailing weather (i.e. radiation) conditions, assuming no shortage of water for the object with the earliest possible emergence date. For the combinations considered this date is always found at the greatest drain depth, i.e. 180 cm, with the highest drain intensity

Q_{pot} - potential dry matter yield obtained, assuming no shortage of water, starting at the actual emergence date of the considered drain depth/intensity combination

Q_{act} - actual dry matter yield obtained at the prevailing soil water conditions starting at the actual emergence date of the considered drain depth/intensity combination

Expressing separately the drainage effects occurring in spring and summer the following relationship holds:

$$\frac{Q_{act}}{Q_{max}} = \frac{Q_{pot}}{Q_{max}} \cdot \frac{Q_{act}}{Q_{pot}} \qquad (7)$$

total=spring·summer

The spring term accounts for the reduction in yield as a result of retardation in the sowing and emergence dates due to too wet soil conditions in spring. The summer term quantifies the shortage of water occurring during the growing period. The total drainage effect including both the influence of earliness in spring and water supply in summer is found by multiplying the spring with the summer-term in eq. (7).

In Table 2 30-years averaged relative yields of potatoes growing on sandy loam and 40 cm loam on sand due to drainage effects in spring, summer and over the total season are presented for five drain depths.

A number of comments can be made:

- the effect of drainage in spring on yield (Q_{pot}/Q_{max}) is much more pronounced on the sandy loam than on the 40 cm loam on sand;

TABLE 2 30-year averages of relative yields of potatoes due to effects of drainage in spring (Q_{pot}/Q_{max}), in summer (Q_{act}/Q_{pot}) and the total combined effect (Q_{act}/Q_{max}) at five different drain depths for a sandy loam and a 40 cm loam on sand

D (cm)	$\frac{Q_{pot}}{Q_{max}}$	$\frac{Q_{act}}{Q_{pot}}$	$\frac{Q_{act}}{Q_{max}}$
Sandy loam			
60	0.83	0.97	0.81
90	0.92	0.95	0.87
120	0.98	0.94	0.92
150	1.00	0.90	0.90
180	1.00	0.87	0.87
40 cm loam on sand			
60	0.93	0.92	0.86
90	0.96	0.90	0.86
120	0.99	0.88	0.87
150	1.00	0.85	0.85
180	1.00	0.81	0.81

- drain depths of 150 cm are minimally required to prevent yield reduction due to retardation of emergence. For explanation of this behaviour see the comments given to Figure 10;
- the reduction in yield due to water shortage during summer (see Q_{act}/Q_{pot}) is largest on the 40 cm loam on sand. The reason for this is the poor capillary supply from the groundwater to the root zone through the subsoil of sand;
- the reduction in yield due to deeper drainage is in both cases of the same magnitude;
- the optimum drain depth for total yield (see Q_{act}/Q_{max} column) is for both soil types about 120 cm. The relative production level at this depth is however highest on the sandy loam;
- yield reduction on the 40 cm loam on sand is caused mainly by water shortage in summer, while on sandy loam yield reduction is mostly affected by differences in emergence date.

In Figure 11, the 30-year averaged data of Table 2 are presented together with comparable data for the very wet year 1965 and the very dry year 1976. The 1965-year can be characterized as a 98% dry year, while 1976 is a 1% dry year. For example: a 1% dry year is defined as a year that has an evapotranspiration surplus for the period April - September inclusive that is exceeded only once in 100 years. The characterization holds especially

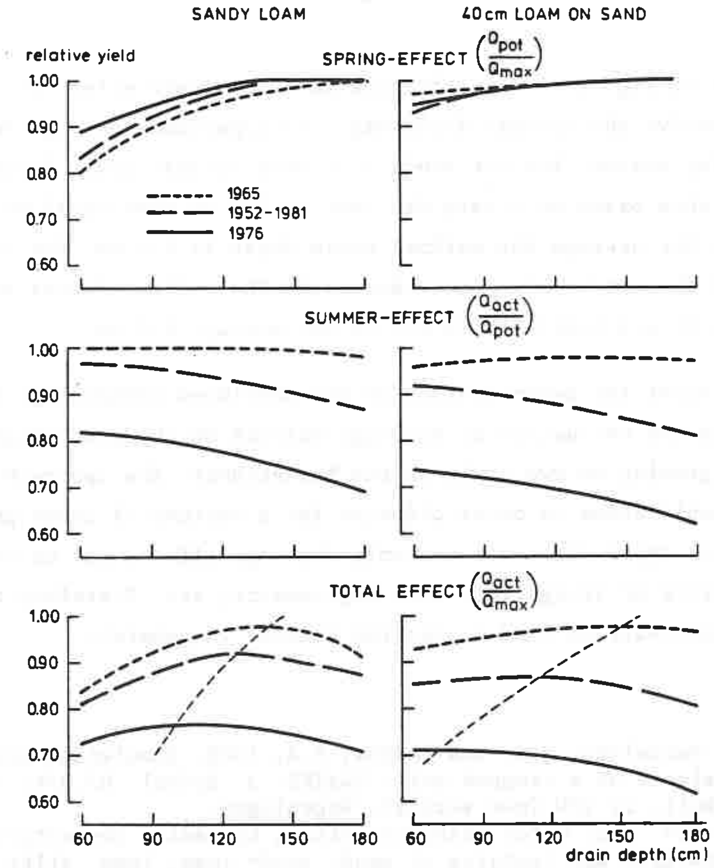

Fig. 11 Relative yield of potatoes growing on a sandy loam and a 40 cm loam on sand profile versus drain depth. Drainage effects occurring in spring, summer and in the total season are presented for the very wet summer of 1965, for the very dry summer of 1976 as well as averaged over the 30-year period 1952-1981

for the summer period and is thus not specific for the spring. A dry/wet spring has no relationship with the dryness/wetness of the summer that follows!

As far as the drainage effect in spring is concerned, the years 1965 and 1976 do not deviate much from the 30-year average. However, other years may give much larger deviations from the average.

The drainage effect on sandy loam in the wet summer of 1965 is negligible, except for a slight reduction at the 180 cm depth. In the dry summer of 1976, however, a yield reduction of 18% occurs at 60 cm depth and of 31% at 180 cm depth. The 40 cm loam on sand shows in 1965 at 0.60 m drain depth a reduction in yield due to poor aeration as a result of too wet conditions. In 1976 the yield reduction at 60 cm drain depth is 26% and at the 180 cm depth 38%.

The part of Figure 11 depicting the total drainage effect on crop yield enables to derive the optimal drain depth in dependence on dryness/wetness of the growing season. For the sandy loam this optimal drain depth varies from 100 cm when based on a very dry year to 140 cm when based on a very wet year. On the average the optimal drain depth is 130 cm. For the 40 cm loam on sand the optima are more widespread. The optimal depths are in dry years 70 cm, in wet years 150 cm and on the average 115 cm.

In this paper the demonstration of the developed methodology has been restricted to the evaluation of drainage effects on the production of a potato crop growing on two soils in the Netherlands. The approach, however, allows for application in other climates for a variety of crops growing on different soil types. Moreover not only drainage effects can be considered, but also effects of irrigation, soil improvement, etc. Therefore the approach is applicable to land evaluation studies in general.

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MODEL APPROACH TO THE EVALUATION OF WATER MANAGEMENT AND CROP YIELD OF SELECTED POLDER

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Abstract

The paper indicates the recent state of modelling of several processes of drainage polder system in field conditions. The influence of ground water level on the production of grassland during a wet year 1973 on a silty soil is presented. Other submodels of water management of the polder are indicated for recent and future research.

1 Introduction

In the area of the Delta of the Vistula River, Poland, land development projects are executed over 170 000 ha. For the evaluation of amelioration plans one needs to be informed quantitatively about the benefits of drainage works and the effects of soil and water management measures upon agricultural crop yield. To achieve this goal, an effort has been put into the development of computer models that simulate crop growth respectively to soil water conditions. The present paper indicates the recent state of modelling of several processes of drainage polder system in field conditions. After the description of the main characteristics of pilot polder, the influence of the ground water level on the production of grassland during the wet year 1973 on a silty soil is presented. Several submodels of water management of the polder are indicated, as well as possible directions of future research.

2 Location and conditions of polders

Polders are located on the fens of the alluvial Delta plateau of the Vistula River. The Delta is located on the 19 deg.E longitude and the 54 deg.N latitude. The shape of the Delta is similar to a deformed triangle, the base of which leans on the shore of the

Gdańsk Gulf of the Baltic Sea. Both the base and the perpendicular of the mentioned triangle are equal to about 56 km, and the surface of the Delta exceeds 1700 square km. The northern border of the Delta from the side of the sea shore is formed by the Vistula sand-bar. Eastern and western borders of the Delta are restricted by the isoline of 10 m above the sea level, where alluvial deposits are separated from the edge of the Pleistocenic moraine. The Delta starts in the south where the Vistula is branching to the Leniwka River and the Nogat River (see fig. 1). The Leniwka flows to the north, but Nogat to the north-east. Alluvial delta plateau falls from the base near Biała Góra, from the height of just over 10 m a.s.l. to -1.8 m b.s.l., forming several depressions, more than 28% of the area of the Delta (Kowalik, 1982).

The average precipitation is about 500 mm per year, but with great variability from 300 to 900 mm per year. Evaporation is about 600-700 mm per year. Winds are strong and frequent, increasing the evaporation. During winter the weather is frequently changing, creating the danger of floods from melted snow and ice. Slight frosts occur in spring. In summer the weather is connected with high radiation intensity and with high intensity of storm rainfalls. The vegetative period with air temperature of above 5 deg. C lasts from the 8th April till the 5th November and the period with air temperature above 10 deg. C lasts 150 days. The ratio between runoff and rainfall is equal to 0.50, but in summer it is about 0.18 and in winter up to 0.85 (locally even to 1.12).

Hipsometric classification divides the Delta into 3 parts: 1) depressive parts below the sea level - 45 thousand ha; 2) near - depressive part with the altitude from 0.0 to 2.5 m a.s.l. - 72 thousand ha; 3) higher part above 2.5 m a.s.l. - 53 thousand ha. Polders are covering all the area of the Delta, but in higher parts water can flow out from the polders by its gravity during most days of the year. In the depression, and near - depression parts, water is being taken away by pumping stations. Typical polders with mechanical pumping of water make together 119 070 ha with 115 pumping stations. All these low - lying areas would be permanently flooded without land reclamation.

Alluvial soils of the Delta are mostly silt deposits, with a clay content of 15-30% or heavy gley soils with about 30-50% of clay, but never higher than 60% of clay. The organic matter content is

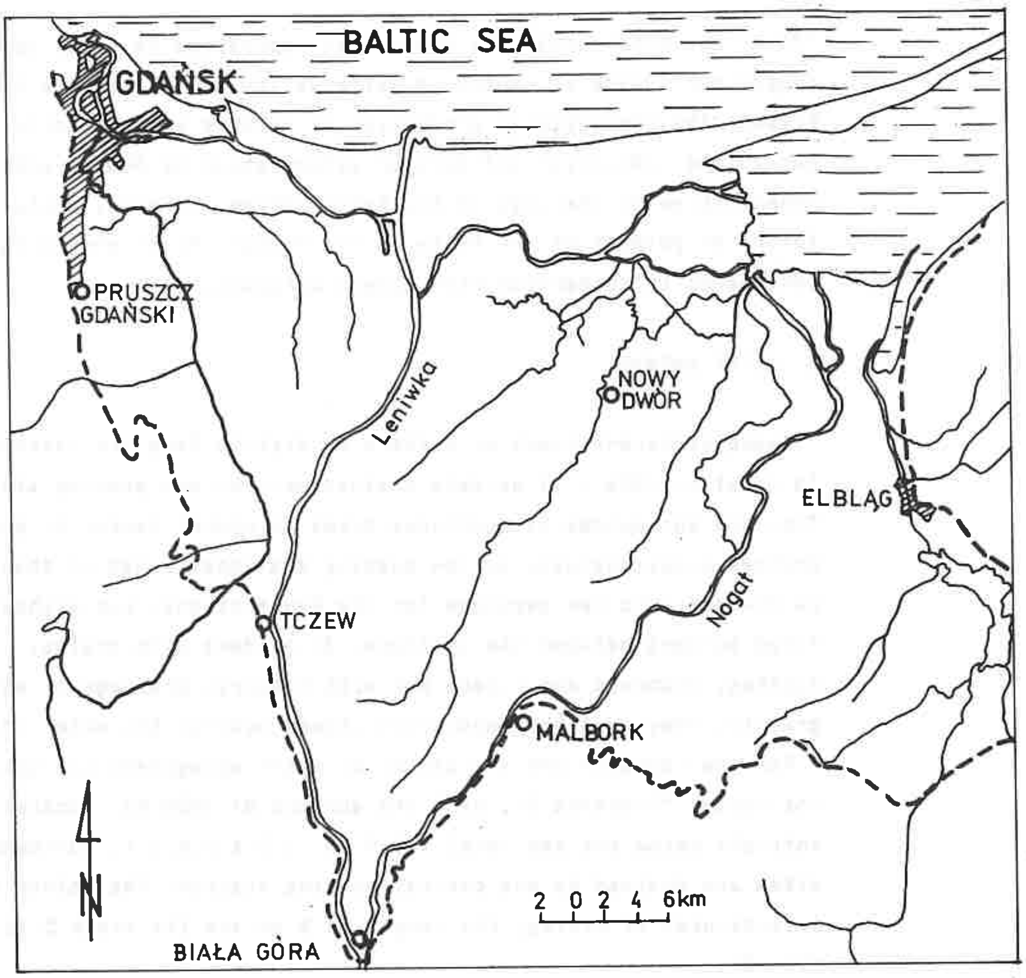

Fig. 1. Delta of the Vistula River, northern Poland.

about 1-5% and in deeper subsoil 0.5-1.5%. Soils have low water permeability, poor aeration and very often a too high water content. The upper part of the soil profile is sticky and greasy after rains, which is a serious obstacle during harvest time and during ploughing too. Fungous disease occurs very often in such conditions. The work of farmers must be in due time and precise here. The yield of agricultural crops can be high, but mainly in dry years, because of good soil fertility and favourable climate. High yield needs appropriate drainage and irrigation system.

Land use is dominated by agriculture. Arable lands are more than

79% of the total area. The density of population is equal to 53 people per square km, which is twice as low as the average for Poland. The agricultural production of polders can be easily sold out to the industrial and harbour aglomeration of Gdańsk and to other cities at the edge of the Delta (Tczew, Malbork, Elbląg). The future of polders of the Delta of the Vistula River should be considered in connection with modern agriculture.

3 Pilot polder

Among different types of polders of Vistula Fens are (according to Cebulak, 1976): 1) polders drained only by one pumping station. They are surrounded by continous dikes or higher lands; 2) polders drained simultaneously by few pumping stations. A net of channels is divided into few sections for the few stations, but without fixed borders between the sections; 3) polders with drains, ditches, channels and rivers but with temporal drainage of water by gravity. They must be temporarily closed against the water inflow.

For the research and evaluation of water management was selected the polder "Fiszewka S", with the surface of 3620 ha, located entirely below the sea level (0.0 to -1.5 m b.s.l.), surrounded by dikes and drained by one central pumping station. The polder is located west of Elbląg, its lenght is 8 km and its width 5 km (see fig. 2).

A pumping station is located in the northern part of the polder. It works with the intensity of 5.5 cubic m per s or about 13.1 mm/day. This pumping station was built on the ground 1 m below sea level. The main polder channel near the pumping station has a depth of 4.5 m and about 3.0 m in the middle and in the southern parts of the polder. The lenght of the main channel coming from the south to the north is above 6 km, the breadth of the bottom from 8.0 to 4.0 m, a slant of the bottom 0.2 promille. The volume of water in the main polder channel is such, that the pumping station should work at least 1/3 day to take away this water. The main channel has a great importance in the retention of water on the polder.

On either side of the main channel, there are confluenced perpendicularly secondary channels, running evenly with a parallel of lattitude, with the distance 800 m between each other. The depth of these secondary channels is 3.0 m at the outlet to the main

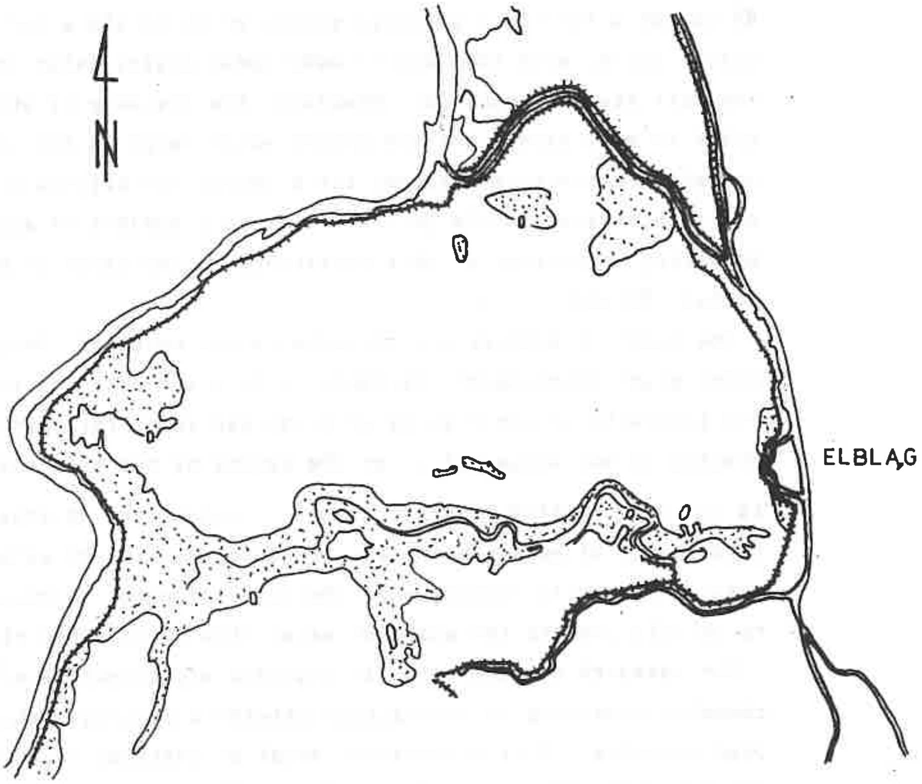

Fig. 2. Pilot polder "Fiszewka 8", west of Elbląg, northern Poland.

channel and about 1.5 m at the beginnings. The breadth of the bottom is 4.0 to 1.0 m, a slant of the bottom 0.3 promille. The system of these channels is draining the polder deeply, intensively and efficiently.

The third stage of the drainage system are ditches or drain pipes with outlets to the mentioned secondary channels. Drains or ditches are running meridionally with the length of about 400 m. The depth of ditches is from 1.1 to 1.3 m and the depth of drain pipes is about 0.8 m. It means, that outlets of ditches and drain pipes are at the depth of 0.8-1.3 m, the outlets of secondary channels at the depth of 3.0 m and the outlet of main pumping channel at the depth of 4.5 m.

The distance between ditches or drain pipes creates a great problem. In the past, a decision was taken to apply a distance of

80 to 160 m for light alluvial soils, or 40 to 100 m for silty or clayly soils, with the idea of additional drains later on, where the soil stays overmoisted. Nowadays, the distance is still too great in many cases, and the ground water level is too close to the surface. The relation between the distance (of ditches or drains) and ground water levels in the fields is a subject of mathematical modelling, described on this Conference in the paper of Dr Zaradny, Gdańsk, Poland.

The depth of ditches and channels is not constant. Because of water plant development the depth is more and more shallow, with the intensity of about 10 cm of slime per year. This particular process of mud accumulation on the bottom of channels and ditches is not only related to plant growth in water, but to erosion of lower parts of escarpes as well, because the flow of water becomes rushing and swift-flowing when the level of water in channels is relatively low and the speed of water flow becomes too high.

Our research on water flow in channels was connected with computer modelling of interaction between a pumping station and open channels. It is a hydraulic model of unsteady flows and it is not described here (see: Jagodziński, 1981). Having done this particular research, we arrived at the conclusion, that the water flows in the channels should be neither too slow (because of the flood danger), nor too speedy (because of the danger of rushing flow, sliding down of escarpes of channels, breaking the continuous flow of water). The accumulation of mud and development of water plants in the channels is giving changes of roughness coefficient in Manning equation from $n = 0.04$ for cleaned channels to $n = 0.12$ for channels filled with growing plants. From our calculations it seems, that if the channels are always filled with water, they should be cleaned once per year during the September - October period, taking away mud from the bottom as well as all plants from water and escarpes. If the ditches are filled with water only from time to time, the plants should be mowed at least three times during the growing season, both from the escarpes as well as from ditch bottoms.

4 Influence of ground water depth on yield of grasslands

Half of the area of the "Fiszewka S" polder is under grassland

and drainage of soil should be related to the high productivity of grass plants.

For a potential yield prediction one must assume that during the growing season optimal soil moisture conditions would occure, as well as adequate fertilization and chemisation. In such conditions solar radiation is transformed into biomass during the photosynthesis process. Calculated potential yields, following book of Feddes et al. (1978) and using CROPR model from this book, for an average year 1972 give 18 t per ha per year of dry biomass for grassland with three mowings. For a wet year 1973 it was 14.4 t per ha per year.

For actual yields with limited growth the method of Visser (1964) can be applied. Taking factors: H - depth of the ground water level, and N - intensity of nitrogen fertilization, potential yield and time influence,an actual yield can be calculated, according to the method described by Visser and Kowalik (1974). The results of such calculations for measurements on the selected polder "Fiszewka S" were published by Brandyk et al. (1981). It gives:

$$\left(1 - \frac{q_i}{Q_i}\right) * \left(1 - \frac{q_i}{a * H_i + b}\right) * \left(1 - \frac{q_i}{c * N_i + d * H_i + e}\right) = D$$

where: i - time index; q_i - actual yield of grassland in time period i , kg/ha; Q_i - potential yield of grassland in time period i, kg/ha; H_i - ground water depth in time period i , cm; N_i - nitrogen fertilization, kg/ha; a,b,c,d,e - parameters, calculated from measured set of valuess of q_i , Q_i, H_i and N_i; D - parameter taken constant = 0.001. The relative yield $x = q_i / Q_i$ is calculated as well. Parameters, for 10-days periods of grass growth experiments during 1973 are:

a = 0.003 752
b = 0.652 192
c = 0.003 484
d = 0.001 191
e = 0.154 858

After multiplication, the third order polinomial is obtained, and the needed solution for q is derived, as a Cardano equation (Gerolamo Cardano, 1501 - 1576). The solution is given in fig. 3,

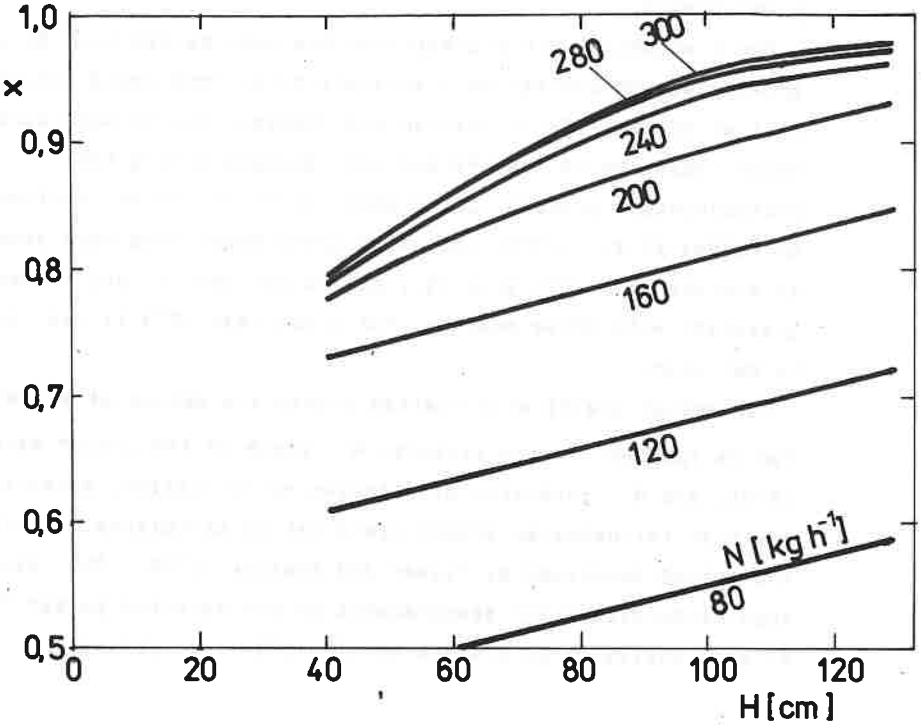

Fig. 3. Effect of the ground water level (H) on relative yield (x) at different nitrogen fertilization levels (N), after experiments of Brandyk et al. (1981).

where nitrogen application N, kg/ha throughout the growing season, the ground water level H in cm and the relative growth x = q/Q (dimensionless, between 0 and 1) are depicted. Fig. 3 is valid only for a wet year 1973 and for grassland. Calculations were made for silty soil with shallow and deeper ground water levels. From fig. 3 one can conclude, that for the low nitrogen fertilization, the response of yield is significant for deeper drainage. For the high nitrogen level the influence of the ground water level is not very distinct.

The ground water level H is determined by the distance between drains or ditches, and this particular problem is the subject of mathematical modelling of Dr Zaradny (see his paper on this Seminar).

5 Conclusions

The water flow in the polder is under the influence of one central pumping station, dredging of the channels, mowing of plants in the ditches, conservation of escarpes and drain outlets, field surface levelling and profiling. The research of the influence of water management on the crop yield is concentrated on the following processes: 1) water contents in the reservoir of the pumping station and the central channel of the polder; 2) water flow in open ditches and channels of the polder with the influence of roughness caused by plant growth in water; 3) ground water level dynamics under the influence of drain and ditches, and meteorological conditions; 4) soil water contents in the field conditions under the influence of the ground water level, root soil water uptake, actual transpiration and evaporation; 5) crop growth and productivity under the influence of actual soil water conditions and actual transpiration. These five processes are simulated using computer models, but in this paper only the process relating yield and ground water levels was given in some details. Other models should be presented separately.

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DRAINAGE MODELING IN RESEARCH AND DESIGN

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Abstract

Computer simulation models can be used to design and evaluate drainage and water table control systems. This paper discusses the philosophy of modeling agricultural drainage systems and the effects of computational and input data requirements on the net benefits of modeling drainage systems. The DRAINMOD model is described and examples utilizing the model to design drainage and subirrigation systems and a drainage system to facilitate land treatment of wastewater are presented.

1 Introduction

The design and operation of agricultural drainage and associated water management systems should depend on soil factors, site parameters, crop factors and climatological factors. Objective methods for considering there factors have evolved from steady state solutions or "models", such as those developed by Dr. S.B. Hooghoudt and Dr. Don Kirkham in the 1940's and 50's, to the comprehensive computer simulation models now available. However, general drainage design practice has lagged far behind advances in our ability to characterize or predict the performance of these systems. In many areas the design of drainage systems is based on local custom or on other guidelines that do not consider many of the factors listed above. While the use of such guidelines may result in systems that satisfy the drainage needs for most cases, the systems may be over-designed for many soils. Furthermore, guidelines or "rules of thumb" that have been developed for conventional drainage by trial and error cannot be directly applied in

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[1] This paper was written while the author was on sabbatical leave in the Agricultural Engineering Department, The Ohio State University, Columbus.

the design of subirrigation and water table control systems, nor in the design of drainage systems for land treatment of wastewater, where the water applied may be two or three times natural rainfall.

One approach to improving the design of agricultural water management systems is to develop user-oriented computer models that can be applied by the practicing engineer or technician. This involves the development of methods to obtained needed inputs to the model as well as modifications to the computer software, which in most cases has been developed for research purposes, to make the model "user friendly." Another approach is for the researchers to use the complex models to develop more easily applied guidelines which are specific to a location, crop and application. Both approaches are currently being applied in the U.S.

The purpose of this paper is to discuss the use of computer simulation models in the design and evaluation of drainage and associated water management systems. The philosophy of model development and application is discussed and factors limiting the application are identified. The DRAINMOD water management simulation model is briefly described. It is used to demonstrate the application of a model in the design of a drainage and subirrigation system and a drainage system for the treatment of waste water.

2 Philosophy of Modeling Agricultural Drainage Systems

The need to taylor the design of drainage systems to soil properties and site conditions is demonstrated by the results given in Figure 1. Long-term average relative corn yields are plotted as a function of drain spacing for a sandy loam soil in eastern North Carolina. While each field has the same soil type, the hydraulic conductivity in Field 1 is five times that of Field 2 and 25 times that of Field 3. Even larger variations in conductivity may be found in the sandy loam soils of this region (Tabrizi and Skaggs, 1973). If the drain spacing is based on soil type alone, then the spacing that would probably be recommended for this soil type would be 20 m or less. Note that although a 100 m spacing would be sufficient for Field 1 and a 40 m spacing for Field 2,

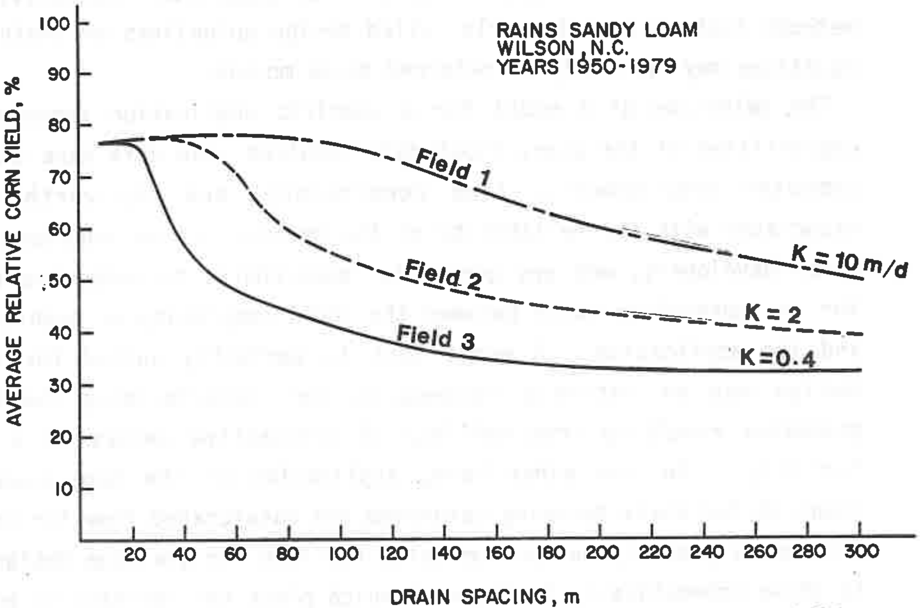

Figure 1. Effect of drain spacing on 30 year average corn yields, as a percentage of the potential yields for 3 fields classified as Rains Sandy loam. The results demonstrate the need to consider soil properties in design, rather than just soil type.

a 20 m spacing would result in nearly maximum yields for all three fields. Since general guidelines are usually conservative, the closer 20 m spacing would probably be recommended for this soil type. The fact that an equally effective drainage system could have been installed for Field 1 at five times the spacing and about one-fifth the cost, reflects the penalty that would result from insufficient consideration of the soil properties in the system design.

Numerous methods, or models, are now available to relate drainage system performance to design parameters such as drain spacing and depth. They span the wide spectrum from the very approximate "models" or guidelines that relate drain spacing to soil type as discussed above, to single event models or solutions, such as those developed Hooghoudt (Luthin, 1973) and by Kirkham (1958), to computer models that simulate the performance of multicomponent systems over a long period of weather record. In this broad context the term "model" is defined as a set of guidelines, equations or computer programs that can be used to quantify the performance of a system in terms of an objective function(s). Thus, methods that we have formerly called design guidelines or drain spacing equations may currently be referred to as models.

The selection of a model for a specific application depends on the capabilities of the user, input data required, the data base available, computer requirements, time constraints, and the worth or risk associated with the reliability of the design. It is important for the model developers, who are generally researchers, to recognize the need for an appropriate match between the model complexity or sophistication and the application. A model that is perfectly suited for drainage design may be entirely inadequate for characterizing the drainage processes resulting from spillage of radioactive wastes at a storage facility. On the other hand, application of the more exact model required for characterizing saturated and unsaturated flow for the waste problem is probably not economically feasible for drainage design. This is shown schematically in Figure 2 which plots the increase in annual

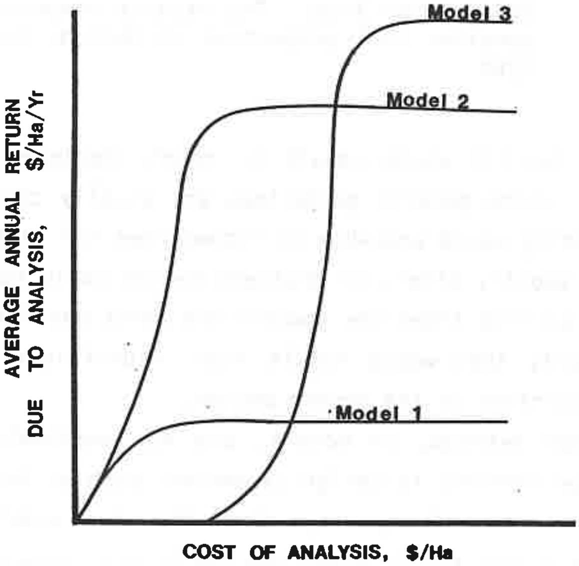

Figure 2. Average annual returns for poorly drained soils in a region can be increased by fitting the drainage system design to the soils, crops and climate. Cost of the analysis includes the cost of collecting the input data, running the model and analyzing the results.

return versus the cost of analysis. The annual return due to analysis considers the amortized cost of the drainage system. It represents the average increase over that which would result if no analysis is conducted and a constant drain spacing is used for all fields requiring drainage in a region. Returns due to analysis will increase with the size of the region and the variability of the soils, crops and weather. The increase in return for an individual field may be far greater or far less than the average, Indeed, the constant spacing selected would likely be ideal for some fields and an analysis would result in no increase in profit, regardless of the model used for those fields.

Average returns are reduced when the analysis (or lack of analysis) results in over-design and the system costs too much, or under-design, in which case yields are reduced and potential income is not realized. This is shown schematically in Figures 3 and 4. By using a model to fit the system design to the soils, crops and climatological conditions for each specific site, it may be possible to reduce the average system cost (Figure 3) and/or increase average yields (Figure 4). The use of more sophisticated models, such as models 2 and 3, will allow a better design for each specific site and a greater return than will simpler approaches such as model 1. The use of these models to improve designs is not free! This is an important factor in choosing or developing a model as is demonstrated by the schematic results in Figures 2-4. The analysis costs considered are those connected with the determination of the proper spacing and depth for the drain tubes. These costs are made up of the sum of the costs associated with setting up and running the model and the costs of determining the necessary input data. Generally, input data requirements increase with the sophistication of the model. Maintaining the proper balance between model sophistication and effort devoted to inputs may be as important as choosing the right model. For example, the simpler model 1 (Figures 2-4) requires less input data than model 2. Collection of data beyond that essential for the application of the model may substantially increase the cost of analysis, without significantly improving the design. This is shown by the plateaus in benefit response to analysis costs in Figures 2-4. On the other hand,

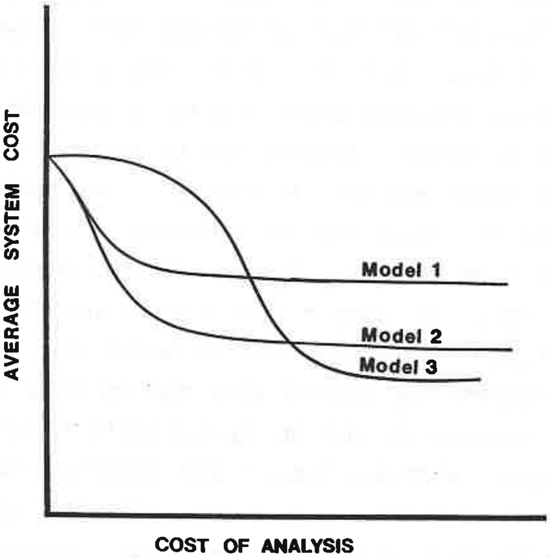

Figure 3. Use of models can decrease the average system cost for a region. The more complex models reduce costs of the system, but their application is more expensive than simpler models.

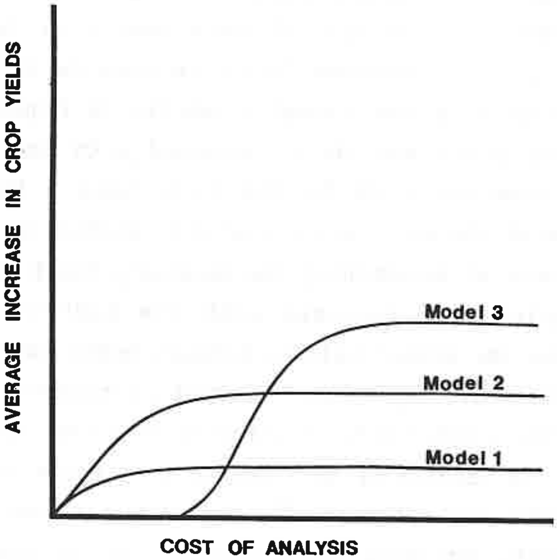

Figure 4. Average yields are improved by fitting drainage system design to the soils, crops and climate. The input data and analysis is more expensive for some models than others.

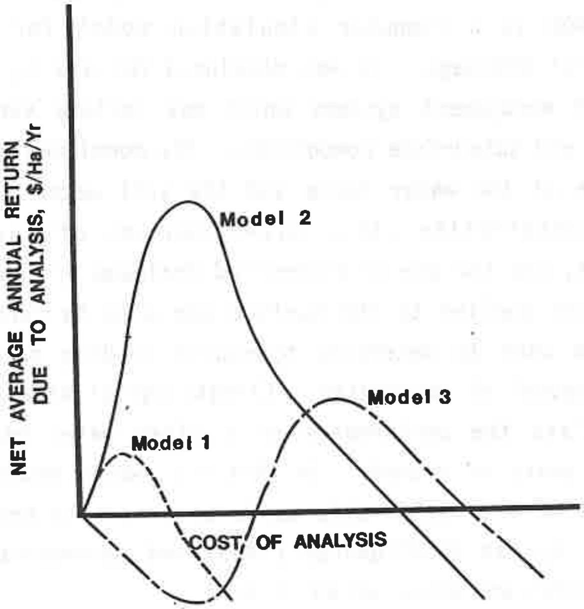

Figure 5. Effect of investment in engineering drainage analysis on the net average annual return. Costs of analysis are considered in the net benefit. Results show the need of matching model selection to the application.

the potential benefit of a given model will not be realized if, in an attempt to reduce costs, the necessary inputs are not provided. Very sophisticated models--numerical solutions to the transient, three-dimensional Richards equation for saturated and unsaturated flow (Freeze, 1971) is an example--have high set up and execution costs, as well as very expensive input data requirements. A relatively high investment in analysis must be made before any benefits can be realized for these models. The return from the design application of such models is demonstrated schematically by model 3 in Figures 2-4.

Results given in Figure 5 show the net average annual return as affected by analysis costs. The cost of obtaining the input data and running the model is subtracted from the average return given in Figure 2. These results emphasize the need for selecting the model to fit the application and for matching the input data collected with the model or design methods selected.

3 The DRAINMOD Water Management Simulation Model

DRAINMOD is a computer simulation model for soils that require artificial drainage. It was developed for use in design and evaluation of water management systems which may include various combinations of surface and subsurface components. The model can be used to predict the response of the water table and the soil water above it to rainfall, evapotranspiration (ET), given degrees of surface and subsurface drainage, and the use of controlled drainage or subirrigation practices. Irrigation applied to the surface can also be considered and the model has been used to determine hydraulic loading capacities of sites for land disposal of wastewater. Climatological data are used in the model to simulate the performance of a given water management system over several years of record. In this way, water management systems can be designed on a probabilistic basis as initially proposed for subsurface drainage by van Schilfgaarde (1965) and subsequently used by Young and Ligon (1972) and Wiser et al. (1974).

The first version of DRAINMOD was written in the early 1970's (Skaggs 1975). Results of further developments including field experiments to test the validity of the model were given by Skaggs (1976, 1980). The model has been accepted by the USDA Soil Conservation Service (SCS) for design and evaluation of drainage and subirrigation systems in humid regions. It is available to all states on the SCS computer system. A recent cooperative effort in the North Central States resulted in the development of a microcomputer version of the model. Users manuals and program documentation for DRAINMOD are available from SCS (1985) and the North Central Computer Institute (NCCI, 1985).

Two important criteria were adopted at the outset of the model development process. First, the model should be capable of describing water movement and storage in the profile so as to characterize the soil water regime and drainage rate with time. And second, the model should be developed such that the computer time necessary to simulate long term processes, and input data requirements, are not prohibitive. The movement of water in soil is a complex process and it would have been an easy matter to become so involved with getting exact solutions to every possible situation that the final answer would have never been obtained.

The guiding principle in the model development was therefore to assemble the linkages between various components of the system and allowing the specifics to be incorporated as subroutines so that they may readily be modified when better methods are developed.

The rates of infiltration, drainage, evapotranspiration, and the distribution of soil water in the profile can be computed by obtaining numerical solutions to nonlinear differential equations (Freeze 1971). However, these methods would require prohibitive amounts of computer time for long term simulations and thus could not be used in the model. Instead, approximate methods were used to characterize the water movement processes.

The basic relationship in the model is a water balance for a thin section of soil of unit surface area which extends from the impermeable layer to the surface and is located midway between adjacent drains. By assuming a shape of the water table between drains, the water balance could just as easily be conducted for the entire profile. The water balance for a time increment of Δt may be expressed as

$$\Delta V_a = D + ET + DS - F \tag{1}$$

where ΔV_a is the change in the air volume or water free pore space (cm) in the section, D is drainage (cm) from (or subirrigation into) the section, ET is evapotranspiration (cm), DS is deep seepage (cm) and F is infiltration (cm), entering the section in Δt.

The terms on the right-hand side of equation 1 are computed in terms of the water table elevation, soil water content, soil properties, site and drainage system parameters, crop and stage of growth, and atmospheric conditions. The amount of runoff and storage on the surface is computed from a water balance at the soil surface for each time increment, which any be written as

$$P = F + \Delta S + RO \tag{2}$$

where P is the precipitation (cm), F is infiltration (cm), ΔS is the change in volume of water stored on the surface (cm), and RO is runoff (cm) during time Δt. The basic time increment used in equations 1 and 2 is 1 hour. However when rainfall does not occur and drainage and ET rates are slow such that the water table position moves slowly with time, equation 1 is based on Δt of 1 day. Conversely, time increments of 0.1 h or less are used to compute F when rainfall rates exceed the infiltration capacity.

Model Components and Input Data. Precipitation inputs to the model are hourly data which are stored and automatically accessed from a data base. Records for 77 stations in the humid region of the U.S. are available on SCS files. Hourly data from many other weather stations are available and are currently being added to SCS files.

Infiltration is calculated using the Green-Ampt (1911) equation. A table of equation parameters as a function of initial water table depth is part of the required input data. These values can be estimated from the saturated vertical hydraulic conductivity and the soil water characteristic.

Surface drainage is characterized by the average depth of depression storage that must be satisfied before runoff can begin. In most cases it is assumed that depression storage is evenly distributed over the portion of the field under analysis. A field study (Gayle and Skaggs, 1978) showed that depression storage varied from nearly 0 for fields that have been land formed or smoothed to > 3 cm for fields with numerous depressions or which have inadequate surface outlets.

The method used in DRAINMOD to calculate subsurface drainage rates is based on the assumption that lateral water movement occurs mainly in the saturated region. The effective horizontal saturated hydraulic conductivity is used, and the flux is evaluated in terms of the water table elevation midway between drains and the water level or hydraulic head in the drains. The flux is calculated with Hooghoudt's steady state equation, as used by Bouwer and Van Schilfgaarde (1963). Hooghoudt's equivalent depth is used to consider convergence near the drains. The fact that drain tubes have a finite number of openings and are not completely permeable is considered by using an effective drain radius in the calculation of the equivalent depth. When the surface is ponded, the drainage rate is calculated by the steady state equation derived by Kirkham (1957). The drainage flux may be limited by the hydraulic capacity or drainage coefficient (D.C.) of the system. The D. C. is a model input, and is taken as the upper limit for drainage flux. Subirrigation rates are calculated with the steady state equation proposed by Ernst (1975). Inputs required to calculate drainage and subirrigation rates are the lateral saturated hydraulic conductivities for each layer, the depth to the impermeable layer and the system design parameters of drain spacing, depth and effective radius of the drain.

The determination of evapotranspiration (ET) is a two-step process in the model. First the daily potential evapotranspiration (PET) is calculated in terms of atmospheric data and is distributed on an hourly basis. Hourly PET is set equal to zero for any hour in which rainfall occurs. After PET is calculated, checks are made to determine if ET is limited by soil water conditions. If soil water conditions are not limiting, ET is set equal to PET. When PET is higher than the amount of water that can be supplied from the soil system, ET is set equal to the smaller amount.

When the water table is near the surface or when the upper layers of the soil profile have a high water content, ET will be equal to PET. However, for deep water tables and drier conditions, ET may be limited by the rate that water can be taken up by plant roots. Approximate methods are used to estimate water available for ET due to upward flux from the vicinity of the water table. The relationship between maximum steady upward flux and water table depth is one of the inputs to DRAINMOD, as in the relationship between drainage volume and water table depth. Both of these functions can be calculated from the soil water characteristic.

The effective rooting depth is used in the model to define the zone from which water can be removed as necessary to supply ET demands. Since the simulation process is usually continuous for several years, an effective depth is defined for all periods. The rooting depth function is read in as a table of effective rooting depth versus date.

Separate models for corn yield response to excessive and deficient soil water conditions, as well as to delays in the planting date, have been incorporated in DRAINMOD (Hardjoamidjojo and Skaggs, 1982). The models for predicting the effects of excessive and deficient soil water conditions are based on the stress-day-index concept (Hiler, 1969). Stresses due to wet soil conditions are quantified by the SEW_{30} concept originally defined by Sieben (Wesseling, 1974). Hardjoamidjojo et al. (1981) used the SEW_{30} as the stress-day factor in combination with crop susceptibility factors for three stages of the corn growing season. The resulting stress-day-index is directly related to corn yield in the model. The stress-day factor for deficient soil water conditions is the quantity (1-AET_i/PET_i) where AET_i and PET_i are respectively the actual and potential evapotranspiration values for a 5-day growth stage i.

The relationships developed by Shaw (1978) are used in the model to predict the effect of deficit soil water conditions an relative yield. The effect of planting date delay is based on experimental data from several U.S. locations Seymour (1986). Equation coefficients relating relative yield to delay in planting date are read into DRAINMOD, along with other data such as the last date that planting can occur without reduction in yield, and the number of working days required for planting. The model counts the number of working days, based on soil water conditions and rainfall, determines when the crop can be planted and calculates the yield loss due to planting delay. Details are given by Skaggs and Tabrizi (1983).

The reliability of DRAINMOD has been tested in several studies. Field experiments were conducted over a 5-year period at three locations in the C.C. Coastal Plains. Three soil types and five different drainage system designs were included in the experiment. The average absolute deviation between predicted and observed water table depths for 21 site-years of data (approximately 7,400 pairs of daily predicted and measured values) was 8.1 cm. Results are described in detail by Skaggs (1982). DAINMOD has also been tested against data on a tight clay soil in Ohio (Skaggs, et al. 1981), a slit loam soil in Louisiana (Gayle et al., 1983), and irrigated soils in California (Chang et al., 1983). Good agreement between measured and predicted results was found in all three studies.

4 Application of DRAINMOD--Input Data

Inputs to DRAINMOD include soil properties, historical weather data, system design parameters and crop data. Certain information concerning the farming operation, such as the number of working days required for seedbed preparation and planting and the beginning and ending hours of a working day, is also required. As indicated earlier, weather data are available for a large number of locations; these data can generally be obtained for a location sufficiently close to the application for design purposes. The system design parameters are generally known by the user. Crop inputs include rooting depth as a function of time. While this relationship can be approximated from data in the literature, it depends on many factors including physical and chemical barriers and the drainage and subirrigation system. More research is needed in this area. Other crop inputs include the susceptibility factors for both deficient and excessive soil water stresses. These factors can be approximated now for corn, soybean, grain sorghum and sugar cane; research is continuing to better define these relationships and to determine them for more crops.

Soil properties are usually the most difficult inputs for the DRAINMOD user. The most important inputs for most applications are the saturated hydraulic conductivity (K), by soil horizon, and the depth to the restricting layer. Since these parameters vary from field to field within a given soil type, it is recommended that they be determined directly for each site. Other soil property inputs include the permanent wilting point in the root zone, the drainage volume-water table depth relationship (or drainable porosity as a function of depth), the Green-Ampt infiltration parameters and upward flux as a function of water table depth. These properties depend on the unsaturated hydraulic conductivity function K (h) (vertical) and soil water characteristic h(θ). These properties are more difficult and expensive to measure. Fortunately the simulation results for most drainage applications are not as sensitive to these properties as to the saturated K (Skaggs, 1981). Methods are available for approximating K(h) and the above inputs from h(θ) and the vertical saturated K. However these inputs still present some difficulty to the user who does not have a good background in soil physics.

Three strategies are currently being used to determine soil property inputs to DRAINMOD for application to design and evaluation. The first is to measure the inputs directly for a given soil and site. This approach is usually taken by researchers or by firms or agencies that have access to soil physical property labs. As these properties are determined and cataloged according to soil type, they may be used by subsequent users to approximate some of the input data for similar soils. As an example, input soil properties for 15 to 20 eastern North

Carolina soil types have been measured and are on file. When a new site is analyzed for drainage or subirrigation, field measurements to determine K and profile depth would typically be conducted. Other soil property inputs might be determined by interpolation from the data on file for similar soil types. This is the second strategy for determining soil inputs.

The third strategy involves the development and use of methods to predict the soil water characteristic and K(h) from soil texture, bulk density, clay mineralogy and other properties that are easier to determine than K(h) and h(θ). These methods can be programmed to automatically produce the DRAINMOD inputs. Such methods have been proposed by Baumer (1985), Brackensiek and Rawls (1985), and Rawls et al. (1983), and others. The major limitation of these methods is that they are based on data heavily weighted toward the dry end of the soil water characteristic. Work is currently being done by Mr. Otto W. Baumer at the SCS National Soil Service Lab to further develop and test these methods for application to DRAINMOD. This approach promises to greatly facilitate the future application of DRAINMOD and similar models.

Methods that are simple, require little input information and are easy to use are often needed for feasibility analyses and to make first approximations for design. A number of these methods are available; the Hooghoudt (Luthin, 1973) and van Schilfgaarde (1963) equations are examples. One of the difficulties in using such methods is in determining appropriate values for equation parameters, such as the steady drainage flux in Hooghoudt's equation, for example. A very useful application of the simulation model is to conduct analyses on several soils for a specific crop and location to determine optimum drain spacings, subirrigation designs, etc. Then equation parameters for the approximate methods can be backed out of the equations and used for other soils and sites in that area. We used this approach to develop shortcut methods for estimating drain spacings needed for both subirrigation and conventional drainage in North Carolina (Skaggs and Tabrizi, 1986). Application of such results is limited to the location considered; similar analyses are needed in other U.S. locations.

5 Application of DRAINMOD--Examples

Three examples are presented to demonstrate the use of DRAINMOD for analyzing conventional drainage systems, combination drainage-subirrigation systems and a drainage system to facilitate the land treatment of wastewater.

The first two examples consider drainage and subirrigation systems on a Brookston silty clay loam near Dayton, Ohio and a Jockvale loamy sand near Ottawa, Ontario. Analyses for both soils were conducted as part of a project supported by the Corrugated Plastic Tubing Association.

A subirrigation or drainage system design is analyzed by reading into the model, soil properties and crop parameters appropriate for the location selected. Design parameters including drain spacing and depth and the time of year and height that the water level is elevated in the drains for subirrigation are also inputs to the model. The crop considered in this study was corn and the effective root depth as a function of time (Skaggs, 1981) was read in as an input. The preferred planting date and the date that tillage operations for seedbed preparation can begin were read as input data. While the number of trafficable days required for seedbed preparation and planting depends on the individual farmer and his situation, eight days were arbitrarily assumed in this study. Historical weather data are used in the model to simulate the performance of the system over a 15 to 25 year period of record. The model automatically determines the actual planting date each year, based on the number of days in which the field is trafficable, and then calculates soil water stresses due to excessively wet or dry conditions. Yearly results include a predicted yield in addition to other information such as the total amount of drainage, the volume of irrigation water pumped, etc. Simulations were conducted for a range of drain spacings and subirrigation control strategies for both soils. In this way the optimum system design for a given soil type and location can be identified. Predicted yields for subirrigation were compared to those obtained with drainage alone for various drain spacings.

Example 1--Brookston silty clay loam. This soil is a Typic Argiaquolls, Fine-Loamy Mixed, Mesic. The Brookston series consists of deep very poorly drained soils formed in glacial drift and underlying glacial till. It is found in Indiana, Michigan, Ohio, Wisconsin in the U.S. and Ontario, Canada. Soil water characteristic data were obtained with the assistance of Dr. R. Wheaton from Wiersma (1985). Input soil properties are listed in Table 1.

Simulations were conducted for 21 years (1953-1973) of hourly rainfall data from Dayton OH. Several drain spacings for both conventional drainage and subirrigation were considered. Subirrigation was simulated by raising the water level in the drainage outlet to a depth 60 cm below the soil surface after corn was planted. The planned planting data was May 1, but the computer program adjusted that date forward if there were not enough suitable working days prior to May 1 for seedbed preparation

Table 1. Some DRAINMOD soil property inputs for Brookston silty clay loam and Jockvale loamy sand.

	Brookston Si. C.L.		Jockvale L.S.	
Water Table Depth (cm)	Drainage Volume (cm)	Upward Flux (cm/hr)	Drainage Volume (cm)	Upward Flux (cm/hr)
0	0.00	1.6500	0.0	1.0
10	0.20	0.9900	0.15	0.2
20	0.40	0.3000	0.40	0.12
30	0.60	0.1830	0.95	0.08
40	0.80	0.0660	1.50	0.035
60	1.73	0.0260	2.75	0.017
80	2.57	0.0124	4.40	0.006
100	3.47	0.0030	6.35	0.002
120	4.60	0.0027	9.00	0.001
140	5.81	0.0012	14.33	0.0003
160	7.33	0.0003	17.59	
180	9.16	0.0002	18.76	
200	11.00	0.00	19.93	
250	17.50	0.00	23.94	

Profile Depth	Hydraulic Conductivity (cm/hr)	
0-0.2m	1.5	7.1
0.2-1.2	1.5	2.2
1.2-2.0	1.5	0.0

conventional drainage is the lack of sufficient soil water during some years. In this case dry conditions are predicted to decrease yields by an average of 20% over the 21 year simulation period.

Use of subirrigation can reduce drought stresses and increase relative yields as shown in Figure 6. Average predicted yields increased with a decrease in drain spacing to the smallest drain spacing attempted (10 m) where the yield was 96%. Note that for drains placed wider than 30 m apart, the differences between yields predicted for subirrigation and for conventional drainage decrease with increase in spacing. By reducing the spacing to a very small distance and using subirrigation, the average relative yield could theoretically be increased to 100%. It is unlikely that such close drain spacings could be justified economically for this soil, however. The recommended spacings for this soil were determined to be 20 m and 15 m for drainage alone and for subirrigation, respectively. These recommendations were arrived at by determining the point at which the worth of increased production due to closer spacing is equal to the yearly investment cost required to place the drains closer together. This determination requires the plots given in Figure 1 plus the following information (assumed values are given in parentheses): Potential yield (12.6 Mg/ha or 200 bu/ac), product price ($3.00/bu), drainage costs ($1.60/m), system life (30 years) and interest on money invested (12%). Since production costs (seed, fertilizer, etc.) are approximately independent of drain spacing, the above information is sufficient to make a good estimate of the optimum spacing.

While the use of the recommended subirrigation spacing would increase yields by about 13% (from 80% to 93%), its effect on the reliability of production may be a more important benefit. Yearly predicted yields are given in Table 2 for three water management treatments: (1) Poor subsurface drainage, spacing, L = 90 m = 300 ft; (2) Good subsurface drainage, L = 20 m = 66 ft; and (3) Subirrigation and drainage with L = 15 m = 49 ft. These results show that good subsurface drainage would increase the number of years with yield greater than 90% from 2 to 9; the use of subirrigation to reduce drought stress would further increase that number to 13 out of 21 years. Furthermore, the use of subirrigation would raise yields to greater than 75% of potential in 20

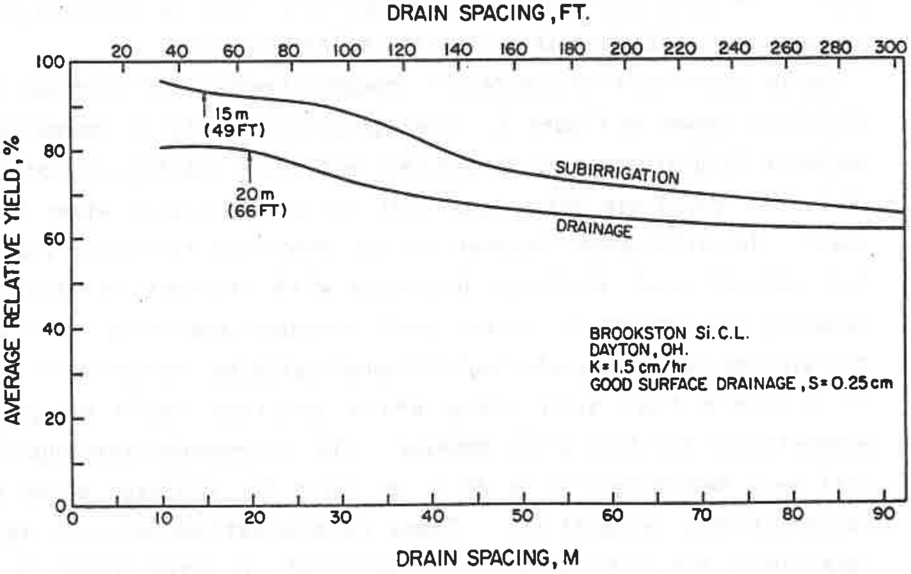

Figure 6. Effect of drain spacing on yield response to conventional drainage and to subirrigation for Brookston Si.C.L. near Dayton, OH. Surface drainage was good in both cases. The water level in the drain was held at a constant depth of 60 cm for subirrigation.

and planting. SCS soil interpretation data for conductivity of the Brookston series ranges between 1.5 to 5.0 cm/hr. A conductivity of 1.5 cm/hr was used for most of the simulations in this study. One set of simulations was conducted for K = 5.0 cm/hr to determine how the higher conductivity would affect the performance of the system.

Predicted relative yields for conventional drainage and for the combination of subirrigation and drainage are plotted in Figure 6 as a function of drain spacing. Good surface drainage was assumed for both cases given in Figure 6. Results indicate that an average yield of about 80% of potential could be obtained by drainage alone with drains placed 15 to 20 m apart. (The potential yield is the average yield that would be obtained if crop stresses due to too much soil water, too little soil water, and delays in planting are eliminated). The reason that the average yield can only be raised to 80% of potential using this soil is clearly shown by the results plotted in Figure 7. Here average relative yields predicted for subirrigation with both good and poor surface drainage are plotted as a function of drain spacing. If surface drainage is poor, a 7.5 m drain spacing would be required to get the 93% average relative yield predicted for 15 m spacing with good surface drainage. Furthermore, comparison with Figure 6 shows that predicted yields, for drain spacings between 30 m and 40 m, were within 2% of those obtained for drainage along with good surface drainage. For spacings greater than 40 m, yields for drainage along (Figure 6) were greater than for subirrigation with poor surface drainage (Figure 7). The conclusion is clear. Good surface drainage should be provided if subirrigation is used on this soil.

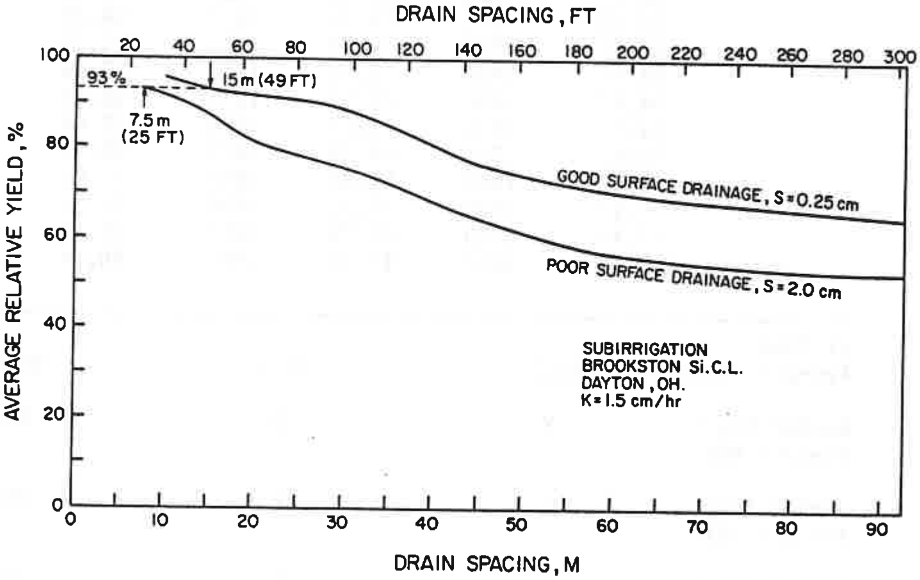

Figure 7. Effect of drain spacing and surface drainage on yield response to subirrigation for a Brookston Si.C.L. near Dayton, OH.

Table 2. Ranked yearly predicted relative yields for poor drainage, good drainage and subirrigation for Brookston silty clay loam near Dayton, OH. The surface drainage is good (depressional storage = 0.25 cm) and the 21 year simulation period is 1953-1973.

	Poor Drainage		Good Drainage		Drainage & Subirri	
	L = 90m = 300 ft		L = 20m = 66 ft		L = 15m = 49 ft	
	Relative Yield (%)	Year	Relative Yield (%)	Year	Relative Yield (%)	Year
	100.00	1960	100.00	1960	100.00	1954
	91.96	1956	99.28	1973	100.00	1955
	78.63	1973	97.13	1955	100.00	1963
	78.07	1955	96.78	1969	100.00	1964
	77.16	1969	96.36	1961	100.00	1965
	76.11	1962	96.18	1956	100.00	1966
	74.48	1968	95.02	1957	99.98	1962
	72.55	1968	92.10	1968	98.56	1962
	71.69	1963	91.41	1972	97.15	1956
	69.13	1957	84.67	1966	96.64	1959
	68.29	1966	80.09	1963	96.34	1971
	66.85	1971	79.93	1967	94.45	1966
	62.95	1972	74.59	1971	90.11	1961
	54.75	1954	73.52	1962	89.86	1972
	54.57	1959	71.97	1959	89.65	1969
	51.17	1970	71.87	1958	89.46	1973
	32/82	1964	69.75	1970	88.95	1953
	32.57	1965	51.87	1953	87.01	1967
	28.11	1958	47.21	1954	84.83	1957
	27.44	1953	46.22	1964	82.15	1968
	18.98	1967	45.42	1965	66.44	1958
21 Year Average Yield (%)	61.3		79.1		93.0	
Number Years Yield > 90%	2		9		13	
Number Years Yield > 75%	6		12		20	
Number Years Yield < 50%	5		3		0	

our of 21 years according to the simulations.

Good surface drainage was assumed in all the results plotted in Figure 6. The need for good surface drainage when subirrigation is used on

Results for the Brookston soil with a higher hydraulic conductivity (5 cm/hr) resulted in predicted yields that were higher than for corresponding drain spacings on the tighter soil. Results showed that the 93% average yield predicted for K = 1.5 cm/hr at a drain spacing of 15 m could be obtained with a 28 m spacing for K = 5 cm/hr.

Example 2--Jockvale loamy sand. Located in the Ottawa - Carleton region of Ontario, this soil has a single grain structure (in excess of 75% sand) for depths less than 1 m. Soil properties including bulk density, soil water characteristic and saturated hydraulic conductivity values were given by Topp et al. (1980). DRAINMOD soil properties are given in Table 1. Analyses were conducted for two depths to the restrictive layer, 1.2 m and 1.8 m.

Predicted average relative yields are plotted as a function of drain

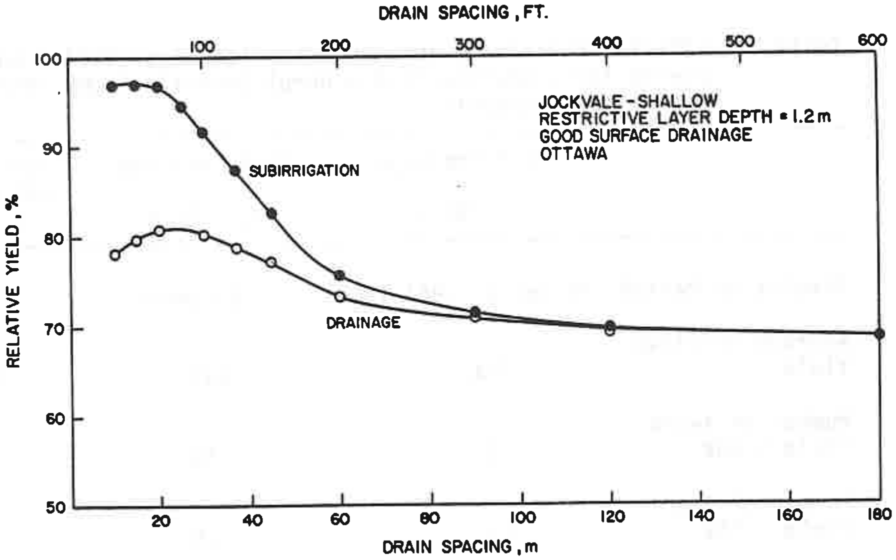

Figure 8. Effect of drain spacing on predicted relative corn yields for drainage alone and for subirrigation on a Jockvale loamy sand near Ottawa, Ontario.

spacing in Figure 8 for both drainage alone and for combination subirrigation and drainage. This soil has only a moderate hydraulic conductivity with a profile depth of 1.2 m, but drains relatively well. The maximum average relative yield for drainage alone was 81%. The optimum drain spacing was determined to be 28 m. This soil showed some effects of over drainage for drains spaced closer than 20 m. This would have been more of a problem if the drains were at a greater depth.

Results for subirrigation show that the optimum spacing is about 20 m for this soil. Trials with several weir elevations showed that holding the water level in the drains 60 cm from the surface starting on about June 10 (30 days after planting) gave the best results. The average relative yield predicted for this subirrigation design and operation was 97%. The statistics for year-to-year variations in predictions are given in Table 3. Use of subirrigation dramatically increased the frequency of producing a good crop. The number of years in which predicted relative yields exceeded 90% increased from 10 of 23 for drainage alone to 21 of 23 for subirrigation and drainage (Table 3).

Table 3. Effects of drainage and subirrigation on predicted corn yields for a shallow (1.2 m deep) Jockvale loamy sand near Ottawa, Ontario.

	Poor Drainage L = 90 m	Good Drainage L = 28 m	Subirrigation and Drainage L = 20 m
Simulation Period	23 years (1961-1983)	23 years	23 years
Average Relative Yield	71%	81%	97%
Number of Years Yield > 90%	8	10	21
Number of Years Yield > 75%	12	16	23
Number of Years Yield > 50%	18	21	23
Number of Years Yield < 25%	2	0	0

The effect of profile depth on the relative yield - drain spacing relationship for subirrigation on the Jockvale soil is given in Figure 9. The optimum drain spacing for the 1.8 m profile depth was 30 m as compared to 20 m for the 1.2 m depth. The optimum spacing for drainage alone was 39 m for the 1.8 m profile depth versus 23 m for the shallow 1.2 m depth.

Example 3 --Waste Water Application on Drained Lands. Land application of agricultural, municipal, processing, or industrial waste water, with appropriate pretreatment, is an economically and technically feasible alternative to conventional waste disposal methods for many situations. A major step in designing a land application system is determining the permissible loading rate for a given site. In some cases, the loading rate is limited by the pollutants in the waste water. In others, the application rate is limited hydraulically by

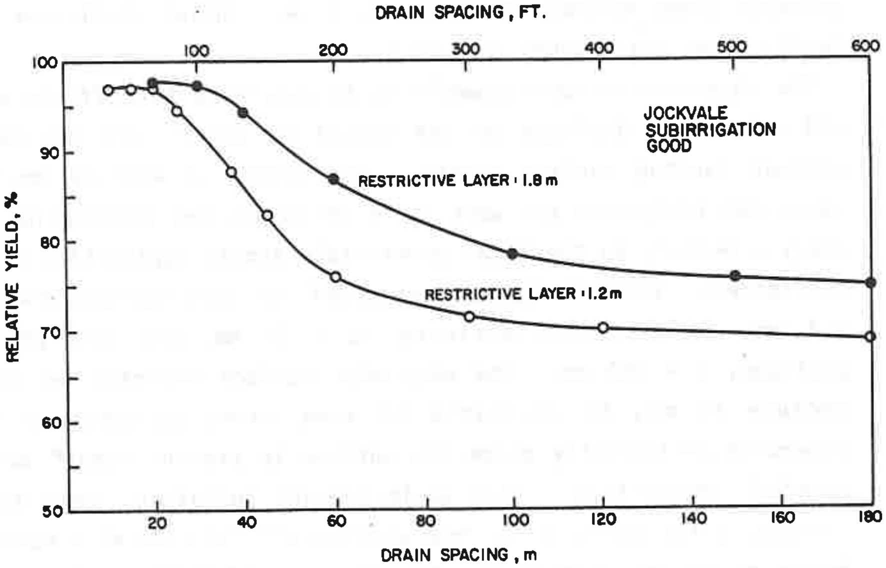

Figure 9. Predicted relative corn yield as a function of drain spacing for two Jockvale loamy sands with profile depths of 1.8 m and 1.2m. Yields were simulated for a 23 year period (1961-1983) using weather data from Ottawa, Ontario. Good surface drainage was assumed.

drainage conditions of the site. In the latter cases, it may be feasible to provide subsurface drainage to increase the amount of waste water that can be applied to a given site and reduce the land area required. Since the costs of land and irrigation systems to apply waste water are relatively high, increasing the application rate by the use of artificial drainage could significantly lower the costs of a land disposal system.

In this example, we consider waste water application to a loamy sand with a saturated hydraulic conductivity of 6.0 cm/hr. The hypothetical site is located near Wilson, North Carolina. Fescue is grown year around and waste water from a processing plant pretreatment lagoon is to be applied (sprinkler irrigation) onto the surface. Consideration of the nutrient levels in the water limit the application rate to 25 mm/week in this example. The water may be applied at any irrigation frequency, but the average must not exceed 25 mm/week. The soil surface is flat and a restrictive layer exists at a depth of 1.8 m so that drainage under natural conditions is slow. Outlet conditions limit the depth of the drain tubes to 1.25 m.

The objective in this example is to determine the effects of surface and subsurface drainage on the amount of water that can be applied without causing surface runoff. The effect of application frequency (e.g. one irrigation per week of 25 mm versus one application of 50 mm every 2 weeks), on the total permissible annual application can also be considered. Simulations were conducted for good surface drainage, $s = 2.4$ mm, poor surface drainage, $s = 25$ mm, and very poor surface drainage, $s = 150$ mm. The very poor surface drainage was considered because it may be desirable in some cases to construct dikes or otherwise artificially shape the surface to prevent runoff during high rainfall intensities. This would prevent pollutants deposited on the surface, grass cover, etc., from washing off the site with runoff water. Waste water application is simulated by DRAINMOD on the application interval, INTDAY, if the drained volume (air volume) in the profile is greater than a given amount, REQDAR, and if rainfall occurring on the scheduled day is less than AMTRN. The parameter values are read into the model as inputs. In this example, the required drained volume, REQDAR, was 10 mm greater than the amount of water to be irrigated.

All simulations were conducted for a 25-year period and the results analyzed to determine the total annual irrigation on a 5-year recurrence interval (5 YRI) basis. The results are plotted in Figure 10 for the 7-day application frequency and all three surface drainage treatments. The results show that, for drain spacings of 25 m or less, water could be applied at every scheduled application for a total of 1300 mm (52 weeks x 25 mm/week) on a 5 YRI basis. In some weeks, waste water application may have to be postponed for one or more days due to rainfall, but the scheduled amount could be applied in all cases. For larger drain spacings, some of the scheduled irrigations could not be applied because there was insufficient water free (drained) volume in the profile. When this happened, application was canceled for that period and conditions were checked on the next scheduled day. For example, only 770 mm could be applied (5 YRI basis) for a drain spacing of 45 m and good surface drainage. Closer inspection of the simulation results showed that most of the cancellations due to wet conditions occurred in the winter and early spring when ET is low. The results plotted in Figure 10 show that the amount of water that can be applied is more dependent on subsurface drainage, as indicated by the drain

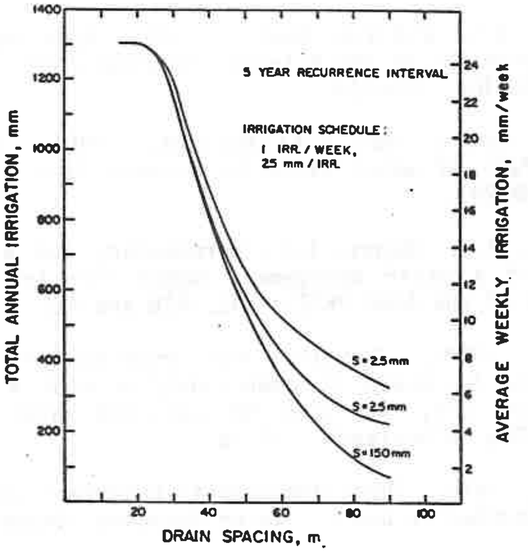

Figure 10. Effects of drain spacing and surface storage on amount of waste water treated annually for irrigation scheduled once per week, 25 mm per application.

spacing, than on surface drainage. However, when subsurface drainage is poor (larger drain spacings), the amount of waste water that can be treated is heavily dependent on the surface drainage. When surface drainage is poor, water may be stored on the surface after periods of high rainfall and can be removed only by evaporation or subsurface drainage. Time required for removal of this surface water may cause the next scheduled waste water application to be canceled due to wet soil.

The results of this example show that DRAINMOD can be used to determine the amount of waste water than can be applied to drained soils. The storage volume required because application is not possible during wet periods can also be assessed. Since simulations are made with actual weather data, designs can be made on a probabilistic basis. By considering alternative systems, DRAINMOD can be used to select the most economical system that will meet the design requirements for a given situation.

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COMPUTER ANALYSIS OF WATER TABLE OBSERVATION WELLS FOR WATER MANAGEMENT

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Abstract

Soil conditions of inhomogeneity and anisotropy with respect to hydraulic conductivity were simulated using finite element techniques for a 0.08 m diameter observation well, 0.6 m deep and terminating 0.4 m or less above an impermeable layer. It was shown that errors in the position of the soil water table as made by measurements in observation wells could be expected due to inhomogeneity and anisotropy. It is recommended that detailed measurements of vertical and horizontal hydraulic conductivity be made in any soil for which accurate water table measurements are desired.

1 Introduction

A common method of determining the adequacy of subsurface drainage is through water table observation wells, or, more simply, observation wells. These are generally placed midway between the buried drains to establish whether or not the drawdown rate is sufficiently rapid to prevent crop damage. In the United States, the drawdown commonly used is 30 cm in 24 hours. The use of measurements based on observation wells has become so common that researchers may not recognize or consider the errors which may be inherent in their research due to the method of measurement. There are those who recognize the possible inadequacy of results obtained in this manner. Armstrong, (1983) examined the technique of measuring water table levels using observation wells which he termed boreholes. He found that where exact measurements of soil water status are required, observation wells are inadequate. Hvorslev (1951) showed that in some soils, the volume of water required for observation wells to respond creates excessively long lag times, sometimes in excess of 40 days for 10 cm auger holes in clay soils.

Detailed information on the behavior of water near an observation well used for monitoring is lacking. Merva and Fausey, (1984) modeled the behavior of a water table near an observation well in a homogeneous, isotropic soil. They showed that even in the ideal soil, excessive lag times were the rule when large diameter wells were used for the determination of water tables. In a very recent work, Rogers, (1985) examined the effect of inhomogeneity and anisotropy on hydraulic conductivity values determined using auger hole methods. He found wide discrepancies from the theoretical values as predicted by Boast and Kirkham's (1971) method derived for a homogeneous, isotropic soil. Because of the widespread use of observation wells as a monitoring tool, and because drainage is often used to remove perched water tables in tight, nonhomogeneous, and often anisotropic soils such as are found in the lake plain soil of the North Central United States, the present study of the behavior of observation wells was undertaken.

2 Objectives

The objectives of the work reported herein were: a) To examine the time to fill of an observation well as a function of soil inhomogeneity and anisotropy with respect to the hydraulic conductivity; b) To examine the interaction between evapotranspiration and apparent water table level as influenced by lag time of an observation well in a nonhomogeneous, anisotropic soil; and c) To examine the effect of lag on predicted water table levels, especially as affected by inhomogeneity and anisotropy.

3 Methodology

Modeling was selected as the most appropriate technique for this study. Several computer techniques are available. Finite difference methods were used successfully by Taylor and Luthin, (1969) to incorporate the effect of the unsaturated layer into a determination of the position of the zero potentiometric head for flow into a pumped well. They used both a variable grid spacing which was a function of the distance from the well as well as a variable time step. Gray and Pinder, (1974) critically examined groundwater flow analysis using computer techniques and compared the finite difference approach to the finite element method (Pinder and Gray, 1975), showing that the finite difference schemes approximate the differential equation at a point, while finite elements approximate an integrated form of the equation. The finite element scheme has received wide attention. It's popularity stems from the ease which which a scheme of nodes can be established for analysis of a problem. Gray and Pinder (1974) cite Gurtin's, 1964 approach to apply finite element techniques in the time domain. They indicate the popularity of a finite difference to approximate the time derivative in groundwater flow, e.g., Zienkiewicz and Cheung, (1967) etc. They use a Galerkin approximation of the time derivative in the analysis of groundwater flow. Rushton and Herbert, (1970) commented on the use of finite time steps and equilibrium solutions at each time step to solve groundwater problems involving a moving water table. This marriage of finite element techniques with a pseudo finite differencing method to solve a time dependent problem is adopted as the method for this study.

It is worthwhile to note that Lapidus and Pinder, (1982) discuss the Boundary integral method as a computer technique in connection with equations such as Laplace's equation. No examples of the Boundary element technique as applied to groundwater flow are given however.

Finally, some researchers have attempted analytic approaches to solve groundwater problems involving a free water surface resulting from water flow into an observation well, see e.g., Hathoot, (1983), Boreli, (1955). Complications introduced when the media is nonhomogeneous and or isotropic make analytic solutions to the problem very difficult to obtain and the present authors know of no existing analytic approach satisfactory for the objectives stated above.

Finite element modeling as presented by Segerlind (Segerlind, 1984) was chosen for the present work. Segerlind (Ch. 13) shows that axisymmetric problems can be solved in a two dimension approach if the hydraulic conductivity, k, in the solution process is replaced by the hydraulic conductivity multiplied by the radial distance to the center of the element in which the conductivity is defined. The program in Segerlind's book was translated into the Pascal language and modified to solve the present problem. In the modified form, the program is amenable to solution on a personal computer. The program was flexible, allowing up to five levels of inhomogeneity and/or anisotropy. Solutions were obtained using a time step finite difference approach wherein the step is controlled by the differences in potential gradients between time steps to prevent oscillations which might be introduced using this method.

In the approach taken, the analysis was limited to 0.6m deep observation well, 0.08 m in diameter in a soil having a drainable porosity of 0.02. It was felt that these dimensions were fairly typical of those used for subsurface water management monitoring. Further, the analysis was limited to situations involving a perched water table at a depth of 1 m or less. In such soils, the assumed value of drainable porosity is typical, and the perched water table conditions are common in the United States, especially in the North Central Region, and indications are that they are common elsewhere also, e.g. Great Britian, (Armstrong, 1983).

In the solution technique, a triangular grid with variable spacing both vertically and horizontally (radially) was used. In the vertical, the spacing was constant from the surface to the bottom of the observation well. At this point it changed to a new spacing which was then held constant from the bottom of the well to the impermeable layer. Depending on the distance from the bottom of the hole to the impermeable layer, the number of nodes from the bottom, of the impermeable layer was varied so that the total number of nodes from the impermeable layer to the initial free water surface was 15. Horizontally, the distance between nodes increases radially. Generally, the horizontal distance was maintained at greater than 3 meters. Although not field tested because of the obvious difficulty of influencing the drawdown being tested with another well which would in itself introduce a drawdown, it was the opinion of the authors that this distance was approximately the radius of influence of the observation well for soils having hydraulic conductivities of 0.02 m/h or less. The solution was carried out using triangular nodes which are adaptable to the axisymmetric solution situation which was adopted. Once a steady state solution had been obtained using the triangular elements, the potential values at the nodes were used, but the diagonals were dropped from the elements and a rectangular element formation was adopted. The advantages of this approach were that the number of computer storage locations needed for the remainder of the solution was reduced while the advantages of a variable gradient across the element were retained.

Gradients at boundary nodes were calculated and used to determine the distance water would travel during the time increment currently in use. From this distance, the potential at the boundary was adjusted to reflect the position of the zero potentiometric line (the free water surface). Gradients at the center of the boundary elements were calculated and used to determine the volume of water which would move through the element during the time interval. From this calculation made on the boundary elements along the well, the volume of water which moved into the well was calculated and added to that already in the well. The total quantity was then used to determine the depth of water in the hole and this value was used to establish appropriate boundary conditions in the well. At this point the new potential values along the boundary were compared to the immediate preceding values, and, depending on the maximum change in potential of all nodes, the time increment was adjusted. This prevented oscillations in the solution. However, a minimum time step was used to prevent long running times. The boundary values thus calculated were written to the disk memory to allow the program to be rerun should it terminate abnormally for some reason. The program was then rerun with the new boundary values and time step. The process was repeated until some predetermined limiting quantity was reached depending on the particular experiment being run, and, when the run was complete, the results were stored on the disk memory for graphing and analysis.

4 Results

Fig. 1 presents the results of the time required to fill the observation well. The situation examined was a soil which was homogeneous but anisotropic with the ratio of vertical to horizontal hydraulic conductivity of 0.1, 0.2, 1, 5, and 10.

For the case where the horizontal hydraulic conductivity is greater than the vertical with the horizontal conductivity held constant at 0.02 m/h, relatively little effect of the anisotropy was seen. While for the isotropic case, the observation well filled to within 96 % of total capacity within 1 hour. The overall time required to reach 96 % of full for the anisotropic condition described above was about 2 times greater than that required for the isotropic situation or about 1.9 hours. It appears that as long as water can move horizontally through the soil, there is sufficient flow to fill the well. This is in sharp contrast to the situation when the horizontal conductivity was less than the vertical. Under this situation, with the vertical conductivity maintained at 0.02 m/h and the ratio of vertical to horizontal having values of 0.2 and 0.1, the time to fill was respectively 5.8 and 95 hours, much longer than it was for the isotropic case. Even though the vertical conductivity was relatively large, the significantly lower horizontal conductivity apparently

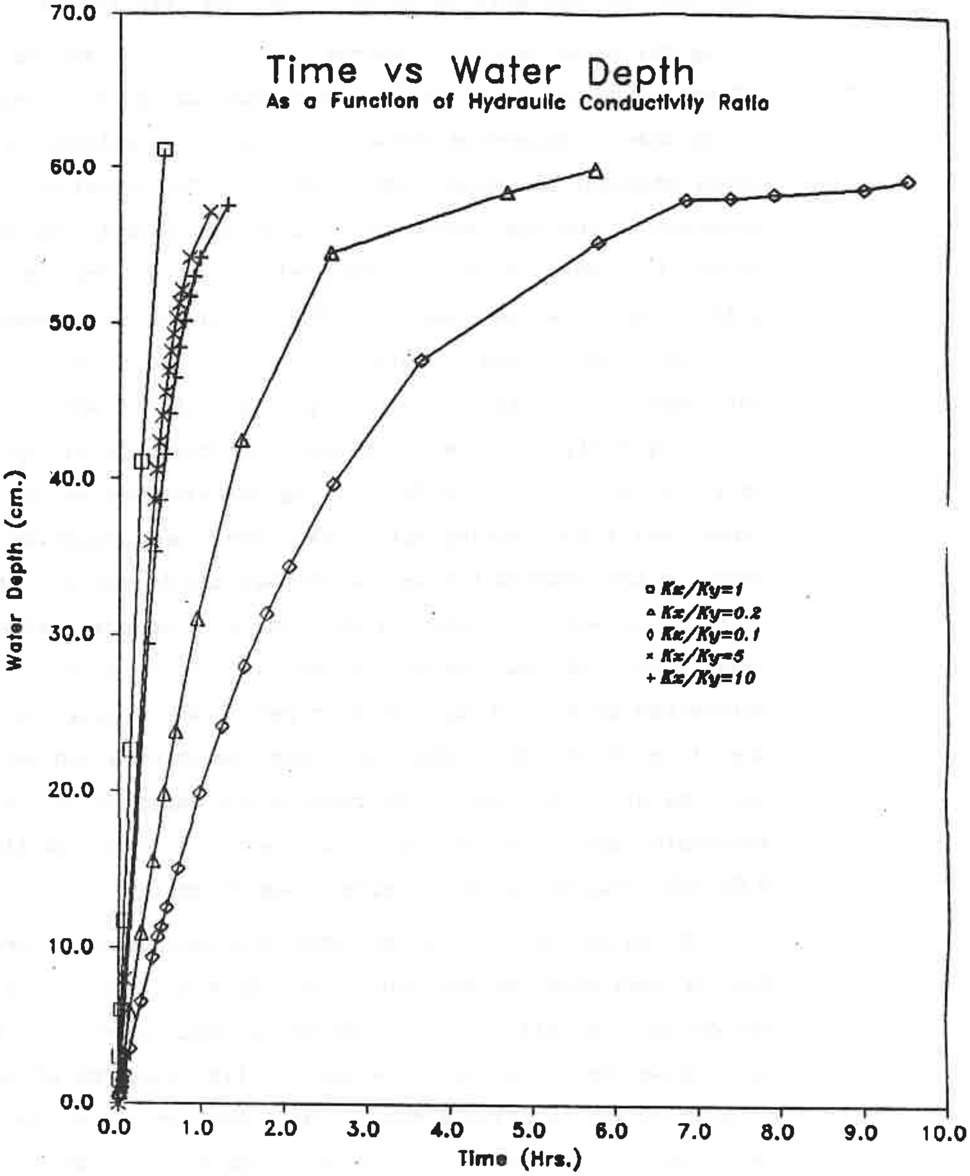

Fig. 1. This figure presents the time to fill of an initially empty observation well 0.6 m deep and 0.08 m in diameter extending to within 0.04 m of an impermeable layer. In all cases where anisotropy is simulated, the largest value of hydraulic conductivity was maintained at 0.02 m/h. In the cases identified above by triangles and diamonds, the lateral conductivity assumed values of 0.002 and 0.001 m/h respectively.

limited the availability of water to flow into the well.

Lag may be an important source of error in estimating the position of the water table in the soil when observation well measurements are being made to determine the water table in an attempt to maintain the level constant for water table control. The situation is most apparent in the case where there is an actively transpiring crop, and where it is desired to know the position of the free water surface to within one or two centimeters. The authors of this paper have observed fluctuations of water table of up to 10 centimeters under the influence of a rapidly transpiring crop with the maximum water level occurring early in the morning and the minimum level taking place late in the afternoon. The effect of lag was examined by inducing a sinusoidally fluctuating soil water level, and comparing the water level in the observation well with that maintained in the soil. An initial lag was introduced by starting with an observation well water level 5 cm less than the soil water level. The effect of lag was determined by simulating a 24 hour period and noting the relative positions of the soil water table and the observation well level when each was at its minimum. The results are depicted in Fig. 2. For the isotropic case, with horizontal and vertical conductivities equal to 0.02 m/h, relatively little effect was found.

In the anisotropic situation, when the horizontal is greater than the vertical with the horizontal at 0.02 m/h, very little effect was noted. The situation is similar to that observed in Fig. 1 where, as long as the horizontal flow was not limiting, the effect of anisotropy was relatively small. When the horizontal conductivity is less than the vertical, however, with the vertical at 0.02 m/h, the effect was significantly magnified. In this situation, the magnitude of the lag was about three hours. More significantly, the difference between the observed water table level in the observation well and the simulated soil water table was about 1/5 of the amplitude of the sinusoidal fluctuation. The effect of anisotropy is that the the combination of lag and fill delay can combine to introduce errors in the determination of the actual free soil water surface.

A situation often found in alluvial lake bed soils in addition to anisotropy is severe layering with the hydraulic conductivity decreasing with increasing depth. This condition was modeled by simulating a soil which was inhomogeneous. To accomplish this, a 4 layer isotropic soil with the magnitude of the conductivity decreasing in each layer was assumed. Then a second run was made with a hydraulic conductivity ratio of 0.5, but holding the vertical hydraulic conductivities the same as in the isotropic case. The

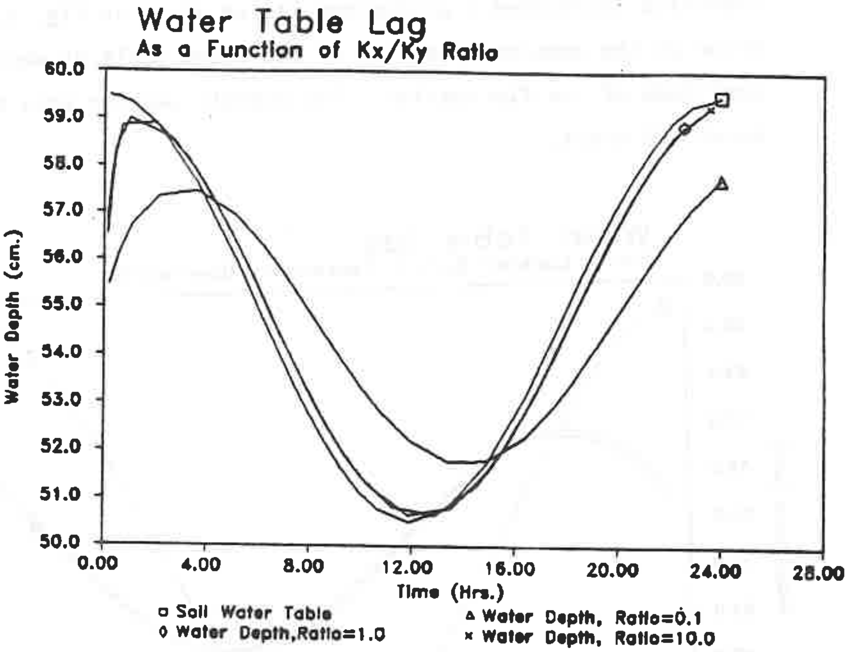

Fig. 2. The effect of anisotropy on the lag of the water table in an observation well as compared to that in the surrounding soil. The fluctuation approximates that introduced by evapotranspiration when the water level in the soil is near the active rooting depth of the crop. The ratio is that of the horizontal to the vertical hydraulic conductivity in an anisotropic soil.

vertical hydraulic conductivity values were; 0.02 m/h through the first 0.225 m, 0.001 m/h through the next 0.3 m to a depth of 0.522 m, 0.005 m/h through the next 0.275 m to a depth of 0.797 m, and 0.0005 m/h through 0.2 m to the impermeable layer. The simulated fluctuation due to evapotranspiration was impressed on the water table. The condition introduced a pronounced lag as shown in Fig. 3, with an error in the apparent position of the water table of about 1/10 of the amplitude of the fluctuation. The overall lag for this situation was about 3.8 hours.

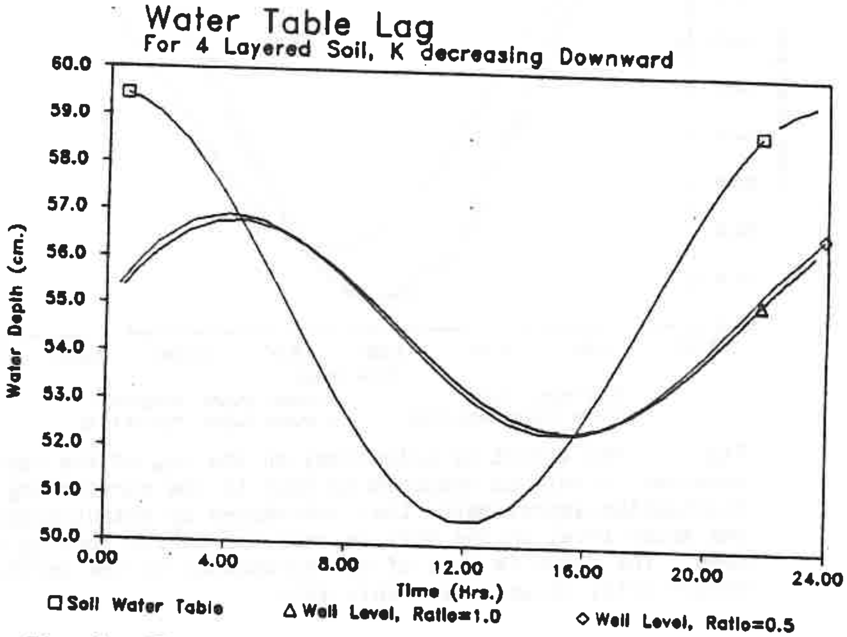

Fig. 3. The combined effect of anisotropy and inhomogenity of the lag of water level in an observation well as compared to that of water in the surrounding soil. The soil was simulated as being layered with vertical hydraulic conductivities (m/h) and the corresponding depth (m) over which the conductivities are effective of 0.02, 0.225; 0.001, 0.3; 0.005, 0.275; and 0.0005, 0.2. The ratio indicated is that of the vertical to the horizontal hydraulic conductivity.

The results of the above simulations suggest that the use of observation wells may introduce severe errors in measurements of the rate of water table drawdown resulting from subsurface drainage, especially if anisotropy is coupled with overall decreasing horizontal hydraulic conductivity downward. To test this hypothesis, anisotropy was introduced into the above simulation and the soil water table was dropped 0.3 m in 24 hours. The results are presented in Fig. 4. The results of decreasing conductivity apparently overshadow all other effects. There was no apparent difference seen between different ratios of anisotropy. The effect of lag, however, caused the observed water table as determined by observation well levels to lag behind the actual soil water table by 0.2 m over 24 hours.

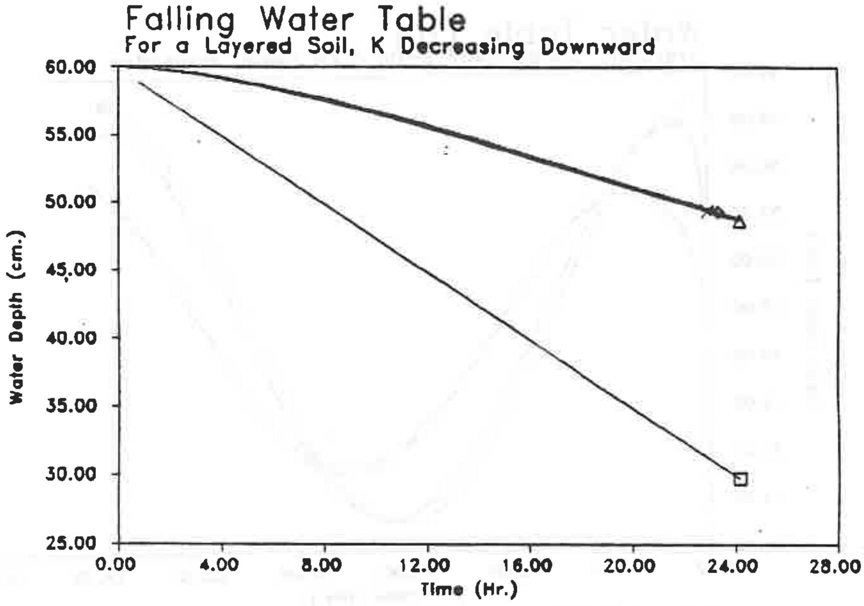

Fig. 4. The influence of inhomogenity and anisotropy on the difference in water table observed in an observation well, and the water table in the soil which is dropping at a rate of 0.3 m in 24 hours. The soil is layered with vertical hydraulic conductivities (m/h) and the corresponding depth (m) over which the conductivitie are effective of 0.02, 0.225; 0.001, 0.3; 0.005, 0.275; and 0.0005 0.2. The ratio indicated is that of the vertical to the horizonta hydraulic conductivity.

One final question involves the effect of the distance from the bottom of the observation well to the impermeable layer. To examine this question, both isotropic and anisotropic conditions were simulated. The depth of the well, H, was held constant at 0.6 m, while the distance, S, from the bottom of the well to the impermeable layer was halved. Fig. 5 presents the results of this set of simulation runs. With isotropy, no appreciable effect of varying the S/H ratio was observed. The maximum lag was about 1 hour. When the horizontal conductivity was less than the vertical, (horizontal conductivity = 0.02 m/h), a maximum lag of 3 hours was found, but the error observed was only about 0.012 meter.

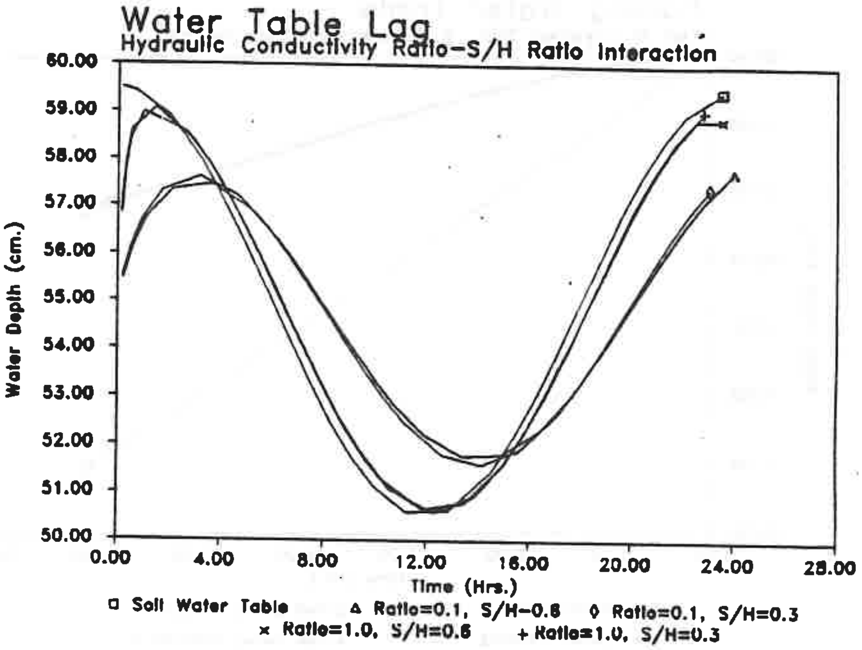

Fig. 5. Results of comparing the interaction of anisotropy with that of distance from the bottom of an observation well to the impermeable layer. The ratio referred to is that of the vertical to the horizontal hydraulic conductivity. The designation S/H refers to the ratio of the distance from the bottom of the observation well to the impermeable layer, to the depth of the well. In all cases, the depth of the well was held constant at 0.6 m.

5 Discussion

This study of the effects of anisotropy and inhomogeneity of the behavior of water table observation wells as a measurement tool revealed little that was unexpected. It did, however, focus attention on the nature of errors that could be introduced into water management work when the investigator is not cognizant of the anisotropic and inhomogeneous behavior the soils in which the measurements are being made. The simulations leading to the results of Fig. 1, the time to fill of a 0.6 m deep, 0.08 m diameter well are probably most important to the measurement of hydraulic conductivity when the auger hole method is being used. The excessively long times required to fill the observation well would confirm the findings of Rogers (1986) that Boast and Kirkham's (1971) values relating water table rate of rise to soil hydraulic conductivity should be used only where isotropy and homogeneity are assured. From Fig. 1, it appears that the time to fill is almost inversely proportional to the hydraulic conductivity in the lateral direction since a lateral hydraulic conductivity 0.2 of that for the isotropic case yielded a fill time over 5 times longer than that for the isotropic case, and then the lateral conductivity was halved, the fill time was approximately doubled.

The interaction of fill time with the correspondingly induced lag is apparent in the remainder of the simulations. It is particularly pronounced where the soil is layered. The effect of decreasing hydraulic conductivity with depth seriously affects measurements of the water table as made with observation wells. While the effect of anisotropy alone is not as serious as that of inhomogeneity, the errors introduced in water table measurements due to anisotropy could lead to confusion in interpreting experimental results. Based on Fig.'s 2 and 3, if the mean water table were at 55 cm water depth, an accurate measurement at any random time would be fortuitous. The results of the information in Fig.'s 2 and 3 make it clear that, for water management purposes, water table measurements should be taken at the same relative time each day, or should be taken continuously so that the nature of the fluctuation which is occurring due to evapotranspiration could be well defined. If the measurements were taken at the same time each day, the effect of the fluctuations would be partially filtered out and only the long term rising or falling water table effect would remain. Of course, depending on the time chosen for the measurement, and the relative effects of anisotropy and/or inhomogeneity, the lag would remain and the actual water table in the soil would be different from the measured value. The long term effect observed, however, would still parallel the actual value.

The results in Fig. 4 speak for themselves. The error of 0.2 m in tracking the falling water table would lead to a gross underestimation of the adequacy of drainage based on the observation well measurements. Possibly, if evapotranspiration were active, the error during the first 12 hours would be still more pronounced, but, based on figure 3, the recovery during the period of low or absent evapotranspiration might compensate for part of the effect. At any rate, the effect of inhomogeneity in this simulation would negate any conclusions which might be made from these data. Since no simulation runs were made incorporating anisotropy alone, it is not possible to make a definite statement regard anisotropic effects on the measurement of a falling water table. However, based on the relative error observed between the simulations presented in Fig.'s 2 and 3, it appears that the effect of anisotropy would still be serious, perhaps causing as much as a 0.1 m error in tracking the falling water table.

Although the effect of diameter on the behavior of a water table well was not simulated in this work, the previously mentioned work by Merva and Fausey, (1984) recommends that only small diameter wells should be used for water table monitoring. The nature of the lag observed in the simulations presented in this paper would be altered if the diameter of the well were reduced since the volume of water required to fill the well would be correspondingly reduced. It is, therefore, highly appropriate to remember that well diameter has an effect on the degree and magnitude of lag, and, therefore, will influence the accuracy of water table measurements.

Probably the most important lesson to be learned from examining the simulation results presented in this paper is the importance of knowing the lateral and vertical hydraulic conductivities of the soil in which measurements are being made. Unpublished data of the authors indicate that anisotropy is far more prevalent in the alluvial lake plain soils of the north central United States than was previously thought. In addition, the layering resulting from alluvial deposition has created inhomogeneity. These influences, coupled with compaction effects resulting from one crop farming practices and/or heavy equipment have created conditions which favor the type of errors which were demonstrated in the simulations presented in this paper.

5. Conclusions

The following conclusions can be drawn from the simulation results of this work:

a) Anisotropy affects the rate of recovery (rate of fill) of a water table observation well with the most predominant effect observed when the lateral conductivity of the soil is less than the vertical although a considerably less pronounced effect is observed when the vertical conductivity is less than the horizontal.

b) Anisotropy causes a measurable lag in the observed water table in an observation well as compared to the soil water table. The effect is amplified by the effects of inhomogeneity where the hydraulic conductivity of the soil decreases with depth into the soil.

c) The combined effects of anisotropy and inhomogeneity can lead to serious errors if observation wells are used to measure the rate of drawdown of the soil water table.

d) It is recommended that both lateral and vertical hydraulic conductivities, by layers if they are present in the soil, be determined in any area where measurements of soil water table are contemplated.

e) It is suggested that small diameter observation well be used for water table monitoring to reduce the effects of lag between the observed water level and the actual soil water level.

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DRAINAGE MODELLING IN HEAVY CLAY SOILS

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Abstract

A computer model has been developed which describes the physical processes involved in the storage, transmission and drainage of water in a fissured drained clay soil. Results are presented showing the sensitivity of the model to input parameters such as the cracking density and rainfall intensity, and the role of tillage in the management of drained clay soils is discussed in relation to the model. Output from the model shows general agreement with field observations of moisture profiles and drain hydrographs in Evesham series clay soil.

1 Introduction

Much of the drainage work carried out in the United Kingdom is concerned with the removal of excess winter rainfall from heavy clay soils. Statistics (Armstrong, 1981) show that in England and Wales drainage installations on impermeable subsoils account for some 60% of all schemes.

British clay soils are characterised by a relatively high bulk density, often a result of glacial overburden, and by a deterioration in structural development with depth. Most of these soils contain a significant proportion of swelling clay minerals, which allows structural cracks to develop during the summer, and in particularly dry years cracks can extend to depths of 1 m or more from the soil surface. From October to March when evapotranspiration is less than rainfall, the soil swells, shrinkage cracks close up and the soil has a much reduced infiltration capacity.

Close spaced drains are required to effectively lower the water table in winter and early spring in clay subsoils of low hydraulic conductivity. In the United Kingdom, a mole drainage technique is commonly used, with drains typically at spacings of 2 m and at 0.5 m depth. In this technique, a vertical narrow leg with a cylindrical foot is pulled through the soil. A cylindrical expander of larger diameter than the foot is trailed behind, remoulding the soil to leave an unlined drain which is circular in cross-section. The leg of the mole plough disturbs the soil, creating localised fissures which extend from the soil surface to the drainage channel (Godwin et al, 1981), and these fissures have been shown to be of great importance in facilitating the rapid removal of excess water from the soil (Leeds-Harrison et al, 1982). In addition, shallow tillage and cultivation operations may alter topsoil structure, disrupting the vertical continuity of existing fissures (Douglas, Goss and Hill, 1980) and/or creating new air porosity by re-arranging and shearing existing peds (Spoor and Godwin, 1984). This in turn may change the balance between water storage in surface layers and the transmission of water in cracks to depth in the soil.

The sensitivity of water recharge and drain response to changes in soil structure, either natural or induced by management practices, is yet to be quantified. Field trials are prone to high variability within plots, and may yield little insight into how soil structure influences the physical processes of water movement, storage and drainage in these soils. This paper first discusses some aspects of the physics of water movement in cracks to drains, and then outlines a model which we have developed to describe the processes involved and finally considers the sensitivity of the model to various input parameters and makes comparisons with mole drain hydrographs observed in the field.

2 Some physical aspects of water flow in clay soils

At the macroscale a saturated pedal clay soil may be simplified to the idealised situation shown in Figure 1, where the crack has a constant width, and where the peds are treated as inert blocks. If water movement in the cracks between the peds is laminar, Childs (1969) has shown that the flow rate is proportional to the cube of the crack width and it is seen that for a saturated

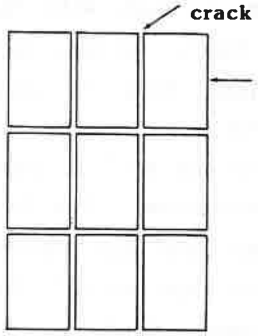

Figure 1 Schematic representation of a cracked clay soil

vertical crack freely drained at its base, the hydraulic potential gradient in the crack is unity. Two adjacent vertical cracks linked by a horizontal crack will have a zero potential gradient between them in this situation and hence no flow.

The imposition of a drainage system on such a network of cracks may change the flow pattern. In particular, the locations of fixed impermeable boundaries and planes of symmetry dictate the relative importance and contribution of individual vertical and horizontal cracks as flow in the network converges to a drain or seepage surface. Shipway (1986) has modelled this simplified situation and has shown that the nature of the potential field around the drain depends on the size and distribution of cracks. For a uniformly cracked soil where all the cracks are of the same size, the potential field is very similar to that predicted for an isotropic homogeneous soil. This conclusion is useful, as it implies that the saturated zone of a well cracked drained clay soil may be modelled in the same way as single grain structureless soils and equations (e.g. Hooghoudt (1940)) to predict drain outflow and water table position may be used with some confidence. This will only be true, however, if the volume of soil between the drains is greater than the representative elementary volume for the measured hydraulic properties (e.g. drainable porosity, hydraulic conductivity).

In dry soils, water may flow down ped faces in distinct bands or rivulets without filling the cracks (Bouma and Dekker, 1978). In this situation, the water in the cracks is at atmospheric pressure throughout so that a unit hydraulic gradient exists vertically and the same situation of no flow in horizontal cracks applies as for the saturated case. Since the water held within the peds is at a lower energy level with pressure potentials less than atmospheric, a hydraulic gradient also exists in the horizontal dimension, resulting in water uptake into peds. This spatial variability in pressure potential is maintained within the time span of a single rainstorm because ped hydraulic conductivities are very low (10^{-3} to 10^{-4} m/day for Evesham clay -Shipway, 1986). Therefore, providing the cracks are open to a source of free water at the soil surface, rapid channelling flow can occur in cracks to depth in the soil, by-passing the surface layers which remain unsaturated.

3 Modelling water movement to drains in clay soil

It is clear from the foregoing discussion that the nature of water movement in heterogeneous cracked clay soils is such that many of the assumptions of classical soil physics cannot be satisfied. For example, it is difficult to define single values of both hydraulic conductivity and hydraulic gradient for a representative elementary volume of soil, particularly in unsaturated topsoil layers during rainfall or irrigation. Great care must be taken, therefore, when applying infiltration and drainage models based on Darcy's law with simple boundary conditions (e.g. Green and Ampt, 1911; Hooghoudt 1940; Skaggs, 1978) to clay soils. Careful selection of input parameters in these equations can allow reasonable agreement with field observations of drain outflow and water distribution in the soil. It is recognised, however, that the actual values of the input parameters chosen may not have physical meaning in terms of the boundary conditions for which the equations were set up. In particular, we recognise that during infiltration a wetting front and transmission zone in the classical sense of one-dimensional flow in which water moves vertically into the soil leaving a saturated zone behind is not likely to occur in a clay soil. Rather, water moves primarily in the crack system, and only slowly diffuses into peds where it is retained against gravity.

Such a movement of water into clay peds causes swelling and a reduction in crack dimensions. Leeds-Harrison et al (1986) showed how continuous ponding for a period of up to forty days resulted in a reduction in apparent hydraulic conductivity of large clay cores to values approaching those of the clay matrix. This process was taken into account in a model developed by Leeds-Harrison et al (1986) to predict mole drain response during wetting and drying cycles in a clay soil. In this model, drain outflow was predicted as a function of the height of the water table above drain depth, hydraulic conductivity and drain spacing using seepage potential theory (Youngs, 1980) and assuming that:

i) the leg slot and associated fissures created at the time of moling (Godwin et al, 1981) act as a seepage surface

ii) the soil peds are inert, and

iii) hydraulic conductivity is a linear function of the crack volume

In deriving the model, Leeds-Harrison et al (1986) also effectively assumed that rainfall or irrigation water falling on the soil surface instantaneously recharged to a water table in the cracks at depth. A sub-model describing infiltration and water movement in the unsaturated zone is now required in order to predict both the time to start of drainage, and also changes in profile moisture content. As has already been discussed, one-dimensional infiltration models based on Darcy's law (e.g. Van Keulen and Van Beek, 1971) cannot be expected to reflect the observed hydrologic behaviour of heterogenous clay soils in which by-passing flow in cracks and ped water uptake in three dimensions are characteristic features (Bouma and Dekker, 1978). In the following sections the drainage model of Leeds-Harrison et al (1986) is further developed to incorporate functions describing the generation of water flow in cracks, and ped water uptake both above and below the level of the water table in the cracks.

In its present form the model (CRACK 12), which is illustrated schematically in Figure 2, is based on a single storm of known intensity and duration. When rainfall intensity (1) exceeds the infiltration capacity of the peds at the soil surface (2), input to cracks begins (3). Water flowing in the cracks (5) is subject to sorption losses to peds within the soil (4). If a water table in the cracks rises above drain depth, drain outflow occurs (6). The following sections describe this model in greater detail.

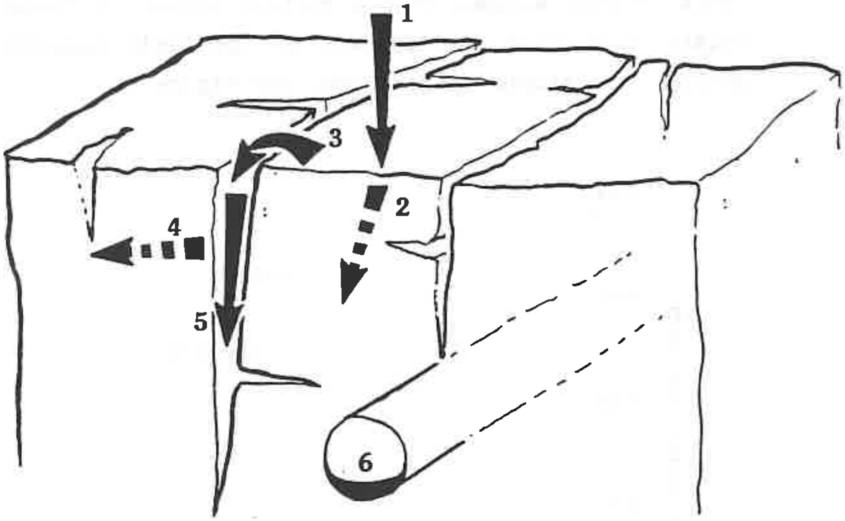

Figure 2 A schematic model of water movement in mole drained clay soils (nos. referred to in text)

i) Soil Structure

In CRACK 12, the soil profile is divided into discrete layers of equal thickness, each layer being ascribed either a cubic or prismatic structure. A prismatic structure is here defined as one in which ped lengths are much larger than ped widths.

Soil structure parameters in the model are dependent on the moisture status of the soil. Thus, the volume of cracks is a function of the difference between the initial moisture content in each layer and the 'field capacity' moisture content (Figure 3). In prismatic soil layers, one-third of the volume of water depleted is accounted for by normal shrinkage in the vertical dimension (Perroux et al, 1974), the remainder by cracking in the horizontal dimensions. In cubic soil layers, the water lost is accommodated by cracking in all three dimensions (see Figure 3). In both cases, individual peds are assumed to shrink normally. CRACK 12 also assumes that a certain amount of fissuring still exists in a fully swollen soil at its field capacity moisture content (the stable crack volume, see Figure 3).

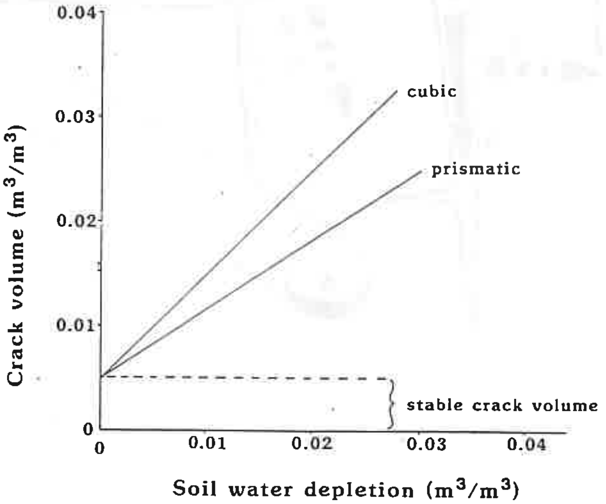

Figure 3 Modelling the effects of soil water depletion on soil shrinkage and cracking.

Assuming that crack spacings are much larger than crack widths, it is easily shown that for cubic structure:

$$V = 3w / d \tag{1}$$

and

$$S = 6 / d \tag{2}$$

where V total crack volume (m^3/m^3)
w crack width (m)
d crack spacing (m)
S total ped surface area (m^2/m^3)

and for prismatic layers,

$$V = 2w / d \tag{3}$$

and

$$S = 4 / d \tag{4}$$

with symbols as above.

In CRACK 12, ped surface areas derived as shown above control the strength of the interaction between the two domains (i.e. the rate of uptake by peds from water flowing in cracks), whilst the crack volume governs the rate of rise or fall of the water table.

ii) Ped Water Uptake

Infiltration into peds at the soil surface is modelled as a simple power law function of time (i.e. Kostiakov's equation; see Figure 4):

$$I_v = A t^n \tag{5}$$

where I_v vertical infiltration rate (ms^{-1})
t time
A, n constants

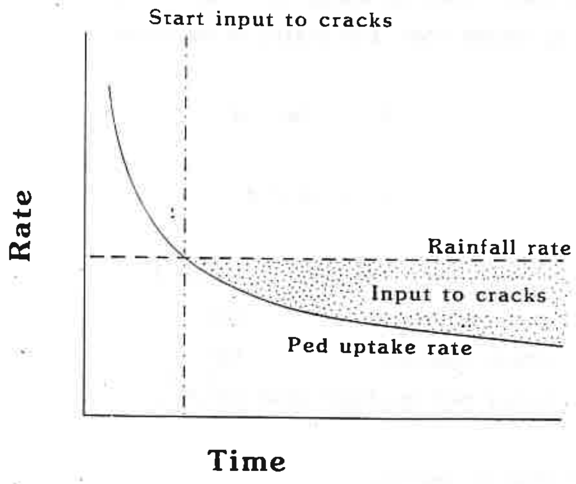

Figure 4 The generation of water flow in cracks.

As a default, the exponent n is set to -0.5 so that equation (5) reduces to the first term of the physics based infiltration equation of Philip (1957), and where the coefficient A is equivalent to half the sorptivity.

Once crack water flow is initiated (see Section iii)), ped water uptake occurs not only through the soil surface, but also through internally wetted surfaces. However, even during prolonged rainfall or irrigation, only a small proportion of the total ped surface area is wetted because of point source inputs at the surface (Bouma and Dekker, 1978) and/or pore necking within the soil (Bouma et al, 1977). The amount of wetted surface area increases with time, so that the normal decay in infiltration rate below a wetted surface (equation 5) is compensated for by the generation of new wetted surfaces (Hoogmoed and Bouma, 1980).

For a given soil layer we may write:

$$I_h = (Z_i \cdot L_i) \cdot (S_i \cdot \alpha) \cdot A_i \cdot (t - t_i)^{m+n} \qquad (6)$$

where I_h horizontal infiltration rate
t_i time to start of input layer i
Z_i layer thickness
m constant
L_i fractional wetted depth in layer i

and α is the proportion of the total ped surface area which is wetted in unit time in a given layer, and other symbols are as defined above.

Experimental evidence suggests that uptake rates rapidly increase to near constant values (Kneale and White, 1984). Therefore, for layers above the water table, a value of m is chosen such that $(m+n) \rightarrow 0$. Our own dye tracing experiments on Evesham clay top soil have given α values as low as 0.02 for a 10 cm layer in 1 hour, similar to those measured by Bouma and Dekker (1978). This is used as input to the model, although it is recognised that α will vary with rainfall intensity, and antecedent moisture content.

For saturated soil layers, $m = 0$ and $\alpha = 1$, as there is no need for 'a priori' assumptions concerning the nature of the change in wetted contact area with time. Here, the wetted contact area is simply a function of the height of the water table in the cracks and the total ped surface area.

iii) Water Flow in Cracks

Water flow in cracks is initiated when the uptake rate into peds at the soil surface is exceeded by the rainfall intensity, which is assumed constant (see Figure 4). In CRACK 12, the rate of advance of a 'wetting front' in the cracks is controlled by the input rate at the soil surface (Figure 4) and ped uptake rates within the soil (equation 6). For successive small time steps, the model calculates the depth in the soil at which input rate at the surface exactly balances the total ped uptake rate.

iv) Water Table Height

The height of the water table in the cracks is controlled by the balance between the input at the soil surface (Section iii) and the loss due to ped water uptake within the soil (Section ii)) and drain outflow. The rate of rise or fall is also a function of the crack volume in the layer in which the water table is located:

$$\Delta H = (I_C - \sum_{i=1}^{i=k} I_h - Q) \cdot \Delta t \,/\, V \qquad (7)$$

where ΔH change in water table height
I_c input rate to cracks
k no. layers
Q drain outflow rate
Δt time interval

and other symbols as before.

If the water table rises to the surface, any further rainfall input is immediately lost as surface run-off.

vi) Water Flow in Peds

Water infiltrating into peds in any given layer is assumed to be stored entirely within that layer. If the layer reaches field capacity, any excess is transmitted to the layer below. If the bottom layer reaches its field capacity moisture content, any further excess is assumed to be lost as deep seepage.

4 Application of the model

We have used a variety of techniques to estimate input parameters required by the model: for example, ped infiltration capacities are determined as a function of the initial moisture content of the soil using closed top infiltrometers which supply water to the soil at negative pressure potentials and which therefore exclude the effects of larger pores (Chong and Green, 1983). We have estimated the contact area parameter α from dye tracing experiments in a similar manner to that described by Bouma and Dekker (1978). Using this information, Jarvis and Leeds-Harrison (in preparation) found a reasonable agreement between model predictions of soil water recharge and drain outflow with data obtained from an instrumented 'natural' lysimeter surrounding a mole drainage channel.

In this paper, the sensitivity of model predictions to changes in input parameters such as rainfall intensity and soil structure will be examined. Two contrasting data sets, based on measurements taken on Evesham (Wicken) series clay soil (King, 1969) at Silsoe (Jarvis and Leeds-Harrison, in preparation), are used here to simulate:

i) recharge of the soil profile in early autumn and

ii) winter drain hydrographs

Unless otherwise stated, the results presented in the following sections refer to a single storm of 10 mm at an intensity of 2 mm hr^{-1}.

The Effect of Rainfall Intensity

Figure 5 shows the effects of changing rainfall intensity from 2 mm hr^{-1} to 1 and 4 mm hr^{-1} (and keeping total rainfall amount constant at 10 mm) on the predicted recharge profile in dry soil. At 1 mm hr^{-1}, the wetting front in the cracks barely penetrates below 10 cm, so that much of the water uptake is confined to the surface layer. As the rainfall intensity increases, the balance between water storage in the topsoil and subsoil shifts. At 4 mm hr^{-1}, a secondary peak or 'bulge' in water uptake is particularly noticeable at the base of the cracked soil profile. This is related to a rising water table in the crack system (which is

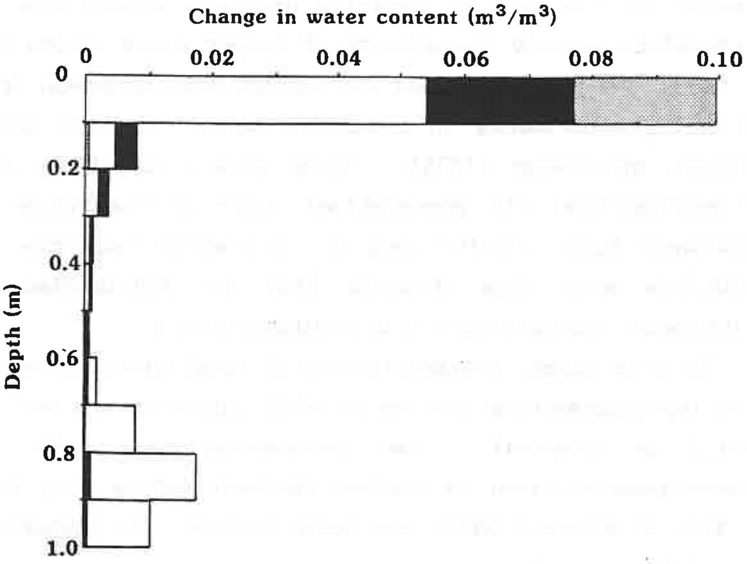

Figure 5 The effect of rainfall intensity on predicted recharge profiles (dotted area = 1 mm hr^{-1}, solid area = 2 mm hr^{-1}, clear area = 4 mm hr^{-1}).

initially set at 1 m depth) and hence an increased surface area over which ped water uptake can occur. Other two-domain models of water movement in structured soils have produced similar results (Edwards et al, 1979; Beven and Germann, 1981), and we have also observed such a pattern of water recharge in cracked clay soils in the field.

It should be noted, however, that the effect of rainfall intensity on water recharge is probably exaggerated in the present version of CRACK 12 since α is maintained constant. In reality, α will increase as rainfall intensity increases (Bouma and Dekker, 1978). Nevertheless, Figure 6 shows that the rate of advance of the wetting front in the cracks predicted by the model is extremely sensitive to rainfall intensity. This is in marked contrast to classical one-dimensional flow models in which the infiltration rate is independent of the rainfall rate once the soil surface is ponded.

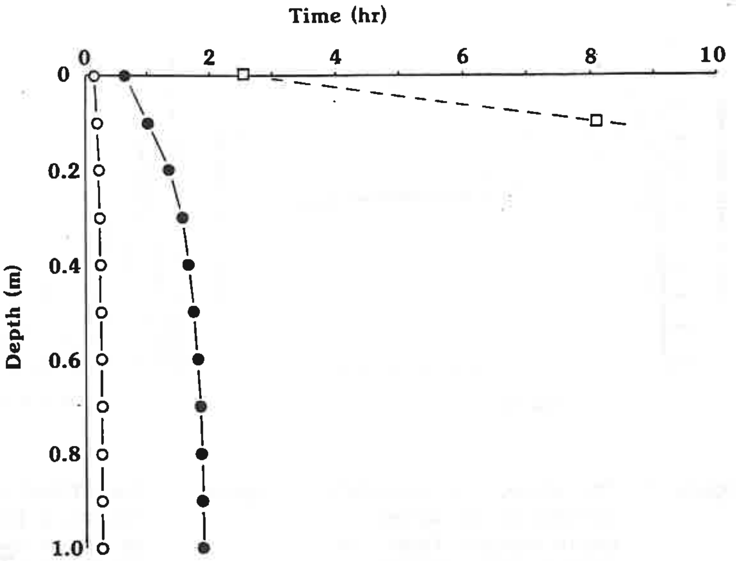

Figure 6 Rate of advance of the wetting front in the cracks as a function of rainfall intensity (□ 1 mm hr^{-1}, ● 2 mm hr^{-1}, O 4 mm hr^{-1}).

For wet soil, Figures 7 and 8 show the effect of rainfall intensity on predicted water table heights and drain hydrographs. It can be seen that drain outflow starts when the water table in the cracks reaches 500 mm from the soil surface, which is assumed to be drain depth. Peak drain outflow rates and water table heights coincide, occurring at the cessation of rainfall regardless of rainfall intensity. A near instantaneous recession in drainage has been observed in the field when constant rate irrigation stops (Fyada, 1985). Under natural rainfall, Shipway (1986) showed how drain outflow rates responded sensitively to fluctuations in rainfall intensity. This is an indication of rapid water flow in cracks between the soil surface and the drain. In another experiment, Beven (1980) noted the appearance of dyed water in a mole channel only 100s after it had been applied at the surface.

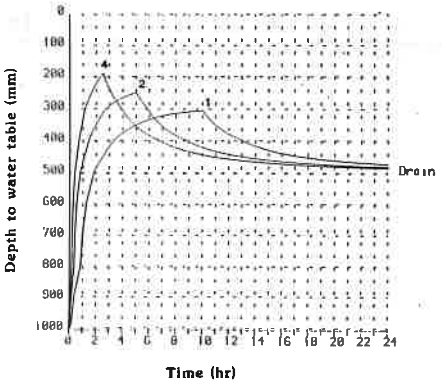

Figure 7 The effect of rainfall intensity on water table height (nos. on curves refer to rainfall intensity in mm hr^{-1}).

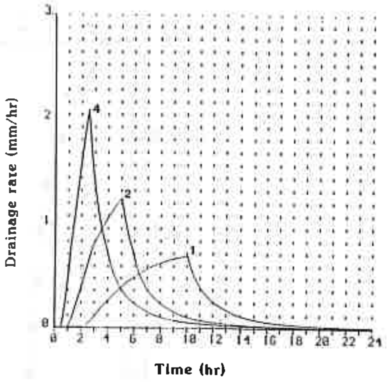

Figure 8 The effect of rainfall intensity on drain hydrographs (nos. on curves refer to rainfall intensity in mm hr^{-1}).

As expected, high intensity, short duration rainfall produces a faster response and higher peaked hydrographs than low intensity, long duration rainfall (Figure 8). However, long duration rainfall gives higher peak drainage rates as a proportion of rainfall rate. In the example shown in Figure 8, peak outflow rates are 70% of rainfall rate at an intensity of 1 mm hr^{-1}, falling to 52% of rainfall rate at 4 mm hr^{-1}. Interestingly, drainage efficiency (total drainflow divided by total rainfall) is little affected by rainfall intensity, increasing from 50 to 54% as it changes from 1 to 4 mm hr^{-1}.

The Effects of Soil Structure

Figure 9 shows model predictions of the recharge profile in dry soil, for crack widths of 1, 2 and 4 mm (crack volume is maintained constant, so that crack spacing is adjusted according to equations 1 & 3). Figure 9 clearly demonstrates that the

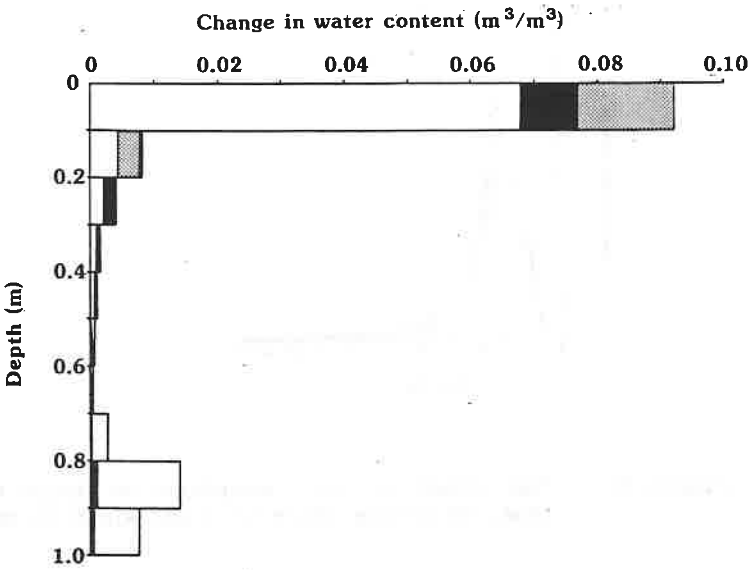

Figure 9 The effect of soil structure on predicted recharge profiles (dotted area = crack width of 1 mm, solid area = crack width of 2 mm, clear area = crack width of 4 mm).

coarse soil structure (crack width 4 mm) promotes rapid penetration of water to the base of the cracked soil profile at 1 m depth, whereas the fine structure stores all the applied water within the top 20 cm. This is due to an increased ped surface area, and hence uptake rates, in the fine structured soil (see equations 2, 4 and 6). Reid and Parkinson (1984a) observed that trampling and poaching of a wet clay soil by cattle resulted in large, widely spaced cracks on subsequent drying. Autumn recharge in this soil was characterised by a secondary 'bulge' of water storage at the base of the cracks, similar to that shown for the coarse structure in Figure 9.

Figure 10 shows that for wet soil, the finer structure results in lower peak outflow rates, again because of higher uptake rates within the soil. Also, drainage efficiency decreases from 63 to 38% as crack widths decrease from 4 to 1 mm.

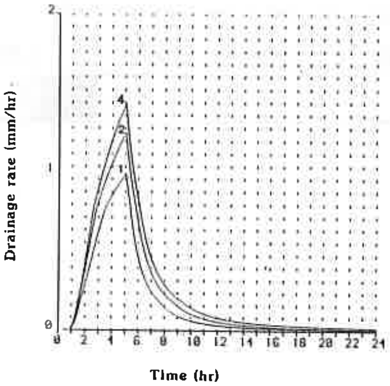

Figure 10 The effect of soil structure on drain hydrographs (nos. on curves refer to crack width in mm).

The Effects of Tillage

The model CRACK 12 can be used to assess the effects of cultivations on water storage and drainage in clay soils. It is assumed that cultivations influence the hydrology of such a soil by altering the structural condition, and in particular the crack volume (see Figure 3). Figure 11 shows the effects of a two-fold increase in crack volume in the top 20 cm on the recharge profile in dry soil. The increased crack volume is assumed to be accommodated by reductions in ped size and crack spacings (i.e. a fine tilth for seedbed), crack width remaining constant. Increases in air content of this magnitude have been observed in the field following autumn tillage in Evesham series clay (Spoor and Godwin, 1984). Figure 11 shows that the cultivated treatment stores all the applied water in the surface layers of the soil, whereas the undisturbed soil allows water to penetrate to 1 m depth. The results of Shipway (1986) confirm this pattern, in that a cultivated topsoil of Evesham series clay was on average 1% wetter than an undisturbed plot, in the period from October to June. Also, increases in moisture content in the top 20 cm of the cultivated soil following a single rainstorm were often as much as 6% greater than those in the uncultivated soil.

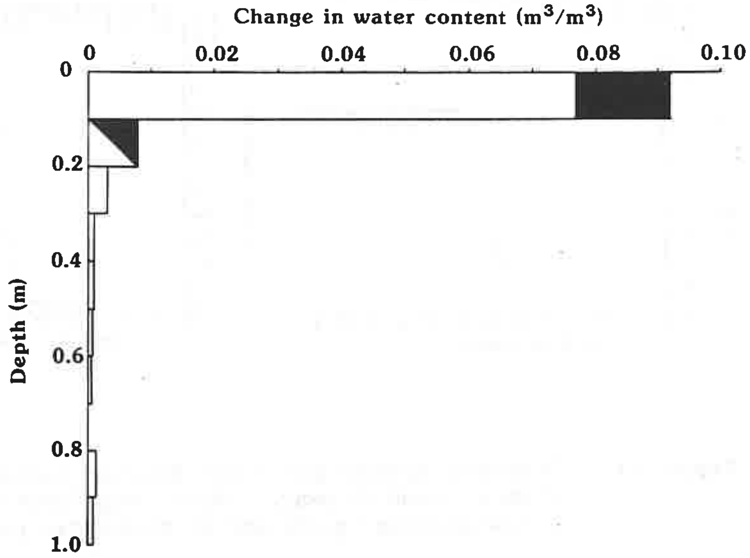

Figure 11 The effect of tillage on predicted recharge profiles (solid area = tilled, clear area = undisturbed).

Figure 12 shows the drain hydrographs predicted by the model for cultivated and undisturbed treatments. Peak flow rates are reduced from 1.25 mm hr^{-1} to 1.1 mm hr^{-1} by the cultivation.

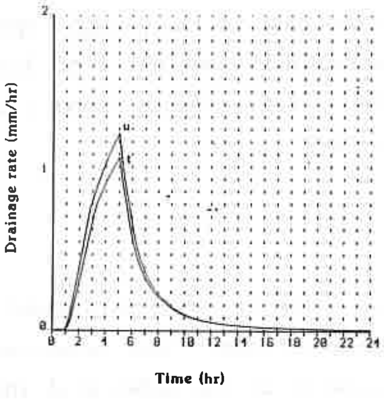

Figure 12 The effect of tillage on predicted drain hydrographs (t = tilled, u = undisturbed).

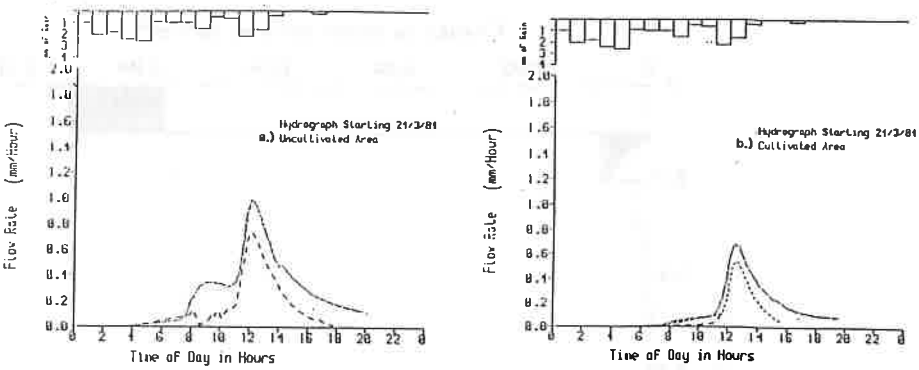

Figure 13 Observed hydrographs from Evesham series clay at Silsoe (from Shipway, 1986). Replicate moles from a) uncultivated plots and b) cultivated plots.

Shipway (1986) has noted a similar effect in a comparison of hydrographs from cultivated and uncultivated Evesham series clay (see Figure 13a,b). The model also indicates a reduction in drainage efficiency from 53 to 46% as a result of cultivations. Reid and Parkinson (1984b) reported that ploughing and seeding for winter wheat reduced drain discharge from a previously grassed catchment from 51 to 30% of the rainfall. An effect of this magnitude, far greater than that predicted by the model CRACK 12, may perhaps be explained by factors such as smearing and compaction at the base of the plough layer with a consequent disruption of the vertical continuity of large pores (Douglas, Goss and Hill, 1980). Such effects cannot, as yet, be predicted by a model such as CRACK 12.

5 Conclusions

We have shown that a simple two domain model can reproduce many features of the observed hydrologic behaviour of a heavy clay soil. Future development of the model will involve incorporating sub-models of evapotranspiration and root water uptake so that its use as a complete water management tool for clay soils may be extended.

From the results of simulation runs presented here, it is clear that both high intensity applications in combination with a soil of coarse structure (but with good vertical continuity of macropores) favour rapid penetration of rainfall and irrigation water to depth in the soil. Management of the soil to achieve these aims would produce an improved drain response and therefore a drier, stronger topsoil better able to support agricultural traffic. In this respect, the model will be developed to allow soil strength and trafficability prediction under different tillage practices.

Acknowledgements

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"DRAINAGE CONSTRUCTION PRACTICES AND TECHNIQUES"

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The slides will show installation of subsurface drainage by many types of machines in both the United States and Canada. Also shown are the many necessary accessories to drainage such as catch basins, surface drainage, open ditches, headwalls, risers, erosion and practices to stop same, automatic grade control, historic tile and boring machines.

Plow Type Installation

1. This shows a need for subsurface drainage.
2. The most popular type of machines used today.
3. Drainage Field Day in Ontario in 1984.
4. An early drainage plow in Ontario.
5. Small plow installing tubing in existing vineyard in Canada.
6. Clay tile being installed by plow in Canada.
7. An early drainage plow in Canada.
8. A Tait Plow in New York starting to drain center of a public road. The operator/owner is inspecting a gravel hopper.
9. Pipe strung along pre-ripped area.
10. Completed job with 2-6% grade.
11. A winter drainage operation in Minnesota.
12. Eddy Oxford's Link 500 Plow.
13. RWF Cable Plow which allows contractor to diversify.
14. Tubing being installed in Wisconsin with a Wolfe Plow.
15. RWF Plow built for Russ Hall of Michigan.
16. Contractor, Dennis Rector with a Tait Plow in Michigan.
17. Werk Brau Plow mounted on a Steiger Rubber Tired Tractor in Michigan.

18. John Cook's Steiger Krac Plow in Michigan.
19. Tait Bros. Contractors carry 2 large rolls.
20. A Canteco Wedge Plow on a big Bud Tractor.
21. Barth TLX Machine
22. Hoes 784 and on board reel with power puller and pusher.
22a. Gentle Giant Michigan Dozer Zor Plow by Russ Hall.
22b. Built by Eddy Oxford for Jim Jacobs of Michigan.
22c. Jim Jacobs's plow.
23. Illustrating a very short coupled plow.
24. Illustrating a very short coupled plow.

Chain Type Installation

25. Chain machine installing plastic tubing in Louisiana.
26. A chain machine installing plastic and filter wrap in Texas. This filter wrap is being installed over the pipe in the field and not in the factory.
27. Chain installing plastic in Texas.
28. Chain machine installing plastic in Louisiana.
29. ZBT Trencher installing plastic in Pennsylvania.
30. Chain Trencher at Field Day.
31. Vemeer and Mastenbroeck Experimental Chain Machine.
32. Hoes Chain Machine
33. New Interdrain just imported to United States from Europe.
34. Zimmer ZBT in Ohio

Slim Line Type Installation

35. Radahl Machine

Wheel Machine Type Installation

36. Speicher 7060--Speichers have more machines in U.S. than any other Company.
37. Speicher 7060 and Brown Bear Auger.

38. Buckeye Super H at Michigan Field Day.
39. Buckeye Super H at Illinois Field Day
40. Laying palletized clay tile with a wheel machine.
41. Clay tile installed--needs to be blinded before backfilling.
42. Backfilling with home made auger attached to farm tractor.
43. Wolffe Man 7000 Wheel Trencher with tilt wheel in Minnesota. It is manufactured in Canada.
44. 1957 Henschen Ohio Ditcher still in use in Illinois.
45. Kenny Davis installing filter wrap in Indiana.

Automatic Grade Control

46. Components of Spectra Physics Laser System
46a. Spectra Physics 945 Command Post
47. Spectra Physics Receiver
48. Michigan Contractor's Laser Surveying Truck which doubles as a plastic spinner.
49. Surveying Mast used on a 3-wheeler.

Deep Drainage of Irrigated Land

50. Wheel Trenching machine, Columbia Basin Project
51. Hollanddrain Trencher, West Oakes Test Area, North Dakota
52. Hoes Trencher, Riverton Unit, Wyoming
53. Hoes Trencher, Hammond Project, New Mexico

Backhoe

54. Backhoe with ditch cage using targets for grade.

Backfiller

55. Speicher Backfiller with backhoe attached.

Large Tile Mains

56. Parson Wheel Machine installing 18" tile in Iowa.
57. Buckeye 318 Wheel Machine installing 27" tile in Ohio.
57a. Buckeye 318 Wheel Machine installing 15" plastic in Ohio.
58. Ram in Bottom shoe to push smooth end tile tight together.
59. Picture taken 1600 ft. (500M) from end.

Accessories

60. Vertical boring machine
61. Large spinner - 3000 ft. (909M)
62. Really large rolls and spinners of 20,000 ft. (6060M), Baughman Tile, Ohio
63. Small spinner

Erosion

64. 2 open ditches joining from rolling and flat terrain
65. Erosion
66. Sheet erosion
67. Open ditch bank erosion
68. Completed grass waterway for surface drainage
69. Stone drop
70. After a heavy rain, shows value of stone drop and grassed waterway.
71. Large open ditch and seeded side slopes
72. Large aluminum drop structure
73. Concrete headwall and drop structure
74. Water inlet
74a. Controlled water inlet
75. Catch basin with round grate
76. Light duty catch basin with flat grate
77. Heavy duty catch basin without grate
78. Riser for Parallel Terrace Outlets (PTO)
79. Aerial photo 100 acres, 40 ft. (13M) spacing

80. Large tile installed approximately 80 years ago.

81. Plow void due to very heavy soil

82. Plow void to top of ground

83. Large tile broke due to poor installation.

84. Silt in plastic pipe, needed proper filter wrap

85. Michigan Land Improvement Contractors Association's tent at field day. MLICA is a state chapter of the Land Improvement Contractors of America (LICA).

86. Dozer in pond winching plow.

87. Dozer in pond winching wheel machine.

88. Result of wet installation

89. Various sizes of clay tile

90. Conveyor backfill on wheel machine

91. Arch pipe

92. Arch pipe installed.

93. Outlet pipe into open ditch

94. Undrained corn field

95. Results of good drainage

COMPUTER-AIDED DESIGN AND APPLICATION OF SYSTEMS FOR AGRICULTURAL DRAINAGE AND WATER TABLE CONTROL

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Abstract

The United States Department of Agriculture, Soil Conservation Service uses the DRAINMOD computer program for design of subsurface drainage systems, water table control systems (subirrigation and subsurface drainage), and other applications. DRAINMOD program availability, data needs, design considerations, and management of water table control systems are discussed.

1 Introduction

The United States Department of Agriculture (USDA) Soil Conservation Service (SCS), uses the DRAINMOD computer program (Skaggs 1978) to help farmers improve drainage systems on individual fields and to establish or revise recommendations data for local SCS drainage guides (W.J. Ochs et al. 1982).

On soils with a naturally high water table in humid areas, SCS staff, contractors, and others are using DRAINMOD to design water table control systems for farmers. These systems use subsurface drainage tubing to subirrigate by adding water to the soil. Thus, the water table can be raised for subirrigation and lowered for drainage.

2 Availability of DRAINMOD

The Soil Conservation Service stores the DRAINMOD program on a mainframe computer at the USDA Washington computer center (WCC) in Washington, D.C. At this time, SCS personnel can access both versions of the program from terminals in all SCS state offices and some field offices. The original or standard version of DRAINMOD evaluates the water balance for precipitation, infiltration, soil-water movement, drainage, subirrigation, evaporation, and plant use. The yield version, which has not been used extensively, can also provide probable yield results.

In addition to access via the WCC, the SCS has both versions of DRAINMOD available for use on IBM (International Business Machines) or IBM-compatible microcomputers. Running the program interactively on a micro seems to be preferred over the batch entry mode of operation available through the WCC mainframe, especially in remote areas where turnaround time on the mainframe may be several days. However, users with immediate access to the mainframe may prefer it because of the short computation time required (1 to 2 seconds per year of simulation versus 2 minutes or more on the microcomputer).

Supplemental programs have been developed for use with the DRAINMOD program on microcomputers (Brink 1985). The supplemental program for data entry or editing, which is available with both versions of DRAINMOD on microcomputer in the SCS, is especially valuable in saving time and reducing the opportunity for errors in re-entry of repetitive data for successive runs. The data are easily modified for use with either the Yield or Standard versions.

3 Data Needs

DRAINMOD uses historical weather data for evaluation purposes. These data are from 152 weather stations in 37 states. They are stored at the WCC. These weather stations are mostly in the eastern, generally more humid part of the United States. Their names and locations are listed in the DRAINMOD Users Manual (SCS 1985). The weather data from each station represents 20 or more years of records for daily maximum and minimum temperatures and hourly precipitation. It is common practice to simulate up to 20 years of weather conditions in an effort to represent expected weather cycles and extremes. In other parts of the world a shorter or longer period may be appropriate.

Local weather data, while necessary for computer runs that fit field conditions, are relatively easy to obtain. On the other hand, accurate field-specific data on soils are much more difficult to obtain, but are critical for proper design of a subsurface drainage system or water table control system. The soils data indicate how water moves into and through the soil. The major soil related inputs for DRAINMOD are—

1. Hydraulic conductivity;
2. Relationship between drained volume (or depth) and water table depth;
3. Relationships between maximum upward flux and water table depth;
4. Infiltration rate; and
5. Drainage volume required for field traffic (used to determine how drainage system design limits the number of days on which field traffic would be advisable).

Hydraulic conductivity should be measured in the field. This is usually done by the auger-hole method (SCS 1971). The infiltration rate should also be measured in the field with a double ring infiltrometer. In addition to these field measurements, clod samples may be sent to a laboratory and analyzed for the amount of air voids, drainable porosity, and water-holding capacity under saturated to droughty conditions.

In the absence of specific field measurements, it is customary to make initial computer runs with approximate data, such as those from benchmark soils, or with data from a completed soil survey. The Soil Conservation Service has been collecting and evaluating data for benchmark soils in the Midwest. Soil-water characteristic information is available for several other soils.

Soil-water characteristic data and drainable porosity can be estimated with a microcomputer program that uses grain size distribution, organic matter content, and clay type involved (unpublished procedure of Dr. Otto Baumer, SCS Soil Survey Laboratory, Lincoln, Nebraska).

While DRAINMOD can be run with estimated soils data to provide some initial guidance for subsurface drain depths and spacings, there is no good substitute for field measurements. The most important field measurement is hydraulic conductivity.

4 Design Considerations

SCS personnel—primarily engineers—in the Eastern United States have been trained to use DRAINMOD. Its principal uses have been for evaluation of subsurface drainage with various degrees of surface drainage and for water table control systems. There is a need, however, to evaluate drainage systems in arid and semiarid areas, where the water table is not always present. In addition the program has virtually untapped potential for evaluation of disposal of wastewater on agricultural land. For this kind of application, DRAINMOD can help determine required temporary storage volumes and optimum land area needed to dispose of a given amount of wastewater. Overall, use of DRAINMOD to evaluate environmental benefits and damages relative to nutrient, pesticide, and sediment movement is becoming more important.

Design and installation of a water table control system require considerable planning and adaptation to specific site conditions. The first consideration is to verify whether a natural high water table has been or is present. At this time, this type of system is recommended only where a natural high water table exists. Besides the soil information discussed earlier, field topography is a major concern. If surface drainage is restricted, land smoothing or another means of improving surface drainage is recommended. For high value crops such as vegetables, precision land leveling may be appropriate despite its cost. Effective surface drainage makes the water table control system easier to design and manage. Furthermore, the efficiency of a subsurface drainage system is impaired by reduced drainable porosity above the drainage tubing whenever the water table is maintained above the tubing. The next consideration may be to determine whether the drainage outlet is adequate or whether a pumped outlet will be required.

Water supply and conveyance needs to be determined. Figure 1 shows a well location along with control structures in the outlet ditch. Figure 2 shows a typical stop-log structure for water stage management. If the main outlet ditch is conveying drainage water from a large enough upstream drainage area, a well may not be needed for supplemental water supply. The point is that there is a logical design sequence for determining the proper number and layout of water management structures along with the most desirable configuration of the subsurface drainage system. For example, figure 1 shows a 50 cm elevation difference between each of the three water control structures, but the land area served by

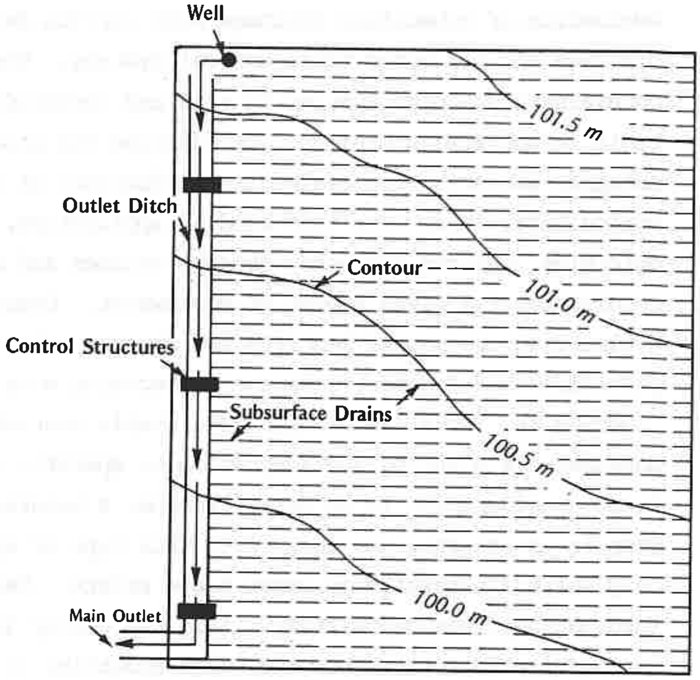

Figure 1 - TYPICAL FIELD LAYOUT

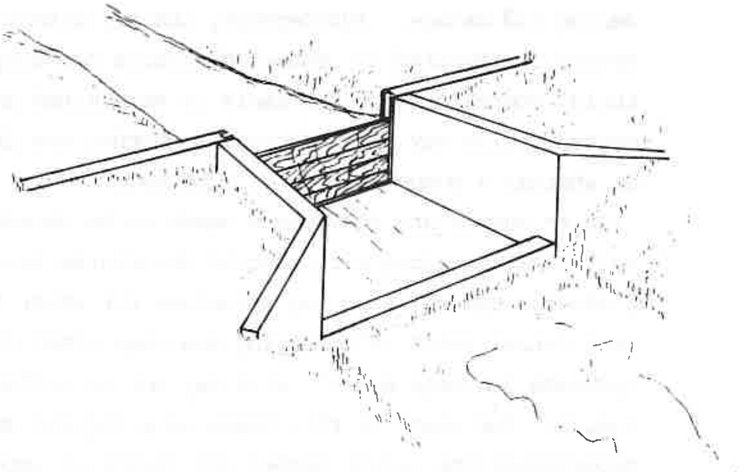

Figure 2 - TYPICAL STOP-LOG STRUCTURE

each structure has a 1-meter elevation difference. Each subsurface drain line has from 50 to 70 cm of elevation change in the ground surface from its beginning to its end. It is common practice to install the drainage tubing at a uniform depth so the grade of the drains would be approximately the same as the ground surface. Setting the water level at a structure at 30 cm below the surface would establish the water stage at 130 cm below the surface at the highest location in the field block. This is deeper than subsurface drains are normally installed (90-120 cm), therefore this layout is not satisfactory. If the subsurface drains were realigned to be parallel to the slope contour, then more structures would be needed to maintain the 50 cm interval between structures, but for the same 30 cm setting the water stage at the highest location would be 80 cm below the surface. This may still be excessive when upward flux, crop consumptive use, and other factors are considered. Further, the latter case may not provide for a minimum desired grade in the subsurface drain line.

5 System Management

In operating a water table control system, prolonged saturation of the root zone must be avoided. For very shallow rooted crops, such as vegetables, the best method of operation may be to raise the water level to a depth of about 30 cm for a short period or until the surface layer of soil reaches its water-holding capacity. Then the level is allowed to recede by evapotranspiration to some preset depth until the crop again needs irrigation. This cycle allows air to move into the soil and root zone. It may be desirable to use an automatic float switch to turn the pump on and off when the water level reaches preset minimum and maximum stages.

For deeper rooted crops, it is customary to maintain the water control structures at a predetermined level for the various crop stages. Thus, variations in the water table result only from rainfall and differing consumptive use rates during any particular crop stage. The greater the acceptable difference between minimum and maximum stages, the greater is the opportunity to store natural precipitation and the less pumping is required.

Water control structures should be designed so that adjustments may be easily made to facilitate rapid removal of storm discharges. Trafficability in the spring and harvest seasons can also be facilitated by timely lowering of the water table. Flashboard or stop-log type structures normally allow for adequate management of the water table.

6 Summary

SCS plans to add features to the computer program to better evaluate potential changes in water quality and to interact with other programs for determining the erosion control benefit of an improved subsurface drainage system.

The DRAINMOD program is an excellent tool for design of subsurface drainage, water table control, and waste-water disposal systems. Its use will naturally increase as input data become easier to find or calculate and as more computers become available to contractors, consultants, and agency personel.

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COMPUTERS IN SURVEYING AND DRAINAGE DESIGN

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Abstract

A new surveying technique to be used in obtaining the data for subsurface drainage plan is described. Benefits and drawbacks of the system are listed. The more irregular the field the better the new system is compared with traditional surveying methods. A computer-based drainage design system is presented. The greatest time-savings can be achieved when compiling the materials catalogue and calculating costs.

Introduction

The applicability of computers in surveying and drainage design has been tested during the last 12 months in the Finnish Field Drainage Centre. In principle, drainage design is well suited for computer applications. The objective of this paper is two-fold. First, the applicability of modern surveying instruments in producing the necessary topographical data is discussed. Second, the potential for computer use for map drawing and for production of a subsurface drainage plan is evaluated. The flow diagram of the whole system developed in the Finnish Field Drainage Centre as shown in Fig. 1 is elaborated upon in the text.

Field survey instruments

The measurement system is composed of an electronic total station (electronic tacheometer), reflecting prism and data collector. We have used the Topcon ET-1 total station which combines electronic angle and distance measurements in a single instrument. It measures and records automatically.

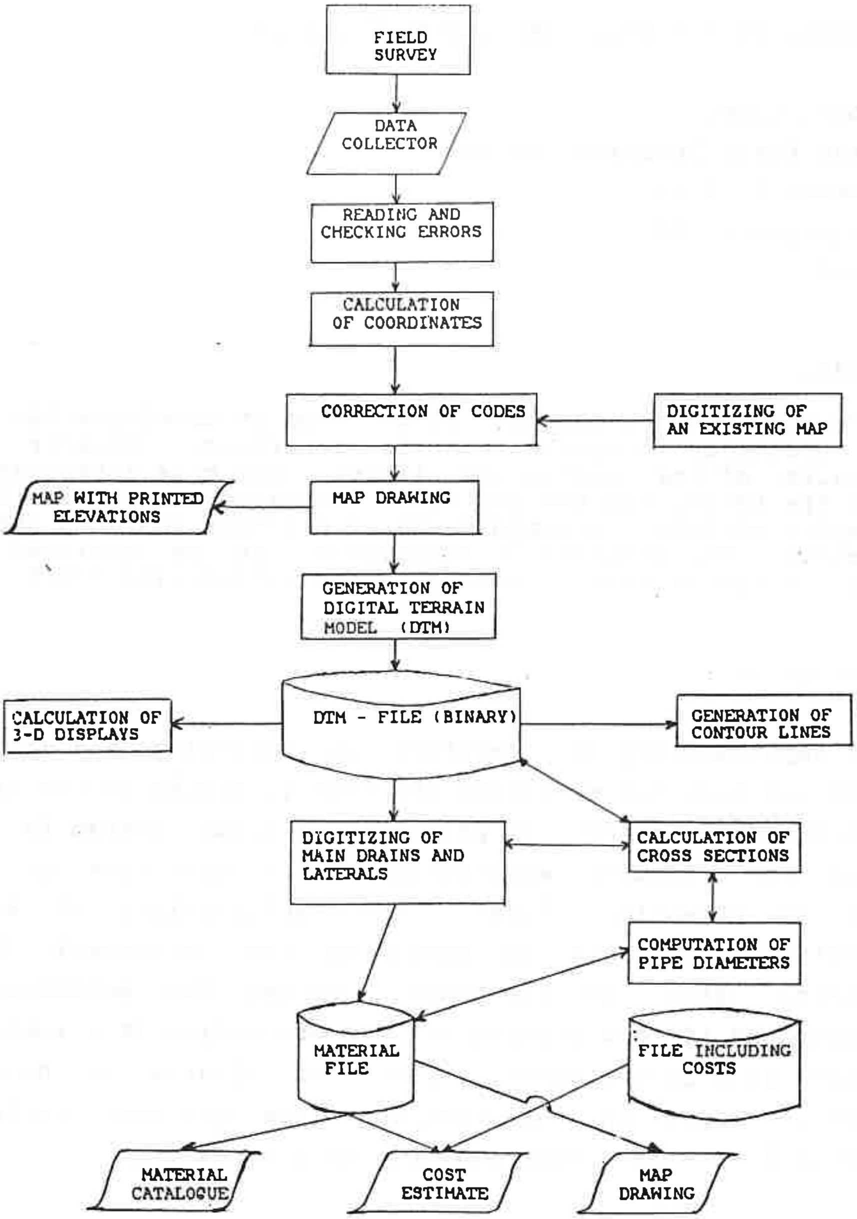


Fig. 1. Flow diagram of the computer based field survey and drainage design system.

All readings with ET-1 can be stored automatically in a 60K data collector (Topcon FC-1) for later inputing into computers. The measurement accuracy is sufficient (on the order of millimeters). ET-1 can measure 1400 m with one prism and 2000 m with three. The data stored in the data collector are distance, vertical and horizontal angle.

The coding system used in surveying

During field survey each measurement point must have special code number so that the nature of the point can be recognized when the map is drawn by computer. The list of codes in use is shown in Table 1. An additional data needed from some points is an extra number which tells if the measured point is the starting point of the border of the field, for example. The data transferred from the data collector to the computer thus include five information items from each point: distance, vertical and horizontal angle, code and an additional number. Based on these data the computer can draw the map. Transfer of data to computer is done via a RS-232 communication port.

Digitizing of an existing map

In the case when it is not possible to use an electonic total station for surveying, we still want to use the computer for actual drainage design. In these cases an existing map can be digitized. The system includes three major components:

- an active surface tablet (either size A1 or A3)
- a digitizer processing unit
- a transducer (multi-button cursor or "mouse") which relays the positional data (XY coordinate pair)

After that it is possible to continue planning in the same way as if we had the data stored by total station. For example, it is possible to change the scale of the map. By digitizer it is also possible to store contour lines if it is not necessary for the computer to draw them.

Table 1. The codes used in field survey.

Code	Explanation
1	Ordinary point of the field
2	Border of the field (surrounded by open ditches)
3	Open ditch
4	Main ditch, left side
5	Main ditch, additional point from the cross-section (left side)
6	Main ditch, additional point from the cross-section (right side)
7	Main ditch, right side
8	Main ditch, bottom
9	Water level in main ditch
10	Open drain collecting additional waters
11	Stone
12	Stone soil or boulder soil
13	Spring area
14	Ochreous area
15	Test dig hole
16	Depth of bedrock
17	Depth of peat layer
18	Boundary of two different soil types
19	Direction of flow
20	Building
21	Road, left side (without open ditches)
22	Road, right side (without open ditches)
23	Border of the field (not surrounded by open ditches)
24	Pipeline
25	Fixed point
26	Direction of north
27	Road sided by open ditches (left)
28	Road sided by open ditches (right)
35	Surrounding area (additional data by an extra number)
36	Bedrock area (depth below 1.5 m)
37	Clay pit
44	Cable

Map drawing

So far we have used only a plotter that can draw maps of size A3. In Finland the scale of the subsurface drainage plans is 1:2000. If the area surveyed cannot be drawn on the scale 1:2000, it is first plotted on a smaller scale and later magnified to the proper scale. An example of a map drawn by our computer system is shown in Fig. 2. This map does not yet include subsurface drains but the existing open ditches only.

Digital terrain model and its applications

In the computer aided planning the elevation of each point in the field is needed. However, it not possible to measure all these. We must have a system by which the elevation of the desired points can be calculated based on actual measured points. This system is called the digital terrain model (DTM). It is necessary to have a DTM for calculation of contour lines, 3-D plots and cross-sections showing e.g. the burial depth of the drain.

Digital terrain model could be generated from a rectangular grid (a very dense measurement net is needed) or preferably a triangular grid. We have chosen the latter alternative, since it is possible to measure more points where needed and only a few points on very flat areas. An example of the triangular system is shown in Fig. 3.

Three basic applications of the DTM used in drainage planning are:

- calculation (and drawing) of contour map (Fig. 4.)
- development of 3-dimensional spatial displays, possibly from different angles (Fig. 5.)
- calculation (and displaying) of profiles of subsurface drains to insure proper installation depth

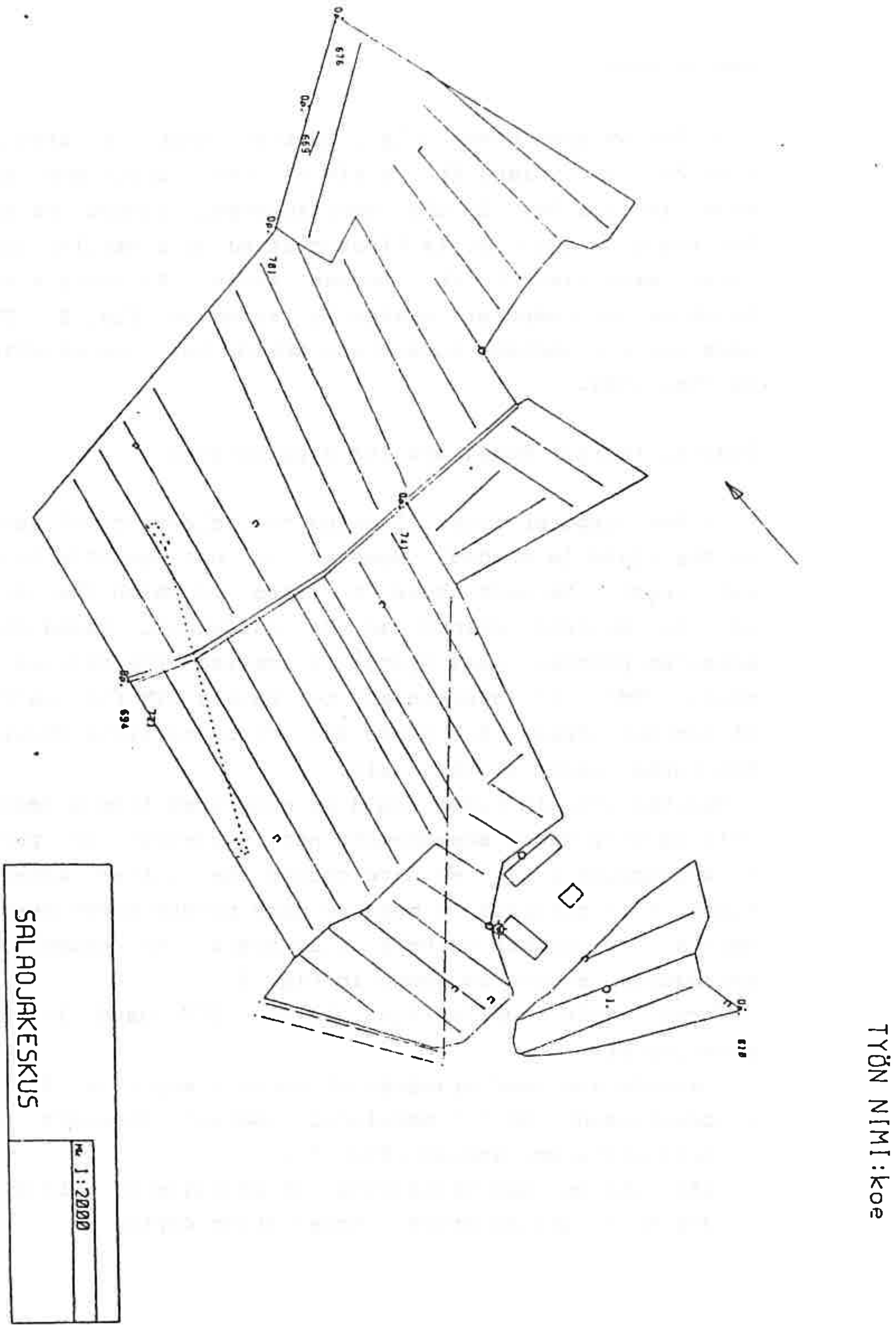


Fig. 2. An example of a map drawn by the computer system.

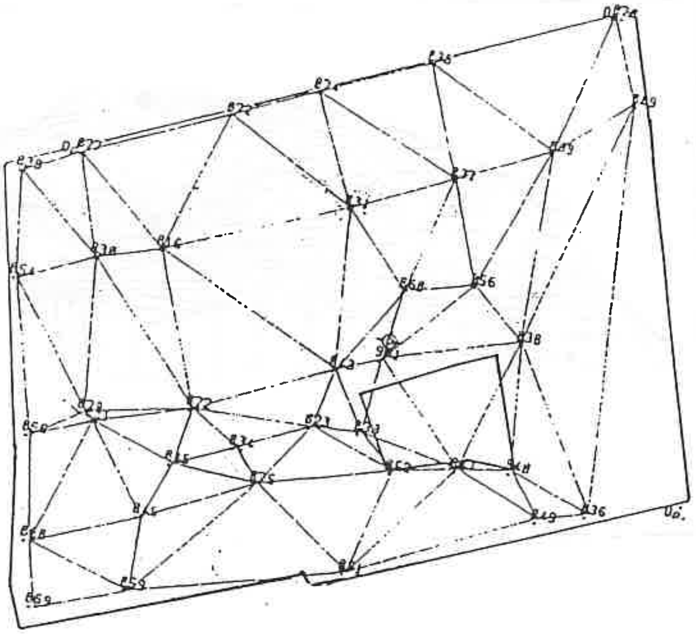


Fig 3. An example of the triangular system used in generation of digital terrain model.

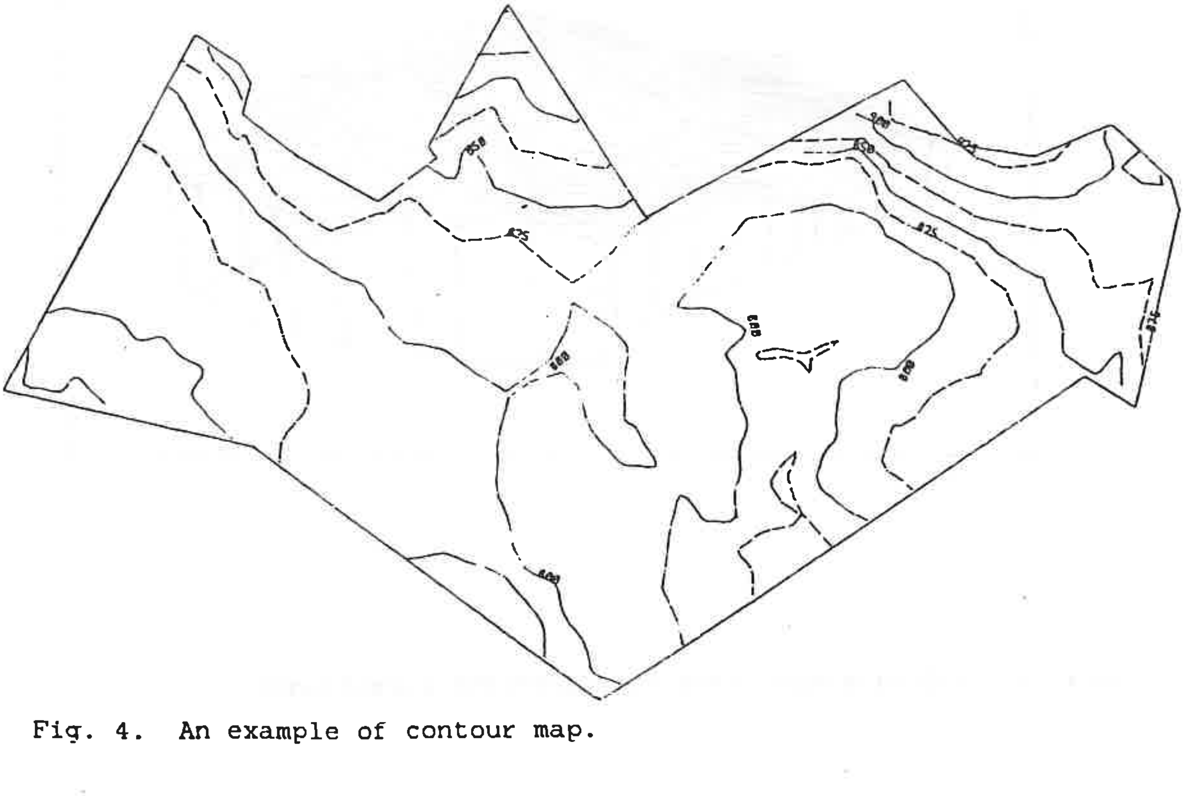
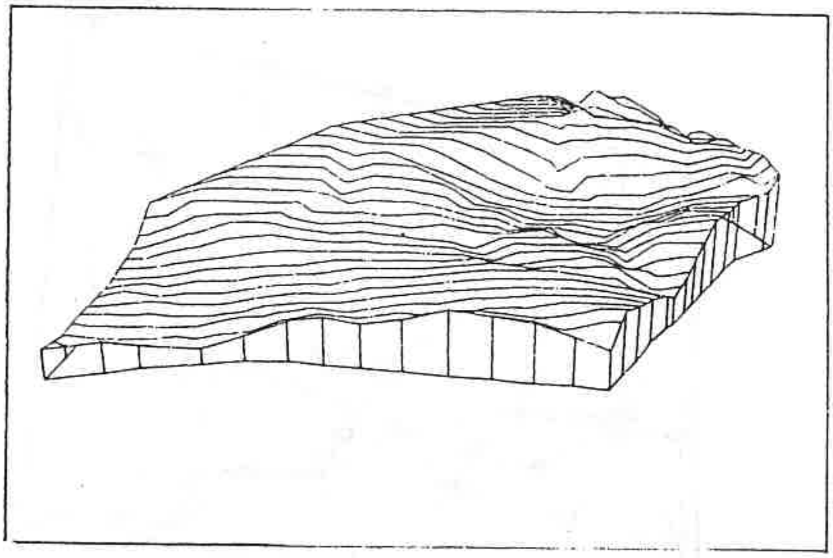


Fig. 4. An example of contour map.



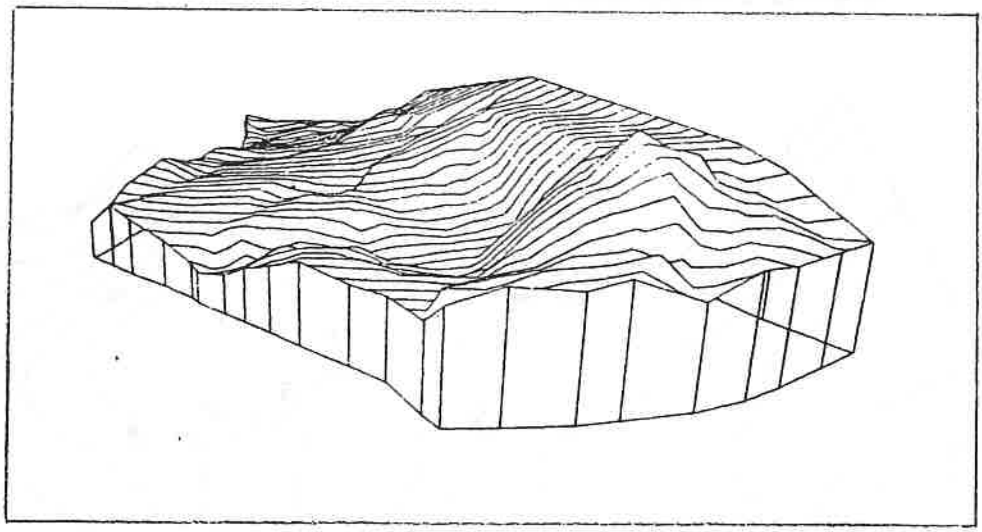


Fig. 5. 3-D displays (from two different directions).

Digitizing of subsurface drains

In the computer aided planning system it is assumed that the designer locates the outlet, mainlines and sublaterals as well as all the wells used in planning. The location is done with a cursor using a "menu" so that the computer system knows what type of information is given. The user "picks" e.g. an outlet from the menu and locates it on the map which is fixed on the active surface of the digitizer. The elevation of the outlet is given. Then the designer shows the main drain from the menu and locates it on the map. The computer suggests a grade and displays automatically the cross-section of the drain on a graphic terminal. The user can change the grade of the drain so that burial depth of the drain is greater than the allowed minimum and smaller than the allowed maximum value. It is also possible to divide the suggested main drain into several parts in cases where the grade is different in each part. The configuration of the drainage system is completely arbitrary. The digitizing of lateral drains can be performed in two basic ways: 1) Location of each sublateral is digitized individually, or 2) Equally spaced laterals can be digitized when drain spacing and the direction of the first lateral are known.

Subsurface plan production

The final sursurface plan delivered to the farmer includes the map, catalogue of pipes required and their sizes and estimation of material and installation costs of the total system. As shown in the flow diagram of Fig. 1, the material needed in the system is collected in a file during the digitizing phase. The computation of the pipe line diameters is based on the data collected in this file. The same file is also used when cost estimate is calculated. This file also includes all wells and other special structures used in planning.

In the next stage the final map is drawn by plotter and all other output data needed by the farmer is printed. After that the plan is archived in digital form (on diskettes).

Computer facilities

The complete computer system must have the following components (in parentheses is listed the currently used equipment by the Drainage Centre):

- computer (Micro-VAX I, and Micro-PDP)
- graphic terminal (2 XK-1 terminals)
- plotter (2 DMP29 plotters, A3)
- digitizer (Calcomp 9000 series, A1 and A3)
- printer (2 LA-100 from DEC)

About 80-90 % of the programs have been made in the Drainage Centre. The programming language used is Fortran.

Experiences, benefits and drawbacks

The first version of the new surveyig technique was tested during summer 1985 . Numerous difficulties were encountered with the coding system and error checking programs. The first error checking program was time-consuming When the number of measured points was about 400, the computation time in Micro-PDP was 3 hours. By making some slight modifications to this part of the program the time could be reduced to a couple of minutes. This was the general trend with the whole system. The newest version of this surveying system has nothing in common with the first version; in fact, everything had to be changed with a much better result. After completing the first version, three technicians have been testing the system and making correction proposals. This interactive way to develop the system has proved to be successful. The technicians are much more interested in accepting new techniques if they can influence actual working procedure in the field. They also know much better than the programmer how the field survey should be carried out. Although progress may be slower with this interactive method, the final system is better and easier to use.

Based on the experience obtained it is already possible to list some benefits of the new surveying technique:

- the more irregular the field, the better the new technique is compared with traditional surveying methods
- differences in elevation have no bearing on the time used for field survey
- the accuracy of the system is high
- computers can be used in map drawing and contour plotting
- testing of new measurement techniques adds to technician motivation

Unfortunately, there are also some drawbacks:

- during field work the technician cannot draw the map (in the so-called traditional method he draws the map during the survey)
- it is necessary to drive to the office almost daily to transfer the data from collector to computer memory (this too takes time)
- in contour plotting the computer is sometimes "blind"

We have not yet enough experience to list all the drawbacks and benefits of the computer aided plan production (dizitizing of drains etc.). Based on the limited experiences obtained so far, it seems that greatest time savings can be obtained in the computation of cost estimate and in making the catalogue of pipes (and their size) needed. This topic will receive more attention at the end of 1986.

However,it is quite obvious that by affecting the mechanical aspects of drainage design (field survey, map drawing, contour plotting, location of drains) the total cost of the drainage system can reduced very little, if at all. The quality of the maps produced by the total station is better due to the fact that more points can be measured where required (the measument net need not rectangular as is the case when "old" methods are used). Because the aim is to reduce the total cost of the drainage system, in future it is equally important to concentrate research on the proper choice of design parameters, especially drain spacing and the drainage coefficient. The drainage coefficient generally used in Finland is 1.0 l/s/ha (= 8.64 mm/d). The potential to use smaller values should be immediately studied.

Future trends

The greatest possible benefit from the technique developed in the Drainage Centre could be obtained if digital data were transferred directly to contractors. Physically this would involve using a diskett containing all information needed (elevation of outlets, grades etc.). A drainage machine equipped with laser-aided depth-control could use this digital data so that marking of drain depth with pegs would eliminated.

More research should be addressed to finding proper drain spacing, drain depth and drainage coefficient. The possible influence of these parameters on the reduction of the total cost of drainage system is most essential.

Conclusions

In the Finnish Field Drainage Centre the applicability of modern computer-based technique in producing subsurface drainage plans has been evaluated. The conclusions drawn were:

1) Field survey can be successfully and accurately performed by an electonic total station and field data collector. The quality of the maps produced by combined use of electronic total station and computer is better compared to maps surveyed by traditional methods due to the fact that all essential points can be measured (restriction of regtangular measurement net is eliminated in the new system).
2) By affecting to the mechanical aspect of drainage design very little can be done to reduce the total cost of the system. In this respect the computer-based system does not offer great savings. More attention should be devoted to finding proper drain spacing and drainage coefficient.
3) The quality of the plan can be influenced in two ways. First, the elevations of the map are more accurate. Second, with the aid of computer-based system it is possible to insure proper installation depth by displaying cross-sectional profiles of subsurface drains.

4) The best possible improvement would be a direct transfer of data from designer to contractor in digital form (on diskettes). This could reduce total costs because marking of drain depth with pegs would then be unnecessary.
5) Interactive working with the programmer and technician in developing the computer-based system proved to be superior. A first version of the system should be completed soon. Following this the users test the system and put forward correction proposals, making the final system better and easier to use. Moreover, technicians are more willing to accept new working methods if they can influence the final computer system.

MICROCOMPUTER BASED DRAINAGE DESIGN: PRESENT STATUS AND FUTURE DIRECTIONS.

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Abstract

Three computer aided drainage design packages are described. The drainage design process can be divided in mechanical (drafting) and judgmental (drain spacing and tile diameter) aspects. The computer software packages were found to be extremely helpful in the tedious and time-consuming mechanical aspects. However, the software did little to help the user with the judgmental aspects of the drainage design. Future improvements are proposed.

Introduction

In 1984 in a lecture entitled 'Are Computers Good for Kids?' Professor Weizenbaum, a well-known computer expert from the Massachusetts Institute of Technology, stated that the new microcomputer technology would make campuses the largest word processing factories in the world and would only be an aid to people when they were used to provide images that otherwise would not be available. The software that is developed to aid in drainage design has partly the latter aim in mind as well as to free the designer from cumbersome and tedious calculations.

Today the situation with microcomputers is in one sense similar to that of mainframes some years ago; that is, once a program has been developed, it can be used in various settings without any modification in the computer code. This is a result of the compatibility between the many microcomputers. The main difference with years ago is that graphics capability has decreased in price a hundred fold and is now available on systems priced below $300.

Drainage design is ideally suited for computer applications: the design is standard and always involves the same steps while the calculations are many and of the same type. The main variable in the design is the topography and type of soil to be drained. Once this has been given, the remaining steps are more or less routine and the computer can take over with a minimum of input from the designer.

Today in the USA and Canada (I am not familiar with what is available in other parts of the world) there are three drainage design packages available. They range from a simple $30 package with limited capabilities to full-fledged computer aided design systems for over $1000. In addition there are several drainage design tools such as DRAINMOD that was developed by Skaggs and coworkers (Skaggs 1979) and is now available through the US Department of Agriculture Soil and Water and Conservation Service.

The objective of this paper is two-fold. First, the identification of shared as well as unique features of the three computer aided drainage design packages. Second, the recognition of the limitations of the current approaches together with possible future improvement.

Computer Aided Drainage Design (CADD) Packages

The three drainage design packages that are discussed are SUBDRAIN (Bottcher et al, 1984), DRAIN(AGE SYSTEM)DESIGN (Kok and Tremblay, 1985) and LANDRAIN (Sands et al, 1985).

SUBDRAIN was the first CADD package for the microcomputer. The program has recently been reviewed by the Northeast Computer Institute (1986) and the following description is based on that review. The use of graphics in SUBDRAIN makes the program very useful for teaching and demonstrations. Based on the topographic features of the field to be drained, the program will compute: mainline configuration, drain spacing, drain diameters, water table heights throughout the field and the total cost of the system. The graphical display includes: 3-D and contour plots of the area, horizontal view of the layout scheme, vertical profiles of each drain line and field locations where the water table is above the design specifications. The design is limited to drainage systems with one main line and equally spaced laterals.

SUBDRAIN allows the designer to overlay several different drainage designs on the same topographical area. The program is quite slow in producing some of the detailed graphical displays; however, no user input is required during this time. Not all of the displays can be saved (but can be regenerated) for review and demonstration at a later time.

The program runs on the IBM PC and most compatible computers using the DOS operating system. It is written in Basic and needs a minimum of 64K of memory. A color graphics board and monitor are required.

LANDRAIN, a cad program for layout and design of subsurface drainage systems, was developed by A B Consulting Company. The program is intended for consulting engineers. The following description of LANDRAIN is taken from (Sands et al, 1985) and LANDRAIN is a part of a larger model called LANDIMPROVE, a microcomputer program for terrain modeling and analysis.

The four design phases of LANDRAIN are: on-screen pipe layout, pipe burial, pipe sizing and design output on maps and in table format. In the on-screen pipe layout phase the program draws the contour map and 3-D pictures from various angles. The contour map is used as a background on which the drainage layout is formulated. Zooming is available. Laterals of any length, spacing and angle can be created to branch from a user-defined main. Laterals are truncated at the field boundary and the field and layout can be rotated.

In the pipe burial routine in LANDRAIN, the drainage pipe is installed from the minimum outlet elevation at the greatest slope possible while keeping the burial depth at all times between the maximum and minimum allowable depth. This process can be viewed in the 3-D mode as it happens. The pipe sizing routine requires equally spaced laterals and the final drain layout can be output on printers and digital plotters.

LANDRAIN has been implemented on a COMPAQ computer with dual disk drives. It is written in Pascal and requires approximately 2 - 3 hours to complete a design for a field of 50 ha with drain spacing of 9 m (Sands et al, 1985).

DRAINDESIGN has been developed by Kok and coworkers at the Department of Agricultural Engineering at McGill University in Montreal, Canada. The package was originally designed for mainframe use but later translated in <compiled> basic and made suitable for use on IBM and compatible microcomputers. This package, intended for consulting drainage engineers may be used for data input and management file manipulation, calculation record keeping, hard copy output, data archiving and map and plan production.

DRAINDESIGN has the following subprograms: 1) Survey data input, output, and correction; 2) Spot elevation calculation; 3) Contour calculation; 4) Hydraulic conductivity data input, output and correction; 5) Hydraulic conductivity and drain spacing calculation; 6) Drain system design calculation; 7) Output in table and map form. The program has many options for correction of faulty data and makes use of a joystick to locate drain pipes graphically within the field. The survey data and water table rise data in an augerhole can be entered as they are collected in the field, Thus not requiring an extra step of calculating the final values. Many graphical screen displays help to visualize the drainage system. Routines are available to draw high quality final design plans on plotters of various makes. Intermediate design steps can be saved

Comparison of Computer Aided Drainage Design Packages

Although there is a wide variety between the computer aided drainage design packages, they all follow more or less the same pattern. Shared phases or procedures between the three programs are:

> Input of field data. Elevation or stage heights are inputted as well as field boundaries.
>
> Translating field data in a map on a graphic display as a a basis for drainage design. Figure 1 and 2 are examples of contour plots and 3-D plots.

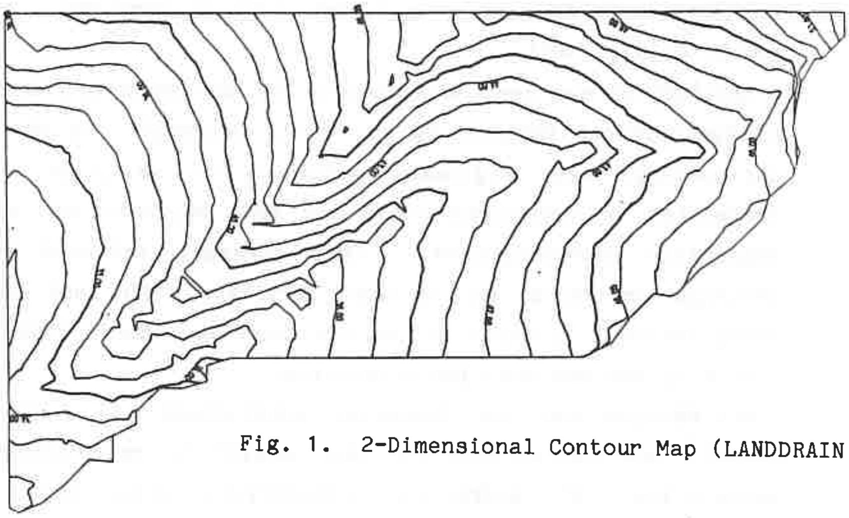


Fig. 1. 2-Dimensional Contour Map (LANDDRAIN).

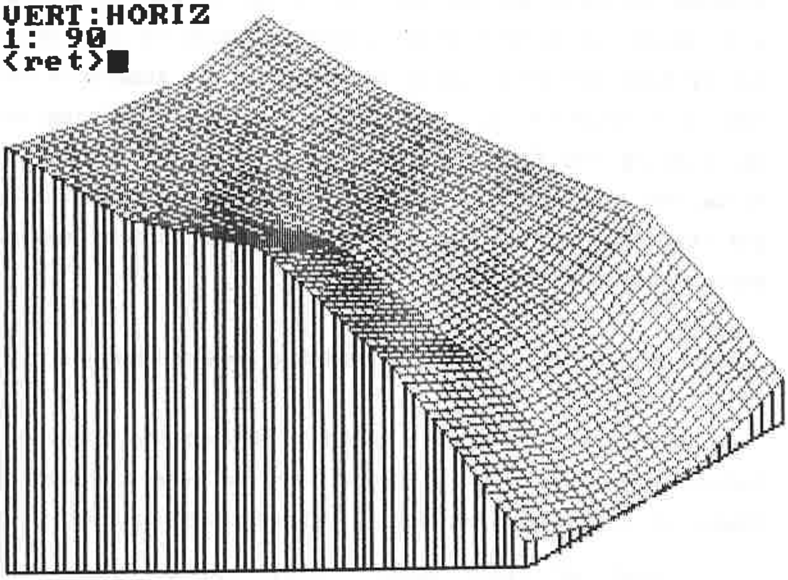


Fig. 2. 3-Dimensional Plot (SUBDRAIN).

Locating outlet, mainline, sublaterals within the field boundaries with arrow keys, mouse or joy stick. Figure 3 shows an example of a finished layout.

Assigning grades (programmed or user input) to the mainline and sublaterals, checking for proper installation depth and displaying profiles of subsurface drains (Figure 4).

Computing tile line diameters based on steady state recharge rate or drainage coefficient. Output is usually given in table form.

Calculating material and installation cost of the total system.

Output of design in a form that can be used by drainage contracters. Figure 5 is an example of the excellent quality of output that may be obtained with DRAINDESIGN.

All three programs are highly interactive and run, using DOS 2.0 or higher, on IBM PC or compatible microcomputers and are written in either Basic or Pascal. The complexity that the various programs can handle is a direct relationship with the price. For example SUBDRAIN ($30) only allows one mainline with a set of sublaterals while the other two programs (over $1000) can have a main line, submain lines, laterals and even sublaterals.

Each program has some unique features. SUBDRAIN will calculate and show design water table depth below the field surface. DRAINDESIGN has the ability to calculate hydraulic conductivities from auger hole experiments and LANDRAIN has the possibility of leveling the surface of the land.

Evaluation of Computer Aided Drainage Design Techniques

In this section the value and drawbacks of computer aided drainage design techniques are discussed. As a baseline for comparison the "draftsman" aided design (i.e., the design technique prior to the use of the computer) is used. In the evaluation it is important to differentiate between the pure mechanical and the judgmental aspects (or designers prerogative) in the design process. The mechanical aspects

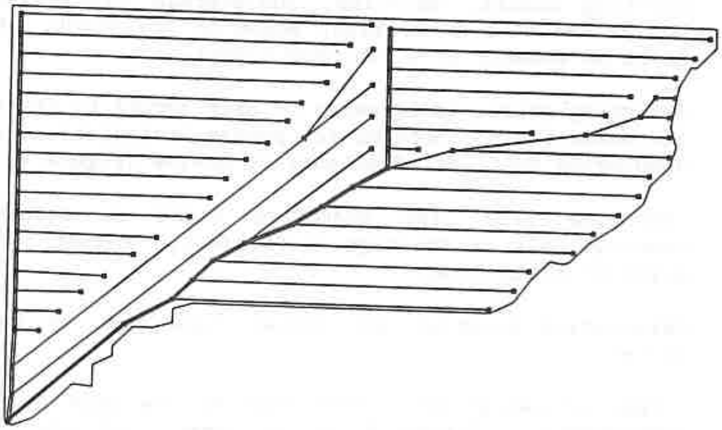
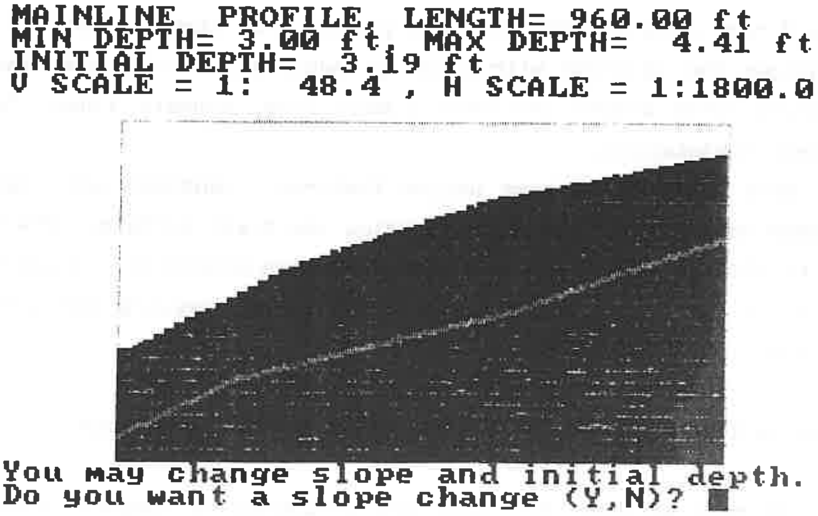


Fig. 3. Drainage System Layout (LANDDRAIN).



```
MAINLINE  PROFILE, LENGTH= 960.00 ft
MIN DEPTH= 3.00 ft, MAX DEPTH=  4.41 ft
INITIAL DEPTH=   3.19 ft
V SCALE = 1:   48.4 , H SCALE = 1:1800.0
```

```
You may change slope and initial depth.
Do you want a slope change (Y,N)? █
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Fig. 4. Cross-section Showing Burial Depth of Drain (SUBDRAIN).

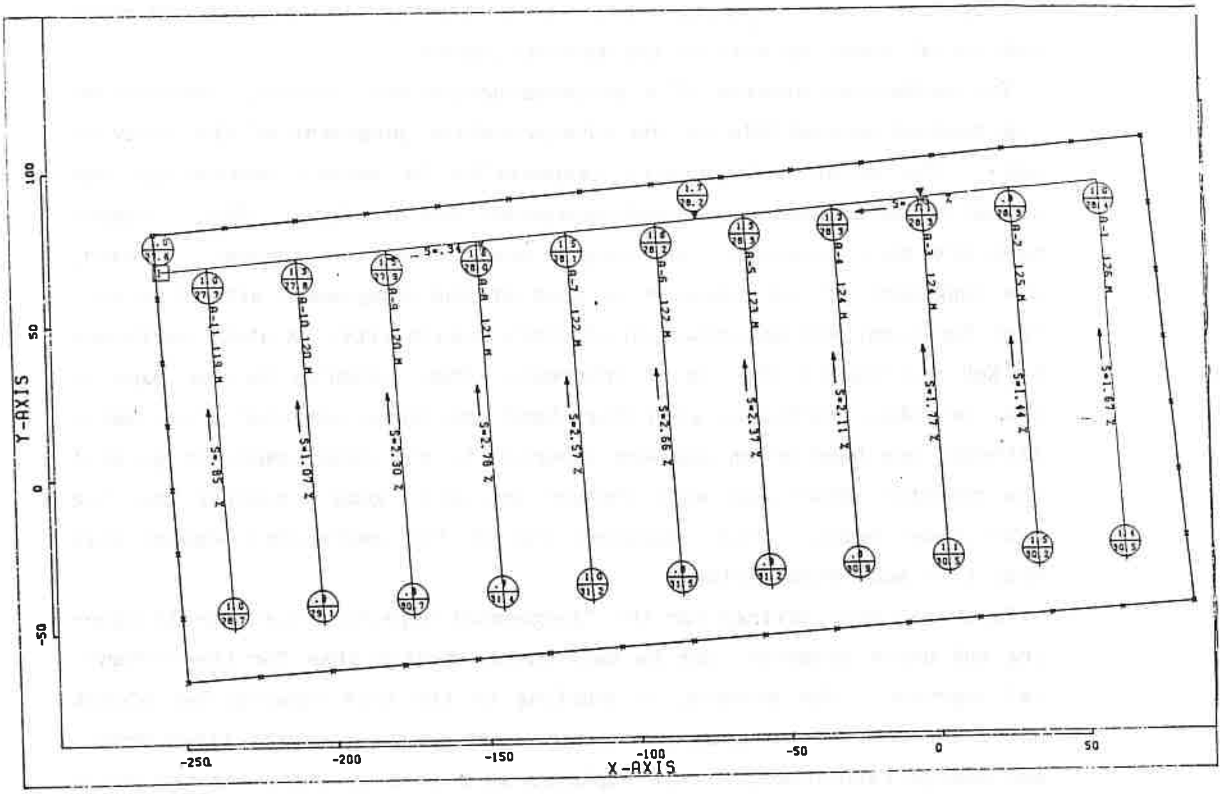

Fig. 5. Drain Plan as Produced by the Plotter (DRAINDESIGN).

consist of drawing contour maps, positioning the tile lines in the field at the proper depth and drawing the final design plans. The designers prerogative are the spacing between tile lines and the minimum and maximum burial depth as well as the general layout.

The mechanical aspects of a drainage design are tedious, time-consuming process susceptible to the interpretative judgement of the individual. The human subjectivity (especially in manual contouring) can either be advantageous or disadvantageous (Kok and Begin, 1981). Computers are more consistent and many times faster than humans. However, the judgement of the computer is that of the programmer without a perfect foresight and anticipation of every possibility. A study performed by Kok and Begin (1981) is of interest. They compared contour maps of real or ideal contours, with four hand and three computer drawn maps. Although one hand drawn map was superior to the other maps, in general the computer drawn maps were cheaper and as of good a quality than the hand drawn maps. Thus computerizing of the mechanical aspect will result in some cost savings.

Potential cost savings for the "judgmental aspects" (i.e., drain spacing and drain diameter) may be many times greater than for the mechanical aspects. For example, a doubling of the tile spacing may almost halve the cost of the drainage system. Yet in the computer aided drainage design techniques, little emphasis is placed on improving the ability to find the drainage spacing. The technique used is the steady state drainage equation. The limitations of this technique is best understood by examining the assumptions on which it is based. These are:

1) impermeable layer at constant depth below the surface and usually horizontal
2) constant recharge rate of 7 mm/day or higher
3) homogeneous soil
4) Dupuit assumptions or energy losses in the vertical direction are neglected

Obviously, these assumptions are only realistic for a very few fields (and these fields probably have drains installed already). Not surprisingly in this regard that in New York State with its shallow, nonhomogeneous and sloping soils (all three in direct contradiction with drainage theory) farmers do not use consulting engineers for drainage design but instead rely on the "experience" of the contractors for spacing and burial depth.

Moreover, the justification of some parameter values is nebulous. For example the origin of the drainage coefficient in the United States has not been very well documented. (At least we have not been able to find it.) The original value of the drainage coefficient of 7 mm/day has been attributed to Hooghoudt who observed that in the Netherlands the drainage rate of a well drained field was 5 mm/day. Hooghoudt added a 2 mm/day safety factor to come to the 7 mm/day. It is likely that the 3/8" (9 mm/day) as used by the Soil Conservation Service in the United States of America is the 7 mm/day used in the Netherlands rounded off above to the nearest eighths of an inch. The half inch as used sometimes carries an additional safety factor of 1/8". These additional safety factors seem to be justified because of the climatic differences between the Netherlands and various parts of the United States. Present research indicate that the 3/8" is justified for North Carolina (Skaggs, personal communication). However, in Upstate New York where the probability of high intensity storms is much smaller than in North Carolina the drainage coefficient of 3/8" is almost two times too high (Steenhuis et al, 1980).

Some of these shortcomings of the drainage coefficients are addressed by the nonsteady state models by Skaggs and coworkers (Skaggs, 1979), Kraaijenhoff van der Leur and many others (for a description of these models see Wesseling, 1973).

FUTURE TRENDS

The mechanical part of the drainage design has been greatly advanced by the computer aided drainage design packages currently on the market and not much improvement in these aspects of drainage design can be expected to occur in the future. The judgmental aspects of the drainage design has not been addressed. Obtaining the correct spacing between tile lines and finding the optimal drain tile diameters can be made easier by combining the nonsteady state drainage models with the current computer aided drainage design packages.

Another improvement needed is that the computer aided drainage design packages models only calculate the cost of a drainage system but also the benefits due to timely planting and improved yields. To do this, a submodel is needed that computes the plant yields with and without drainage for a minimum of 20 years.

The physical parameters that are used for drainage design are subject to measurement errors and variability within the field. If the parameters are not directly measured then we have an additional error due to uncertainty in the estimation. Thus a feature in the computer aided drainage design techniques should deal with the uncertainty of the parameters measured (or estimated) for the field.

Finally, shortcomings in the drainage theory itself need to be addressed so that the spacing calculations can be extended to soils with one or more of the following characteristics: impermeable layers within 1 meter from the surface; soils where waterflow through macro-pores dominate; and finally sloping shallow fields where overland is significant in the drainage of the field.

SUMMARY AND CONCLUSIONS

The present computer aided drainage design techniques are what their name implies: an aid in drainage design. They do not revolutionize nor improve the design itself. They only take the tedious and time-consuming mechanical part out of the drainage design. More work is needed to overcome the present shortcomings in drainage theory and the ability to deal with spatial variability on a small (macro pores) and large scale.

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A METHOD FOR DIMENSIONING OF SUBSURFACE DRAINAGE IN HEAVY SOILS CONSIDERING THE REDUCTION IN POTENTIAL TRANSPIRATION

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Abstract

A method is presented for calculating ground water table and the ratio of actual - to potential transpiration rate for subsurface drainage problem. Non-steady saturated-unsaturated water flow in slightly compressible soils with water taken up by roots is considered. The problem is solved by a Galerkin-type finite element approach. The example of solution is given for the Delta area of River Vistula (layered heavy soil profile) for a growing season during crucial conditions. It was found the crucial conditions appear for wet years. Estimated values of grass dry matter yield versus the spacing between drains are also presented.

Introduction

One of the important questions in the design of subsurface drainage is its dimensioning for layered profiles of heavy soils with anisotropy and different soil materials arranged in arbitrary patterns. Drainage can be recommended for these soils, depends on economic, atmospheric, plant and soil factors.

In order to attain a maximum crop yield drainage must perform specific functions. In spring drainage affects mainly the time of cultivation of soil which determines the time of workable days available for sowing and planting operations. In summer drainage effects on moisture condition in soil profile which in its turn influences on a reduction in potential transpiration. This reduction will cause a depression in crop yield. In autumn drainage effects on yield losses by trampling for grassland or on time of harvest.

From literature are known the models consider all those effects (e.g. Feddes and Van Wijk, 1978, 1984) but they have respect to one-dimensional water flow. In this work two-dimensional model considering the reduction in potential transpiration is presented. The model can be applied to any drainage flow region composed of nonuniform soils which can have arbitrary degrees of anisotropy, with time-dependent boundary- and plant-conditions.

Model description

The problem under consideration, in two-dimensional x-z system, in slightly compressible unsaturated or partly-saturated soils, with water taken up by roots, can be described by (e.g. Neuman et al., 1975):

$$L(\Psi)=\frac{\partial}{\partial x_i}[k^r(\Psi)k^s_{ij}\frac{\partial\Psi}{\partial x_j}+k^r(\Psi)k^s_{i3}]+S(\Psi)-(C(\Psi)+\beta S_s)\frac{\partial\Psi}{\partial t}=0 \qquad (1)$$

$$i,j=1,3$$

where L - a quasilinear differential operator defined in the flow region, $k^r(\Psi) = k(\Psi)/k^s$ - relative hydraulic conductivity, k^s_{ij} - hydraulic conductivity tensor at saturation $\theta = \theta_{sat}$, θ - water content, Ψ - pressure head, $S(\Psi)$ - sink term, $C(\Psi)$ - specific moisture capacity ($C = d\theta/d\Psi$), β - factor ($0 \leq \beta \leq 1$, $\beta = 1$ at saturation, S_s - specific storage which reflects the combined elastic properties of the medium and the water when one is willing to assume that lateral strains are negligible, x_j - spatial coordinates ($x_3 = z$ - the vertical), t - time.

In our case, S - represents the volume of water taken up by roots per unit bulk volume of the soil in unit time. In modeling water uptake by roots one can use several functions which are listed by Molz (Molz, 1981). Among others, one can use the function proposed by Feddes et al., 1978. In our case, extended version of latter extraction function which takes into account additionally the root distribution function versus rooting depth RDF and variable limiting point linearly dependent on the actual value of the potential transpiration rate, is applicated. It can be briefly written

$$S(\Psi) = f\ (\ ET^{pot},\ DRZ,\ RDF, \Psi\ ) \qquad (2)$$

where ET^{pot} - potential transpiration rate, DRZ - depth of the roots, RDF - root distribution function and Ψ - actual soil water potential at point under consideration.

To obtain solution, Eqn. (1) must be supplemented by appropriate initial and boundary conditions, as well as soil and plant characteristics.

As initial condition (at t = 0) the pressure head is specified as a function of coordinates (x_i):

$$\Psi (x_i,t = 0) = \Psi_0 \tag{3.a}$$

or $$\Phi = \Psi(x_i,t= 0) +z = \Psi_0 +z \tag{3.b}$$

Where Φ - hydraulic head, $z=x_3$ - gravitational head.

As boundary conditions one can distinguish between three types:

- Dirichlet condition :specification of the dependent variable, the pressure head $\Psi(t)$,
- Neumann condition : specification of the derivative of the pressure head, which for the soil water problem condition means a specification of the flow through the boundaries q(t),
- 'mixed condition', a combination of both types.

In our problem, the upper boundary condition is governed by the meteorological, soil and plant conditions. Thus, the exact boundary condition to be assigned at the soil surface is not known a priori, but a solution must be sought by maximizing the absolute value of the flux (Hanke et al., 1969, Feddes et al., 1978).

One can notice that Eqn. (1) is a non-linear partial differential equation because the parameters $k(\Psi)$, $C(\Psi)$ and $S(\Psi)$ depend on the actual solution of $\Psi(x_i, t)$. This equation is always parabolic type in unsaturated part and either parabolic (if $S_s \neq 0$) or elliptic type ($S_s = 0$) in saturated part of flow region.

The majority of practical field problems can only be solved by numerical methods. Because of nonuniform flow region having irregular boundaries and arbitrary degrees of local anisotropy, the problem is solved by a Galerkin-type finite element approach. Method of solution is given in literature, for example Neuman et al., 1975, Zaradny and Feddes, 1979, Zaradny et al., 1986.

Computer program has been written in Fortran, the computation was performed on computer RIAD-32.

Example of solution

As was mentioned the model takes into account a local climatological condition as for example precipitation and potential evapotranspiration.

For the Delta area of River Vistula (north part of Poland, latitude $54^o10'$N and average altitude about 0.0 m) it was found that crucial conditions appear for wet years. There is interestic that during growing period (April 1 - September 30), precipitations are often above average value (about 340 - 350 mm). For the last 23 years 1963-1985 twelve years exceed the mentioned value, for example, there was measured in 1970 - 525 mm, 1981 - 475 mm, 1985 - 468 mm, 1980 - 465 mm, 1972 - 450 mm etc. (Zaradny, 1985). From field observations, it is known that for dry conditions investigated area characterized a good crop yield. Similar results have been obtained by discussed numerical model (high ratio of actual to potential transpiration). For wet conditions both results, from field observations and from numerical model, were less satisfactory (wet soil moisture conditions effect negative crop growth and trafficability and workability). Our objective was to find an influence of drain spacing on the ratio of the actual- to potential transpiration (ET^{act}/ET^{pot}).

A grass growing on layered heavy soil profile was investigated for growing season (from April 1 to September 30) for wet conditions.

Values of the potential evapotranspiration and precipitation used in calculation are illustrated in Fig. 1. There are also presented results for 1985 as well as average values for 1963 - 1985 growing season.

Because the model is working for daily values it was estimated:

$$P_d = \frac{P_m}{n_m} \quad \text{and} \quad EV_d^{pot} = \frac{EV_m^{pot}}{n_m} \tag{4}$$

where d, m - indexes for daily and monthly values, n_m - number of days in considered month, P, EV^{pot} - precipitation and potential evapotranspiration.

Boundary condition at the top was found:

$$FLUX = P - INTER - EP^{pot} \tag{5}$$

where INTER - amount of water intercepted on leaves, EP^{pot} - potential soil evaporation.

The potential soil evaporation EP^{pot} was assumed as a function of soil cover (Feddes, 1971) and height of grass (Eagleson, 1970). It was assumed three mowings of grass and that grass needs 20 days to

4

reach its final height and final soil cover.

Part of potential evaporation which effects on evaporative flux by roots was estimated:

$$ET^{pot} = EV^{pot} - EP^{pot} - INTER \quad (6)$$

Estimated values of ET^{pot} and averaged values of precipitation for 24 hours are depicted in Fig. 2.

Soil moisture characteristics and relative conductivities k^r versus water content are illustrated in Fig. 3. For each soil layer was assumed the hydraulic conductivity at saturation $k^s = 0.4\ m \cdot d^{-1}$ ($k^s_{ii} = k^s_{jj}$). Soil layers were arranged in the profile as it is shown in Fig. 4. The impervious floor was found 3.0 m below drain level.

Because of grassland, it was assumed that depth of rooting zone is constant and equal to 60 cm. Depth of 2.5 cm at the top of the profile was considered as non-active roots. The active rooting zone was taken with roots uniformly distributed versus depth.

For each soil layer (1, 2 and 3) sink term S (Ψ) was characterized by certain values of Ψ as it is depicted in Fig. 5. The value of S_{max} (in Fig. 5) was estimated:

$$S_{max} = \frac{0.1 \quad ET^{pot}}{DRZ^{eff}} \quad (d^{-1}) \quad (7)$$

where DRZ^{eff} - effective rooting zone ($DRZ^{eff} = DRZ - DRZ^{neff} = 60 - 2.5 = 57.5$ cm) and DRZ^{neff} - non-active rooting zone.

Limited value of Ψ_3 as in Fig. 5, for the potential transpiration $1.0 < ET^{pot} < 5.0$ mm d^{-1}, was interpolated in the model from formula:

$$\Psi_3 (ET^{pot}) = 400 + 150 (5- ET^{pot}) \quad (8)$$

where Ψ_3 - limited value of the pressure head at which soil water begins to limit plant growth, cm. It was assumed (Yang, de Jong, 1972) the value of Ψ_3 is in fact not a constant but it varies with the evaporative demand of the atmosphere.

Because of some external conditions (fixed depth of open ditches transport the water out of the area) in calculations the depth of pipe drains equal to $H_d = 0.76$ m was assumed.

Calculated values of ground water table for drain spacing L = 10, 20, 30, 40, 50, 60 and 70 m are illustrated in Fig. 6. For the same spacing the values of ratio actual ET^{act} to potential transpiration ET^{pot} are presented in Fig. 7.

From the results one can notice:

- wet July (167 mm precipitation) and wet August (153 mm) were effected on the heights of ground water table for greater spacing than 30 - 40 meters. However, for spacing L = 10 m and L = 20 m the rise of water table was only a few cm for L = 10 m, up to over a dozen centimetres for L = 20 m.
- minimum values of ET^{act} / ET^{pot} range from 0.9 (L = 10 m) and 0.81 (L = 20 m) to 0.18 - 0.10 (L = 50 - 70 m).
- for the first three months of growing season, from computation, the higher values of ET^{act} / ET^{pot} were obtained for greater spacing. If one looks in Fig. 6, one can find lower height of water table for greater spacing, for the same period, that means that for soil, plant and atmospheric conditions under consideration the depth of pipe drain H_d = 0.76 m is too small. Satisfactory depth should be at least 1.1 m if one assumes the pipe drains work for draining and for irrigating, which depend on the ground water table in the immediate vicinity of the drain. This is in good agreement with contemporary tendency of subsurface drainage practice in heavy soils (e.g. Van Wijk, Feddes, 1984, Ivitsky, 1976, Fukuda, 1967, etc.)

From calculated values of ET^{act} / ET^{pot} one can estimate grass yield. According to the formula of Rijtema, 1971:

$$Q = 13.5 \ (ET^{act} / ET^{pot})^2 \qquad (9)$$

Influence of drain spacing L on the dry matter yield (ton ha^{-1}) is presented in Fig. 8.

Ivitsky, 1976, suggests that from the technical and economical point of view the depth of installed subsurface drains in heavy soils should be not less than 1.3 - 1.5 m with spacing L range 10 - 14 m. I think that the problem is much more complicated. The criterion must depend upon the excess of water to be expected, upon soil conditions, crops and the cost-benefit ratio of the drainage system. The benefits of a drainage system are difficult to calculate as drainage effects not only crop yield but also tillage conditions on arable land and grazing possibilities on grassland. For this reason final drainage criteria have generally been established on the basis of field observations and farmers' experience, so the reader does not find in this work "the optimal value of spacing L between the drains" yet.

Conclusion

The presented model seems to be a good tool for estimating effective depth and spacing of subsurface drainage for real atmospheric, plant and soil conditions. The method is recommended for situations for which other, simpler methods (e.g. Dumm, Winger, 1963, Tokzös, Kirkham, 1971, etc.) cannot be used.

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Legend list

Fig. 1. Precipitation P and potential evapotranspiration EV^{pot} during growing season for the area under consideration.

Fig. 2. Precipitation P and potential transpiration roots ET^{pot} as input for wet conditions for grassland.

Fig. 3. Soil moisture characteristic pF (A) and relative conductivity k^r (B) versus water content for soil layers 1, 2, 3 and 4.

Fig. 4. Root distribution function RDF versus depth (DRZ - depth of root zone).

Fig. 5. Function S = $.S_{max}$ for soil layers 1, 2 and 3.

Fig. 6. Calculated ground water table versus the spacing between the drains L.

Fig. 7. Calculated values of ET^{act} / ET^{pot} versus the spacing between the drains L.

Fig. 8. Estimated (according to Rijtema's formula) grass dry matter yield Q versus the spacing between the drains L.

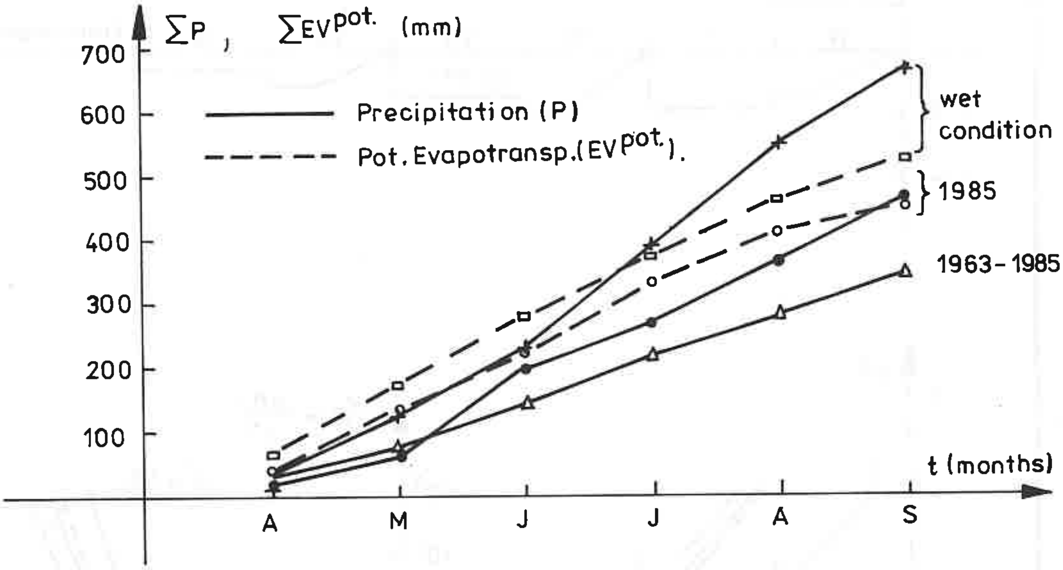
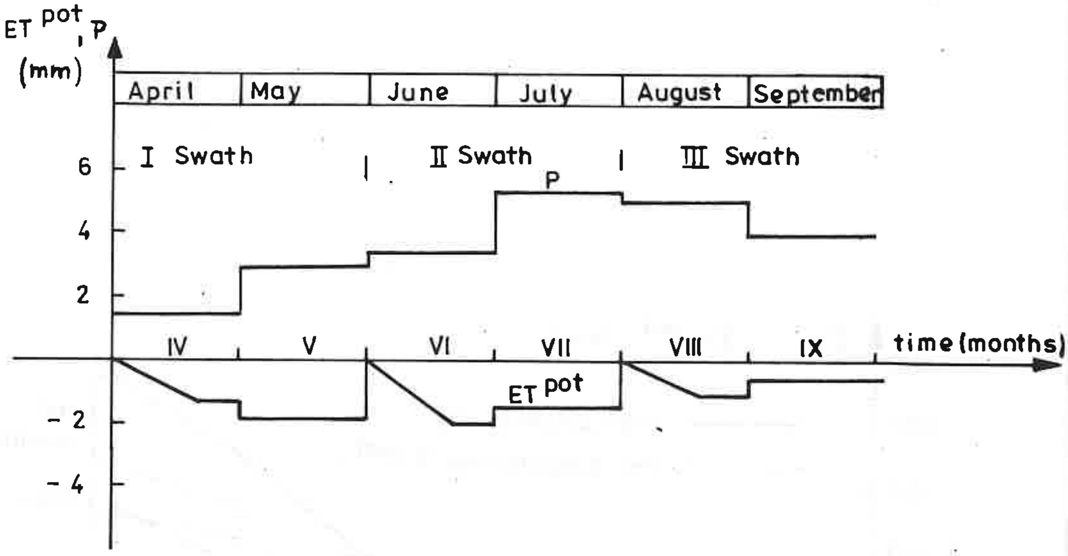
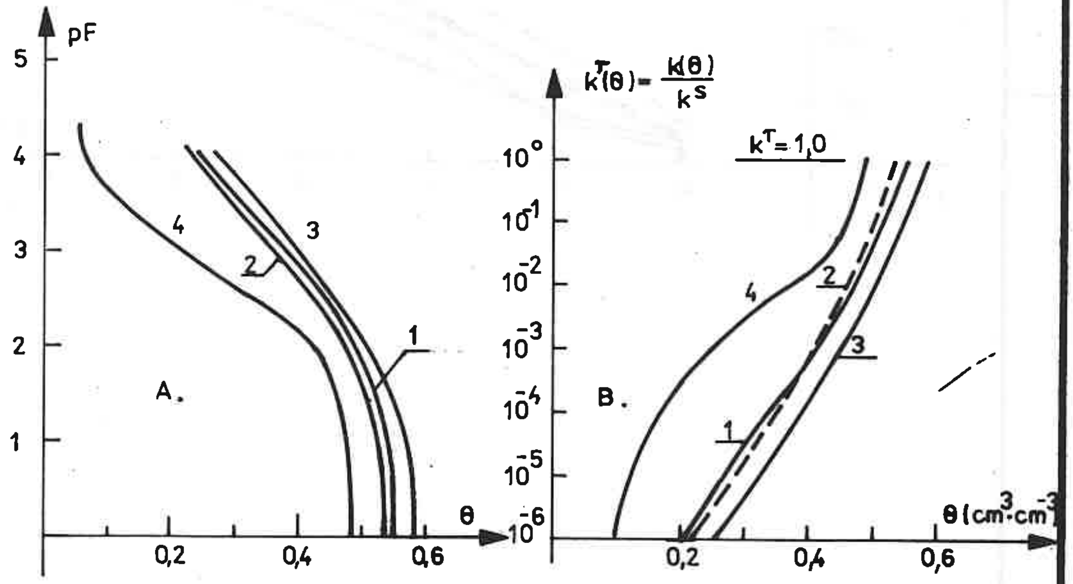

$\sum P$, $\sum EV^{pot.}$ (mm)
700
600
500
400
300
200
100
Precipitation (P)
Pot. Evapotransp. ($EV^{pot.}$).
wet condition
1985
1963-1985
t (months)
A
M
J
J
A
S

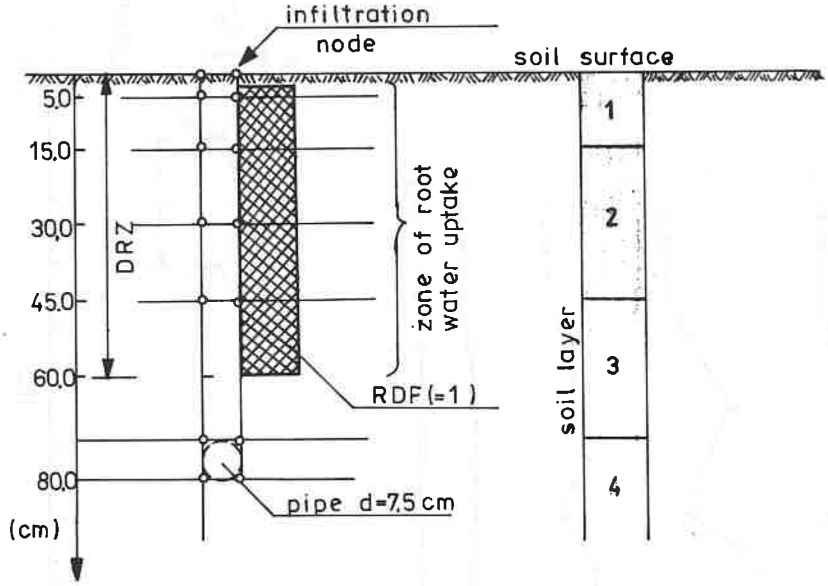
FIG. 4


ET pot, P
(mm)
April
May
June
July
August
September
6
4
2
- 2
- 4
I Swath
II Swath
III Swath
P
IV
V
VI
VII
VIII
IX
time (months)
ET pot

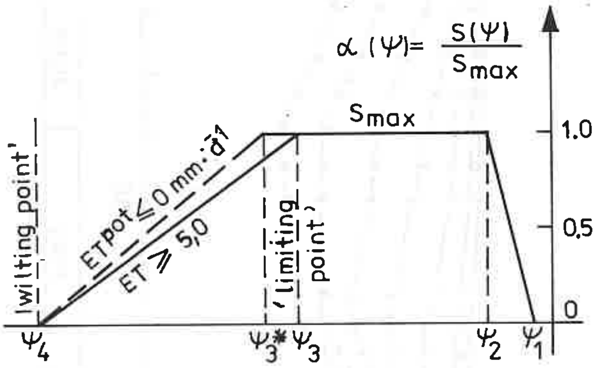
IG.2


pF
5
4
3
2
1
4
3
2
1
A.
θ
0,2
0,4
0,6
k^T(θ) = k(θ) / k^s
k^T = 1,0
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
4
2
3
1
B.
θ (cm^3·cm^-3)
0,2
0,4
0,6

IG.3



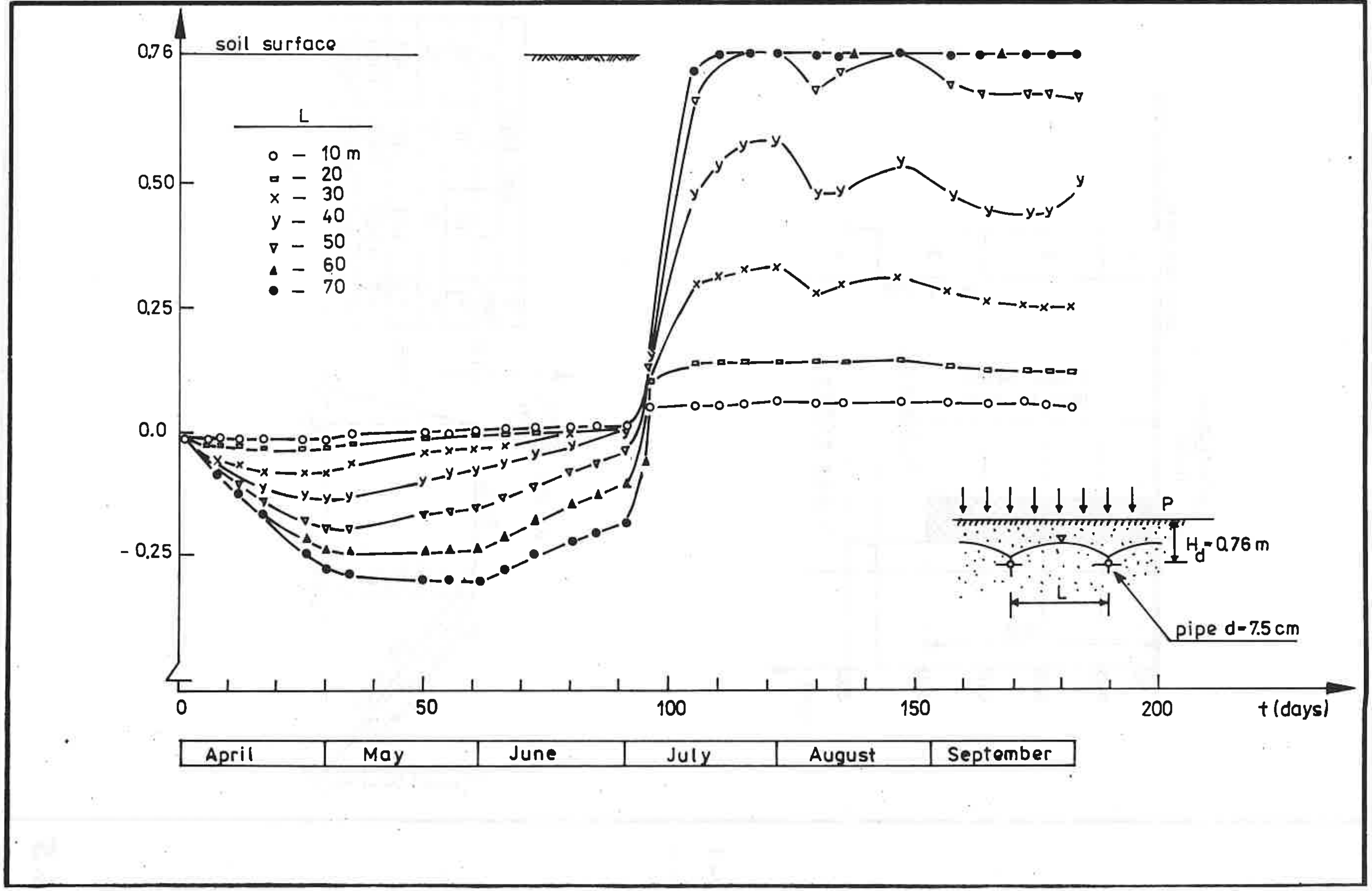
.4



Ψ (cm)	soil layer		
	1	2	3
Ψ_1	10	10	12
Ψ_2	30	30	30
Ψ_3	400	400	400
Ψ_3^*	1000	1000	1000
Ψ_4	15850	15850	15850

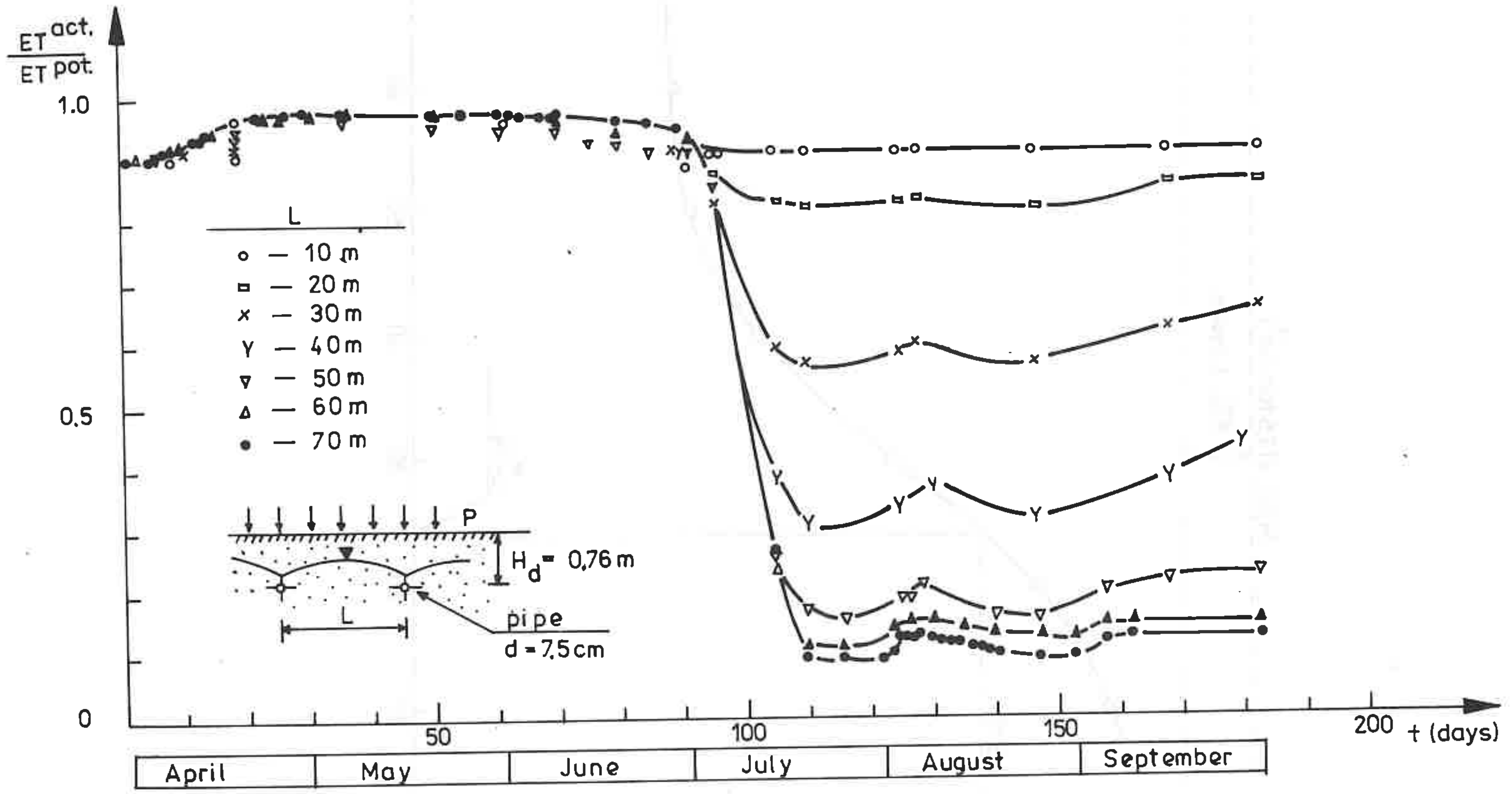
6.5

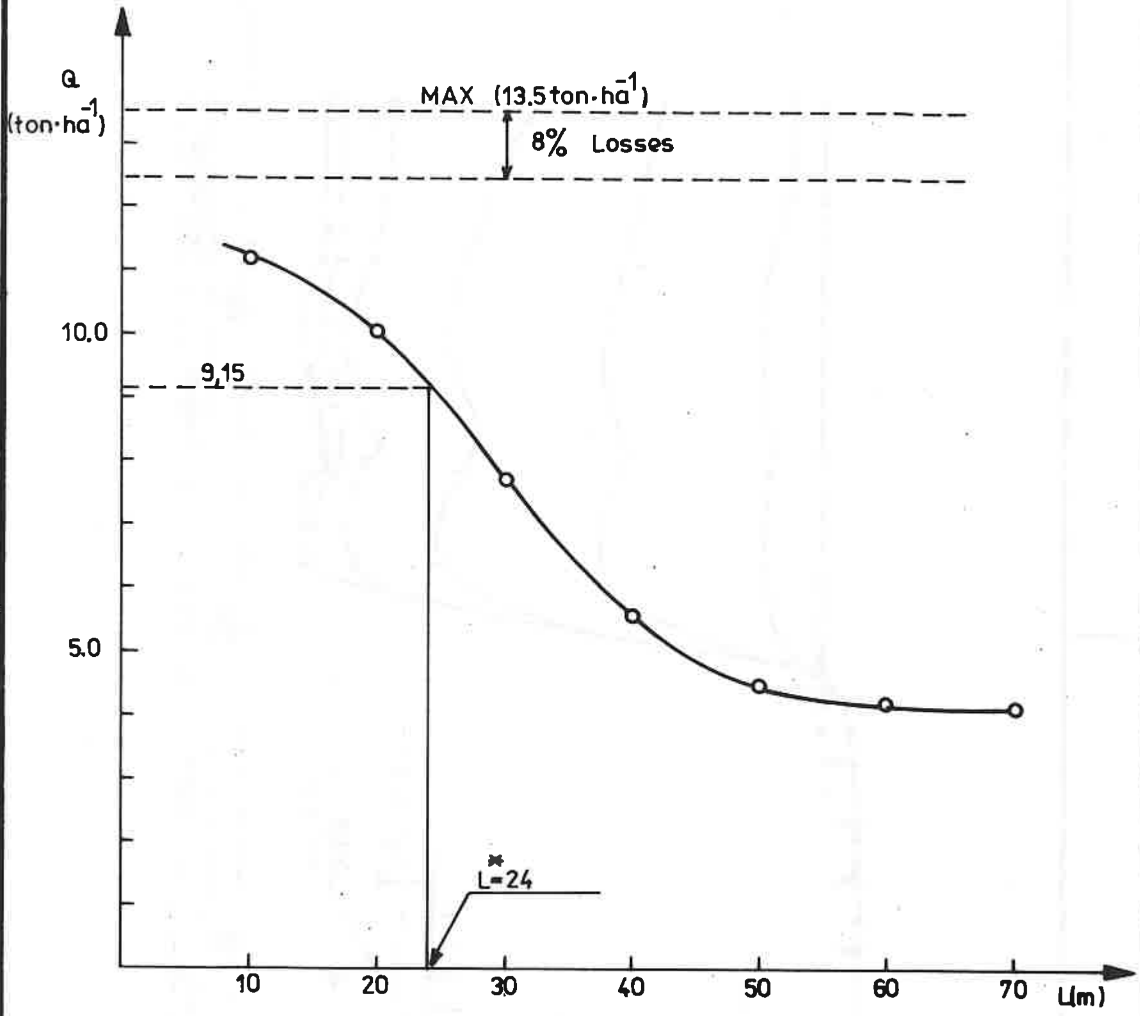
FIG. 6



0.76
0.50
0.25
0.0
- 0.25
soil surface
L
o — 10 m
▫ — 20
x — 30
y — 40
▽ — 50
▲ — 60
● — 70
0
50
100
150
200
t (days)
April
May
June
July
August
September
P
H_d = 0.76 m
L
pipe d = 7.5 cm

FIG.7


$\frac{ET^{act.}}{ET^{pot.}}$
1.0
0.5
0
50
100
150
200
t (days)
April
May
June
July
August
September
L
○ — 10 m
□ — 20 m
× — 30 m
Y — 40 m
▽ — 50 m
△ — 60 m
● — 70 m
P
H_d = 0,76 m
L
pipe
d = 7,5 cm


Q
(ton·ha^{-1})
MAX (13.5 ton·ha^{-1})
8% Losses
10.0
9,15
5.0
L^*=24
10
20
30
40
50
60
70
L(m)

IG.8

THE REASONS BEHIND INADEQUATE DRAINAGE AND SOME METHODS OF SOLVING THEM

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Abstract

The most frequent problems behind unadequate drainage in Finland are the malfunctions due to soil compaction. Disrupting the compacted layer with blind inlets over the existing drains has been a successful and economical method compared to laying new drains between old drains.

The past rainy years have arisen a rather active discussion about the malfunctions in underdrainage. Because subsurface drainage is a fairly large investment even the slighfest doubt about it's reliability will easily make the farmers hesitant. In order to assist the drainage design and to make the function of drainage more reliable a research was started in 1981 at the Department of Agricultural Engineering, University of Helsinki. The object was to find out the reasons which have lead into drainage malfunctions.

Most frequent problems were compaction difficulties, iron ochre and siltation. In most cases (40,3 %) these reasons prevented water from reaching the drains.

Table 1. Percentage distribution of effects of malfunctions in underdrainage.

Water cannot flow through the outlet	3.5 %
Water does not flow in the pipe drain	22.4
Water cannot flow into the pipe drain	15.5
Water cannot reach the pipe drain	40.3
Other	18.3

The most significant problem was the soil compaction especially with clay and peat soils. Therefore in the successive research different methods of disrupting the compacted layer has been studied as an instant amendment. This procedure must be followed by suitable cultivation methods in order to avoid further compaction.

On fields where compaction problems have caused drainage problems following methods were studied:

1. Laying new drains between old minor drains
2. Laying new drains with gravel backfill up to the surface
3. Laying new drains with blind inlets made of gravel
4. Blind inlets over the old drains
5. Trenches filled with gravel

The methods of solving the drainage problems have been on trial on fairly homogeneous and level sites. The subsoil about 25 cm below the surface has most frequently been muddy or heavy clay. On the experimental fields the drainage problems have usually appeared as soon as 2-4 years after the underdrainage has been carried out. Compaction in subsoil as well as in backfill hinder water from reaching the pipe drain, which is usually in perfectly good shape. Drainage problems have always delayed the seeding, causing the crop to ripen later. Therefore harvest becomes more complicated and some of the crop will remain unharvested.

In Fig.1. is shown one of the experimental sites on which different methods of solving the drainage problem were studied. The site includes 16.7 ha which has been underdrained in the mid 1970's. The first drainage problems appeared as soon as 3 years after the drainage was carried out. The minor drain spacing was 16 m and the average depth 100 cm. In order to solve the problem in the drainage system A new minor drains were laid into every second minor drain spacing. In addition blind inlets of gravel were made in 20 meter intervals. In the system B new minor drains were laid in every spacing and blind inlets were used in 20 meter intervals as well. The new systems were carried out in such a way that it was possible to register the drain-flow in the new and old systems separately (Fig.2). In the drainage system C blind inlets of gravel were added over the old minor drains in 12 and 20 meter intervals. The blind inlets were made with an excavator digger and gravel consumption was about 1 m3 per blind inlet. In the systems D and E different sizes of blind inlets were studied. In the drainage system E inlets were laid in 10 meter intervals with the excavator digger as in the system C, in total 47 blind inlets per hectar. In the system D inlets 35 cm in diameter were laid with a tractor mounted post-hole digger. Inlets were made with 5 meter spacing about 100 inlets per hectar and gravel consumption was about 0.1 m3 per inlet. Gravel consumption per hectar was in the system D about 10 m3 and in the system E close to 50 m3.

In the drainage system F about 50 cm deep and 14 cm wide trencheswere laid in 8 meter intervals. The aim was to dig the trenches in straight angle to the old minor drains. Since the work was carried out in summer 1986 there are no results as yet available.

The efficiency of the improvements

The efficiency of the improvements have been studied so far during two growing seasons since the improvements were carried out. Accordingly these results are given by way of reserve because the bulk density in the trenches is still lower compared with surrounding subsoil. During this short period compaction in the trenches and siltation in the blind inlets is not very likely. The efficiency of the drainage systems were analysed by studing the moisture content, drainflow and carrying capacity of the fields.

Drainflows in different drainage systems were not registered continuously during the drying process and the momentarily results are consequently questionable. In an efficient drainage system the drainflow can be very high immediately after a rainfall or melting of snow. On the contrary a poorer percolation rate causes the drainflow to even out for a longer period. The soil moisture content at the seeding represents fairly well the efficiency of the drainage system provided that the soil textures have the same water storage capacity and percolation rate.

Table 2. Average soil moisture content in the studied drainage systems

Date	System	Moist.cont. %	Deviation	Freq.
23.5.1985	A topsoil	32,91 *	2,23	12
	subsoil	33,19 *	0,95 *	12
	B topsoil	31,68	0,49	8
	subsoil	32,61	1,33	8
	C topsoil	30,25 *	1,25	8
	subsoil	30,90 *	1,86 *	8
24.9.1985	A subsoil	35,80 *	2,13	8
	B subsoil	35,71 *	1,69	8
	C subsoil	33,25 **	1,57	8

Soil moisture content in the drainage system D, where only blind inlets were added, was lower than in the systems A and B with new minor drains (Table 2). The difference was statis-

tically significant both in spring and autumn measurements. On the contrary new minor drains did not seem to have any effect on the average soil moisture content. In the system B the moisture content was however more uniform than in the system A (deviations in Table 2.)
Observations made of the drying process in the spring confirmed the results of the measurements. At the harvesting time the carrying capasity of the field A was lowest between minor drains where no new minor drains were laid. Since the blind inlets in the systems D and E were made in early summer, no reliable results are available. These systems will be studied starting summer 1986 in order to confirm the effects of the improvements during a longer period.

Of the improvements, the new complete drainage system with the blind inlets in short intervals seems to be quite reliable when working with mineral soils. Almost as effective are the blind inlets of gravel over the existing drainage system. Twenty meter spacing seems to be adequate since no difference was discovered between 10 and 20 meter spacing. Adding blind inlets of gravel in the existing system will cost about 50 % less than laying a new, complete drainage system. New experiences of gravel filled trenches may rander an even cheaper method for solving less effective drainage systems.

Figure 1. The layout of underdrainage system at the experimental site in Urjala

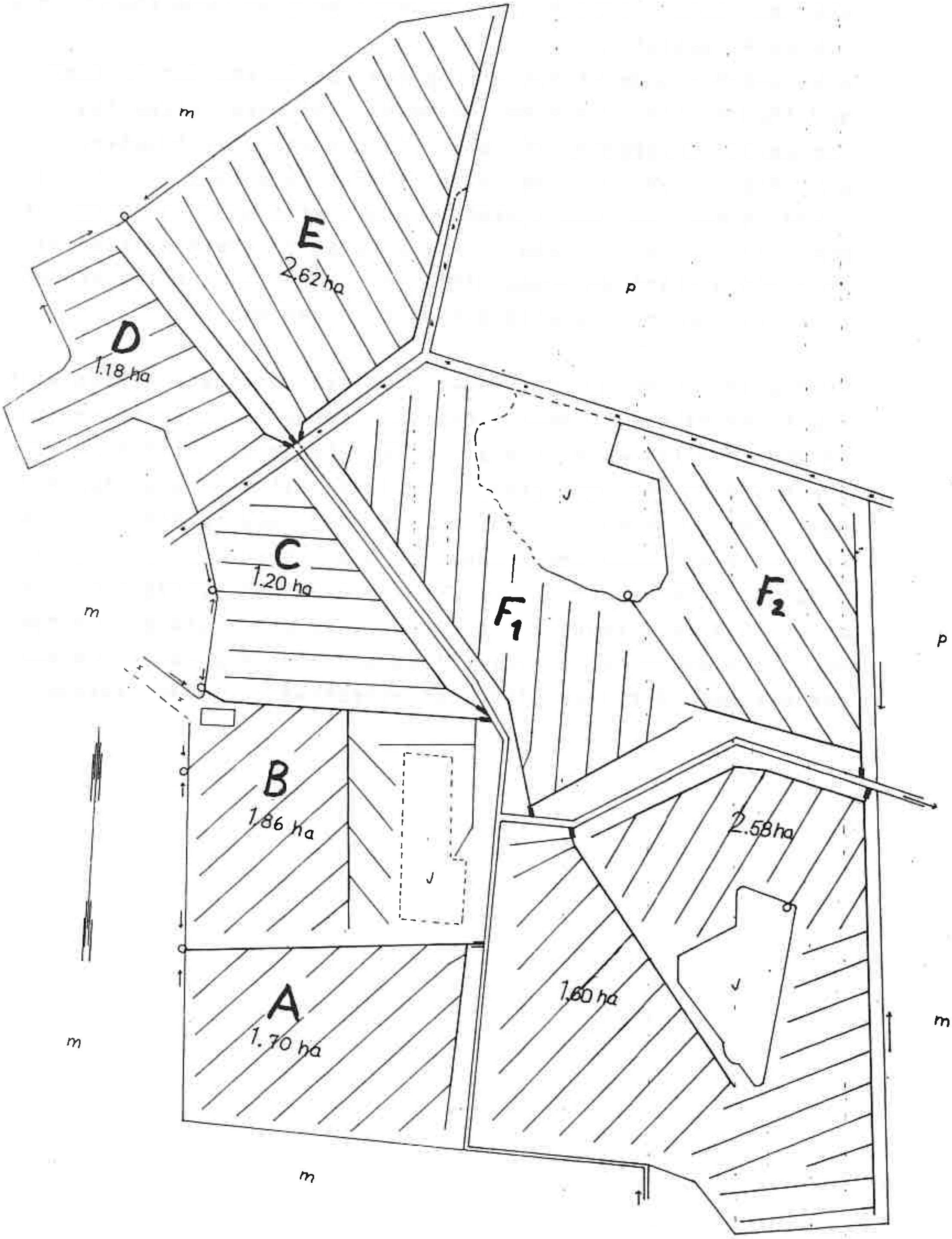
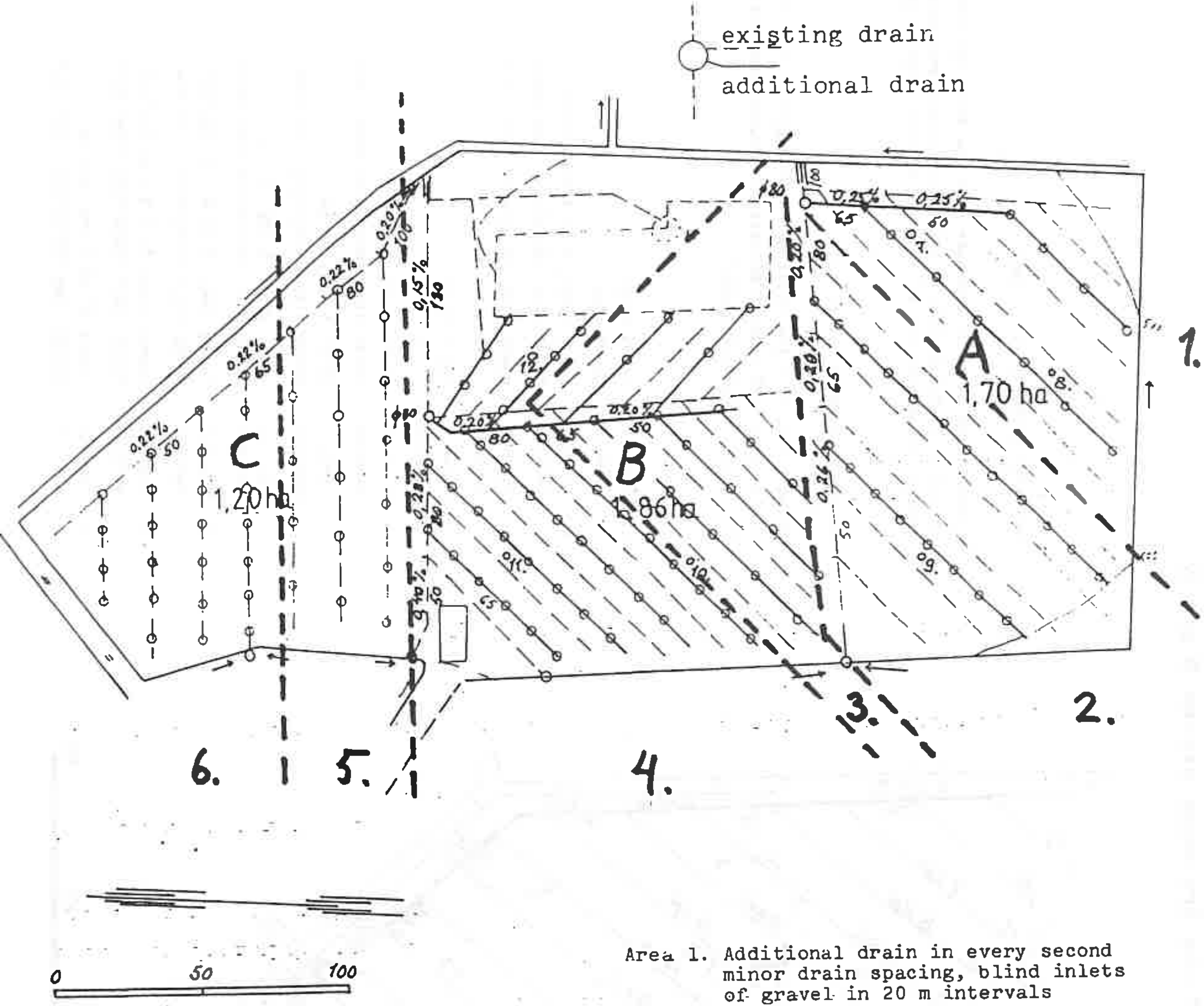


Figure 2. The layout of the drainage systems A, B and C



Area 1. Additional drain in every second minor drain spacing, blind inlets of gravel in 20 m intervals

2. Additional drain in every second minor drain spacing, blind inlets in 12 m intervals

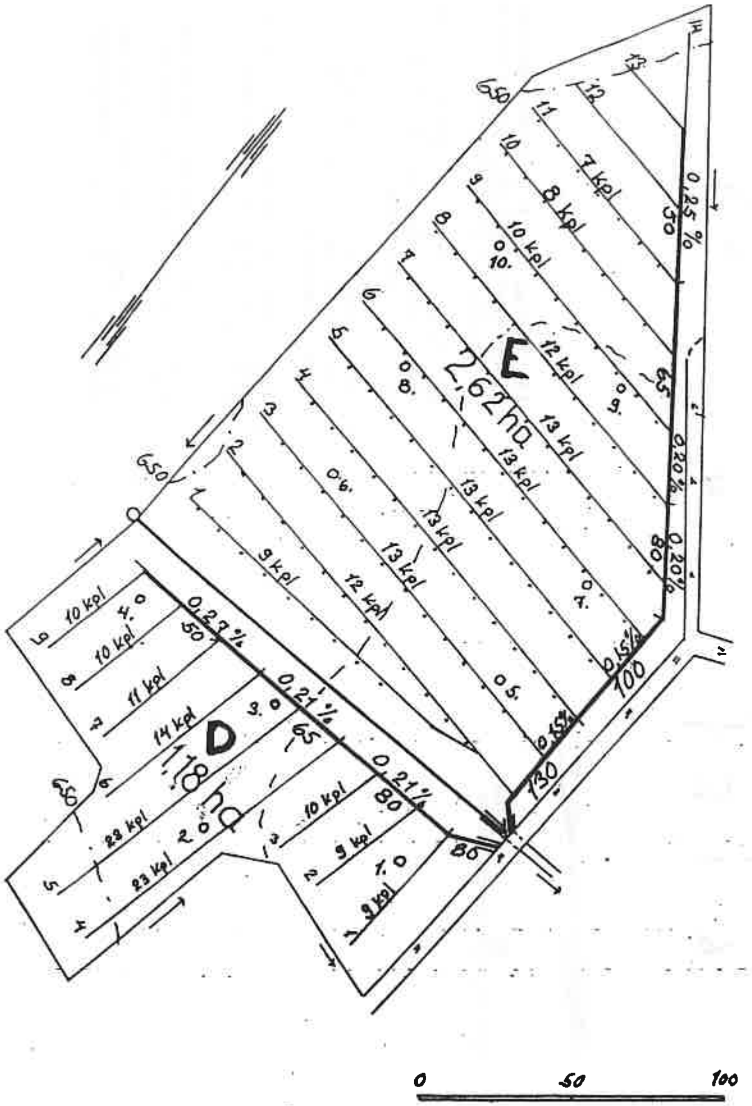
3. Additional drain in every minor drain spacing, blind inlets in 20 m intervals

4. Additional drain in every minor drain spacing, blind inlets in 12 m intervals

5. Blind inlets over the existing minor drains in 20 m intervals

6. Blind inlets over the existing minor drains in 12 m intervals

Figure 3. The layout of the drainage system D and E



DRAINAGE SYSTEM D (1.18 ha)

Blind inlets 35 cm in diameter over the existing minor drains 1 - 9 in 5-6 m intervals, 119 in total (100 inlets per hectar). Gravel consumption 0.1 m^3 / inlet. Tractor mounted post-hole digger.

DRAINAGE SYSTEM E (2.62 ha)

Blind inlets over the existing minor drains 1 - 11 in 10 m intervals, 123 in total (47 inlets per hectar). Gravel consumption 0.8-1.2 m^3 per inlet, excavator digger.

1.	Topsoil	heavy clay
	subsoil	heavy clay
2.	Topsoil	heavy clay, 6-12 % org. matter
	subsoil	muddy clay containing fine sand
3.	Topsoil	muddy clay containing fine sand
	subsoil	"
4.	Topsoil	heavy clay
	subsoil	"
5.	Topsoil	20-40 % org. matter
	subsoil	muddy clay containing fine sand
6.	Topsoil	20-40 % org. matter
	subsoil	muddy clay containing fine sand
7.	Topsoil	clay, 20-40 % org. matter
	subsoil	muddy clay containing fine sand
8.	Topsoil	heavy clay, 6-12 % org. matter
	subsoil	muddy clay containing fine sand
9.	Topsoil	heavy clay, 6-12 % org. matter
	subsoil	muddy clay containing fine sand
10.	Topsoil	clay, 20-40 % org. matter
	subsoil	muddy clay containing fine sand

THE MALFUNCTIONS OF FINNISH SUBSURFACE DRAINAGE

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Abstract

In Finland underdrainage malfunctions, either permanent or temporarly appear in about 5 % of the arable land. The reasons behind the malfunctions are in most cases related to the compaction of the topsoil and to such risks due to the topography, location, and peat soils that are difficult to drain, iron ochre and tendency of siltation which cannot be solved in a underdrainage project of average capital costs.

1. Introduction

The deficient function of the underdrainage system can be easily discovered when the malfunction is severe. As a whole malfunctions are on the contrary very difficult to inspect. The appearance of the malfunctions depend greatly on the momentarily climate especially precipitation, cultivated crop and the cultivation method. Thus the malfunction term is very relative. The same technical deficiency can cause in different situations varying drainage problems.

This paper is based on the study done by M.Sc. Markku Puustinen and the undersigned at the Dept. of Agr. Engineering. In this paper the drainage malfunction has been regarded as a situation where according to the farmer dysplasia or carrying capacity problems in different cultivation phases haveappeared due to wetness. On these premises it has been estimated that in Finland appr. 5 % of the underdrained arable land have either temporary or permanent drainage problems.

The malfunctions in subsurface drainage came into highlight in the rainy summers of the early 80's. At that moment there was no system in the country for clearing the reasons behind the malfunctions nor for solving the discovered problems. At the same time a new underdrainage system, trenchless drainplough, was introduced and the marketing of the coated, so called filter pipes increased rapidly. Thus farmers confidence in Finnish underdrainage systems started to falter. During this situation a research was started at the Dept. of Agr. Engineering, Univ. of Helsinki, in order to verify the reasons behind the malfunctions in the planned subsurface drainage and trough this develop the possibility to solve the discovered malfunctions and to prevent them.

2. The sample of the study

The farms of this study were chosen from the fault reports that the technicians of the Salaojakeskus had received. These 92 farms represented different pipe materials and underdrainage areas in relation to the fault reports. Thus the study had 51 clayware pipe, 31 plastic pipe and 10 drainage systems made of board pipes or different materials together. The material was gathered during 1982 and 1983 and thus the malfunctions (all but one) that appeared represented the traditional underdrainage method. The drainage systems had been laid by continuous trenchers except for 9 older systems dug by hand and had gravel as permeable fill.

The way the problem was approached can be compared to that of a doctor trying to find out what is wrong with the patient, in this case the ineffective drainage system and what has caused the problem. In the study the farmers were intervieved to verify the history of the drainage system and the cultivation methods that could have caused the drainageproblem. In the field study one main drain and one minor drain were dug open. In the test holes the soil structure, drain depth, pipe gradients, percolation rate, pipe size, size and condition of perforation or joints and condition of of the gravel fill were stated. The factors which could have caused problems to the drainage system were estimated on the basis of the trench structure and observations of the surrounding area.

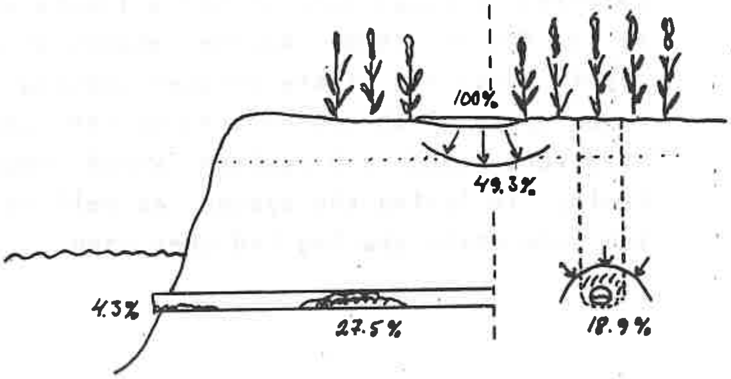
The oldest drainage system had been laid in 1939 and the latest in the previous year. A system with drainage problems was in average 11 years old. The average field size was 4.8 hectars varying from 0.6 to 35 ha. The actual problem area varied as well from a fraction to the whole of the field. In some cases the drainage system has worked effectively and the malfunctions appeared after several years. In other cases the system never worked the way it was planned.

3. The common deficiencies in subsurface drains

Of the 92 drainage systems 459 such faults or deficiencies were found which alone or together cause a malfucntion. On the average 5.0 deficiencies per system were discovered. Thus an inefficient drainage system is a typical consequence of many unfavorable coincidences, a certain kind of multihandicap patient.

When these deficiencies are examined by their influence (Fig.1) it can be discovered that in about half of the cases the underdrainage as a technical system has been in good shape. In these cases the malfunction has been mainly caused by the compaction and the water has not been able to reach the drains fast enough. Wide spacings between the drains and small distance between soil surface and groundwater level are associated to this problem. Thus the topsoil of the field is wet when cultivated and the risk of compaction increases.

Figure 1. The discovered faults and deficiencies grouped by water movements.



The majority of the causes of faults and deficiencies were related to the materials; pipes and gravel filling (Table 1). Typical problems were siltation in the pipes and plugging of the gravel filling, pipe joints or perforation. Breakages of pipes were found only in drainage systems made of boardpipes.

Table 1. The discovered faults and deficiencies gruoped by their appearance

Fault is associated to	Number of faults n	%
Laying the system	109	23,7
Materials	171	37,2
Cultivation	76	16,6
Field	83	18,1
Field location	20	4,4
In total	459	100,0

Faults or deficiencies in average 5,0 per system

The most typical mistakes made during different phases of drain laying were those associated with the trench structure or the leading of surface water. The lack of backfill of topsoil and or gravel were the most typical faults in the trench. This was mostly due to extremely difficult laying conditions where the trench had collapsed before the backfilling of topsoil or even before the backfilling of gravel.

The main reasons of the problems with the surface water were either a total lack of blind inlets of gravel or there were too few of them. Another essential problem was the deficient levelling of the ditches causing surface flow into the lower spots. Problems related to the gradient and the pipe size were found in 9 systems which equals appr. 10 % of the faults in laying the system. As well in 10 cases a clearly too wide drain spacing had been used.

About 65 % of the problems associated to the field involved soil texture. More than half of these were either raw or poorly humificated peat soils to which is characteristic a poor carrying capacity. On peat soils the ground water caused in 9 systems special problems locally. Topographic problems of the field appeared in slope bends or in vast low spots.

The problems associated with the location of the field are mainly caused by the fact that due to the high surroundings or high water level in the nearby waterway the main drain and the outlet have remained too low. Thus the distance between soil surface and groundwater level has remained too small or the water has been unable to discharge through the outlet at all times.

About 3/4 of the problems with the cultivation were related to soil compaction. This problem appeared both on mineral and peat soils. On mineral soils the compaction involves especially clay. On these soils the worst compacted layer was usually immediately beneath the topsoil in the top layer of the subsoil. On peat soils the problem appeared mainly as poor infiltration. Also wrong ploughing direction caused in certain cases (5 %) problems with the water reaching the subsurface drains.4. The reasons behind malfunctions

If the underdrainage is regarded along with other construction activities as a result of human labor input the faults and deficiencies causing malfunctions are also due to mistakes and neglects in different phases. Approaching the problem in this way in appr. half of the cases (51.2 %) the factors causing malfunction derive from planning. Although actual planning mistakes appear rarely. In appr. 16 % of the malfunction cases different degree planning mistakes had been made. In other words actual planning mistakes occur in less than 1 % of the whole underdrained area. On the contrary a much more serious problem is the lack of knowledge during the planning phase. Of the deficiencies in the drainage systems about 35 % involved such situation. The system has been planned according to standard methods although it has not been proven that a drainage system laid by it would work in exceptional situation.

Of the faults and deficiencies causing malfuntion appr. 1/4 (27 %) is associated with mistakes made in different phases of laying the drainage system and appr. 1/5 (22 %) is associated with the cultivation. In this respect the compaction is an essential problem as mentioned before but deficiencies occurred also in the maintenance of the underdrained area. Underdrainage is thus a simillar technical system as other corresponding structures. It also demands maintenance. According to the results of this study the significance of the maintenance has not been fully understood.

As a whole the result of this study emphasizes clearly how important planning is. The planner has to receive adequate information of the site to be underdrained. The research must be able to give to the planning also solutions for difficult conditions such as compacting peat soils, heavy clay with poor percolation rate or areas with iron ochre. This will be clearly emphasized during next few years in our country as laying underdrainage systems will move towards east and north, to areas where previously mentioned exceptional conditions occur more frequently than in the traditionalunderdrainage areas.

According to the results of this study no functional differences between the pipe materials cannot be shown. If there is a tendency of siltation blockages, they will occur as well in clayware pipes, plastic pipes and pipes made of boards although blockages differ in shape. In clayware pipes the siltation is usually at the bottom and in joints of pipes. In plastic pipes it covers the whole inner surface of the pipe. Instead the results indicate that gravel on top of the pipe is not sufficient in all situations. Even in a pipe with proper backfilling of gravel can occur siltation due to the incoming material from underneath. On certain areas filtering materials seem to be necessary even under the pipe.

According to the results no clear relationship was verified between the malfunctions and cultivation methods on the farm. If such connections occurred they could be explained by factor of local conditions and soil texture. The results can be explained so that different ways of normal arable farming (grain crops, grassland etc.) do not set such different demands on drainage system which would make it necessary to plan a system for a particular rotation or on the contrary would restrict the rotation and cultivation methods according to the drainage system. Situations clearly different from normal arable farming such as intensive root crop growing seem on the other hand to set demands on the drainage system that normal a drainage system for normal arable farming does not always fulfill.

The basic reasons of the malfunctions are mainly associated to the location and the topography of the area to be drained, to the poor percolation rate of the soil, to soil texture that is difficult to drain and to certain local problems. The most significant of those are iron ochre and pressurised groundwater.

The greater number of these risk factors exist simultaneously on the area to be drained, the greater the probability of malfunctions seems to be. As mentioned before the planning has not always had possibilities to take these special demands into consideration. The climate has a definite effect on the malfunctions. In rainy summers there appeared clearly more malfunction cases especially if the rainfalls occurred at times when machinery had to be used on the fields. Climatic factors seem to have an effect also on the success of the drain laying. If the drainage system was laid in poor conditions the malfunctions seem to be more frequent because all phases cannot be done carefully enough.

5. The malfunctions can be solved and prevented

Possible methods of solving the afore mentioned malfunctions has been preliminarily studied during the past couple years. For the most common malfunctions fairly simple remedies can be found. Disadvantages of compaction can be prevented by lowering the stress on the soil for example with dual wheels. Adding blind inlets of gravel has also proved to be an effective way of solving surface water problems. Siltation can be removed by rinsing. These are relatively inexpensive choices. An expensive redrainage seems to be necessary only seldom as an solving method. Even in severe cases adding new minor drains seems to be adequate. In order to bring back farmers confidence into underdrainage in Finland a quality-guarantee system has been created. According to it the planner,material suppliers and the contractors guarantee together that drainage system actually performs as desired and these participants agree to solve the malfunctions which appear within guaranteed time. It has been looked forward that this system will prevent malfunctions as laying subsurface drainage in Finland moves to new difficult areas.

DOCUMENTATION FOR THE WATER MANAGEMENT SIMULATION PROGRAM DRAINMOD

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Abstract

A three-year project to develop the design documentation and distribute the water management simulation program DRAINMOD is reviewed. The project was carried out by representatives from seven state universities and two federal agencies. At the conclusion of the project, a workshop was conducted to present the documentation, user's manual and sample program runs and provide an opportunity for participants to use the program.

1 Introduction

Computer programs developed in a research environment frequently need revision, improved documentation and a user's manual to adapt them for Extension program, public agency or industry use. There is widespread interest in the application of computers to drainage and water management system design and analysis among university faculty, agency personnel, drainage industry specialists and land improvement contractors. Researchers have developed useful programs, many of which are on main frame computers.

This paper reports the process of adapting a water management simulation program DRAINMOD developed at North Carolina State University for use in the North Central Region, U. S. (Skaggs 1978, 1980, and Nolte et al., 1985).

2 Situation

The design of subsurface drainage systems has been largely based on farmer and contractor experience and the judgment of engineers, technicians and conservationists. Over the years, these experiences and judgments have been combined with drainage research and soil inventory information to develop drainage guides.

More recently, research has shown wide variation in the drainability of fields with the same soil type (Schwab et al., 1982, Nassehzadeh-Tabrizi and Skaggs, 1983). Soil survey reports also show that a given soil type may have widely varying hydraulic conductivity.

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During the last decade, researchers at North Carolina State University have developed a water management simulation model DRAINMOD (Skaggs, 1978). This model has been tested in Ohio (Skaggs et al., 1981) and other locations. Use of DRAINMOD permits site specific analyses of drainage and water management systems, provided adequate soil and weather data are collected. This procedure is particularly useful for "problem" soils where farming practices have changed soil conditions, to improve drainage guides, and to design subirrigation systems.

The difficulty in 1982 was that the DRAINMOD program would only run on a main frame computer, the reference materials were scattered in research reports, bulletins and journal articles, and no user's manual was available for the program.

3 Approach

The author spent 10 weeks during the autumn, 1981 working with DRAINMOD at North Carolina State University. About the same time the North Central Computer Institute (NCCI) was developed. In January, 1982 the Director of NCCI was approached regarding an Agricultural Engineering Computer Workshop. That workshop was conducted August 18-20, 1982 and included information on how regional computer projects could be conducted. Before leaving the workshop, the author, Carroll Drablos, and Rolland Wheaton drafted a proposal for "adapting the North Carolina State University Water Management Simulation Model (DRAINMOD) to the North Central States for research, extension and resident instruction applications". This proposal was circulated among agricultural engineers interested in drainage at land grant universities in the North Central Region. Engineers from the United States Department of Agriculture (USDA) Soil Conservation Service (SCS) and Agricultural Research Service (ARS) were invited to participate. The two incentives for participation in the project were (1) interest in the subject matter applying the latest technology and (2) the fact that NCCI would pay travel and communication costs to carry out the project.

There was voluntary participation in the project from land grant universities in Illinois, Indiana, Iowa, Michigan, Ohio and Wisconsin; USDA, ARS, Ohio; and USDA, SCS, Ohio and regional offices in Lincoln, Nebraska and Fort Worth, Texas. An advisory committee to the project included representatives from North Carolina, Louisiana and Michigan.

A key to the success of the project was semi-annual meetings of the project team where progress reports were given and assignments were accepted by project team members.

4 Activities

Prior to approval of the project, NCCI sponsored a workshop in April, 1983 at The Ohio State University, Columbus, Ohio, to review its technical feasibility. This workshop provided an opportunity for the team members to become better acquainted with each other, the project, its scope and the potential benefits. This also provided lead time so project activities could be coordinated with other team member activities.

The project was approved in June, 1983. The team activities began with the first meeting August, '83 at Indianapolis, Indiana. The project was initially divided into three tasks and subcommittees were appointed to carry them out. The tasks included (1) installing the software on a main frame computer, (2) preparing a user's manual, and (3) writing the design documentation.

By the time of the April, 1984 meeting at Michigan State University, it was shown that the program could be written in BASIC and run on a microcomputer. This greatly increased the potential for use of the program and created the need to standardize input formats for weather, soils, crops and related data.

At the August '84 University of Illinois meeting, the scope of the project was enlarged to include making the program available on both the microcomputer and main frame computer. The program was in use on three university main frames in the region.

In April, 1985 at North Carolina State University, the final draft of the design documentation and the user's manual were reviewed and approved. It was shown that the FORTRAN language version of the program could be down-loaded to a microcomputer and run directly. This made it possible to offer either the BASIC or FORTRAN language version of the program, which was of particular interest, because the FORTRAN language version included the prediction of a relative corn yield index (Hardjoamidjojo, S. and R.W. Skaggs, 1982).

The final project activity was a workshop to introduce the software and documentation. The workshop was held in August, 1985, at the University of Wisconsin. It attracted 37 participants from 17 states and 2 Canadian provinces. Participants included personnel from universities, ARS, SCS and industry.

5 Accomplishments

A large project team worked cooperatively to make a main frame research computer program available to resident instruction and Extension audiences. In the process, standard formats and terminology were developed for use by universities and USDA agencies. This will ease communication and reduce confusion for years to come. Design documentation and a user's manual were completed and program disks were made available for a microcomputer. Since completion of the workshop in August, 1985, nineteen people have purchased copies of the documentation and the program disks.

6 Current Status

The design documentation for the water management simulation program DRAINMOD and program disks are available from the North Central Computer Institute, 610 Walnut Street, Madison, Wisconsin 53705. The current cost is $25.00.

The program is available in two versions. One is in BASIC and FORTRAN language and estimates water table level, dry days, wet days and soil wetness index values. An error has been discovered in the BASIC program and is being corrected. The second version is in FORTRAN language and estimates a corn yield index in addition to the above factors.

The program runs very slowly on standard IBM PC* compatible equipment with 256K of memory using DOS2.0 or later, requiring about 15 minutes per year of simulation. If the machine has an 8087 math co-processor it will run a year of simulation in 2-3 minutes.

7 Future

Keeping the documentation and program up-to-date as research finds possible improvements is not provided by any currently available university, government or industry organization. That job rests on the collective shoulders (brains) of engineers and scientists concerned with drainage and water management design and analysis.

We have the same need for maintenance of computer programs that we have for drains and roads. We have developed procedures to obtain funding for

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*Use of trade names is for the benefit of the reader and does not imply endorsement or preferential treatment of the product.

new programs, but the need to maintain and update programs is not as well recognized in the budgeting process. It is just as important to maintain useful programs as to write new ones.

As computer programs deal with more complex systems, it becomes more difficult to assemble a team of colleagues to develop comprehensive computer programs at one university. It is essential for future development that funding support be provided for travel and communication to encourage cooperation among faculty of several universities on programs of mutual interest. Such support will help develop more and better programs that will be more widely used.

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TECHNOLOGY TRANSFER FOR CONSERVATION TILLAGE ON POORLY-DRAINED SOILS IN NORTHWESTERN OHIO, U.S.A.

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Abstract

Sediment loss and excessive soil wetness are problems on poorly drained soils in the United States. Conservation tillage systems which are economically feasible can be effective in controlling erosion on these soils. Innovative technology transfer methods are required to insure adoption of conservation tillage by farmers.

Introduction

Soil erosion and inadequate drainage are the two most limiting factors for crop productivity on cropland in the eastern United States. These problems of soil and water management have been known for many years, and were officially brought to the attention of the public in a U.S. Department of Agriculture publication (U.S.D.A. Circular 33) in April, 1928, entitled "Soil Erosion, A National Menace." This gave impetus to the establishment of ten erosion research stations, the Civilian Conservation Corps, the Soil Erosion Service (now Soil Conservation Service) in 1933, and the locally-governed soil conservation districts.

Soil Erosion and Wetness on U.S. Cropland

A National Resource Inventory was conducted by the Soil Conservation Service (SCS) in 1977 to appraise the current uses, conditions and trends of soil, water, and related resources in the United States (U.S. Dept. Agr., 1981). This survey indicated that an average of nearly 4.5 x 1012 kg of soil are lost annually due to water erosion in the U.S. - or an average of 10.5 Mg ha-1 by sheet and rill erosion. The study also indicated that 3.8 million hectares of cropland in the U.S. were losing over 11.2 Mg ha^{-1} of soil per year from sheet and rill erosion.

About 107 million hectares in the U.S. are classified as wet soils, having a potential wetness limitation for use as cropland. Wet soils make up 42 million hectares, or 25 percent of all cropland in the U.S., and are some of the most productive soils in the world with proper drainage and water management. They are generally more fertile, contain more organic matter, have a less serious erosion hazard, and often need less energy input for crop production (U.S. Dept. Agr., 1981).

Soil Erosion and Wetness on Ohio Cropland

Ohio shares the same problems of cropland soil erosion and soil wetness as other states in the eastern cornbelt. The 1977 Natural Resource Inventory indicated that soil erosion is a major problem on 40 percent of the 4.8 million hectares of cropland in Ohio. On nearly 22 percent, or 1.0 million hectares, erosion is occurring at rates above the tolerable soil loss level (T-value). An estimated 269,000 hectares have erosion rates in excess of 22.4 Mg ha^{-1} per year (Ohio Dept. Nat. Res., 1982).

The erosion on the 1.0 million hectares of cropland in Ohio is contributing an estimated 23.6 x 10^9 kg of soil annually. If erosion could be reduced to the T-value (6.7-11.2 Mg ha^{-1} per year) on these acres, soil loss would be reduced by 62 percent to 9.1 x 10^9 kg per year.

An estimated 2.7 million hectares of Ohio's 4.8 million hectares of cropland have a wetness limitation. Further drainage improvement is needed on at least 1.6 million of these hectares for sustained high-efficiency crop production. Crop yields can often be 50 to 100 percent higher on adequately drained soils than on similar soils without adequate drainage.

Soil erosion losses and water quality are also affected by adequate drainage. Studies in northwestern Ohio on selected Hoytville and Lenawee soils showed that 1 1/2 times more water can be removed through tile drains than by surface runoff. Surface water carried 3.3 times more sediment than tile water (ODNR, 1982).

Ten years of data summarized from a 25-year drainage field experiment on Toledo silty clay in north central Ohio (Schwab et al., 1985), showed that quality of water from tile drains was better than that from surface drains. Nitrate nitrogen losses averaged 17.4 kg ha-1 from tile drainage and 11.1 kg ha-1 in surface drainage runoff. Losses during the growing season (April through October) of sediment, total phosphorus, soluble potassium, atrazine, and dicamba were greater in surface runoff than in tile drainage. Only nitrate nitrogen losses were higher from tile flow. Over 58% of the annual losses of sediment and nutrients occurred during the April through October growing season in the north central Ohio studies.

Conservation Tillage for Control of Erosion and Water Quality

Increasing concern in the U.S. about soil erosion and water quality as related to agricultural crop production has caused increasing emphasis on the use of conservation tillage systems as a replacement for the conventional systems using the moldboard plow. Conservation tillage is defined as "any tillage system which reduces loss of soil or water compared to unridged or clean tillage" (Soil Cons. Soc. Am., 1976). The Conservation Tillage Information Center (Ft. Wayne, Indiana, USA) more recently defines conservation tillage as "any tillage and planting system that maintains at least 30 percent of the soil surface covered by residue after planting to reduce soil erosion by water..." (CTIC, 1986).

The development of effective chemical herbicides for weed control and effective conservation tillage planting equipment which permits proper seed placement in heavy surface crop residues have been major factors in the successful adoption of conservation tillage by farmers. Conservation tillage has been shown to be highly effective in reducing soil erosion losses. Especially effective is the use of no-tillage in which all crop residue is left intact on the soil surface and only a narrow slot is opened through the surface residue by a knife or rolling coulter opener for seed placement. No-tillage has been shown in many research studies to significantly reduce soil erosion on sloping soils, often to almost zero. Studies on research watersheds near Coshocton, Ohio using five years of continuous no-tillage for corn (Zea mays) production showed erosion losses on a 7 x 10^{-2} rad slope during the growing season decreased from 4.3 Mg ha^{-1} on conventionally moldboard plowed watersheds to 0.07 Mg ha^{-1} on no-tilled watershed (Harrold et al., 1970). Soil losses can vary greatly from year to year with differences in rainfall pattern. However, as noted in Table 1, conservation tillage or no-tillage provide greater erosion control during years with high rainfall and runoff.

Table 1. Soil loss from conventional (moldboard plowed) and no-tillage watersheds in corn, Coshocton, Ohio, USA, 1964-66 (Harrold et al., 1967).

	Soil Loss (kg ha^{-1})	
Year	Conventional Tillage	No-Tillage
1964	6,377	132
1965	144	0
1966	0	0
Total	6,522	132

Even on level, poorly-drained soils where soil erosion is much less severe, no-tillage has been shown to be effective in reducing erosion and loss of sediment and nutrients in drainage water (Schwab et al., 1985). As shown in Table 2, no-tillage corn reduced sediment losses to about 25% of those with conventional tillage.

Table 2. Quality of tile drainage water as affected by tillage systems for corn on Toledo silty clay in northwestern Ohio, U.S.A., 1969-71 (Schwab et al., 1985).

Tillage System	Average Drain Flow (mm)	Average Annual Losses (kg ha^{-1})			
		Sediment	NO_3-N	Total P	Soluble K
Conventional*	139.7	1143	21.3	0.7	7.5
No-Tillage	157.5	280	17.8	0.6	4.4

* Conventional tillage includes moldboard plowing plus secondary tillage for seedbed preparation.

Since one of the major factors identified as a contributor to the degradation of water quality in Lake Erie was high phosphorus loadings, the U.S. Army Corps of Engineers has intensively studied means of reducing non-point sources of phosphorus (U.S. Army Corps of Engineers, 1979). The adoption of conservation tillage and no-tillage practices were identified by the Corps study as economically feasible methods of reducing potential erosion and associated phosphorus loads into Lake Erie. Therefore, the Corps, U.S. Soil Conservation Service, local soil and water conservation districts, and other agencies and organizations have been strongly promoting and encouraging farmers and landowners to adopt conservation tillage practices.

Much research in Ohio, Indiana, and surrounding states has been conducted on the soil characteristics and factors affecting the successful use of conservation tillage. Three factors have been shown to be critical to successful use of conservation tillage for row crops: (1) successful initial plant stand, (2) weed control, and (3) matching the tillage system to the soil type. Both Ohio and Indiana agronomists recognize that soil properties, especially soil wetness, can greatly affect crop yields under conservation tillage systems, and have developed guidelines to match tillage to soils. The Ohio guidelines classify soil series into five tillage suitability groups based on natural drainage chracteristics, since no-tillage corn production is most successful on better drained soils, but least successful in poorly-drained soils (Triplett et al., 1973).

Most of the soils in the Lake Erie basin in northwestern Ohio and adjacent parts of Michigan and Indiana are classified in tillage Groups 2 and 4 in the Ohio system. Tillage Group 2 soils are somewhat poorly drained and poorly drained soils that normally require drainage improvements for optimum production of crops regardless of tillage. With adequate drainage, crop yields from conservation tillage may equal those of plow-based systems, but without drainage, will have significantly lower yields with conservation tillage. Soils in Tillage Group 4, are very poorly drained, fine textured and relatively high in organic matter. These soils also require drainage, and crops may yield less with conservation tillage than conventional tillage, especially in no-till continuous corn or soybeans. Normally, yields are improved by rotating crops and/or tillage systems, as shown in Table 3. Therefore, research data have shown that, with proper management including improved drainage, a large proportion of the soils in the Lake Erie basin can have crop yields with conservation tillage approaching those of moldboard plowing systems.

Adoption by Farmers of Conservation Tillage Systems

Considerable research data and knowledge have, therefore, been developed concerning the development and use of conservation tillage systems on soils requiring improved drainage in the Lake Erie basin. Because of the growing concern with soil erosion, sediment loss, and water quality in that area, plus the economic benefits in savings in fuel, labor, and time with conservation tillage, it has become important to develop effective means of technology transfer of this information to users. It is important

Table 3. Corn and soybean (*Glycine max*) yields as affected by tillage and cropping sequence on drained Hoytville clay, northwestern Ohio, U.S.A. (Bone et al., 1977).

	Corn Yield (kg ha^{-1})			Soybean Yield
Tillage	Cont. Corn	Corn-Soybean Rotation	Corn-Oat-Hay Rotation	Corn-Soybean Rotation
Plow-Disk-Plant	6648	7025	6899	2383
Plow-Plant	6711	7025	6899	2321
No-till	5645	6774	6836	2321
LSD .05		383		314
Plow-Disk-Plant	8467	8530	8969	2446
Plow-Plant	8404	8718	8844	2572
No-Till	7150	8216	8593	2132
LSD .05		590		220

to understand which methods are most effective for technology transfer, and the factors which encourage or hinder the adoption of conservation tillage systems by farmers on these soils.

Conservation tillage has been adopted on cropland in the U.S. more rapidly than most recent innovations in American agriculture. The U.S. Department of Agriculture estimated that about 2.23 million hectares of U.S. cropland was in no-tillage in 1973, and projected that 62 million hectares or 45 percent of the total U.S. cropland will be in no-tillage by 2000 (Phillips et al., 1980). Another estimate cited by Nowak and Korsching (1985) estimated that from 38 and 51 million hectares were in some form of conservation tillage in 1983, with predictions of from 60 to 100 percent of all U.S. cropland in conservation tillage by 2000.

In Ohio, the use of no-tillage and other conservation tillage for corn and soybeans has also increased greatly, especially in recent years. No-tillage was used on an estimated 40,500 hectares (or 2.5 percent) for corn in 1972 (Triplett et al., 1973), and is now used on over 317,600 hectares, or nearly 19 percent of the land planted to full-season corn in Ohio.

Ridge-tillage, in which the crop is planted on ridges with a height of 100-150 mm with crop residue left in the furrows between ridges, has shown great promise as a conservation tillage technique for corn and soybean production, especially on more poorly-drained soils as in the Lake Erie basin (Eckert, 1981). On poorly drained soils, ridges provide a drier and warmer environment for root and seedling development, and permit earlier planting in the spring season. As shown in Table 4, ridge tillage for both corn and soybeans has shown rapid growth in Ohio in the last three years, largely on soils with poor drainage characteristics. Conservation tillage of all types was used on 46 percent of the full-season corn in Ohio in 1985.

The adoption of no-tillage and conservation tillage for soybeans started later than for corn in the U.S. and Ohio due to the lack of effective herbicides for weed control in soybeans. With the introduction of new weed control materials and post-emergence herbicides for soybeans, the use of conservation tillage for soybeans increased rapidly. Over 100,000 hectares of soybeans were planted with no-tillage in 1985 in Ohio (Table 4), while over 440,000 hectares or 28 percent planted using conservation tillage systems of all types.

According to data from various sources, conservation tillage is being widely adopted by farmers in the U.S. However, a recent study in Iowa by Nowak and Korsching (1985) indicated that estimates on the use of conservation tillage may often be too high. In the Iowa study, only about 26 to 47 percent of the farmers claiming to use conservation tillage were actually using tillage systems that left adequate crop residue cover to qualify as

Table 4. Use of conservation tillage and no-tillage systems for corn and soybeans in Ohio, U.S.A. in 1979-85.

Year	Hectares by Tillage System				
	No-Tillage		Ridge Tillage		Total Area
	Ha (000)	%	Ha (000)	%	Ha (000)
Corn					
1979	82.0	6.0	---	---	1,525
1980	102.2	6.0	---	---	1,575
1981	139.5	9.0	---	---	1,543
1983	157.2	---	4.4	---	---
1984	268.4	16.4	10.2	0.6	1,637
1985	317.6	18.8	13.8	0.8	1,686
Soybeans					
1979	27.9	3.0	---	---	1,485
1980	28.5	2.0	---	---	1,556
1981	30.0	2.0	---	---	1,566
1983	52.3	---	3.2	---	---
1984	95.6	6.5	4.1	0.3	1,477
1985	100.9	6.5	5.2	0.3	1,542

* Data for 1979-81 from: Ohio Cooperative Extension Service Publication MM - 399, "Tillage Practices and Equipment Used in Corn, Soybean, and Forage Production," published in 1980, 1981 and 1982.

Data for 1983-1985 from: National Survey of Conservation Tillage Practices, Ohio County Summary, published annually.

true conservation tillage. Thus, actual adoption of conservation tillage may need careful evaluation before determining appropriate educational and technology transfer programs used by university Extension specialists and conservation agencies.

The adoption of conservation tillage is influenced by three covariables, according to Nowak and Korsching. First, is the degree of development in the technologies making up the conservation tillage system. As discussed earlier, adoption was delayed until adequate tillage and planting equipment and effective herbicides were developed. Especially critical for the adoption of conservation tillage on poorly-drained soils is the development of adequate drainage systems. Ridge tillage and the use of crop and tillage rotation may be other new technologies that will enhance the performance and adoption of conservation tillage on poorly-drained soils.

Secondly, adoption relates to how these technologies are distributed among farmers. The generation and distribution of technologies are different processes, according to Nowak and Korsching. Whereas the generation of conservation tillage technology through research has been innovative, many of the technology transfer techniques to distribute this knowledge to farmers have changed little despite a quickly changing agricultural environment. New methods and systems for disseminating information are needed, with much closer coordination among the agencies involved to prevent confusing, or even conflicting recommendations and information.

The third condition identified by Nowak and Korsching as influencing adoption relates to the socio-economic factors that effect farmer's decisions. These include: social standing in the community, availability of resources, type and profitability of the farm operation, and such community characteristics as available support from conservation organizations, and formal and informal communications networks. Technology transfer methods need to carefully take these factors into account in order to direct the proper type of information in the best manner so as to be most effective. In other words, proper packaging and targeting of information is important if adoption of conservation tillage practices is to be achieved.

Many authors cite surveys and studies noting that most farmers adopt conservation tillage systems for economic reasons, while conservation and environmental objectives are often fortunate, secondary benefits (Nowak and Korschung, 1985). Mueller, et al. (1985) agreed that acceptance and use of conservation tillage depends in part on its economic feasibility under actual farming conditions. They showed in Wisconsin that greater short-term costs for conservation as compared to conventional tillage could be a barrier for farmer's acceptance, but lower long-term costs from reduced machinery and fertilizer costs, along with better timeliness of operations, with conservation tillage makes production costs nearly equal to conventional tillage.

A study of Ohio farmers by Napier et al. (1986) on the importance of environmental concerns in making decisions on the adoption of farm technologies showed that concern about risk-taking was higher among those having environmental concerns. Therefore, educational programs on conservation tillage aimed at this group must focus on reducing risks attached to the adoption of conservation tillage systems. Research on demonstrations showing how conservation tillage can be profitable without introducing more uncertainty into their operation will be necessary. This is particularly true for farmers having poorly-drained soils where risk of lower yields with conservation tillage is a concern, and may give more impetus to the use of promising alternatives, such as ridge tillage on these soils.

Speakers at a symposium on socioeconomic research on soil conservation in Illinois in 1985 (Lovejoy and Napier, 1985) noted that the users of no-tillage tend to be risk-takers (the reverse of the characteristics of those concerned with environmental quality cited earlier), have higher education and incomes, travel more widely, and seek widely for information. However, economic considerations were a major factor used by no-tillage adopters, while environmental and soil erosion concerns were given lower priority. Thus, education and awareness programs are inadequate in bringing about adoption of soil conservation practices where few short run benefits are seen by farmers for their investments.

Farmers are also seeking out new and sometimes wider networks of information sources on conservation tillage. No longer do they look only to traditional agencies, such as the U.S. Soil Conservation Service, Extension Service, or local soil conservation districts, but are increasingly using such sources of information as magazines, input supply dealers, consultants, and other farmers. In a 1978 survey (Kroetz et al., 1979) of farmers in northwestern Ohio on their attitudes toward conservation practices and water quality, 52% of the respondents listed magazines as their most reliable source of information, while 28% preferred individual contacts. Other sources listed included meetings and government publications, with newspapers, radio, and television listed as lower priority sources.

These studies all indicate that future educational programs to transfer technology concerning conservation tillage, especially to farmers with soils having limitations due to wetness or inadequate drainage, will require new methods.

Technology transfer is defined by Krugman and Creighton (1985) as the adaptation of existing knowledge or technology to serve a new purpose, or its adoption and use by a new group of people. This is certainly true for conservation tillage.

One of the most effective organizations for technology transfer in the U.S. has been the Cooperative Extension Service, as an integral part of the land-grant universities in each state. Extension faculty work alongside researchers, (and at Ohio State University are often involved directly in research themselves) to pass on new findings from the laboratory and field directly to farmers and the public for immediate application at the local level. One of the greatest values of Extension programs is to maintain a close communication between the university and society in general.

Traditional technology transfer techniques used by Ohio State University Extension agronomists have emphasized direct meetings with farmers, field days, field demonstrations, and publications. The direct contact by specialists with farmers at meetings, field days and field demonstrations has been very effective, because of the opportunity for interaction and discussion of questions. However, such methods require large investments of travel and time by Extension specialists, and are often inefficient in terms of the number of persons contacted and served. With budgetary and personnel restrictions, more efficient and effective means of technology transfer will be required in the future. New electronic and communications technology offer such possibilities, and are now being used and evaluated by Ohio State University Extension agronomists.

With the assistance of information specialists at Ohio State, Extension specialists initiated the use of two-way audio broadcasts via satellite to local meetings being held simultaneously at several counties throughout the state. Two way telephone linkage permitted question and answer discussion between members of the audience and specialists at the Columbus campus. The audiences at all locations were able to hear these discussions, and feedback later showed this to be a valuable educational experience.

Increased use is being made of video tapes and cassettes on subject matter topics presented by specialists. This permits local Extension or other personnel to present discussions by the Specialists as part of the programs at local meetings without their direct presence. The development of new videodisc technology will also permit the use of interactive video as a new media for instruction in the future. Interactive video links microcomputer equipment and videotape or videodisc devices, with direct learner involvement for effective educational purposes. Interactive video could provide an effective adjunct to traditional instruction in classrooms or meetings by permitting self-instruction at home by clientele on such subjects as selection of proper conservation tillage techniques.

Computers certainly provide a new, potentially powerful means of technology transfer in conservation tillage. Ohio State Extension agronomists have developed software programs on selection of corn and soybean varieties, and soil fertility recommendations for use by County Extension agents on microcomputers in local Extension offices and at educational meetings, or by farmers on their personal microcomputers at home. More emphasis in the future needs to be placed on the development of more software that teaches concepts and interactions, such as tillage-crop-soil interactions, rather than only being a management tool.

Future Extension programs, to be most effective, must also rely more on well-trained and knowledgeable local leaders. This means more emphasis on in-service training of local personnel, and preparation of subject matter teaching materials for them by Extension specialists.

Finally, effective generation and distribution of knowledge on conservation tillage and water management must involve a coordinated effort among all involved disciplines; agronomists, agricultural engineers, plant pathologists, entomologists, economists, sociologists, natural resources specialists, and others. This is being done through a new Program for Conservation Tillage Systems at The Ohio State University. This program will coordinate the research, extension, and teaching activities related to conservation tillage among the various disciplines to encourage the use of an integrated systems approach in developing and conducting research and educational programs in conservation tillage. To encourage wider adoption of the knowledge developed by this integrated program, public conservation agencies and private industry are being included to cooperate with this program through an advisory committee.

In conclusion, conservation tillage systems can be adopted and have been shown to be effective in reducing sediment loss and controlling water quality on poorly-drained soils. Effective integrated research and technology transfer programs must be developed to make such practices economically feasible for such soils, in order for widespread adoption to occur.

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LAND DRAINAGE QUALITY AND DURABILITY WITH REGARD TO METHODS OF PLANNING AND TECHNIQUES OF INSTALLATION

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Contents

1. Abstract

Practical evidence shows that pipe draining sometimes can maintain a perfect function still after more than 150 years. In a period when drainage costs rise quicker than grain prices efforts must be done to improve and preserve the function and life length of land drainage. High quality demands must be put on planning, materials and installation techniques. In small countries (like Sweden) it's a big advantage if the responsibility for drainage directions, planning and staff training is linked to one only national authority - as it is today.

2. 150 years of land drainage life length

Pipe drainage with tiles was first introduced in Sweden about 1830. Some of those drainage systems are still working quite perfect with very few completings. One can make two important conclusions: Already the drainage pioneers knew how to obtain a correct drainage intensity. Precision in installation give prospects for extreme long length of life. Todays average length of life - about 40 years - should be able to extend.

3. Quality and economy

Calculations show that the average cost for land drainage in Sweden is 550 SEK per year and hectare. The influence of real interest (= the difference between bank interest and general inflation) and the time for writing off is shown below. Calculations are made for a total drainage cost of 8 500 SEK/hectare. (8 SEK = 1 USD)

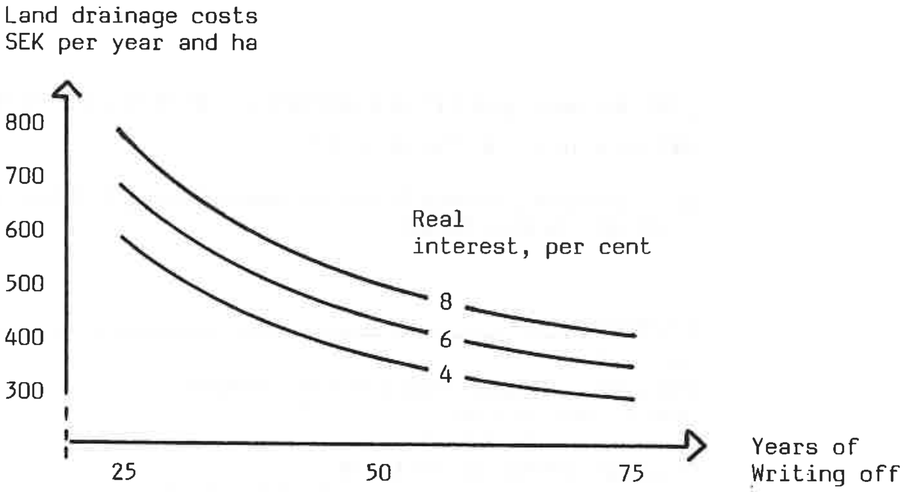

Figure 1. The influence of real interest and period of writing off in swedish land drainage costs.

From figure 1 we ca read that it is profitable to increase the length of life in a drainage project, at least to 50-60 years. The costs for improving quality is normally much lower than the economic benefit obtained.

4. Surveying and planning

Between 10 and 20 per cent of totally 15 000 hectares yearly drained area is performed without planning - or with a plan that exists only in the contractors head. Planning is not compulsory for the single farmer, but land drainage as a longlasting and expensive investment should always be well planned and well ducumented.

A drainage plan has at least three important functions:

- Optimal exonomic output based on demands from climate, soil properties, crops and field traffic.
- Document for making a reliable agreement with a contractor.
- Resisting archive document for the future. This is very important in areas where cables, pipelines and roads can be expected.

New installation methods such as laser-control and trenchless installation, has increased the demands on accuracy in surveying and design.

A standard guide for quality surveying and planning has resently been worked out together with a standard guide for drawing up, for detail-drawings and for sign-interpretation.

Surveying is normally done by terrester, computer-aided, methods. Surveyor and designer should preferably be the same person. Good knowledge in local conditions is essential as also a good cooperation with the farmer. Following minimum demands must be put for a drainage plan:

- The drainage design must be carried out with consideration to the actual soil, climate and plant production and to the expected traffic load.
- Full technical information must be given about positions, dimensions and slopes of pipes, ditches and drainage details.
- Information about filter material and backfilling should be given in the plan or in an enclosed general instruction.
- Enough information about previously existing pipes, cables and other installations to prevent damage.
- Fixed points in height and plane to enable correct setting out before installation.
- The plane must be drawn up in a quality to permit very long lasting documentation. Suitable drawing scale is 1:2 000.

A piece of a normal swedish drainage plan (clay soil in SW Sweden) is reproduced on next page.

5. Drainage intensity criteria

Scientific large scale field experiments has been carried out in different soil and climate conditions since about 40 years ago. Together with a close collecting of practical experience we now have framed some design criteria, among which following can be mentioned:

- In mineral soils lateral pipe spacing vary from 10 to 24 meters depending on soil permeability. Wider spacing can sometimes be used in sandy soils and young organic soils.
- 0.9 to 1.0 meters depth in laterals gives the best economic benefit in mineral soils. The biological optimum is deeper. In organic soils put laterals 0.2 to 0.5 meter deeper, owing to expected soil oxidation.
- Collector pipes should always lay 0.05 meter deeper than laterals.
- The slope of lateral pipes must not be below 1:2 000. In silty soils not below 1:5 000.
- Collector pipes with surface water inlet are calculated for a run off between 1.5 and 3.0 lit per sec and hectare depending on climate, topography and soil properties. Laterals, designed for ground water only, are calculated for a run of between 0.6 to 1.0

lit per sec and hectare.

- In laterals 50 mm pipes can be used to a maximum length of 250 meters.

Above mentioned criteria indicate the big design variation in a country where soil- and climate conditions vary from south to north and from sea level to high altitude mountain valleys.

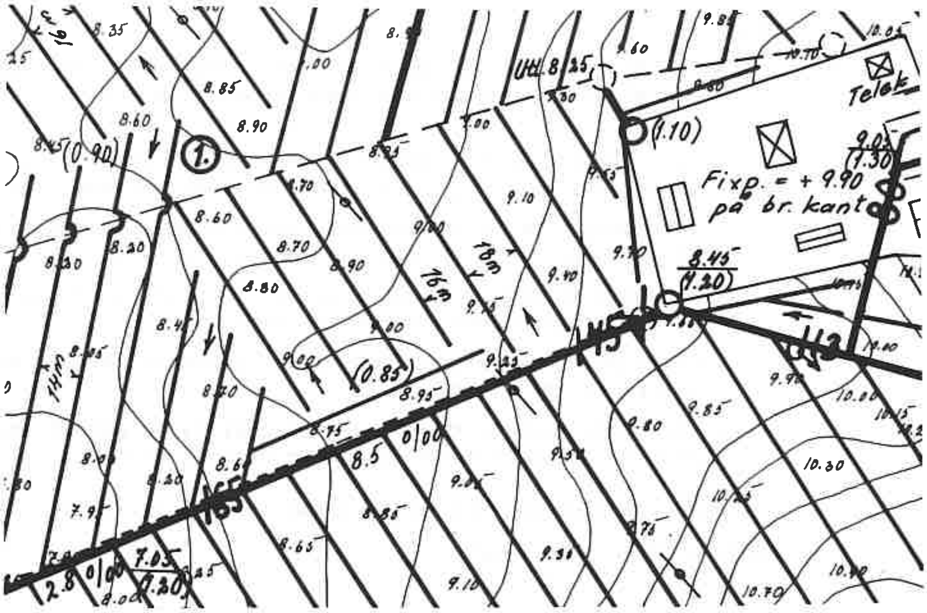

Figure 2. A piece of a normal drainage plan designed for clay soil in SW Sweden.

6. Bad functioning drainage and re-draining

About 50 per cent of all land drainage performed today is redraining. Average age of the older systems is 30 to 50 years.

We are anxious for not repeating the same mistakes that might have been done the first time. In field examinations we have found four major reasons for re-draining:

- Drainage intensity (lateral spacing) is not corresponding to todays demand in drying-up and in heavy machine trafficability.
- Permeability close around the pipes has been lost.
- Soil compaction in a zone from 25 to 40 cm depth owing to heavy traffic in the field under moisture conditions.
- Iron clogging (a difficult problem in local areas).

When designing a drainage plan you should try to look in the future. To prolonge length of life we have found it anxious to think about:

- Design the lateral spacing 10 - 15 per cent closer than calculated from actual demands. A reduction of pipe spacing from 16 to 14 meters will increase the total costs only about 7 per cent but the soil is already prepared for tomorrows demands. It's no risk you will drain the soil too dry.
- Filter materials with big volumes and high permeability (e.g. gravel) will allow the pipes to function efficiently for very long time. Filter properties are essential to life length in drainage and good filters are allowed to be expensive - up to 30 per cent of the total lateral drain costs.

7. Pipe material standard and drainage quality

The national Board of Agriculture is authorized to approve pipes which are produced according to a standard act. That act describes dimensions, water inlet capacity, tenacity and some handling properties of pipes and fittings. The act has given an important contribution to the high quality pipes, that now completely dominate our market. Corrugated pipes can be approved in 8 different dimensions from 50 top 210 mm and with water inlets in three different classes, from 1.0 to 2.7 mm width.

8. Installation techniques and drainage quality

After a short period of hesitation and field examination we now know that laser-controlled depth-regulation and trenchless installation both give quite acceptable drainage accuracy. Our standard act for installation works has recently been modernized with higher demands in accuracy - which was accepted also by the contractors.

9. Organization and training of planning staff and contractors

Well functioning and long lasting drainage can be achieved only with well educated planning staff and contractors. Planning should preferably be (as today) organized by one reliable organization or authority. Education must be carried through in close cooperation with scientists from universities and field experiment stations, with contractors and with pipe and machine producers.

EXPERIMENTS WITH DRAINAGE MATERIALS AND SUBMERGED DRAINS ON OCHREOUS SITES

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Abstract

Experiments with field drainage on ochreous sites showed that the problems of ochre clogging of perforations were minimized by using drain pipes with large perforations (up to 3.0 mm). The choice of filter material was less important on the experimental site - a fine sandy soil with small content of clay and organic material and high hydraulic conductivity. By submerging the drainage system the rate of ochre formation decreased in some cases.

1 Introduction

Precipitation of ochre in drainage systems is a big problem in connection with many drainage works. The drains, the water entry points and the filter material will block up and the drainage efficiency will decrease. Regular cleaning by high pressure jetting of such systems is needed. The ochre problems arise when the drainage water contains soluble ferrous compounds. Ferrous-rich drainage water can either be due to pyrite containing soils or to seepage of ferrous ground water.

When draining pyrite-rich soils, oxidation of the pyrite will produce sulphuric acid and iron sulphates. In case of low oxidation potential, ferrous sulphate will be produced, and if the oxidation potential is higher, ferric sulphate will be formed. The ferrous compounds are soluble under the pH conditions normally found in soils and drainage water. Ferric compounds, however, are only soluble when the pH is low (<pH 3.0-3.5); at a higher pH they will precipitate as ochre in the soil. When the soluble ferrous compounds reach the drainage system, ferrous iron can be oxidized to ferric iron and precipitated as ochre.

2 Anticipation of ochre problems

When planning drainage schemes on ochreous sites precautions should be taken to minimize difficulties.

Drain pipe: Previous experiments have shown that it is important to use pipes with large water entry points, i.e. oversize perforations in plastic pipes and open joints between clay tiles lines (Andersen, 1976; Talman, 1972). When selecting pipe size, it is also important to make allowance for a reduced diameter due to ochre deposition in the pipes.

Filter materials: It is generally accepted that thin mesh filters for sand exclusion should be avoided on ochreous soils since they block up easily with ochre. Also, it is known from practical drainage works that some of these filters, e.g. fibertex, cannot always be jetted clean. Voluminous organic filters such as sawdust, straw, coconut fibre etc. are believed to resist blocking longer due to their gradual decomposition. In Denmark it is recommended to backfill drains on ochreous soils with sawdust. In Germany special ochre-preventing pipe envelopes have been manufactured which consist of an organic filter retainer, such as straw, and chips of bark from mimosa and oak species (Kuntze, 1972). The bark fragments release chemicals which combine with dissolved iron preventing its oxidation and keeping it in solution. In Denmark, however, this filter wrap did not prove efficient on a soil with severe ochre problems (Andersen and Waagepetersen, 1985).

Submerged drains: Permanently submerged drains will have low oxygen availability and in theory reduced ochre formation rates. In Finland submerged drainage systems are widely used on soils with ochre problems (Mäenpää, 1974, 1977). In Germany, however, Kuntze (1968) found very little effect on the ochre formation by submerging the drains. From Denmark no previous experience on submerged drains has been available.

It is evident that there is still a need for further investigations on the suitability of various drainage materials and methods on ochreous soils. The present experiment aims at clarifying how drainage of these soils can be carried through in order to postpone the time of jetting the drain pipes as long as possible. The main points of the experiment are outlined in this paper whereas a more detailed description is given by Grant and Andersen (1985).

3 Experimentation

3.1 Soil conditions

The experiments were carried out on an ochreous low-laying soil at Ulfborg in West Jutland. The soil consisted of 30-50 cm of peat on top of fine sand. The hydraulic conductivity was high, about 0.1 m/h. Before drainage, the peat and the sand layers contained 0.2-4.9% and 0.04-0.2% of pyrite, respectively. There was a heavy inflow of ferrous ground water to the area. The drainage water contained 15-50 mg/l of dissolved iron.

3.2 The experimental lay-out

The experiments were conducted on three sites using the following experimental variables: drain perforations (Ulfborg II), filter materials (Ulfborg II and III), and submerging of drains (Ulfborg I, II and III).

Ulfborg I

This site was drained in 1971. The drainage depth was about 110 cm, the pipe slope 0.3%, and the drain spacing 18 m. There were 2 plots each with 3 PVC pipes (diameter = 85 mm, perforations 0.7-1.5 mm) and 1 clay pipe (diameter = 80 mm); all drains had non-woven sheet filter envelopes. After jetting in 1978, the drains of one plot were submerged by raising the outlets 30 cm by means of S-shaped bends.

Ulfborg II

This site was drained in 1976. The drainage depth was about 110 cm, the pipe slope 0.2%, and the drain spacing 20 m. All drains consisted of corrugated PVC pipes (diameter = 80 mm). The following drainage materials and submerging of drains were tested.

Perforation size: There were 2 pipes with 1.5 mm perforations, 5 pipes with 3.0 mm perforations and 3 pipes with one line of 5.0 mm circular holes, the remaining perforations were 3.0 mm. These drains had non-woven sheet envelopes.

Filter materials: Three types of filter materials were tested (i) the hydraulic envelope, Filtan (sheet filter + a peat layer) (2 drains); (ii) the non-woven sheet filters, Fibertex (100 g/m²), CH 100S (100 g/m²) and CH 200 (200 g/m²) (8 drains); and (iii) three woven sheet filters (mesh size 0.03-0.5 mm) (5 drains). The perforation size of these drains were 3.0 mm.

Submerging of drains: Three submerged drains were compared with 5 normal drains. The submerged drains were placed 30 cm deeper than the normal drains, but the outlets were raised 30 cm by means of S-shaped bends. These experimental drains had 3.0 mm perforations and non-woven sheet envelopes.

Ulfborg III

This site was drained in 1980. The drainage depth was about 120 cm, the pipe slope 0.2%, and the drain spacing 18 m. All drains consisted of corrugated PVC pipes (diameter = 80 mm) with 2.7 mm perforations. At this site three filter materials and submerging of drains were tested:

Filter material: One non-woven sheet filter, Typar (68 g/m²), and two hydraulic envelopes, sawdust and Aqua (polypropylene), were employed. There were 4 drains with each of these envelopes.

Submerging of drains: There were 8 normal drains and 8 submerged drains (4 with sawdust and 4 with Aqua envelope). The submerged drains were placed 30 cm deeper than the normal drains, but the outlets were raised 30 cm by means of S-shaped bends.

3.3 The control measurements

The length of the experimental drains varied from 60-100 m; they all had individual outlets. About 30 m from the outlets, piezometer tubes were placed in the drains and 75 cm from the drain center. Once a month the water potentials were measured and the discharge from each drain was monitored. The drainage water was analysed for pH and dissolved iron four times a year.

4 Results and discussion

4.1 The efficiency estimate of the drains

The efficiency of a drain is taken as the ratio between the run-off (l/s.ha) and the head of ground water (cm) 75 cm from the drain. The method has been described by Håkansson (1969) and Andersen (1976), and a discussion of its application is given by Dieleman (1976). This efficiency estimate is an arbitrary value depending on the resistance to the flow of water into and in the drains and on the soil conditions. On a uniform area, the efficiency of the drains may be used for comparing the effect of various treatments.

In the present experiments the results could not be given a statistical approach because there were only few replications of most treatments and because there were some variation in the hydraulic conductivites within the experimental site. Therefore, any initial difference between treatments should not be given too much attention; more important are the changes of the efficiency in time. It was found that immediately after drainage the efficiency of all experimental drains was high, but due to deposite of ochre the efficiency of several drains fell to an unaccept-ably low level within 3-4 years.

4.2 The perforation size of the drains

The effect of using various sizes of perforations in the drain pipes is shown in Figure 1. The efficiency of drains with normal perforations (1.5 mm) had decreased by 70% after 3 years, whereas the efficiency of drains with large perforations (3.0 mm) had decreased by 27% only during the same period of time. The drains were then cleaned by high pressure jetting and both types of drains again obtained almost the initial level of efficiency. During the following years the efficiency again decreased at a faster rate for drains with normal perforations than for drains with large perforations.

The efficiency of drains with one line of 5.0 mm circular openings - 5.0/3.0 mm perforations - was similar to that of drains with 3.0 mm perforations. However, in the years 1978/79 a very large decrease of efficiency was observed for drains with 5.0/3.0 mm openings. A visual inspection of the pipes at a few points did not explain this observation.

4.3 The filter envelopes

An analysis of the soil texture at drainage depth showed that it was necessary to protect the drains against siltation by fine sand (Figure 2). The effect of the employed filter materials are outlined in Figure 3a and b for Ulfborg II and III, respectively.

At Ulfborg II three types of filter materials were tested (i) the non-woven sheet filters, Fibertex, CH 100S and CH 200, (ii) three woven sheet filters, and (iii) the hydraulic envelope, Filtan. The effects of the individual filters within each group were similar and in this paper only the average effects are described. It may be seen from Figure 3a that drains with the non-woven sheet filters had a higher

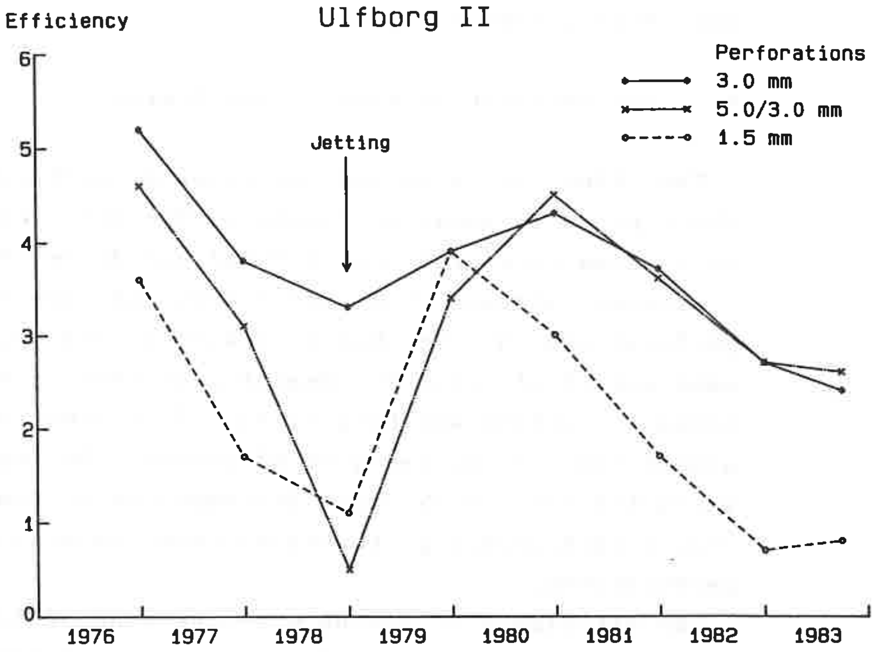

Figure 1. The efficiency of drainage pipes whith various perforation size, Ulfborg II. (The efficiency is taken as the ratio between the run-off from the drain and the head of water 75 cm from the drain).

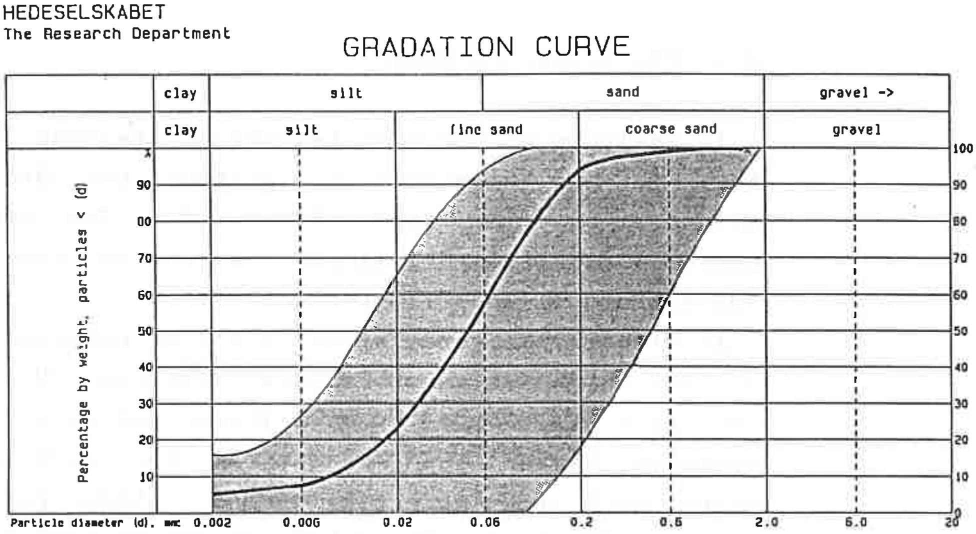

Figure 2. Soil texture at drainage depth. Within the shaded area there is a risk of silting up of drains.

efficiency than drains with the hydraulic filter during the first experimental period of three years. After jetting, however, it appeared that the effect of the hydraulic filter decreased at a slower rate than the effect of the non-woven sheet filters, and after 4 years the efficiencies of drains with these two types of filters were at the same level. Drains with the woven sheet filters had lower efficiencies than drains with both the non-woven sheet filters and the hydraulic filter throughout the research period. This indicates that woven sheet filters should be avoided at ochreous sites.

At Ulfborg III (Figure 3b) it was found that the effects of the organic filter, sawdust, and the artificial hydraulic filter, Aqua, were almost similar throughout the research period, and the sheet filter Typar appeared to function even better. The result obtained using Typar, however, may be due to the position of these drains within the experimental site - they were all placed in an area where the hydraulic conditions were likely to be different from those of the remaining area of this site.

The experimental drains were jetted after 3-4 years and it was found that all drains - irrespective of filter envelope - obtained almost their initial level of efficiency. This means that all the tested filter materials could be jetted almost clean. The results of the present experiments - carried out on soils with fine sand of uniform particle size, small contents of clay and organic material, and large hydraulic conductivity - can probably not be transferred to other soil types.

4.4 Submerging of drains

The effect of submerging the drains is shown in Table 1. First, it may be seen that the initial efficiencies for the submerged drains were much higher than for the normal drains. Secondly, it was found that during the following years the efficiency of the submerged drains decreased at a slow rate than the efficiency of the normal drains at Ulf-

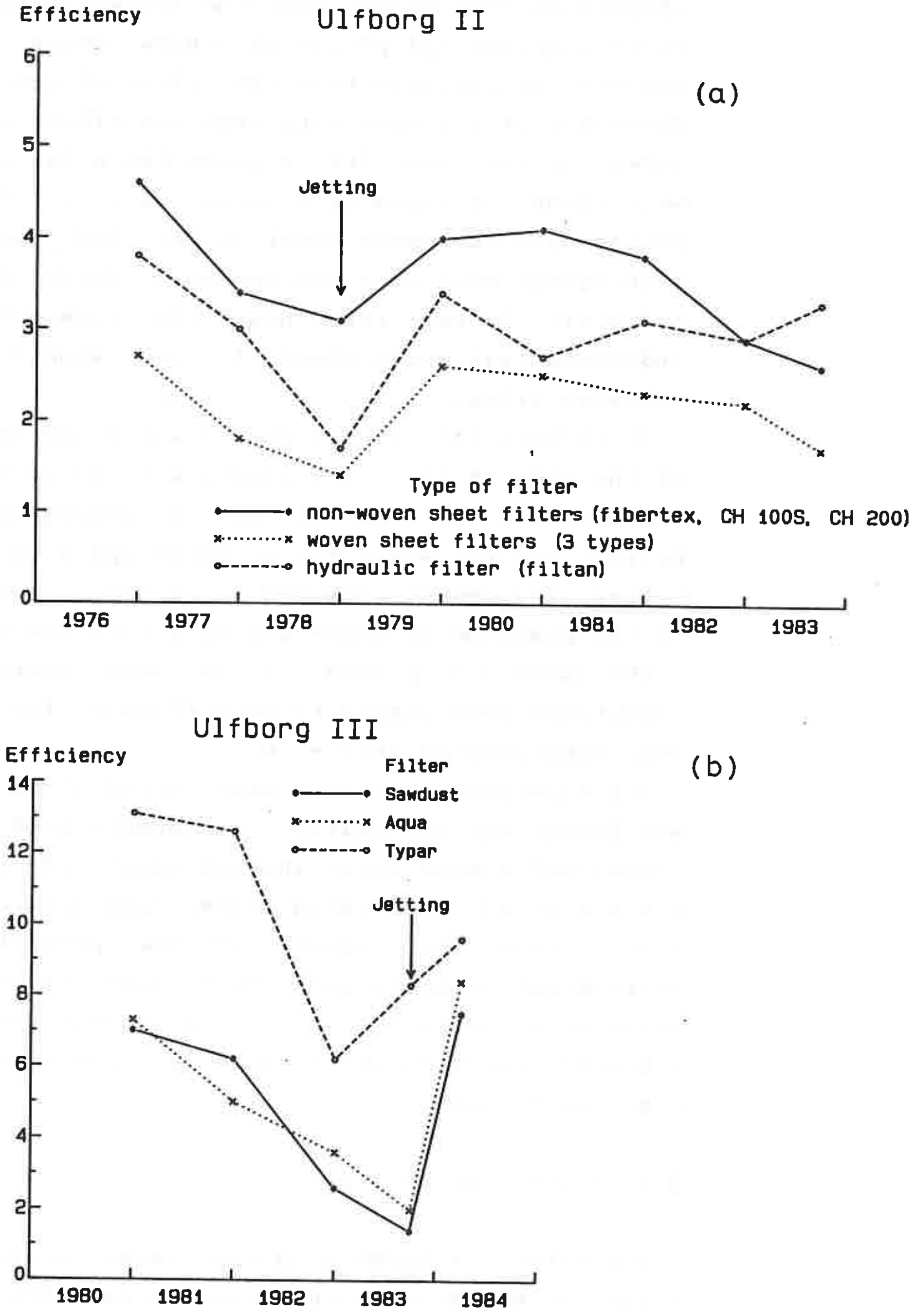

Figure 3. The efficiency of drainage pipes with various filter envelopes at (a) Ulfborg II and (b) Ulfborg III. (The efficiency is taken as the ratio between the run-off from the drain and the head of water 75 cm from the drain).

borg I and II, whereas this was not the case at Ulfborg III. Thus, after 3-4 years the drain effect at Ulfborg I had decreased by 53% for the submerged drains and by 66% for the normal drains; at Ulfborg II the drain effect had decreased by 10% for the submerged drains and by 56% for the normal drains; and at Ulfborg III the drain effect had decreased by approximately 75% for both submerged and normal drains.

The initial difference between the effect of the two drainage methods is likely to be a hydraulic effect of submerging the drains. At a normal drain the water entry takes place primarily through the bottom and the sides of the pipe. At a submerged drain, however, there is a more radial water flow towards the pipe and the entry of water takes place through the entire circumference of the pipe (Burghardt, 1976). This causes a reduced resistance to the entry of water, which again results in a higher efficiency of the submerged drain.

Table 1. The efficiency and the reletive effect at the end of the experimental periods for submerged and normal drains. (The efficiency is taken as the ratio between the run-off and the head of water 75 cm from the drain.

Site	Drain method	No. of drains	Efficiency						% effect **	
			-/78	78/79	79/80	80/81	81/82	82/83	1980-83	
ULFBORG I	Submerged	4	7.0	5.1	4.5	3.5	3.5	2.7	47	
	Normal	4	6.5	3.9	2.6	2.4	2.1	2.1	34	
			76/77	77/78	78/79	79/80	80/81	81/82	1978-79	1981-82
ULFBORG II	Submerged	3	11.2	10.9	10.4*	8.1	7.2	9.0	90	67
	Normal	5	5.2	3.8	2.8*	4.4	4.3	3.7	44	57
			80/81	81/82	82/83	83/-	-/84		1982-83	
ULFBORG III	Submerged	8	16.0	9.3	4.9	2.7*	10.0		26	
	Normal	8	7.0	5.5	2.9	1.8*	7.5		30	

* The drains cleaned by high pressure jetting

** "% effect" relative to the initial efficiency

At Ulfborg I and II the slower decrease of efficiency of the submerged drains compared to the normal drains is an indication of a reduced ochre formation rate around the submerged drains. At Ulfborg III, however, submerging did not seem to have any effect on the rate of ochre formation.

A visual inspection of the submerged drains showed the same trend. At Ulfborg II the soil profile was clearly oxidized - with ochre deposits and low pH (3.0-3.5) - down to the ground water level. Then there was an abrupt change into reducing conditions - the soil was bluish with no ochre deposits and the pH increased to about 6.0. The water level was approximately 40 cm above the drains. At Ulfborg III the pattern was less clear. The water level varied from 20-40 cm above the submerged drains but the soil profile was more or less oxidized - with ochre deposits and low pH (3.0-4.0) - right down to the drains.

Various reasons may have caused a better effect of submerged drains at Ulfborg II than at Ulfborg III. First, the concentration of dissolved iron in the drainage water was lower at Ulfborg II (20 mg Fe^{2+}/l on an average) than at Ulfborg III (30 mg Fe^{2+} /l on an average). Secondly, measurements of the water potential 30 m from the drain outlet showed that the drains at both sites had been submerged constantly throughout the experimental periods. The effective depth by which the drain pipes had been submerged was, however, larger at Ulfborg II (39 cm above the bottom of the pipes) than at Ulfborg III (29 cm above the bottom of the pipes). Thirdly, the run-off from the submerged drains was found to be much higher at Ulfborg II (6100 mm/year) than at Ulfborg III (1700 mm/year). The high run-off figures due to seepage may have hampered ferrous iron oxidation and therefore resulted in less tendency to form ochre deposits. Also the high run-off figures may have increased the self-cleansing effect of these drains.

It was observed that a slurry of ochre had formed in the submerged drains at all three experimental sites. However, when the ground water level was lowered by removing the S-shaped bend, it appeared that most of the ochre slurry was washed away in a few hours. The importance of regular cleaning of submerged drains is also evident from the experience from Finland. Mäenpää (1974, 1977) indicates that the submerging must be removed for a few days each year in order to get the slurry washed out of the drains.

On the basis of the results obtained the following guidelines for application of submerged drainage systems can be drawn up:

(i) Submerged drains function just as well or even better than normal drains.

(ii) To obtain a good drainage effect by submerging the following conditions seem necessary to be fulfilled: The pipes should be submerged constantly in their entire length and at a rather large depth (presumably at least 30-40 cm of water above the drains).
The submerging should be removed for a short time, e.g. for a couple of days once a year to permit flushing away of ochre sediments.

(iii) Under all circumstances it can be recommended to apply submerged drainage systems on low-laying, deep organic soils. After a few years of soil subsidence the drainage depth may need to be lowered. This can be obtained immediately by removing the raised outlet.

5. Summary

In the years 1976-84 the Danish Land Development Service carried out research work on field drainage of ochreous sites. Various drainage materials and submerged drains were tested at three sites (I, II, III) of fine sandy soils near Ulfborg in West Jutland. Here the hydraulic conductivity was high and there was a high seepage rate from the neighbouring areas. The drainage water contained 15-50 ppm of ferrous iron. The following results were obtained:

Perforation size of the drains: It was found that after 3 years the efficiency of drains with normal perforation size (1.5 mm) had decreased by 70%, whereas the efficiency of drains with large perforations (3.0 mm) had decreased by 27% only. There was no positive effect by using pipes with larger openings. All pipes -irrespective of perforation size - could be jetted almost clean.

Filter envelopes: In Denmark it is normally recognized that sawdust is the best filter material for drain pipes on ochreous sites. However, at Ulfborg III it was found that the artificial envelope, Aqua, and the sheet filter, Typar, functioned just as well as the sawdust filter. The filter materials at Ulfborg II included three non-woven sheet filters (Fibertex, CH 100S, CH 200), three woven sheet filters, and one hydraulic filter, Filtan. The trend was that the drains with the hydraulic filter decreased in efficiency at a slower rate than the drains with the sheet filters. The woven sheet filters appeared to be less suitable than the non-woven filters. Most of the ochre formations could be removed from all filters by high pressure jetting.

Submerged drains: The efficiency of submerged drains was equal to or higher than the efficiency of non-submerged drains. Submerging the drains had caused the ochre formation rate to decrease in some cases, whereas the effect was neglible in other cases. In order to obtain a positive effect of submerged drains it is suggested that the entire drain must be constantly submerged by 30-40 cm of water, and that the water table must be lowered occasionally for short periods (e.g. one day) so that the ochre deposited in drains and filters may be flushed out.

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INFILTRATION INTO A SEASONALLY FROZEN SOIL AND MODELING OF SOIL FREEZING AND THAWING PHENOMENA

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Abstract

The process of soil freezing and thawing is desribed. Soil temperature, total soil moisture content and infiltration into a frozen sandy soil were measured at an experimental field station. A new method for solving the combined mass and heat balance equations was developed. The method is based on dividing the total energy into latent and sensible fractions so that the functional relationship between unfrozen water content and soil temperature is fulfilled. The model was tested against the results obtained at the experimental station.

1 Introduction

Frost has a prominent role in the hydrology of northern latitudes because of its effects on runoff phenomena. It also alters the infiltration characteristics of soils but it does not totally prevent the infiltration process during the snowmelt period.

As well as meteorological factors, snow depth and density, vegetation and soil characteristics also have an inluence on the formation and melting of soil frost.

In part I of this study infiltration into frozen soil was measured using a double ring infiltrometer, the neutron method and a lysimeter. In part II a mathematical model was developed

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to describe and simulate the process of soil freezing and thawing.

2 Factors affecting the infiltration capacity of frozen soil - a short literature review

According to several papers frozen soil is permeable. Infiltration capacity of frozen soil has been studied most in Canada and the Soviet Union (e.g. Kuznik and Bezmenov, 1963; Zavodchikov, 1962; Williams and Burt, 1974, ref. Nilsson, 1979.).In these studies the soil type being investigated was either clay or silt. The basic results obtained were:

- exact values of the infiltration capacity of different soils cannot be given, because infiltration depends on many factors
- soils frozen in a state of low water content are more permeable than soils which were wet before freezing
- the amount of fine material in the soil is inversely proportional to infiltration capacity
- in coarse textured soils the permeability decreases more rapidly at sub-zero temperature due to their lower content of unfrozen water
- if the frost depth is small the infiltrating water may melt the frost thus increasing the permeability rapidly

The infiltration capacity of frozen soil has been studied very little in Finnland. Some experiments were carried out in the 1930's by the Finnish Field Drainage Centre (Juusela, 1941). The soil was mainly composed of clay. As can be seen from Fig. 1, the outflow from subsurface drains followed very rapidly the changes in air temperature (and thus snowmelt) during spring 1935.

Seuna and Kauppi (1981) studied the influence of subdrainage on water quantity and quality in a cultivated area in southern Finland. The soil at the experimental station was composed mainly of heavy clay. During the snowmelt period 59% of the total runoff came from drains.

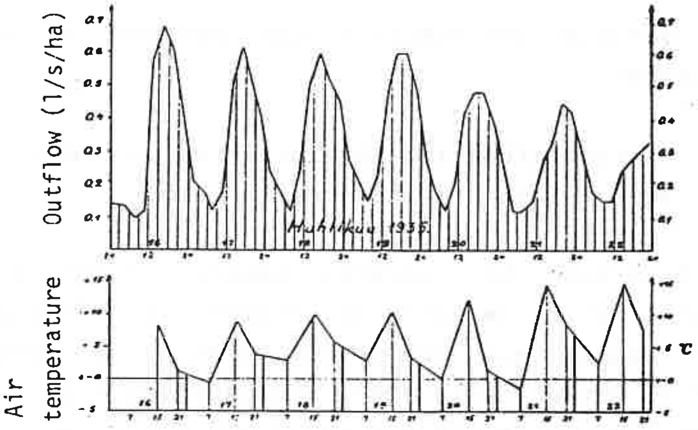

Fig. 1. Outflow from drains and air temperature in Jokioinen during 16 - 22.4. 1935 (Juusela, 1941).

During springs with deep soil frost the percentage of surface runoff was greater than average. In some years, when the upper layer of soil frost had already melted before the spring maximum runoff, the percentage of surface runoff was very small (Fig. 2.), although the total depth of the soil frost was still considerable.

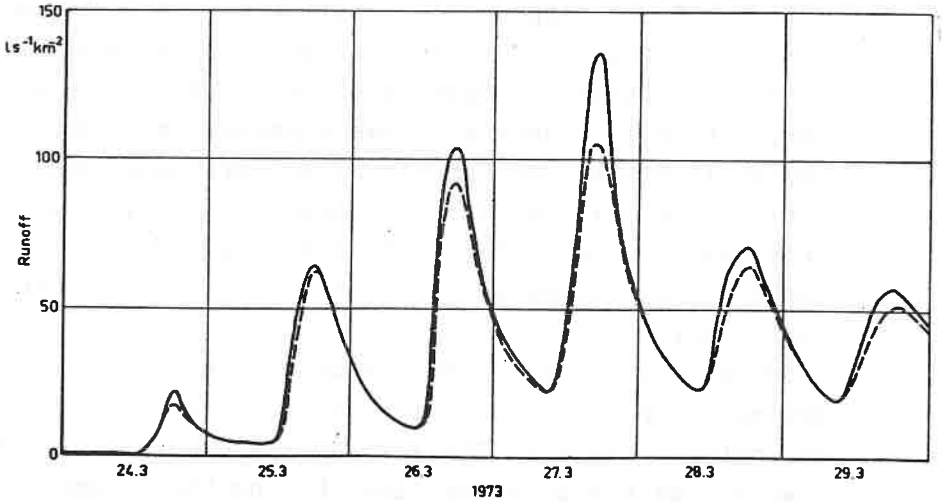

Fig. 2. Distribution of runoff during snowmelt at the Hovi basin in 1973. The solid line indicates total runoff and the dotted line outflow from subsurface drains (Seuna and Kauppi, 1981).

3 Experimental field station and measurements

The field station is situated in southern Finland (60°23′ N and 25°02′ E) on a glacifuvial delta formation. The dominant textural composition of the soils was sand and fine sand. The dominant vegetation at the station was lichen and heather.

The following measurements for the years 1969 - 1973 were used in this study: Air temperature, shortwave radiation, precipitation, snow thickness and density, snow and soil temperature, the depth of frost and changes in soil moisture at different depths. The grain size distribution, porosity, volume weight and pF-curves of the soil were also known. The mean depth to the groundwater level was generally over 6 m.

Snow temperatures at heights of 0, 2, 8, 12, 20, 30, 40, 50 and 60 cm and soil temperatures at depths of 1, 5, 20 40, 80, 150 and 250 cm were measured using copper-constantin thermocouples. The precision of the measurements was ±0.1°C. Methylene blue tubes were used to measure the depth of soil frost with the precision of 0.5 cm. The soil water content was measured along the vertical profile with a neutron probe at 10 cm intervals. This indirect way of determining soil moisture content was calibrated using gravimetric techniques (Lemmelä, 1970).

The infiltration measurements were made with a double ring infiltrometer (Lemmelä and Tattari, 1986). The percolation through a 1 m soil column was registered with a cubical 1 m^3 lysimeter. The soil moisture retention curves expressing the energy relations of soil water from pF 0 to pF 4.2 were measured according to the recommendations in "West European methods for soil structure determination" (1967), (Lemmelä, 1970.)

3.1 Infiltration into frozen soil

Examples of infiltration into a seasonally frozen ground as measured by double ring infiltrometers are shown in Fig. 3, as measured by soil moisture measurements in Fig. 4 and by the lysimeter in Fig. 5. The following conclusions can be drawn from the results (Lemmelä and Tattari, 1986). Frozen coarse-

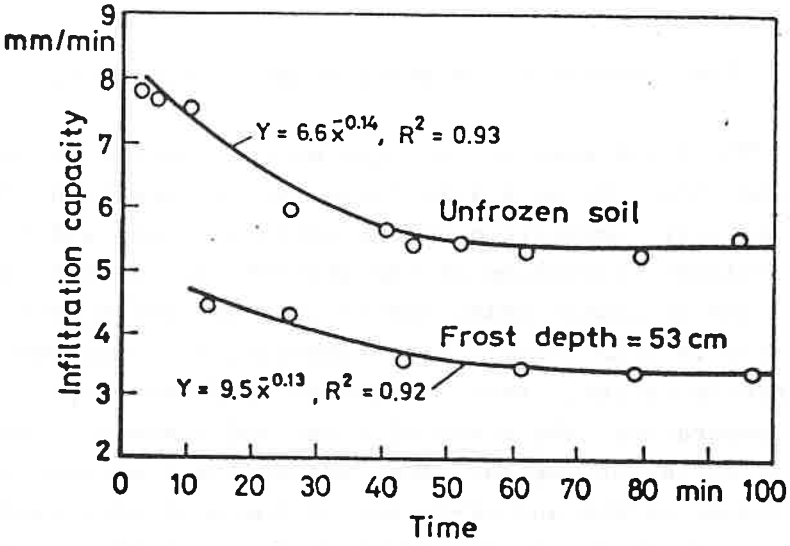

Fig. 3. The mean infiltration capacity of soil during the frozen and unfrozen periods (Lemmelä and Tattari, 1986).

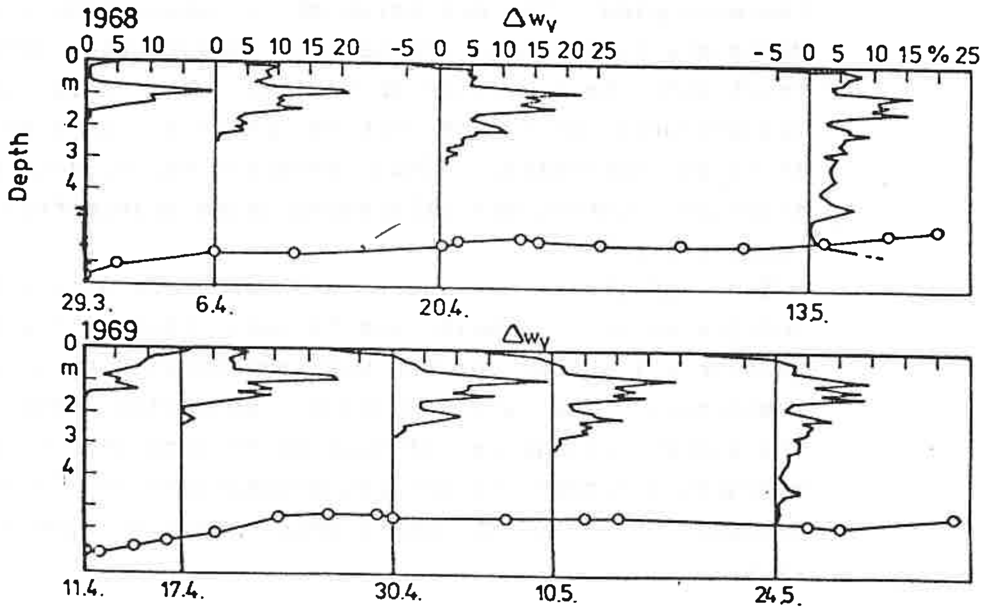

Fig. 4. Changes in soil moisture content[1] and groundwater level during the thawing periods in 1968 and 1969 (Lemmelä, 1970)

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[1] Comparison in soil moisture content is made with the soil moisture content just before the snow begins to melt.

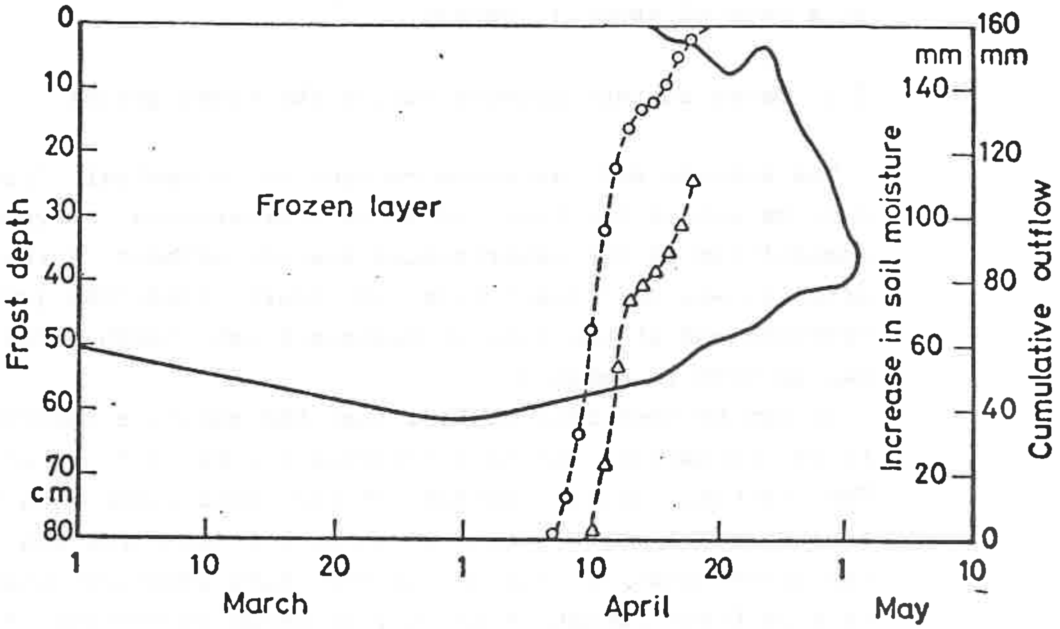


Fig. 5. Frost depth(▬▬), increase in soil moisture(o---o) and cumulative outflow (Δ---Δ) from the uppermost 1 m layer in spring 1969(Lemmelä and Tattari, 1986).

grained soils are relatively permeable and during the thaw period the final infiltration capacity greatly exceeds the maximum snowmelt intensity. According to ring infiltometer-measurements, the approximate mean value of the final infiltration capacity during the frost period was about 3 mm/min, the maximum daily snow melting varying from 8.4 to 29.3 mm. During the years from 1969 to 1973 the frost depth varied between 32 and 92 cm just after the snowmelt period. The increase in soil moisture content in the first 1 m layer varied between 70 and 135 mm and the cumulative outflow from the lysimeter varied between 31 and 74 mm before the frost layer started to melt from the surface.

According to the field measurements made in different spring seasons during the frost period, the depth of frost did not influence infiltration capacity as much as the initial water content of the frost layer.

The snowmelt progressed towards the groundwater surface at a rate of about 10 cm/day.

3.2 Water content changes during the frost period

The average soil moisture content in a typical frost layer 0-50 cm and in the layer 20-40 cm representing a typical soil composition at the experimental station without surface layer effects, was calculated from the years 1968-1984 just before freezing and at the date of maximum frost depth. The results can be seen in Table 1.

It can be seen from Table 1 that the moisture content during frost formation varied considerably , by 5.8 % at most. The initial water content of the soil layer when the soil freezes has a major influence on soil frost formation, because the latent heat of fusion is the most important heat budget term in frost formation as will be shown in Section 3.3. The moisture content did not change markedly during the frozen period. In the topmost 20 cm layer the measured moisture content increased but the reason for this was that no snow corrections were made to the water content measurements. The layer between 20 and 40 cm dries on average 1 % due to the movement of water downward under influence of gravitation.

Table 1. Average water content in two soil layers from 13 winters just before freezing and at the time of its maximum depth ($h_f = h_{f,max}$), their standard deviations and maximum and minimum values.

Layer cm	Water content w (vol. %)							
	Before freezing				$h_f = h_{f,max}$			
	w	st.dev	max	min	w	st.dev	max	min
0 -50	13.0	1.6	15.9	10.1	14.1	2.3	18.0	10.6
20-40	11.4	1.8	14.6	9.0	10.4	2.2	13.6	6.7

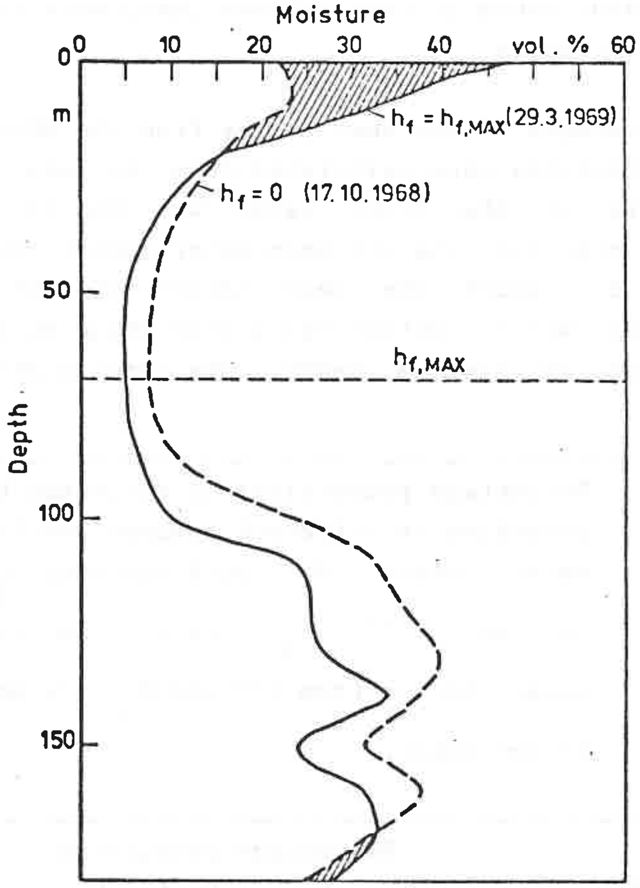


Fig. 6. Typical soil moisture curves before soil freezing and at the date of maximum frost depth

This phenomenon can also be seen in Fig. 6. The curves are from the winter of 1968-69, but they are typical for all the years.

Moisture changes were also calculated when groundfrost was at its maximum depth and when it had a value of maximum-10 cm in the layers $h_{f,max}$ -10 cm to $h_{f,max}$ and $h_{f,max}$ to $h_{f,max}$ +10 cm were also calculated. No moisture movement towards the freezing front was observed although theoretically a freezing-induced soil moisture redistribution should occur. The moisture content remained at a constant value in both layers.

3.3 Measurements of heat balance components during freezing and thawing

The averages of the heat losses from the whole frost layer during freezing were calculated from the data. The average thickness of the frost layer was 66 cm. Two different assumptions for the unfrozen water content were used (0.8 % and 1.5 % being the mean values in the calculations). The total water content had a mean value of 12.4 % when the frost had its maximum depth. The results are summarized in Table 2.

Table 2. Percentage proportions of different heat loss terms according to different assumptions for the unfrozen water content. H_1 = soil cooling, H_2 = water cooling to 0°C, H_3 = ice cooling from 0°C, H_4 = water cooling from 0°C and H_5 = latent heat of frozen water.

Unfozen	Percentage proportion					
water (%)	H_1	H_2	H_3	H_4	H_5	H
0.8	7.6	2.7	0.4	0	89.3	100
1.5	8.0	2.8	0.3	0.2	88.6	100

The latent heat had a dominant role,as can be seen from the table. It is also very important to know the amount of unfrozen water if the absolute values of changes in heat terms are to be calculated, because the difference in the amount of total energy losses reached 5.4 % when these two assumptions for unfrozen water content were compared.

The cold content of the frost layer when the frost was at its maximum depth was also calculated. This average cold content could freeze only about 1.8 mm of the meltwater as an average during these five years. The percentage proportions of this 1.8 mm were: layer 0-10 cmm 30 %, layer 0-50 cm 87 %

and layer 20-40 cm 30 % and 100 % for layer between 0 and 66 cm. The percentage of the soil itself in this cold content was about 80 %, and the percentages of ice and unfrozen water were 17 and 3 %, respectively.

4 Modeling of soil freezing and thawing phenomena

The possibility of numerically modeling the complex processes which occur in simultaneous heat- and soil-moisture transport in a freezing soil has received much attention during the past decade (e.g. Harlan, 1973; Guymon and Luthin, 1974; Taylor and Luthin, 1978; Guymon et al., 1980; Jansson and Halldin, 1980; Gilpin, 1980; Hromadka et al., 1981; O'Neill and Miller, 1982). Special attention has been devoted by Motovilov (1978, 1979) and Engelmark (1984) to the calculation of infiltration into a frozen soil.

4.1 Heat and water flow

The equations describing the combined heat and water flow are given by (1) and (2):

$$c_T \frac{\partial T}{\partial t} - \delta_i L \frac{\partial I}{\partial t} = \frac{\partial}{\partial z}\left(K_h \frac{\partial T}{\partial z}\right) - c_w q_w \frac{\partial T}{\partial z} \qquad (1)$$

$$C(\psi)\frac{\partial \psi}{\partial t} + \frac{\delta_i}{\delta_w}\cdot\frac{\partial I}{\partial t} = \frac{\partial}{\partial z}\left(K(\psi)\frac{\partial \psi}{\partial z} - K(\psi)\right) \qquad (2)$$

where z is a space coordinate, t is time, T is temperature, K_h is soil thermal conductivity, L is latent heat of fusion of water, c_T is volumetric specific heat of soil, the indices w and i refer to water and ice, respectively, δ is density, c is specific heat , q is flow of water, I is volumetric ice content, ψ is soil water potential, $C(\psi)$ is differential moisture capacity (a derivative of moisture content w with respect to potential ψ) and $K(\psi)$ is unsaturated hydraulic conductivity of the soil matrix.

A difficulty in the numerical solution of (1) and (2) is the inclusion of the ice term,since it generally dominates the solution as shown in Section 3.3. To avoid excessive numerical difficulties the assumption is often made that there exists a unique relationship between unfrozen water content w and soil temperature T in a frozen soil.

$$w = w(T) \quad ; T < 0°C \tag{3}$$

This means that all the water in soil will not freeze at zero temperatures. The lower the temperature the smaller will be the amount of unfrozen water. Since it is very difficult to measure the form of this function it is necessary to be able to predict it from other data that can be measured more easily. An assumption that is used in this study is that the functional form of (3) can be estimated from a known pF-curve. The validity of this estimate should be examined more carefully.

4.2 Freezing point depression in unsaturated soil

The formula expressing freezing point depression can be obtained thermodynamically from the generalized Clausius-Clapeyron equation (e.g. Miller, 1978):

$$u/\gamma_w - u_i/\gamma_i = (L/K)\Delta T \tag{4}$$

where u and u_i are pore water and pore ice pressure, respectively, K and ΔT are temperature in Kelvin and Celsius degrees. It can be assumed (e.g. Kinosita and Ishizaki, 1980) that ice pressure in unsaturated soil is zero. Then the freezing point depression is given by the following theoretical equation where u is expressed in centimetres. Thus u is equal to soil water potential.

$$\Delta T = \Psi/12200 \tag{5}$$

where T is in °C and potential in cm. If the pF-curve of the soil is known, a relationship between unfrozen water content and soil temperature (below °C) can be obtained from (5).

The freezing point depression curve calculated as a function of the soil water retention curve and based on equation (5) is shown in Fig. 7. For Bensby Silt the approximation is very good, but for Tomakomai Silt the estimated curve gives too low temperature values almost throughout the whole potential range. According to Kinosita and Ishizaki (1980) the reason for this is that some pressure acts on the soil-ice matrix owing to the adsorption of pore water to the surface of soil particles.

Unfortunately we did not find any other measured curves from the literature, so that the validity of equation (5) could not be tested thoroughly. Although it is quite obvious that equation (5) will not give fully accurate results in all cases it is used in the numerical calculations presented in Section 5. More research is necessary before freezing point depression can be estimated from generally measured quantities.

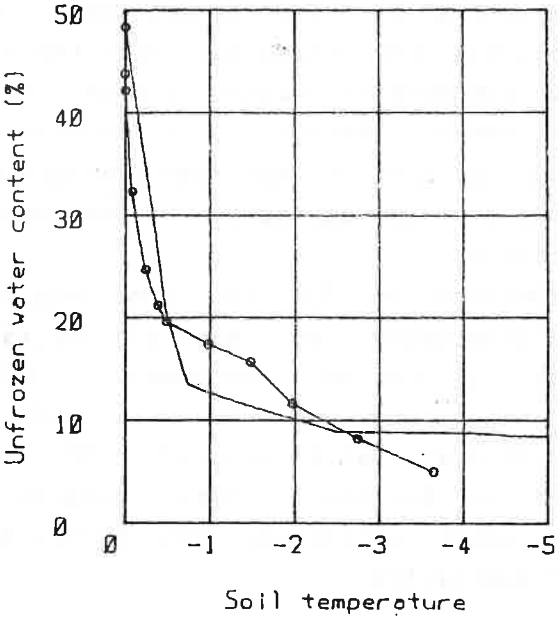
4.3 Energy concept for estimating the amount of unfrozen and frozen water content and soil temperature

Two basic alternatives exist for solving the combined heat- and mass transfer equations if a relationship between unfrozen water content and soil temperature is used. In the first version the derivative $\partial I/\partial t$ can be eliminated using the known $w = w(T)$ curve. This results in the so-called apparent heat capacity c_a, defined by

$$c_a = c_T + L\cdot\partial w/\partial T \qquad (6)$$

As was shown by Hromadka et al. (1981) the equations (1) and (2) can be combined into a single equation in a frozen zone. Engelmark (1984) has also used this concept. However, according to Guymon et al. (1980) numerical methods employing this approach require exceedingly small time steps, and small space discretization. Instability problems may result in lengthy simulations, involving time spans of a week or more.

On the basis of the foregoing experiments another method of solution was adopted. It was originally proposed by Karvonen (1986a). This method is based on the total energy



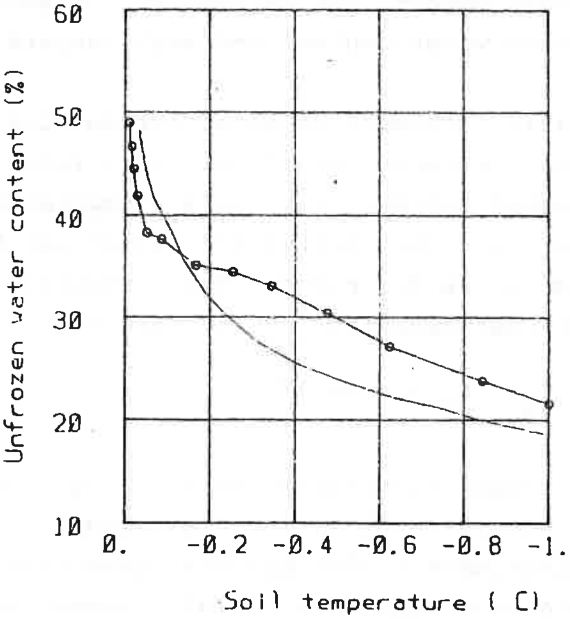


Fig. 7. Measured and estimated freezing point depression curves.(———) Measured. (o---o) Calculated based on equation (5) and the measured pF-curve.

a) Bensby silt (Engelmark, 1984.)

b) Tomakomai silt (Kinosita and Ishizaki, 1980).

concept, in which the total energy is divided into latent and sensible fractions using the known relationship between unfrozen water content and soil temperature. Consider the total energy needed to raise the temperature of a soil sample to 0°C from a negative temperature. Moreover, it is assumed that the total water content is known,whereas both the amount of frozen and frozen water and the soil temperature are not known. Then the energy E needed can be expressed as

$$E = - f_s \cdot c_s \cdot T - w \cdot c_w \cdot T - I \cdot c_i \cdot T + L \cdot I \tag{7}$$

$$= - f_s \cdot c_s \cdot T - w \cdot c_w \cdot T - (W-w) \cdot c_i \cdot T + L \cdot (W-w)$$

where the subindices s, w and i refer to soil, water and ice, respectively, f is the volumetric fraction of soil, w is the unfrozen water content, I is the ice content, W is total water content (water + ice) and c the specific heat of different constituents. In equation (7) the amount of ice is expressed as the amount of frozen water (i.e. the volumetric amount of ice is about 9 % greater).

Equation (7) can be used in the model when the unknown unfrozen water content and soil temperature are calculated using known values of total water content W and energy state E. Equation (7) contains only two unknowns (w and T) and if the relationship w=w(T) is used, there exist two equations for solving the unknowns. The iterative solution is obtained by the Newton-Raphson method. The methods of obtaining the total water content W and the energy state E are described in Section 4.4.

4.4 Numerical solution method

The proposed model solves the mass and energy balances using the finite element method. This method was selected because different types of boundary conditions can easily be adopted into this technique.

The actual solution proceeds through a three-stage process.

1) Solve the mass balance equation assuming no change in the ice content (the total amount of water W is thus obtained).

2) Solve the heat balance equation neglecting the latent part. By solving the new temperature profile the amount of energy lost from the system can be calculated (i.e. the energy state E can be calculated).
3) Solve the actual unfrozen water content w and ice content I as described in Section 4.3.

Two possibilities exist when iterating during one time step. In the first version stages 1) and 2) are solved and after that w and I are solved without further iterations. In the second version stages 1)-3) are repeated iteratively until convergence is attained. In calculating the energy state the amount of latent heat generated during the time step is taken into account. The first version can be considered as explicit with respect to the calculation of the energy state of the system. It is preferable when the simulation of long time intervals is needed.

4.5 Initial and boundary conditions

The intial state of the system must be known at time t= 0. This implies that either the soil moisture content or total hydraulic head (e.g. steady-state situation) must be given for each nodal point for the solution of the mass balance equation. Moreover, it is necessary to define the initial temperature profile.

Different types of boundary conditions can be used,depending on the available data. At the upper boundary, the maximum possible infiltration capacity (rainfall + snowmelt) is prescribed. In the numerical solution the true infiltration capacity is maximized by a method proposed by Neuman et al. (1974). The upper boundary condition for the heat equation is the measured soil surface temperature, or if this is not measured then the air temperature can be used.

At the lower boundary, three types of boundary conditions can be used: prescribed groundwater level (outflow from the system is calculated), no-flow boundary (groundwater level calculated) or outflow to parallel drains calculated by the Ernst (or Hooghoudt) formula (depth of groundwater level is calculated). The latter alternative can be considered to be a quasi-two-dimensional solution in the case of a system where drain spacing and depth are given and groundwater level is the variable to be calculated. In the heat flow equation temperature or zero heat-flow can be used as the lower boundary condition.

4.6 Input and output data

Again, different types of input data can be used, if available. The minimum meteorological input data needed are precipitation and air temperature. Moreover, it is necessary to have the pF-curves of the soil and the saturated hydraulic conductivities, thermal conductivities and specific heat values for soil, water and ice. The unsaturated hydraulic conductivity is calculated by a method originally proposed by Sigvard Andersson (1969) and slightly modified by Karvonen (1986b). According to a comparison made with 30 measured curves the Andersson method gave at least as good results as the well-known Mualem method (1976).

The primary aim of the model is to simulate the effects of soil heat extraction on an annual scale in a case where the depth and spacing of subsurface drains are given. The most important output data needed are soil moisture, groundwater level and soil temperature. With the model it is possible to compare e.g. the effect of different drain spacing (and/or depth) on soil moisture and soil temperature. This model can be used together with a potential crop production model to calculate the actual yield when drain spacing and depth (and the necessary soil data) are known (Karvonen, 1986c).

The additional output data from the model include e.g. the outflow to the drains and soil trafficability criteria.

5. Numerical experiments

5.1 Experiment 1

The model was tested against the experiment carried out by Kalyuzhnyi et al. (1984). The column was 50 cm long. Measured temperature were given both as an upper and a lower boundary condition in the heat balance equation. No-flow boundary was used an an upper boundary condition in the mass flow equation. At the lower boundary constant hydraulic head was given. As a result of flow of water to the freezing front sharp increase in the total water content was observed (e.g. from 4.5 % to 14.1 % at the depth of 16 cm, see also Fig. 9).

Changes in temperature and water content were measured during soil freezing. The soil moisture retention curve was estimated from measured steady-state initial profile. The unsaturated hydraulic conductivity was calculated using the method proposed originally by Andersson (Karvonen, 1986b). The thermal conductivity of frozen soil was estimated using formulas given by Kersten (1949) (ref. Jansson and Halldin, 1980). The objective of this simulation example is two-fold. First, the applicability of the model to simulate freezing induced soil moisture redistribution was tested. Second, the sensitivity of the solution to small variations in the unsaturated hydraulic conductivity values was evaluated.

The results of the soil temperature simulations are shown in Fig. 8, and measured and computed total water content in Fig. 9 and 10. However, since the soil temperature was defined both at the upper and lower boundary condition the deviation between measured and calculated values should be very small. In this respect the simulation results can be considered to be only satisfactory.

The simulation of total water content is uncertain as can be seen from the results. The system is very sensitive to small variations in the unsaturated hydraulic conductivity. The original curve (B in Fig. 11) gave too small increase in the total water content at the freezing front (see Fig. 10). When slightly higher values (curve A in Fig. 11) were used the simulated soil moisture redistribution is very near the measured one (Fig. 9 and 10). It is obvious that the most important parameter in the combined heat and mass transfer is the unsaturated hydraulic conductivity. Unfortunately the shape of this function is very difficult to measure and it is usually estimated indirectly from measured pF-curve.

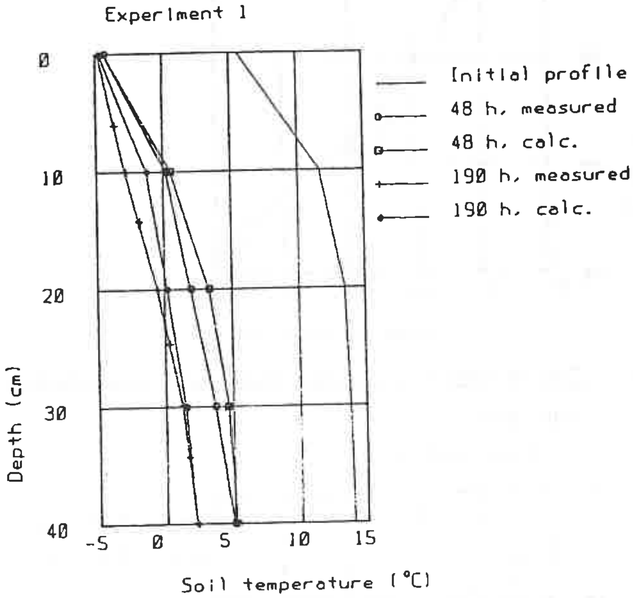


Fig. 8. Experiment 1, measured and calculated soil temperature.

5.2 Experiment 2

The second simulation example is from the experimental station referred already in Section 3. The calculated and measured cumulative outflow from the uppermost 1 m layer in spring 1969 are shown in Fig. 12. In the simulations the lower boundary condition was defined as a flux-boundary. The outflow from the system was calculated assuming a unit gradient (i.e. outflow equals the hydraulic conductivity of the lowest node). The simulations are in quite good agreement with the measured values. The depth of soil frost during the simulation interval is shown in Fig. 5.

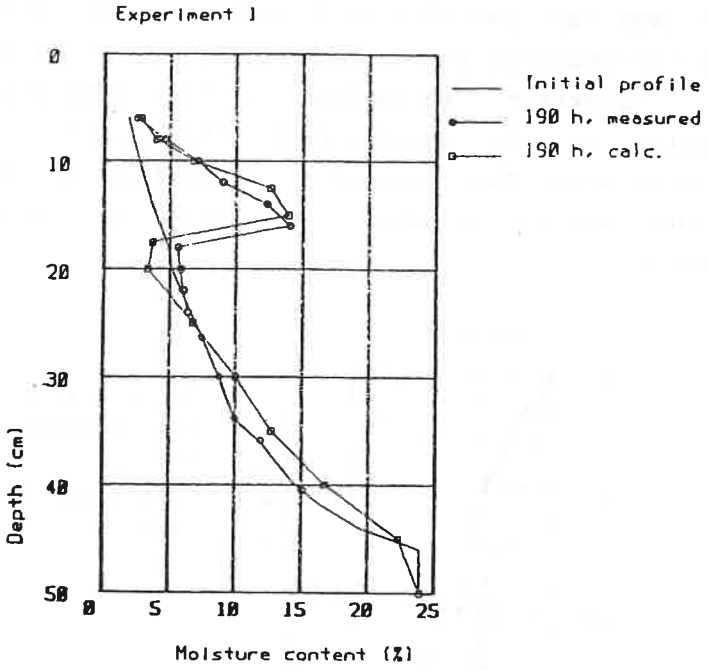


Fig. 9. Experiment 1, measured and simulated total water content.

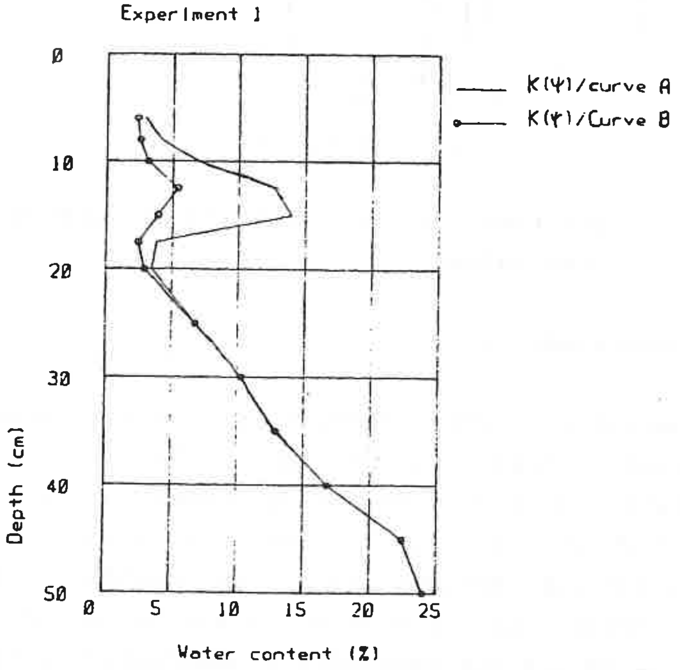


Fig. 10. Experiment 1, simulated water content using two different curves for unsaturated hydraulic conductivity.

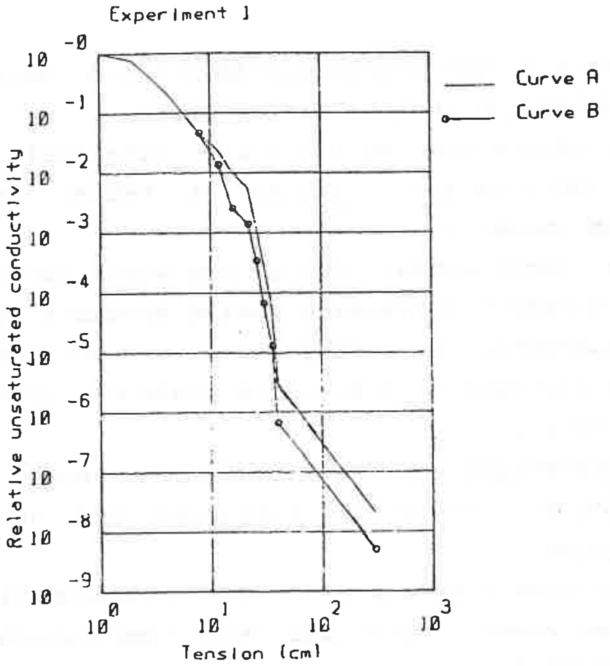


Fig. 11. Experiment 1, two different unsaturated hydraulic conductivity functions.

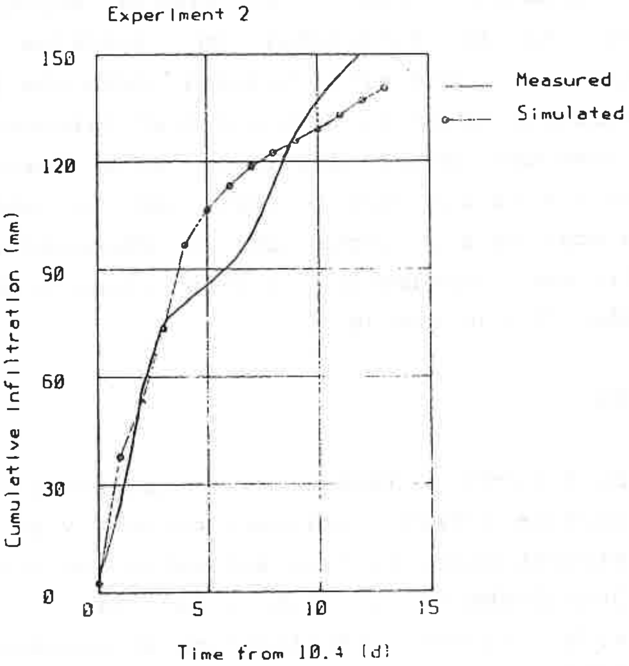


Fig. 12. Calculated and measured cumulative outflow from the uppermost 1 m layer in spring 1969.

6. Conclusions

On the basis of the field experiments and computer simulations, the following conclusions can be drawn:

1° Frozen coarse-grained soils are relatively permeable and the infiltration capacity of frozen soil exceeds the maximum snowmelt.

2° At the experimental field the water content changes were small during the freezing period probably due to the depth of groundwater level (the original soil water potential was so low that soil freezing could not draw water to the frost zone).

3° The percentage of the latent heat (phase change of water into ice or vice versa) dominates the energy balance of the system.

4° An approximate estimate of the relationship between the unfrozen water content and soil temperature below zero can be obtained on the basis of the measured soil water retention curve and equation (5). More research is needed to verify this assumption.

5° A method based on the total energy state of the system proved to be successful in avoiding the numerical difficulties generally arising from the inclusion of ice accumulation terms in mass and heat balance equations.

6° The computer model developed is a reasonable basis for larger simulation model that can be used in optimizing drain spacing and depth and in choosing optimum drainage coefficient (naturally, a crop production model must be included in the system).

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OCHRE AND SUBSURFACE DRAINAGE IN FINLAND

R.Peltomaa and V.Veijalainen

Abstract

The risks of ochre deposition in subsurface drains are common on the sandy and peaty soils of Central and Northern Finland. The iron concentrations of ground water on sandy soils, the mean for 14 fields with subsurface drainage being 23.2 ppm, were found to be high compared with the threshold values for the risk of ochre deposition in Central Europe. The problems have, however, been small, which can be assumed to be due to the climatic conditions and the method of underwater drainage, which has been applied systematically.

1 Introduction

In the history of subsurface drainage in Finland, the ochre problem has been present and acknowledged for several decades. The different alternatives to deal with this problem were analyzed in the early 1950's (Puustjärvi and Juusela 1952). In practice, the method that has been used almost exclusively to prevent ochre deposition in Finland has been underwater drainage. The experiences obtained with it have been favourable. The formation of deposit has decreased notably, with the consequense that there has been hardly any need for maintenance. Over the past ten years, subsurface drainage has become increasingly common on the sandy and peaty soils of Central and Northern Finland, while the previous focus used to be on the clay-containing soils of Southern Finland (Figure 1). On the basis of the soil type distribution, it can be postulated that the risk of ochre deposition will continue to increase, as subsurface drainage has only been begun on the sandy soils of the northern coastal area and the morainic and peaty inland soils.

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The number of subsurface drains non-functional because of ochre deposits has been quite small. Their number is increasing, however, and the percentage of non-functional drains out of the total annual new drainage over the past few years has been of the order of 0.5 %, i.e. 100 - 200 hectares/ year. Applying the classification presented by Kunze (1982), the coastal sandy areas can be classified as areas of temporary risk and the peaty soils as areas of permanent risk.

The recent development has provided new ways of prognosticating the risk of ochre deposition. Also, washing equipment to remove the deposits from the drains have been developed. The widespread application of flushing equipment has also made it possible to replace the expensive construction of underwater drains with cheaper subsurface drainage that can be kept functional by means of continuous maintenance.

2 Iron in ground water

Water supply arrangements have revealed that the excessively high iron concentrations of ground water in Finland are bound to bring about problems (Hatva and Niemistö 1973). The data on the iron concentrations of ground water on the cultivated fields in Finland are scant, however. The data to be presented here are based on the water samples collected from the northern coastal area during 1980 - 1984 (Table 1).

The sampling points were located on fields with subsurface drainage of a known history and with observable deposits in the drainage pipes. The water samples were collected from a ground water pipe installed for this particular purpose. In addition to laboratory analyses, the total iron concentrations were also monitored with field measurements[1].

One goal of the project was to find out the possibilities of applying the field measurements of ground water iron concentrations to estimate the local ochre problem. The total iron concentration was selected because it is easy to determine. It was known, moreover, that the ground water table is close to the drainage depth, which means that the water sample can be obtained as unaerated as possible, and that the iron concentartions may be relatively high. No attempt was therefore made at this stage to carry out Fe^{++} assays.

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[1] Iron test kitt, model IR-18B, cat No 1.464-01 Hach Company P.O.Box 389 Loveland, Colorado 80593 U.S.A.

As it can be seen from the summary on Table 1, the Fe concentrations were high, the mean for 33 samples being 23.2 ppm and their range 1.0 - 111.0 ppm. As the material is so small, it is not expedient to try to explain the factors responsible for the wide range of variation. It could be pointed out, however, that the ground water status seems to have an obvious effect in such a way that the deeper the ground water table was, the higher was the iron concentration. The mean pH of the water samples was 5.5 and the pH range 3.3 - 6.6. The Mn concentrations assayed for part of the samples were 1.3 ppm and 0.29 - 4.3 ppm, respectively.

3 Functional state of drainage

The subsurface drainage on the farms presented in Table 1 varied from 3 to 22 years of age. No drains that were completely non-functional or clogged were found. The drainage on eight farms was of the underwater type, and six farms lacked submerged outlets. If we pick out of the material the cases with identical conditions, i.e. the farms with pure sandy soil and no artesian ground water, we can see that after five years more than half of the pipe cross-section was filled by deposits in the drains lacking submerged outlets. The Fe concentrations of the water samples collected from these areas were 12 - 26 ppm. Where underwater drainage had been used, the precise amount of deposition was difficult to estimate, because part of it could have been eliminated by the removal of back-flooding, but even in these cases signs of deposition were detectable at the bottom of the pipes of corresponding age. As to the minimal iron concentrations, it was not possible to point out in Table 1 the iron concentration at which the ochre risk would be non-existent. Field measurements carried out in other connections suggest that in pure sandy soils the Fe concentration can be 2 - 3 ppm without there being any need for special measures in the construction of subsurface drainage.

The deposits mainly consisted of reddish amorphous mass, which was pulverized when dry. The ochre deposits in Finland are mostly pure, i.e. they seldom include soil matter, which is due to the liberal use of filtering gravel. Large mare's tail-type occlusions (Ivarson and Sojak 1978) caused by micro-orgamisms have also been rare.

4 Discussion

It is generally known that ochre formation is essentially due to the concentration of soluble iron in the ground water and the bacterial activity associated with its precipitation (Ford 1985, Kuntze 1982). It remains unknown, however, to what extent the different physical, chemical and biological factors are responsible for ochre formation. The essential raw material can be said to be ferrous iron. The determination of ferrous iron concentration has therefore been adopted as a prognostic measure of the ochre risk.

Kuntze (1982) reviewed Central European findings where the ochre risk had been classified relative to the Fe^{++} concentrations. The concentrations at which the risk is termed as 'slight' are 0.5 - 5 ppm, while in the class of 'very great' risk they range from 6 ppm to more than 14 ppm. The concentrations presented above for the Northern Finnish conditions are quite high compared with the Central European values despite the differences in the methods of analysis. On the basis of the practical experience acquired by the Field Drainage Centre, it can be claimed that in the northern coastal area there are several thousands of hectares of drained fields where the iron concentrations of the ground water exceeds 10 ppm. Some hypotheses can be presented concerning the relatively small number of cases of ochre glogging.

Of the microbes that have been found to be present in ochre formation, the analyses of ground water in Finland have revealed e.g. Leptothrix, Gallionella and Thiobacillus (Hatva and Niemistö 1973, Carlson et al. 1980), and drain deposits have been found to contain Leptothrix and Gallionella (Ford 1984). The explaining factor thus cannot be an absence of microbes, but climatic factors may contribute to microbial activity. The average depth of subsurface drainage in Finland is 1.0 - 1.2 m and the soil temperature at this depth is near $0^{o}C$ for a large part of the year (Figure 2). The soil is also frozen throughout the winter months, when there is only minor flow in the drains. In addition to this, the summer months of June and July typically have sub-average precipitation, which also results in sub-average drain flow at this time of the year.

As regards the drainage tehnique, the underwater system compined with abundant gravel around the pipes as well as the clay piping that was used in a majority of the drainage systems until the mid-1970's have been factors that have been found to minimize the problems due to ochre deposition (Kuntze 1982).

On the basis of the survey that was made, it appears that the classifications of ground water iron concentrations made in Central Europe for prognosticating the ochre risk are not as such applicable to the conditions prevailing in Nothern Finland. In the ligt of the experience so far obtained, it seems that the principles being applied in the Leningrad region on the Soviet Union are partly more compatible with the present findings. In the Leningrad region subsurface drainage requires no special measures if the Fe concentration of ground water is below 3 ppm (Peltomaa 1984).

It would be of primary importance to diagnose the presence of the ochre problem at the planning stage. A method for this purpose is being developed in Finland on the basis of findings made by Ford (1982). The major difficulty seems to lie in the application of the international concentration threshold values to different soils and climatic conditions. In addition to this, there is a need, even within Finland, to create different scales for the drainage of sandy and peaty soils. The risk levels will probably be lower for peats than for sands (Tanskanen 1985). In addition to these two types, there are an estimated 50 000 hectares of acid sulphate soils in Finland, where ochre deposits will be a true problem because of the abundant and easily soluble pyrite contained in the soil.

Acknowledgements

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Table 1. Fe, Mn and pH of the water samples, soil type of the sampling site and difference between the water level in the sampling vial and the ground surface.

Sampling site		Fe^{totl}/laborat. ppm	Fe/field assay ppm	Mn ppm	pH	Water table m	Soil type	N.B
Kalajoki	Rauhala	13.0-111.0			5.5-6.5	0.4-0.7	sand	
	Kivioja	53.0-66.0		1.3	6.2-6.4	0.9-1.0	sand	
Pyhäjoki	Pirkola	34.8			5.7	0.6	sand	
Ruukki	Agr.Res.St.	2.3-22.8		0.43-4.3	5.3-5.9	0.7-1.1	sand	
	Isohuumola	2.8	2.5	0.29	4.5	0.8	sandy loam	artesian water
	Roppola	3.5	3.8	0.67	5.7	0.7	silty clay loam	
Liminka	Heikkilä	14.0-46.0		0.96	6.1	0.7-1.2	sand	
	Jurvala	1.0-11.8	1.0	1.3	4.5	0.9-1.0	silty clay loam	
Tyrnävä	Potato Res.St.	14.3-26.0	13.0	1.0	4.5-4.7	0.8-0.9	silty loam	
	Kotila	1.6	2.5		5.9	0.5	sand	
	Jokela	7.4-50	9-50		3.3-3.5	1.0	silty loam	
	Eriika	1.3			6.6	1.0	silty loam	
Paltamo	Hannila	9.4-22.2			3.5-4.8	0.2	silty clay loam	artesian water
Tornio	Mörtti	2.3-25.8			5.2-6.6		silty loam	
Average		23.2			5.5	0.7		
Range		1.0-111.0	1.0-50	0.29-4.3	3.3-6.6	0.2-1.2		

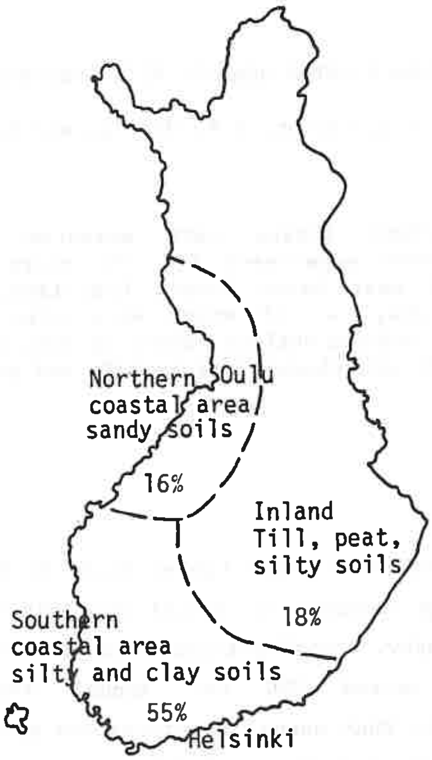

Figure 1. The main soil and types the percentage of subsurface drainage fields in the different parts of Finland

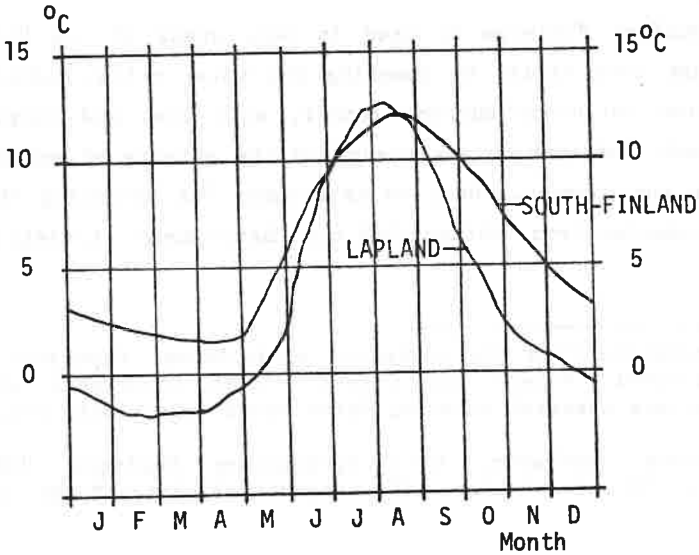

Figure 2. Soil temperature at a depth of 1 meter in Southern and Northern Finland

IMPROVING SURFACE WATER QUALITY WITH SUBSURFACE DRAINAGE[1]

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Abstract

Sediment and nutrient losses were measured from a subsurface drainage-runoff-erosion experiment for the years 1981 to 1985. The experiment, located near Baton Rouge, Louisiana, consisted of four surface drained plots, two of which were also subsurface drained. Subsurface drainage reduced surface runoff by 32%, soil loss by 30%, nitrogen loss by 19%, phosphorus loss by 33%, and potassium loss by 30%.

1 Introduction

Severe problems with high water tables exist in the Lower Mississippi Valley due to large amounts of annual precipitation and low lying, nearly level topography. Annual precipitation usually exceeds 150 cm and may occasionally exceed 200 cm. Annual evapotranspiration is approximately 100 cm, thus annual precipitation exceeds evapotranspiration by 50 to 100 cm. A portion of this excess water infiltrates the soil and frequently causes the water table to rise to near the soil surface for extended periods of time. This high water table reduces crop yields and causes soil and nutrient losses due to increased surface runoff.

Subsurface drainage is used in many areas of the United States to increase crop yields by lowering the water table. Subsurface drainage may also influence surface runoff, soil loss and nutrient loss from cropland. Information was needed on the effects of subsurface drainage on the environment, thus, an experiment for obtaining this information was conducted from 1981 to 1985 near Baton Rouge, Louisiana. The

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objectives of this experiment were to evaluate the effectiveness of subsurface drainage on (a) reducing surface runoff, (b) reducing soil erosion, and (c) reducing total nitrogen, phosphorus and potassium losses.

2 Literature Review

Mackenzie and Viets (1974) reported that the composition and concentration of materials contained in surface drainage waters differ from those found in subsurface drainage waters. Surface drainage water passes quickly over the soil surfaces without infiltrating into the soil. The surface drainage water contains suspended as well as soluble materials brought into dissolution through suspension, erosion, and solution from brief contact with soil, plants, and plant residues. The slow movement of subsurface drainage water percolating through the soil affords intimate and long contact with clays, organic matter and microorganisms. Soluble nutrients and other chemicals applied to or contained in soils may be dissolved by soil water and leached from the soil profile. On the other hand, some materials will be removed from solution by adsorption and may form precipitates. The composition of subsurface drainage water may depend on the aeration status of the soil being drained. Water from a drain that flows continuously from a saturated soil profile may have a different composition than water from a drain that flows only intermittently and is exposed to aerated soil.

Schwab et al. (1980) measured an average sediment loss of 2548 kg/ha from plots with surface drains only and 1529 kg/ha from plots with one meter deep drains, a reduction of 40% due to subsurface drainage. Annual losses of 12.1, 2.2, and 31.6 kg/ha nitrate nitrogen, total P, and total K, respectively, occurred with surface drains only. Corresponding losses from areas with one meter deep drains were 18.7, 1.2, and 22.5 kg/ha, for nitrate nitrogen, total P and total K. Subsurface drainage increased the loss of nitrate nitrogen by 54% and reduced the loss of total P and K by 45 and 29%, respectively.

Bottcher et al. (1981) measured a mean annual sediment loss of 94.0 kg/ha from a subsurface drained area near Woodburn, Indiana. Mean annual nitrogen and phosphorus losses were 8.66 and 0.22 kg/ha, respectively. Approximately 70% of the phosphorus loss was associated with sediments compared to 10% for nitrogen. The analysis showed that losses of sediment and nutrients were reduced by subsurface drainage. They recommended that on suitable soil types, subsurface drainage may well be the preferred best management practice for water quality control.

Schwab and Logan (1982) reported that in Ohio; sediment, phosphorus, and potassium losses from tile outflow were considerably less than from surface runoff, but the nitrate losses were higher. In general, on medium to heavy textured soil on slopes of less than 2%, subsurface drains reduced soil erosion and the loss of plant nutrients except nitrogen.

3 Procedure

A 4.4 ha site on Commerce clay loam soil, which had been precision graded to 0.1% slope several years earlier, was selected for this experiment. The area, located 6 km south of Baton Rouge, Louisiana, was partitioned into four plots, each about 200 m long. Earth dikes at least 30 cm high were constructed around each plot to define the plot boundaries and to insure that runoff passed through the flumes where it could be measured and sampled. Plots 1 and 3 were about 0.7 ha in size and plots 2 and 4 were about 1.5 ha.

Subsurface drains were installed in plots 1 and 2 using a ladder type trencher. In each of these plots, three 10 cm diameter, corrugated, perforated, polyethylene drain tubes were installed one meter below the soil surface on a grade of 0.1%. The drains were spaced 10 m apart in plot 1 and 20 m apart in plot 2. The drain outflow was discharged into 1.2 X 1.2 X 3 m metal sumps and pumped into a surface drainage ditch by electric pumps. In summary, two plots contained both surface and subsurface drainage (drained plots) and two control plots contained surface drainage only (nondrained plots).

Hydrological parameters measured during the experiment included rainfall, surface runoff, drain outflow, and water table elevations. Rainfall was measured with a weighing type recording rain gage; surface runoff was measured with H-flumes and water stage recorders; drain outflow was measured with utility-type water meters as outflow was pumped from the sumps; and water table elevations were measured with a water stage recorder with its float inside a 20 cm diameter by 1.2 m deep cased well in each plot.

Surface runoff was sampled at 20 minute intervals with an automatic water sampler installed at each flume. Outflow from the center drains from plots 1 and 2 was sampled using the grab technique. Runoff and drain outflow samples were analyzed in the laboratory for sediment, nitrogen, phosphorus, and potassium. Total nitrogen was determined by an automated method developed by Wall and Gehrke. Sample preparation for P and K were by method 2.020 (Horwitz, 1980). Phosphorus was determined by method 2.025 and potassium was determined by the atomic absorption method 3.006 described in Horwitz (1980).

Corn was planted in April each year. It was fertilized at planting with 217, 38, and 76 kg/ha of N, P, and K, respectively. The corn was cultivated once in May each year to control weeds and was harvested for silage in late July. The plots were cultivated periodically from harvest until frost to control weeds and Johnsongrass.

4 Results and Discussion

From 1980 to 1985, the average annual rainfall was 1458 mm (Table 1) which was 106 % of normal. The annual rainfall ranged from a high of 1811 mm in 1983 to a low of 1162 mm in 1984. Each of the months of February, April, May, June, August, September, and December had average rainfalls greater than 125 mm.

The average annual surface runoff was 277.0 and 404.4 mm (Table 1) for the drained and nondrained plots, respectively. The subsurface drains reduced surface runoff by 32%. However, when the average annual subsurface discharge of 248.4 mm from the 20 m spaced drains was included, 525.4 mm of water left the plots. This meant that 30% more water left the drained plots than the nondrained plots. The surface runoff from the drained and nondrained plots was 19% and 28% of the rainfall, respectively. The hydrographs were analyzed to determine the time during a runoff event when the runoff amounts from the plots with and without subsurface drains differed. Surface runoff differences occurred during the recession portion of the hydrograph. Surface runoff lasted an average of 6 hours longer on the nondrained plots.

Subsurface drainage also reduced soil and nutrient losses. From 1981 to 1985, surface runoff carried an annual average of 3025.2 kg/ha of sediment from the drained plots (Table 2). Subsurface discharge accounted for 372.7 kg/ha or 11% of the total loss which was 3398.0 kg/ha. The nondrained plots lost 4870.8 kg/ha of soil for a 30% reduction due to subsurface drainage. The largest portion of the soil was lost in April and December when 38% of the average annual loss left the fields.

The average annual total nitrogen losses from the drained and nondrained plots were 6.65 and 8.20 kg/ha (Table 3), respectively, for a 19% reduction due to subsurface drainage. The subsurface discharge contained 1.98 kg/ha or 30% of the total N lost from the drained plots. It should be noted here that the grab sampling technique used may have biased the results. The majority of the nitrogen (57%) loss occurred in April and May, the period with intense rainfall soon after the application of nitrogen fertilizer. Nitrogen loss did not correlate well with surface runoff or sediment loss. The correlation coefficient between surface runoff and nitrogen loss was 55% and between sediment loss and nitrogen loss was 45%. Nitrogen loss is most sensitive to fertilizer application in that rainfall soon after nitrogen is applied results in high N losses.

The potassium losses from the drained and nondrained plots were 31.65 and 45.51 kg/ha (Table 4), respectively, for a 30% reduction due to subsurface drainage. The subsurface discharge contained 3.00 kg/ha or 9% of the drained plots' total. The largest monthly loss was in April when 22% of the annual total loss occurred. However, unlike nitrogen, the losses occurred throughout the year. For example, 23% of the total potassium was lost during the winter as opposed to only 16% of the nitrogen. The amounts of potassium loss are correlated with the amounts of surface runoff and soil loss with a correlation coefficients of 78% and 94%.

The average annual phosphorus losses from the drained and nondrained plots were 5.31 and 7.92 kg/ha (Table 5), respectively, for a 33% reduction due to subsurface drainage. The subsurface discharge contained 0.35 kg/ha or 7% of the lost phosphorus. The greatest monthly loss (21% of the annual total) occurred during April when 23% of the soil was lost. Also 27% of the phosphorus was lost during the winter. There is a highly significant relationship between phosphorus and soil losses. They were correlated with a correlation coefficient of 85%. However, phosphorus did not correlate as well with surface runoff; the correlation coefficient was 59%. Wetzel (1975) listed increased phosphorus loading as the major cause of rapid lake eutrophication. He concluded that algae in lakes could be reduced by decreasing phosphorus loading. Since subsurface drainage was very effective in reducing phosphorus loading, it should be considered a "best management practice" for improving the quality of the water coming from watersheds with heavy textured soils with slopes of less than 2% with high water tables.

5 Summary and Conclusions

Subsurface drainage reduced surface runoff by 32%. The associated reduction in losses of soil (sediment), nitrogen, potassium, and phosphorus were 30, 19, 30, and 33 percent, respectively. Losses of phosphorus and potassium were correlated to the loss of surface soil.

Based on the study, we conclude that:

1. Subsurface drainage reduces surface runoff, soil and nutrient loss by substantial amounts.
2. A complete subsurface drainage system on certain soil types may be the preferred "best management practice" for improving the quality of water leaving agricultural watersheds.

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TABLE 1
AVERAGE MONTHLY RAINFALL AND RUNOFF
1981 to 1985

Month	Rainfall**	Runoff Drained Plots Surface	 Subsurface*	 Total	 Nondrained Plots Surface
	mm				
January	89	12.9	34.5	47.4	23.5
February	136	42.0	59.2	101.2	76.3
March	104	4.8	19.0	23.8	10.1
April	138	32.1	23.1	55.2	45.4
May	127	12.1	17.0	29.1	22.1
June	138	25.2	11.7	36.9	34.5
July	111	19.8	2.8	22.6	12.9
August	146	34.0	6.4	40.4	45.5
September	129	18.4	9.4	27.8	23.8
October	118	27.3	12.4	39.7	42.7
November	75	8.9	6.9	15.8	10.7
December	147	39.5	46.0	85.5	56.9
Total	1458	277.0	248.4	525.4	404.4

* 20 m Spacing Drained Plot

** Normal Annual Rainfall = 1373 mm.

TABLE 2
AVERAGE MONTHLY SOIL LOSS
1981 to 1985

Month	Soil Loss Drained Plots Surface	 Subsurface	 Total	 Nondrained Plots Total
	kg/ha			
January	178.8	45.9	224.7	375.1
February	195.1	89.0	284.1	693.0
March	43.8	11.6	55.4	122.0
April	757.7	33.6	791.3	937.9
May	139.6	30.7	170.3	208.2
June	165.1	9.7	174.8	247.9
July	264.7	0.2	264.9	236.5
August	315.3	12.9	328.2	268.0
September	207.3	17.1	224.4	293.5
October	305.9	41.0	346.9	776.6
November	5.2	13.3	18.5	51.8
December	446.8	67.7	514.5	660.3
Total	3025.2	372.7	3398.0	4870.8

TABLE 3
AVERAGE MONTHLY NITROGEN LOSS
1981 to 1985

Month	Nitrogen Loss Drained Plots Surface	 Subsurface	 Total	 Nondrained Plots Total
	kg/ha			
January	0.17	0.11	0.28	0.25
February	0.13	0.20	0.33	0.32
March	0.05	0.02	0.07	0.41
April	2.25	0.61	2.86	3.55
May	0.49	0.43	0.92	1.80
June	0.50	0.24	0.74	0.56
July	0.23	0.02	0.25	0.12
August	0.09	0.01	0.10	0.12
September	0.35	0.03	0.38	0.36
October	0.19	0.08	0.27	0.24
November	0.01	0.01	0.02	0.04
December	0.21	0.22	0.43	0.43
Total	4.67	1.98	6.65	8.20

TABLE 4
AVERAGE MONTHLY POTASSIUM LOSS
1981 to 1985

Month	Potassium Loss Drained Plots Surface	 Subsurface	 Total	 Nondrained Plots Total
	kg/ha			
January	1.01	0.26	1.27	3.16
February	1.42	0.75	2.17	5.41
March	0.21	0.08	0.29	1.71
April	6.86	0.19	7.05	8.91
May	1.16	0.11	1.27	1.89
June	1.93	0.33	2.26	3.13
July	4.65	0.04	4.69	3.82
August	3.09	0.04	3.13	3.22
September	1.45	0.06	1.51	2.42
October	3.65	0.45	4.10	5.69
November	0.06	0.01	0.07	0.23
December	3.16	0.68	3.84	5.92
Total	28.65	3.00	31.65	45.51

TABLE 5
AVERAGE MONTHLY PHOSPHORUS LOSS
1981 to 1985

Month	Phosphorus Loss Drained Plots Surface	 Subsurface	 Total	 Nondrained Plots Total
	---------------------kg/ha	----------------------	----------------------	----------------------
January	0.28	0.05	0.33	0.86
February	0.41	0.08	0.49	1.81
March	0.10	0.03	0.13	0.20
April	1.09	0.04	1.13	1.53
May	0.17	0.00	0.17	0.24
June	0.18	0.00	0.18	0.32
July	0.99	0.00	0.99	0.67
August	0.51	0.00	0.51	0.44
September	0.22	0.00	0.22	0.28
October	0.47	0.04	0.51	0.58
November	0.01	0.01	0.02	0.04
December	0.53	0.10	0.63	0.95
Total	4.96	0.35	5.31	7.92

AGRICULTURAL CHEMICAL LOSSES THROUGH SUBSURFACE DRAINS FROM AGRICULTURAL WATERSHEDS AND THEIR IMPACTS ON WATER QUALITY*

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Abstract

Leaching of farm chemicals, especially nitrate-nitrogen and pesticides, through subsurface drains in agricultural areas of the world is of growing concern because of the effect on water resources quality. This paper presents data from field experiments on the quality of subsurface drainage from cropland and its influence on surface and groundwater quality. Management practices to improve the quality of subsurface drainage water are briefly discussed.

Introduction

The intensive use of agricultural chemicals to improve crop yields has increased water quality concerns in recent years. Agricultural activities on the land are being recognized by the public as a potential cause of water pollution. A report prepared by the U.S. Environmental Protection Agency (1984) indicates that virtually all U.S. states have water-quality problems caused by nonpoint sources, and agricultural sources are identified as the most pervasive in every region. Kanwar (1985), Baker and Johnson (1983, 1980) among others have reviewed the impacts of agricultural practices on water quality.

Surface and subsurface water sources have always contained nutrients required by plants. The increased application of plant nutrients in agriculture through use of fertilizer potentially contributes more nutrients

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to water sources because plants do not absorb all the nutrients available to them. The major chemicals of concern in agricultural drainage water are nitrogen, phosphorus, and pesticides. Nitrate-nitrogen (NO_3-N) contamination of drainage water may originate from nitrogen fertilizers, soil organic matter, crop residue, manure, and other sources. Many pesticides that have helped increase agricultural production are found in trace (µg/L) concentrations in groundwater. But, despite the presence of certain pesticides in some groundwater supplies at or near health-advisory concentration, few verified adverse health effects are on record (CAST, 1986). However, several problems with one particular insecticide, aldicarb, have been documented (Holden, 1986).

Pesticides and NO_3-N are potentially hazardous pollutants when present in drinking water supplies at sufficiently high concentrations (U.S. Environmental Protection Agency, 1982). Potential water-quality effects of NO_3-N include stimulation of excessive plant growth and toxicity to human infants. There are no water-quality criteria related to the role of nitrogen in stimulating plant growth, but the human-health criterion for NO_3-N in drinking water supplies in the United States is 10 mg/L (U.S. Environmental Protection Agency, 1982).

Providing artificial subsurface drainage is a necessary water management practice to increase the productivity of poorly drained soils of the United States in general and the upper midwest in particular. Without good artificial drainage, not only is the timeliness of planting and harvesting operations hindered, but poor growing conditions in very wet years may result in total crop failure (Kanwar et al. 1983b and 1984b). The use of subsurface drainage to remove excess soil water from intensively cropped areas (receiving applications of fertilizers and pesticides) also increases the chances of removing soluble chemicals through the subsurface drains. The quantity and quality of subsurface drainage waters discharged from agricultural watersheds depend on soils, crop and tillage management practices, precipitation patterns, and the types of subsurface drainage system used. The chemicals that leave the agricultural watersheds with subsurface drainage waters are considered to be water pollution sources and environmental concerns. Therefore, the purpose of this paper is to provide background data on the loss of NO_3-N, pesticides and other farm chemicals through subsurface drains and to examine the overall impact on water quality associated with the waters discharged from subsurface drainage systems.

Farm Chemical Losses Through Subsurface Drains

Nitrate-Nitrogen (NO_3-N)

Several studies have been conducted in the United States on NO_3-N losses through subsurface drains (tiles), and as might be expected from the wide range of study conditions, the results are highly variable (Baker et al., 1975; Baker and Johnson, 1981; Baker and Austin, 1984; Bottcher et al. 1981; Burwell et al. 1976; Gast et al. 1978; Gold and Loudon, 1982. Hallberg et al. 1984; Hanway and Laflen, 1974; Kanwar et al. 1983; Logan et al. 1980; Randall and Nelson, 1985; Schwab et al. 1973, 1980; and Schwab and Logan, 1982). The results of these studies have supported the public concern that the increased use of nitrogen fertilizers on agricultural watersheds is a major cause of the increased NO_3-N levels in streams and groundwater

As early as 1969, Willrich reported high levels of NO_3-N in tile effluent in Iowa, with concentrations ranging from 1 to 66 mg/L in 10 different tile drainage outlets. Hallberg et al. (1984) reported total NO_3-N losses with subsurface drainage water ranging from 31 to 49 kg/ha/yr in the Karst area of northeastern Iowa. In another Iowa study, Hanway and Laflen (1974) found that NO_3-N concentrations and losses in tile drainage water were sometimes high and varied widely, but the concentrations in the drainage water were not directly related to the amounts of fertilizer applied. Baker et al. (1975) found that with modest fertilization of 112 kg N/ha/yr on corn, rotated with unfertilized oats and soybeans, NO_3-N concentrations in subsurface drainage water averaged 21 mg/L. They also concluded that the loss of NO_3-N through subsurface drains was highly tile flow dependent, and it was not possible to assign NO_3-N losses to the use of fertilizer alone.

Table 1 presents the data from this 1975 study and from a follow-up study for the period 1970-78 (Baker and Johnson, 1981). These data come from two plots established on silt loam soil and drained by 10-cm diameter clay tile drains installed at a depth of 1.2 m. The area of each plot was about 0.42 hectare. The results of this study show that annual NO_3-N loss from tile area no. 1 (receiving an average of 89 kg N/ha/yr) was about 36 kg/ha/yr, with an average NO_3-N concentration in the drain water of 31 mg/L. The average annual NO_3-N loss from tile area no. 2 (receiving an average of 56 kg N/ha/yr) was about 28 kg/ha/yr, with an average NO_3-N concentration

Table 1. Measured annual subsurface drain flow and NO_3-N in subsurface flow.

Year	Crop	Annual Precipitation, cm	N-Application Rate, kg/ha		Subsurface drain flow, cm		NO_3-N in Subsurface flow, kg/ha	
			TILE 1	TILE 2	TILE 1	TILE 2	TILE 1	TILE 2
1970	Corn	90.4	112	112	7.3	9.0	10.9	14.2
1971	Oats	70.8	0	0	0.0	0.1	0.0	0.1
1972	Corn	94.3	112	112	10.7	18.7	29.9	44.9
1973	Soybeans	115.6	0	0	24.8	37.4	42.2	61.6
1974	Corn	94.7	250	100	18.1	21.6	31.3	32.2
1975	Soybeans	77.2	0	0	14.6	16.7	71.6	40.4
1976	Corn	60.0	240	90	8.4	9.3	31.9	21.4
1977	Oats	94.3	0	0	10.9	9.0	67.2	18.0
1978	Corn	88.7	90	90	10.1	11.4	37.6	21.0
Total		786.0	804	504	104.9	133.2	322.2	253.8
Average		87.3	89.3	56	11.7	14.8	35.8	28.2

in the subsurface drain water during the follow-up study of 19 mg/L. These results indicate that larger N-fertilizer applications do result in larger NO_3-N losses through subsurface drainage water.

Table 2 shows similar results for NO_3-N losses through subsurface drains from another long-term field experiment, this one in Minnesota conducted by Randall and Nelson (1985) on clay-loam soils for continuous corn production. They measured NO_3-N losses through subsurface drains from differentially fertilized plots for 1973-84. The data given in Table 2 show that larger applications of N resulted in larger NO_3-N losses through tile drains, and these losses amounted to about 21 to 23 percent of the applied N during the period of 1973-79 when the plots received 112, 224 and 448 kg N/ha/yr. This table also shows that significant amounts of NO_3-N were found in the subsurface drainage water during the 1980-84 period even though plots received no N-fertilizer from 1980-83 and only 45 kg N/ha in 1984. Application of 224 and 448 kg N/ha/yr resulted in much increased NO_3-N concentrations in the tile drainage water,increased losses through the tile, and greater NO_3-N accumulations in the soil profile. The results of this study also support the findings of Baker et al. (1975) that artificial subsurface drainage would be expected to result in the movement of NO_3-N from agricultural fields even in years when no N-fertilizer was applied. Zwerman et al. (1972) collected data that showed that NO_3-N concentrations in the tile water from areas receiving 243 kg N/ha/yr were significantly greater than from the areas receiving 86 kg N/ha/yr; the differences in tile flow rates, however, were not significantly high.

The large NO_3-N leaching losses with subsurface drainage waters are important because tile drainage water can be a significant portion of the stream or river water, especially during lower flows. Harmeson et al. (1977) reported that very high NO_3-N concentrations were found in river waters during lower flows, which was attributed to the subsurface drainage waters from the intensely cropped watersheds.

In certain areas of the United States, NO_3-N contamination of subsurface drainage is a growing concern because subsurface drainage can represent the quality of water directly recharging aquifers. Subsurface drainage waters are also entering the deeper groundwater aquifers via drilled agricultural drainage wells (Baker and Austin 1984; Baker et al. 1985) or sinkholes (Hallberg et al. 1984). Agricultural Drainage wells (ADWs) provide

Table 2. NO_3 losses through subsurface drains as a function of time and rate of N application from 1972 to 1984 at Lamberton, Minnesota, U.S.A. (Randall and Nelson, 1985).

Plot No.	Total N-fertilizer applied, kg/ha (1973-79)*	Total NO_3-N lost with subsurface drainage water during 1972- 84, kg/ha**	% of applied N lost w/ subsurface drainage water for two periods	
			1973-1979	1980-1984
1	141	187	-	-
2	785	335	23	20
3	1569	603	21	17
4	3138	1430	23	23

*Annual N rates of 20.2, 112.1, 224.2, and 448.3 kg were applied from 1973 to 1979. No application of N was made between 1980 and 1983, 45 kg/ha of N was applied in 1984. This column does not include the 45 kg/ha of N applied in 1984.

**21.38 hectare-cm of drain flow during the period 1973-79 and 44.2 hectare-cm of drain flow in 1980-84.

outlets for subsurface drains in areas where other outlets do not exist. Baker et al. (1985) found that the NO_3-N concentrations in water entering these wells exceeded the 10 mg/L standard for 85 percent of the samples taken. Sampling of farm drinking water wells in the vicinity of ADWs indicated that NO_3-N in drainage water increased the NO_3-N levels in the local aquifers.

The subsurface drainage water that is not intercepted by subsurface drains will eventually percolate down and join the deeper groundwater sources. The actual amount of NO_3-N leached to the deeper groundwater sources will depend on the infiltration recharge, its NO_3-N concentration, and any attenuation that takes place enroute. Agricultural watersheds are considered to be the largest nonpoint sources of elevated NO_3-N levels in groundwater (Madison and Brunett, 1984). Although NO_3-N can enter the groundwater systems from a variety of sources, the principal sources are natural soil nitrogen and nitrogen from agricultural and industrial activities. Madison and Burnett (1984) also reported that 40 percent of the sampled wells in Wisconsin and 16 percent of the sampled wells in the predominantly agricultural state of Nebraska had NO_3-N concentrations in excess of 10 mg/L.

Table 3 summarizes subsurface drain flow and NO_3-N concentration data for studies in various midwestern states of the United States as a function of different agricultural activities in the watersheds. These data show that NO_3-N concentrations in subsurface flow from intensively row-cropped areas usually exceed the 10 mg/L drinking water standard, and losses commonly exceed 20 kg N/ha/yr. It is also evident, as previously discussed, that the higher the application rates, the higher NO_3-N concentrations and losses through subsurface drainage.

Pesticides

After pesticides are applied on plants and soil, water is the principal agent for their further movement. Water transports pesticides by eroding the soil and by dissolving pesticides. Water, and pesticides dissolved in it, may seep through the soil to reach the subsurface drains or recharge the groundwater. Bottcher et al. (1981) detected a herbicide (Lasso) and an insecticide (Furadan) in tile drainage water. They concluded that these two chemicals must have passed fairly directly through the soil profile to the tile drains, since these chemicals are normally adsorbed by the soil. However, the total loss of these two chemicals through subsurface drainage water was only on the order of one percent of that applied. Schwab et al. (1973) found 2 to 6 percent of the applied atrazine and 2 to 7 percent of applied dicamba in the tile drainage water. Nearly insignificant quantities (less than 0.01 percent) of aldrin and dieldrin, and heptachlor and heptachlor eposide were also found by Schwab al. (1973) in the tile drainage water.

Muir and Baker (1976) monitored the concentration of the herbicides cyanazine, cyprazine, atrazine and metribuzin in tile drainage water. They found a maximum of 1.5 ug/L of atrazine in tile water after a heavy rain 6 days after herbicide application. Gold and Loudon (1982) observed atrazine concentrations in tile water generated by a heavy rainstorm of 0.5 to 4.0 ug/L before planting and 80 to 170 ug/L 4 days after planting and atrazine application. The high tile flows evidently caused the early appearance of atrazine in the drain water at these higher than normal concentrations.

Hallberg et al. (1984) reported that several pesticides (atrazine, cyanazine, alachlor, metalachlor and fonofos) entered the groundwater through subsurface recharge. They also observed that on the average 0.5 and 0.2 ug/L of atrazine and alachlor, respectively, were present in

Table 3. NO_3-N in subsurface flow from agricultural watershed in the midwestern states of the United States.

State	Crop and fertilizer management practices in the watershed	Subsurface flow, cm	NO_3-N concentration, mg/1	Reference
Iowa	Corn-oats-corn-soybean rotation 56 kgN/ha/yr	14.8	21.0	Baker & Johnson, 1981
	Corn-oats-corn-soybean rotation, 87 kgN/ha/yr	11.7	40.5	Baker & Johnson, 1981
	Continuous corn, conv. tillage 448 kgN/ha/yr	11.8	5.8	Burwell et al., 1976
	Continuous corn, conv. tillage, 168 kgN/ha/yr	9.9	21.0	Burwell et al., 1976
	Continuous corn, terraced, conv. tillage, 448 kgN/ha/yr	17.6	20.0	Burwell et al., 1976
	Corn and soybean rotation	7.3	13.0	Hanway & Laflen, 1974
	Mixed cover watersheds	-	12.1	Baker et al., 1978
	Mixed cover watersheds	-	19.0	Willrich, 1969
Minnesota	Continuous corn, 20 kgN/ha/yr	7.8	17.5	Gast et al., 1978
	Continuous corn, 112 kgN/ha/yr	8.2	21.5	Gast et al., 1978
	Continuous corn, 224 kgN/ha/yr	8.3	37.3	Gast et al., 1978
	Continuous corn, 448 kgN/ha/yr	9.3	61.2	Gast et al., 1978
Illinois	Mixed (corn and soybeans), 168 kgN/ha/yr on corn	-	9.0(2-14)	Duffy et al., 1975
	Mixed cover watersheds	-	5-22	Harmeson et al., 1971
Ohio	Corn-soybean-oats rotation, 93 kgN/ tillage, 84 kgN/ha/yr	18.4	30.1	Schwab et al., 1973
Michigan	Corn-soybean rotation, conserv. tillage, 84 kgN/ha/yr	16.6	6.1	Gold & Loudon, 1982
	Corn-soybean rotation, conserv. tillage, 84 kgN/ha/yr	13.7	6.4	Gold & Loudon, 1982

in subsurface flow in the Big Spring basin of northeastern Iowa.

Table 4 presents data on the water quality parameters of water entering agricultural drainage wells in central Iowa (Baker and Austin, 1984). There were marked differences in the concentrations of pesticides between subsurface and surface drainage waters. As shown in Table 4, several pesticides were found in subsurface drainage water, but the concentrations were either less than 1 ug/L or below the limit of detection (about 0.01 ug/L). Pesticide concentrations were highest in samples taken soon after rainfall when surface drainage or preferential flow through larger pores could be an influence.

Phosphorus

The principal adverse effect of phosphorus (P) on water quality is the stimulation of excessive aquatic plants. The U.S. Environmental Protection Agency (1984) has suggested that total P concentrations generally should not exceed 0.05 mg/L in rivers if they enter a lake or reservoir and 0.10 mg/L elsewhere in the river. Phosphorus movement in soils is largely due to the orthophosphate (PO_4^{-3}) ion; however, this ion can form insoluble salts with cations such as Mg^{+2}, Ca^{+2}, Ca^{+2}, Al^{+1}, and Fe^{+3}. Therefore, PO_4-P concentrations in soil solutions usually are less than 0.1 mg/L; and the PO_4^{-3} ion is not as readily leached through soil (except sand) as some other negative ions (Baker et al., 1978). P fertilizers remain close to the point where applied (usually in the top 10 cm).

Schwab et al. (1973) reported that soluble P in all drainage water was less than 1.12 kg/ha/yr, and the average total P concentration in the tile drainage water was less than 0.6 mg/L. Baker et al. (1975) found that the annual P losses with subsurface drainage water were negligible because PO_4-P concentrations of individual tile water samples ranged from 0 to only 30 ug/L. Hanway and Laflen (1974) reported similar findings (PO_4-P concentrations of 11 ug/L) because subsoil layers through which water must move to reach the subsurface drain were generally low in PO_4-P. Schwab et al. (1980) reported that the average total losses of P with pipe drainage water ranged from 0.8 to 1.2 kg/ha/yr. Bottcher et al. (1981) reported average annual P losses of 0.22 kg/ha/yr with tile drainage water. Baker et al. (1985) also found very low concentrations of PO_4-P in the agricultural drainage waters (Table 4) and concluded that the presence of PO_4-P in the drainage water is not a great water quality concern.

Table 4. Concentrations of nutrients, pesticides, and bacteria in water entering the four monitored agricultural drainage wells located in central Iowa.

Constituent	Average concentrations in well no.			
	1	2	3	4
NO_3N, mg/L	10.8	14.8	20.1	17.9
NH_4N, mg/L	0.14	0.12	0.39	0.06
PO_4P, mg/L	64.0	183.0	333.0	180.0
Cl, mg/L	7.6	40.1	36.0	29.0
Ca, mg/L	47.0	121.0	110.0	96.0
Ee, mg/L	0.15	0.11	0.24	0.14
Atrazine, ug/L	0.02	0.01	0.01	0.03
Cyanazine, ug/L	11.8	0.43	0.54	0.49
Alachlor, ug/L	0.15	0.21	3.01	0.08
Dieldrin, ug/L	0.004	0.001	0.001	0.001
Metribuain, ug/L	0	0	0.06	0
Dicamba, ug/L	0.11	0.21	0.78	0.12
Fecal Coliform, #/100 mL	105	23	15,800	134
Total Coliform #1/100 mL	24,800	860	32,100	460

Other Chemicals

Other major inorganic compounds of dissolved solids found in the subsurface drainage waters are Na, K, Ca, Mg, CO_3, HCO_3, Fe and SO_4 ions (Schwab et al. 1973 Baker et al. 1975; Schwab et al. 1980; Schwab and Logan, 1982; and Baker et al. 1985). The major sources of these consitituents in agricultural watersheds are the mineral substances in soil, organic matter, rainfall, and agricultural fertilizers. When water percolates through the subsoil, it can dissove solids and leach them through to subsurface drains. The presence of these dissolved solids in high concentrations in water sources can result in increased water treatment costs for municipalities and industrial users.

Schwab et al. (1973) found generally higher losses of K, Cl, Na, Ca, Mg, S, and HCO_3 as 4.5, 24, 13, 188, 59, 64, and 125 kg/ha/yr, respectively in subsurface drainage water. Baker et al. (1975) observed SO_4-S losses of about 20 kg/ha/yr through subsurface drains. Schwab et al. (1980) reported losses of K, Na, Ca, and Mg in tile drainage water as 33, 50, 345, and 106 kg/ha/yr, respectively. Baker el al. (1985) also reported that quite large quantities of C1 and Ca are entering into the groundwater systems through agricultural drainage wells.

Water Quality Impacts

From a water quality viewpoint, nutrient and pesticide concentrations as well as the total quantities lost through subsurface drainage systems are important concerns, both for those making agricultural management decisions and for subsequent water users. The current domestic water-supply criterion in the United States for NO_3-N is 10 mg/L. A limited number of pesticides have established water-supply criteria, such as 100 ug/L for 2,4-D; 100 ug/L for methoxychlor; 10 ug/L for 1, 4, 5-TP; 5 ug/L for toxaphene; 4 ug/L for lindane; and 0.02 ug/L for endrin. For others, such as aldrin/dieldrin, chlordane, DDT, and Heptachlor, the U.S. Environomental Protection Agency suggests that persistance, bioaccumulation potential, and carcinogenicity call for caution for minimum human exposure. Criteria have not been established for any of the six most-used insecticides in Iowa and have been established for only one (2,4-D) of the 13 most used herbicides (Baker et al. 1985).

The primary sources of nitrogen in rivers of agricultural watersheds are agricultural and sewage effluents. The quantity and quality of subsurface drainage waters is important because, in most cases, it is discharged to streams and rivers. Except during surface-runoff periods from heavy rains, tile drainage water can represent a significant portion of the stream flow. Baker and Johnson (1981) reported that the amount of water annually intercepted by two subsurface drains for a 9-year period (1970-78) averaged 13.2 cm/yr (also given in Table 1). Annual stream flow for the Skunk River, draining an 83,000-ha north-central Iowa watershed, two-thirds of which is tile drained and intensively cropped, averaged 24.1 cm for the same 9-year period. The stream flow, which includes surface runoff and drainage from both tile and deep percolation, correlated well with measured tile flow. This indicates that the quality of subsurface drainage waters would very much affect the quality of a stream such as the Skunk River, which receives such drainage flows. In Iowa, NO_3-N concentrations of as high as 10 mg/L have been observed recently in water from the Des Moines River, which also drains an intensively cropped, very large agricultural watershed.

Chichester (1976) sampled a number of spring and stream base flow sites within a 123-ha drainage watershed to assess the contribution of subsurface drainage to nitrogen content of stream base flows. This study concluded that the effect of N-fertilizer application to upland agricultural watersheds on downstream water quality is shown to be dependent upon subsurface water flow rates.

Madison and Brunett (1984) have reported that many of the highest mean NO_3-N concentrations in U.S. rivers are in the Mississippi River and its tributaries, which drain intensely farmed watersheds that receive heavy nitrogen applications and produce large quantities of nitrogen-rich livestock wastes. All these reports and studies suggest that subsurface drainage waters are sources of NO_3-N water pollution and influence the quality of receiving waters.

Model simulations, using 23 years of precipitation data and assuming annual applications of atrazine to continuous corn, predicted atrazine concentrations in total drainage (surface runoff plus subsurface flow) of 9.2 ug/L (Kanwar et al., 1986). This value (also close to the measured value by Baker et al 1985) is at least 20 times lower than the proposed criterion.

Farm Management Practices to Reduce Chemical Losses

There is a need for improved management practices to reduce the chemical losses in water percolating to subsurface drains and to groundwater. Under the present economic conditions, only a limited number of alternatives may be available. Lower chemical application rates, better application timing, use of multiple applications, incorporation of chemicals, and better methods of application might be used to reduce chemical leaching. Conservation tillage may also have some benefits.

Conservation tillage has been used successfully to increase the infiltration rates, which could actually enchance leaching. In one instance, however, Kanwar et al. (1985) have shown that the amount of NO_3-N leaching under no-till conditions was far less than under moldboard plowing. Therefore, by selecting the right conservation tillage system along with better nitrogen management practices in agricultural watersheds, NO_3-N losses to the subsurface drainage and groundwater systems could be reduced.

NO_3-N leaching losses to subsurface drains could be reduced by better timing the application of N-fertilizers to match crop needs. Kanwar et al. (1984) conducted simulation studies and predicted that NO_3-N losses through subsurface drains can be significantly reduced either by using lower N-application rates or by using multiple N applications during the growing season. An irrigation experiment (Timmons and Dylla, 1981) showed a reduction of about 20 percent in NO_3-N leaching when four N applications were made during the corn growing season compared with a single application of the same total N amount. Other studies have shown that lower N application rates result in lower NO_3-N losses through subsurface drains (Baker and Johnson, 1981; Gast et al., 1978; Randall and Nelson, 1985). Accurately testing the soil for NO_3-N before planting could help to determine the right input of N fertilizer.

The use of nitrification inhibitors with ammoniacal fertilizers is a useful practice. These inhibitors decrease the rate of conversion of ammonium ions to nitrate ions. The careful choice of pesticide formulation or additives can also be used to increase their adsorption to soil. More efficient use of insecticides with better crop rotation practices and use of herbicide banding (lower rate) should also result in less leaching of these chemicals.

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SUBSURFACE DRAINAGE and LAND FORMING FOR POLLUTION CONTROL

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Abstract

Farm surface water runoff is a pollution source, called non point. Well known water quality benefits are available using subsurface drainage as compared to surface drainage. Can plants survive excess rainfall and/or irrigation depending only on subsurface drainage? Not without Laserplane Precision Land Forming says the author.

Introduction

The author and his wife using the name NANLO PROPERTIES purchased an 80 acre (32 hectare) farm in January 1979. It was planned to be a private experimental farm. The farm was very wet and had a history of crop failures due to late plantings, crop drownings and wet harvest conditions.

The aerial photo on the next page was taken April 7, 1979. Please notice the parallel streaks of dryness over the subsurface tile drains on the surrounding land.

Photo is of the farm before any construction began

Topographical Survey

It was not possible to make the laser made topographical survey on the next page until May 28, 1979, because of standing water previous to that date. And even then, the rodman had to walk very carefully rather than use pickup mounted laser survey equipment.

PAGE 3

Kraft. Inc.

DRAINAGE CONTRACTORS

"Tile Drainage By KRAFTsmanship"
Phone 453-3641 Pigeon, Mich. 48755

Name: NAI - 384 - TIES
Address: BROOKFIELD
80 Acres
Sect. 17
T. 15 R. 10
Scale: ⅜ inch

Installation Date ________

Field Book Notes Page _______

Survey Date MAY 28, 1979

Right of Way Line &/or Int. Div. Line ————
Farm Boundary ————
Permanent Fence x——x——x——x——x
Over 4' Deep Ditch ═ ═ ═
Less 4' Shallow Ditch ---> ——> -·-> ----->
Prev. Installed Tile --o-- —o— —o—
Proposed or New Tile --o——o——o——o
Dir. & Flow of Lats —o--> &/or <--o—>
Ditch Bot. ______w/______ Flow, Use_____

Critical Pt.				
H.O.I. Corr.				
Total Elev.				
Cut				
Grade ___%				
Corners				
Tot. El.				
Knoll El.				
Knoll Cut				
1' Freeboard				
Total Elev.				
Allow to Fill				

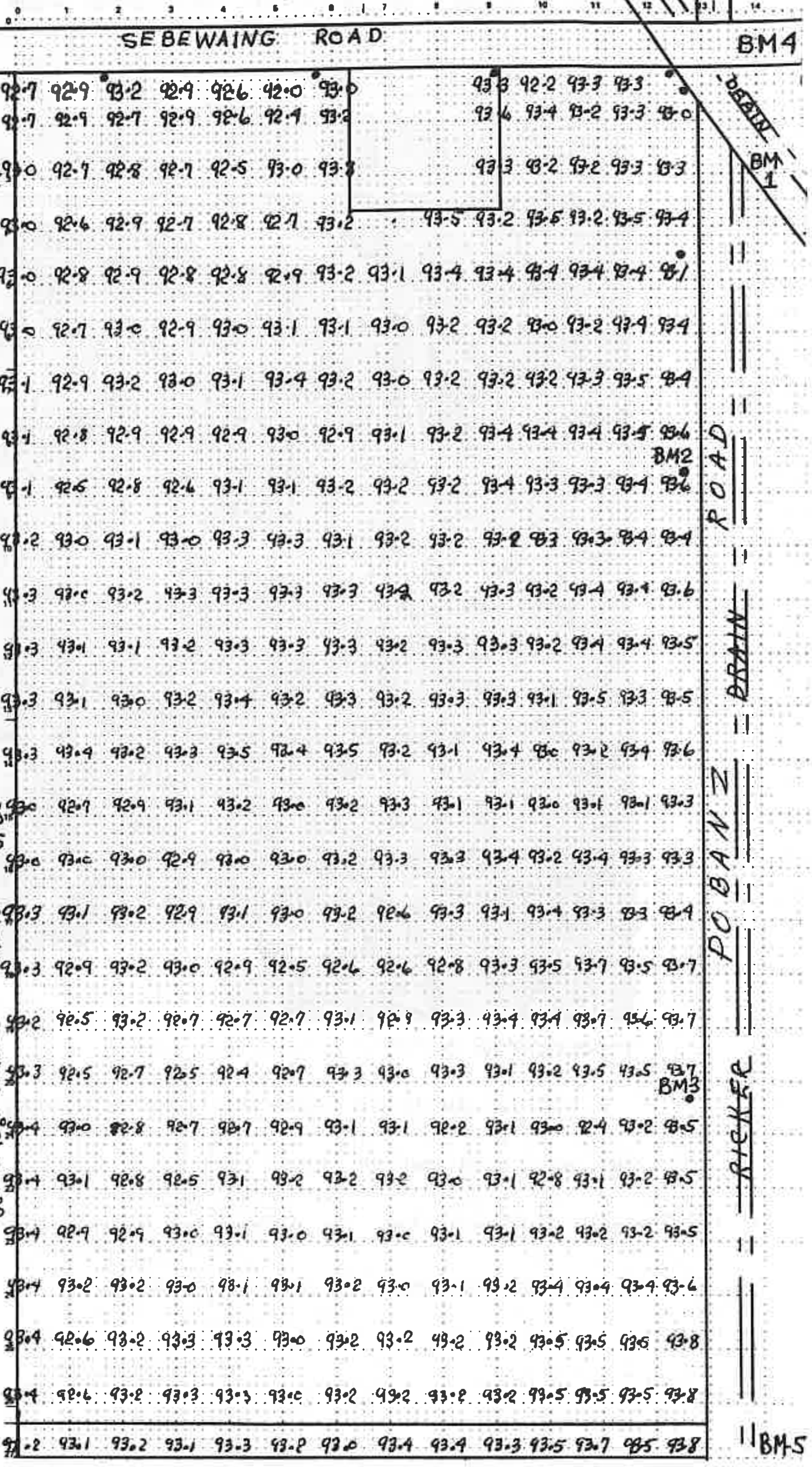
	Size	A. Dr.	Gr. or Spac.	Quantity	V
A	BM	1 Top of 5' CMP - S. END			930
B		water line			855
C					
D		Nail on SW Side			
E	BM	3RD POLE FROM N. END			952
F	2	CENTER OF RD			952
G		waterline - RICKER			872
H					
I		Nail on NW SIDE			
J	BM	2nd Pole FROM S. END			961
K	3	center of RD			957
L		water line - Ricker			875
M				S. SIDE EDGE	
N	BM	center of SEBE. RD. BR. FLOOR			9950
		WATERLINE SHEBEON			832
O	4	DITCH BOTTOM			820
P					
Q	BM 5	TOP OF 4' CMP N. END Water line			896 880

ABBREVIATIONS

D.S.T. - Double Strength Tile
C.M.P. - Corrugated Metal Pipe
W.L. - Water Line
T.T. - Top of Tube Rd. - Road
T.C. - Top of Concrete Abutment
D.B. - Ditch Bottom C.P. - Critical Point

Surveyor WCD

Rodman LEK



0	1	2	3	4	5	6	7	8	9	10	11	12	13
92.7	92.9	93.2	92.9	92.6	92.0	93.0			93.3	92.2	93.3	93.3	
92.7	92.9	92.7	92.9	92.6	92.4	93.2			93.6	93.4	93.2	93.3	93.0
93.0	92.7	92.8	92.7	92.5	93.0	93.3			93.3	93.2	93.2	93.3	93.3
93.0	92.6	92.9	92.7	92.8	92.7	93.2		93.5	93.2	93.5	93.2	93.5	93.4
93.0	92.8	92.9	92.8	92.8	92.9	93.2	93.1	93.4	93.4	93.4	93.4	93.4	93.1
93.0	92.7	93.0	92.9	93.0	93.1	93.1	93.0	93.2	93.2	93.0	93.2	93.4	93.4
93.1	92.9	93.2	93.0	93.1	93.4	93.2	93.0	93.2	93.2	93.2	93.3	93.5	93.4
93.1	92.8	92.9	92.9	92.9	93.0	92.9	93.1	93.2	93.4	93.4	93.4	93.5	93.6
93.1	92.6	92.8	92.6	93.1	93.1	93.2	93.2	93.2	93.4	93.3	93.3	93.4	93.6
93.2	93.0	93.1	93.0	93.3	93.3	93.1	93.2	93.2	93.2	93.3	93.3	93.4	93.4
93.3	93.0	93.2	93.3	93.3	93.3	93.3	93.2	93.2	93.3	93.2	93.4	93.4	93.6
93.3	93.1	93.1	93.2	93.3	93.3	93.3	93.2	93.3	93.3	93.2	93.4	93.4	93.5
93.3	93.1	93.0	93.2	93.4	93.2	93.3	93.2	93.3	93.3	93.1	93.5	93.3	93.5
93.3	93.4	93.2	93.3	93.5	92.4	93.5	93.2	93.1	93.4	93.0	93.2	93.4	93.6
93.0	92.7	92.9	93.1	93.2	93.0	93.2	93.3	93.1	93.1	93.0	93.1	93.1	93.3
93.0	93.0	93.0	92.9	93.0	93.0	93.2	93.3	93.3	93.4	93.2	93.4	93.3	93.3
93.3	93.1	93.2	92.9	93.1	93.0	93.2	92.6	93.3	93.1	93.4	93.3	93.3	93.4
93.3	92.9	93.2	93.0	92.9	92.5	92.6	92.6	92.8	93.3	93.5	93.7	93.5	93.7
93.2	92.5	93.2	92.7	92.7	92.7	93.1	92.9	93.3	93.4	93.4	93.7	93.6	93.7
93.3	92.5	92.7	92.5	92.4	92.7	93.3	93.0	93.3	93.1	93.2	93.5	93.5	93.7
93.4	93.0	92.8	92.7	93.7	92.9	93.1	93.1	92.2	93.1	93.0	92.4	93.2	93.5
93.4	93.1	92.8	92.5	93.1	93.2	93.2	93.2	93.0	93.1	92.8	93.1	93.2	93.5
93.4	92.9	92.9	93.0	93.1	93.0	93.1	93.0	93.1	93.1	93.2	93.2	93.2	93.5
93.4	93.2	93.2	93.0	93.1	93.1	93.2	93.0	93.1	93.2	93.4	93.4	93.4	93.6
93.4	92.6	93.2	93.3	93.3	93.0	93.2	93.2	93.2	93.2	93.5	93.5	93.6	93.8
93.4	92.6	93.2	93.3	93.3	93.0	93.2	93.2	93.2	93.2	93.5	93.5	93.5	93.8
93.2	93.1	93.2	93.1	93.3	93.2	93.0	93.4	93.4	93.3	93.5	93.7	93.5	93.8

Topographical

The topographical survey elevations were fed through a Hutchinson, Kansas data link to an Ann Arbor, Michigan based computer with a land forming program. It printed a "cut and fill" elevation sheet, a portion of which is attached. There were 15,559 cubic yards (11,896 (M 3)) to make and 10,667 cubic yards (8,160 (M3)) of fill or a shrinkage factor of 45%. Final elevation was 93.1'.

The surface slope of the farm was changed from an average .03% (.3/1000) westward and an average .065% (.65/1000) northward to zero north-south and also zero east-west. A maximum surface cut of .7' (8 1/2") (21cm) was made in the SE corner of the 80 acres (32 hectare) and a maximum 1.0' (30cm) fill was made in the NW corner of the farm. All other cuts and fills were less.

No top soil was stripped and replaced which is a common practice in land forming but at higher cost. The cost for the land forming was $12,472.00 or $166.00 per acre. ($411.00 per hectare). Approximately 80 cents per cubic yard. ($1.05 per cubic meter).

C .10 F [illegible]

CUT & FILL

93.20 93.10 C .10	93.00 93.10 F .10	93.10 93.10	93.10 93.10	93.00 93.10 F .10	92.70 93.10 F .40	93.00 93.10 F .10	92.70 93.10 F .40	93.00 93.10 F .10	+ +.40
93.40 93.10 C .30	93.10 93.10	93.20 93.10 C .10	92.90 93.10 F .20	92.80 93.10 F .30	92.80 93.10 F .30	92.90 93.10 F .20	92.80 93.10 F .30	93.00 93.10 F .10	− −.20
93.50 93.10 C .40	.00 .00	93.20 93.10 C .10	92.70 93.10 F .40	92.80 93.10 F .30	92.70 93.10 F .40	92.90 93.10 F .20	92.60 93.10 F .50	93.00 93.10 F .10	+ +.10
.00 .00	.00 .00	93.80 93.10 C .70	93.00 93.10 F .10	92.50 93.10 F .60	92.70 93.10 F .40	92.80 93.10 F .30	92.70 93.10 F .40	93.00 93.10 F .10	+ +.40
.00 .00	.00 .00	93.20 93.10 C .10	92.40 93.10 F .70	92.60 93.10 F .50	92.90 93.10 F .20	92.70 93.10 F .40	92.90 93.10 F .20	92.70 93.10 F .40	+1.3
.00 .00	.00 .00	93.00 93.10 F .10	92.10 93.10 F 1.00	92.60 93.10 F .50	92.90 93.10 F .20	93.20 93.10 C .10	92.90 93.10 F .20	92.70 93.10 F .40	+1.6

1.00 MC .70

+7.60 +
−26.10 −

OWELL

15 559 CY Cut × 80¢ CY = $12,472 ÷ 75 ACRES = $166.29

OUR AVERAGE ACRE COST THIS AREA IS BETWEEN $160 AND $200 PER ACRE.

J.D.

1252 cu. yd. = .01′ elevation change
↳ 8% of Total

Goals

1. Introduce Laserplane Precision Land Forming as an applicable land conservation practice in Michigan.

2. Eliminate ponding as a water management problem. (It seems to make sense to apply rainfall and irrigation evenly to the entire farm, rather than allow the excess to pond in the low spots or run off the surface or allow the high spots to suffer drought).

3. Utilize the Shebeon and Ricker Drains on the east side of the farm as subsurface drainage outlets. (The farm was assessed into the Blasi Drain, one mile (1.6km) west of here. The assessment was later changed. A 3/4 mile (1.2km) long - 12" (300mm) diameter off premise $12,000.00 main drain would have been necessary to provide an outlet at the edge of the property. Plus 12" (300mm) and 10" (250mm) interior mains. This long main would have provided only a 3/8" (10mm) drainage coefficient. As designed, no main drain is larger than 8" (200mm). The main drains provide a drainage coefficient approximately 267% greater than normal for Michigan. The extra coefficient is for drainage safety insurance if a large summer storm occurs when irrigating. To date, the largest has been 4" (10cm) on June 18, 1984.

4. Design uniform hydraulic flow loading to the subsurface drainage system including the 3" (76mm) laterials. No lateral or main drain ever has an overload due to ponding.

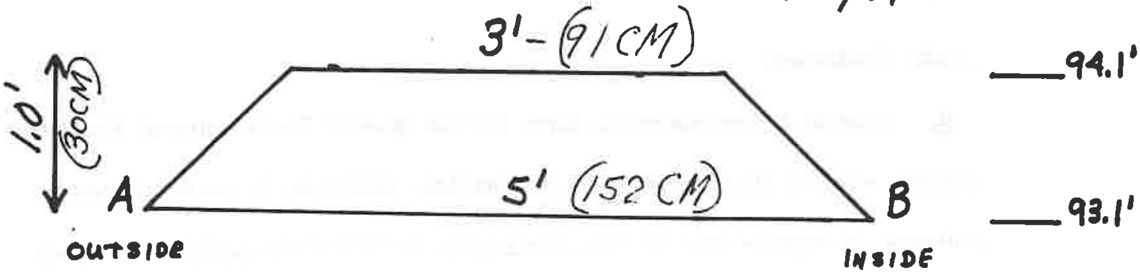
.....Continued

Goals (Continued)

5. Utilize the subsurface drainage system as the only method to remove excess water from the farm. No surface water runoff is possible on this farm because a 1' (30cm) high dike has been constructed around the perimeter. Subsurface drainage without the additional help of surface drainage had never been recommended up until this time.

K3

DIKE 2-18-82



A= ON ROW LINE & FARM BOUNDARY

B= EVEN WITH MAN HOLE INSIDE LINE
(POBANCZ ROAD ONLY)

Goals (Continued)

6. Provide a demonstration farm for the Special Environmental Practices Project Area of Huron and Tuscola Counties, Michigan to show reduced pollution of Saginaw Bay by the elimination of NON-Point pollution sources from this farm. Therefore prove to the Environmental Protection Agency that subsurface tile drainage is a Best Management Practice. Farmers in these two counties have been accused of increasing the amounts of sediment in the Bay as well as propagating the growth of algae with the passing of nutrients into the Bay waters.

7. Help disprove the misconception that subsurface tile drainage systems cause flooding. When in fact subsurface tile drainage systems reduce peak flows and the amount of total water leaving the farm.

8. Utilize deep 30" (76cm) subsoiling as a land conservation practice. The farm was subsoiled every 8' (2.4m) N-S direction after the land forming and before the subsurface drain tile were installed. A Steiger KRAC KS-500 drainage plow was utilized for the subsoiling. Approximately 305,700 feet (93,177m) was traveled by the plow in 24.5 hours of work. Cost @ $125.00 an hour was $41.11 an acre ($101.54 hectare). The soil surface heaved approximately 1' (30cm) due to the loosening caused by the subsoiling.

9. Utilize Agri-SC soil conditioner as a means to improve permeability and tilth. In the deepest cut area, the good black color of the top soil that is again evident is credited to the soil conditioner.

.....Continued

Goils (Continued)

10. Utilize the Shebeon Drain as a water source for a subirrigation system.

11. Provide an ideal control system for both drainage and irrigation. (CIDS = Combination Irrigation and Drainage Systems)

12. Install an all plastic tubing drainage system including the first local installation of 18" (450mm) corrugated tubing in a heavy load environment. Two 18" (450mm) are installed flowing east across the Pobanz Road into the Ricker Drain serving as outlets for the two inspection and water management manholes at the center and southern end of the farm. Now, almost seven years later, visual inspection from the outlet toward the manholes, shows little or no deflection. The 18" (450mm) used, was the short 30" (750mm) lengths that were first produced in North America. Today, even higher quality culvert tubing is available.

Drainage Drawings

Attached are the "as built" drainage drawings for this farm showing a double scale, N-S and single scale E-W. The double scale, N-S was necessary because of the very close spacing of the laterals which are only 36' (11m). The drawings would have been difficult to show detail at single scale. Since then, close spacing has become a trend. Kraft, Inc. has designed 11" (28cm) x 17" (43cm) drainage drawing graph paper to accommodate the 2 times width common size of 80 acre farms. With only one fold, the drawing will fit into a standard file folder.

Laterals 1 through 23 (24.2 acres) (9.8 hectares) drain into a manhole at the NE corner of the farm where the manhole drains through a 48" (122cm) concrete tile under Shebeon Road into Shebeon Ditch Drain. Half the diameter of the large concrete tile is always submerged in water because it was installed 2' (61cm) lower than the Shebeon Ditch Drain.

Our irrigation pump (one B. & K. 4" (100mm) diameter - 1 1/2 H.P.) (approximately 200 GPM (750 LPM) delivery) is in this MH which is also a head or control stand. (Shebeon Ditch Drain flows northwest all year long and is our irrigation water source). Laterals 24 through 48 (26.7 acres) (10.8 hectares) drain into a MH - head stand at "H".

Laterals 49 through 73 (26.3 acres) (10.6 hectares) drain into a MH - head stand at "A".

Kraft. Inc.

DRAINAGE CONTRACTORS

"Tile Drainage By KRAFT-manship"
Phone 453-3641 Pigeon, Mich. 48755

Name LOV - 393 - IFT Address 8010 DRURY LANE PIGEON, MI
NORTH 40 Acres Sect. 17 BROOKFIELD Twp., T15N R. 10E
Scale: 3/8 inch = HORZ. = VERT.

Installation Date SEPT 1979

Field Book Notes Page

Survey Date

Right of Way Line &/or Int. Div. Line ————————

Farm Boundary ————————

Permanent Fence x----x x x - x

Over 4' Deep Ditch

Less 4' Shallow Ditch > -- > > >

Prev. Installed Tile o - o o

Proposed or New Tile - o - o - o - - o

Dir. & Flow of Lats - o > &/or < o - >

Ditch Bot. ______ W/ ______ Flow, Use. ___

Critical Pt.	
H.O.I. Corr.	3" LATERALS CONNECTED
Total Elev.	TO 6" MAIN "N" CROSS OVER
Cut	8" MAIN "M"
Grade	
Corners	
Tot. El.	
Knoll El.	
Knoll Cut	
1' Freeboard	
Total Elev.	
Allow to Fill	

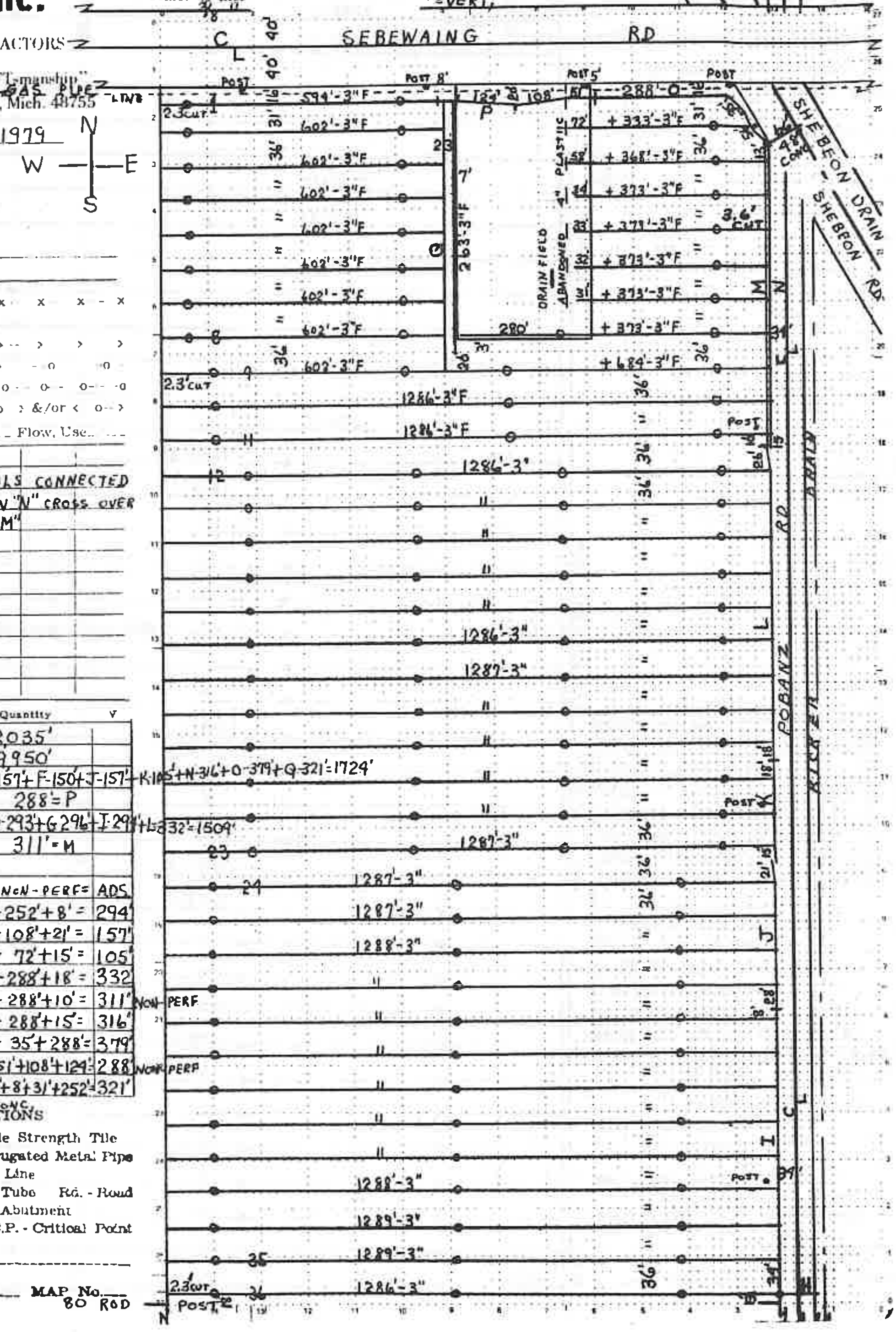
	Size	A. Dr.	Gr. or Spac.	Quantity	V
X	3"	FILTER		12,035'	
X	3"	PERF.		79,950'	
X	6"	PERF=C-139'+E-157'+F-150'+J-157'+K-105'+N-316'+O-379'+Q-321'=1724'			
X	6"	NON PERF		288'=P	
X	8"	PERF=B-294'+D-293'+G-296'+I-294'+L-332'=1509'			
X	8"	NON PERF.		311'=M	
G					
H	18"	26.7	.20	57' NON-PERF=	ADS.
I	8"	12.8	.20%	34'+252'+8'=	294'
J	6"	4.3	.20	28'+108'+21'=	157'
K	6"	3.2	.20	18'+72'+15'=	105'
L	8"	12.8	.20	26'+288'+18'=	332'
M	8"	12.8	.20	13'+288'+10'=	311' NON-PERF
N	6"	5.4	.20	13'+288'+15'=	316'
O	6"	5.2	.20	56'+35'+288'=	379'
P	6"	4.6	.20	5'+51'+108'+124'=	288' NON-PERF
Q	6"	4.6	.20	7'+23'+8'+31'+252'=	321'
	48"	24.2	.00	66' CONC.	

ABBREVIATIONS

D.S.T. - Double Strength Tile
C.M.P. - Corrugated Metal Pipe
W.L. - Water Line
T.T. - Top of Tube Rd. - Road
T.C. - Top of Concrete Abutment
D.B. - Ditch Bottom C.P. - Critical Point

Surveyor ____________________

Rodman ______________ MAP No. ___



Kraft. Inc.

DRAINAGE CONTRACTORS

"Tile Drainage By KRAFTsmanship"

Phone 453-3641 Pigeon, Mich. 48755

Name: LOW - 394 -

SOUTH 40 Acre

Scale: 3/8 inch

Address: 8010 DRURY LANE PIGEON, MI

Sect. 17 BROOKFIELD Twp., T.15N R. 10E

Installation Date SEPT. 1979

N
W — E
S
6" CONC.

Field Book Notes Page _______

Survey Date ___________

Right of Way Line &/or Int. Div. Line ___________

Farm Boundary ___________

Permanent Fence x——x——x——x——x

Over 4' Deep Ditch

Less 4' Shallow Ditch – > – – – > – – – > – – – >

Prev. Installed Tile – o – – – o – – – o –

Proposed or New Tile –o——o——o——o

Dir. & Flow of Lats – o –> &/or < – o – – >

Ditch Bot. ______w/______ Flow, Use_____

Critical Pt.				
H.O.I. Corr.				
Total Elev.				
Cut				
Grade ____%				
Corners				
Tot. El.				
Knoll El.				
Knoll Cut				
1' Freeboard				
Total Elev.				
Allow to Fill				

	Size	A. Dr.	Gr. or Spac.	Quantity	✓
A	18"	26.34	.20%	57' NON-PERF	ADS
B	8"	10.5	.20	34'+252'+8' =	294'
C	6"	3.9	.20	28'+108'+3' =	139'
D	8"	10.8	.20	34'+252'+7' =	293'
E	6"	4.3	.20	29'+108'+20'=	157'
F	6"	4.3	.20	26'+108'+16'=	150'
G	8"	12.8	.20	11'+23'+252+10'=	296'
H	18"	26.7	.20	57' NON-PERF =	ADS
I					
J				ALL 3" LATERALS	
K				END ON WEST LINE	
L	ALL	3"	LATE	RALS HAVE .10%	GRADE
M				MAINS ARE 1' WEST	
N				OF POBANZ ROW.	
O		ALL	TUB	ING BIG "C"	BRAND
P	EXCEPT	18" &		ENGELHARDT-4" =	ADS
N	ALL	75.4		95,997'	

ABBREVIATIONS

D.S.T. - Double Strength Tile

C.M.P. - Corrugated Metal Pipe

W.L. - Water Line

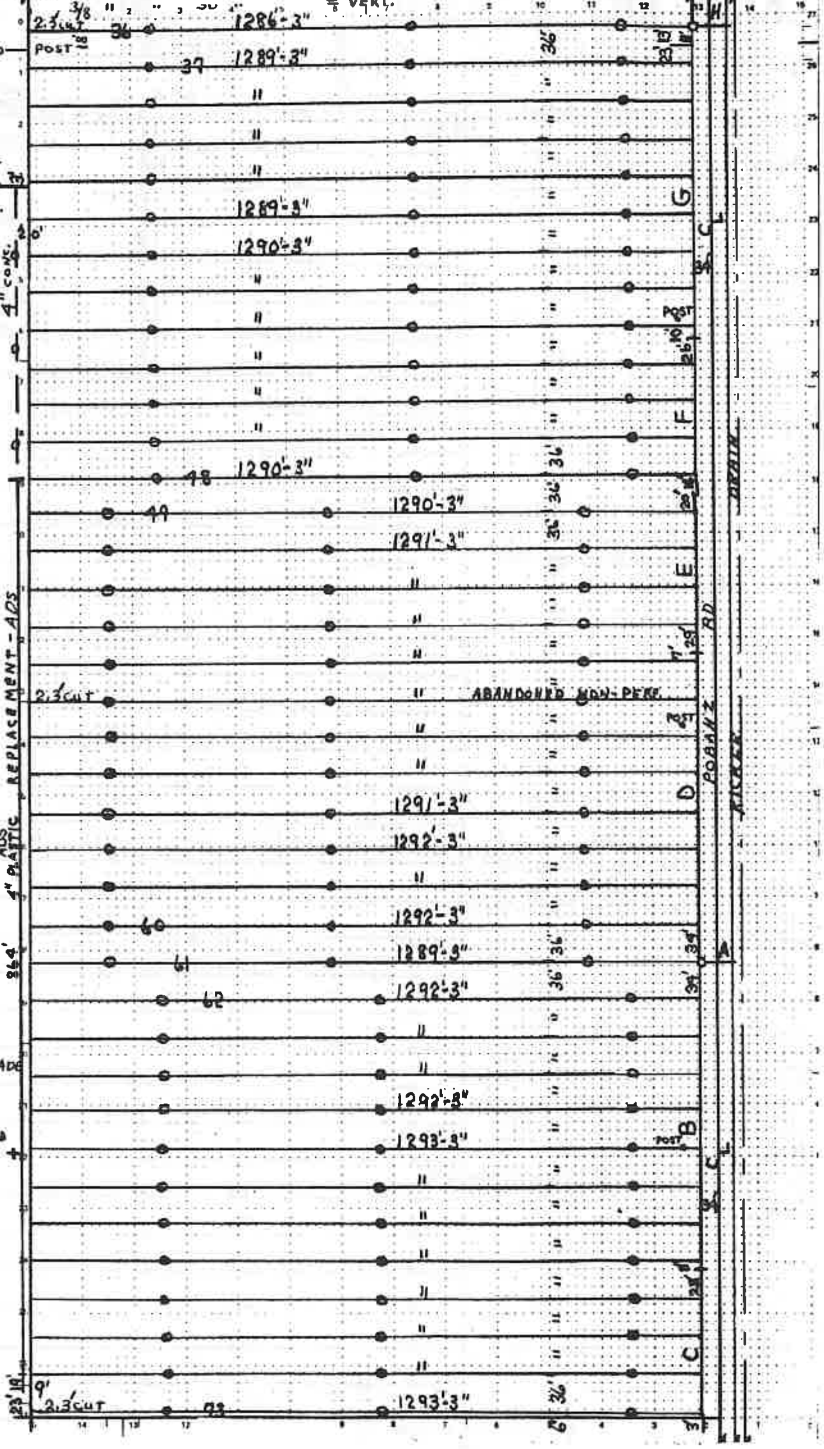
T.T. - Top of Tube Rd. - Road

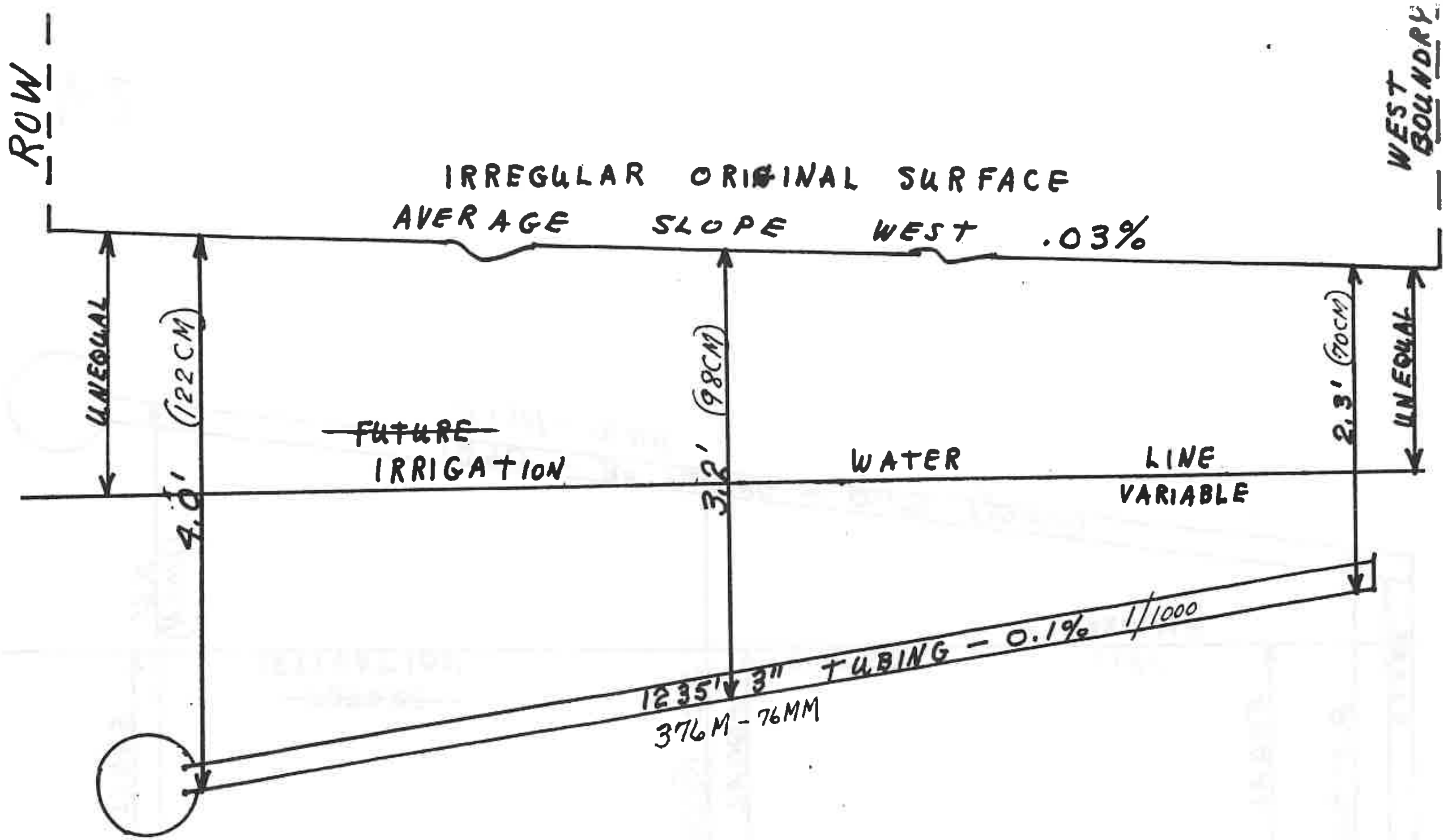
T.C. - Top of Concrete Abutment

D.B. - Ditch Bottom C.P. - Critical Point

Surveyor ___________

Rodman ___________ MAP No.___



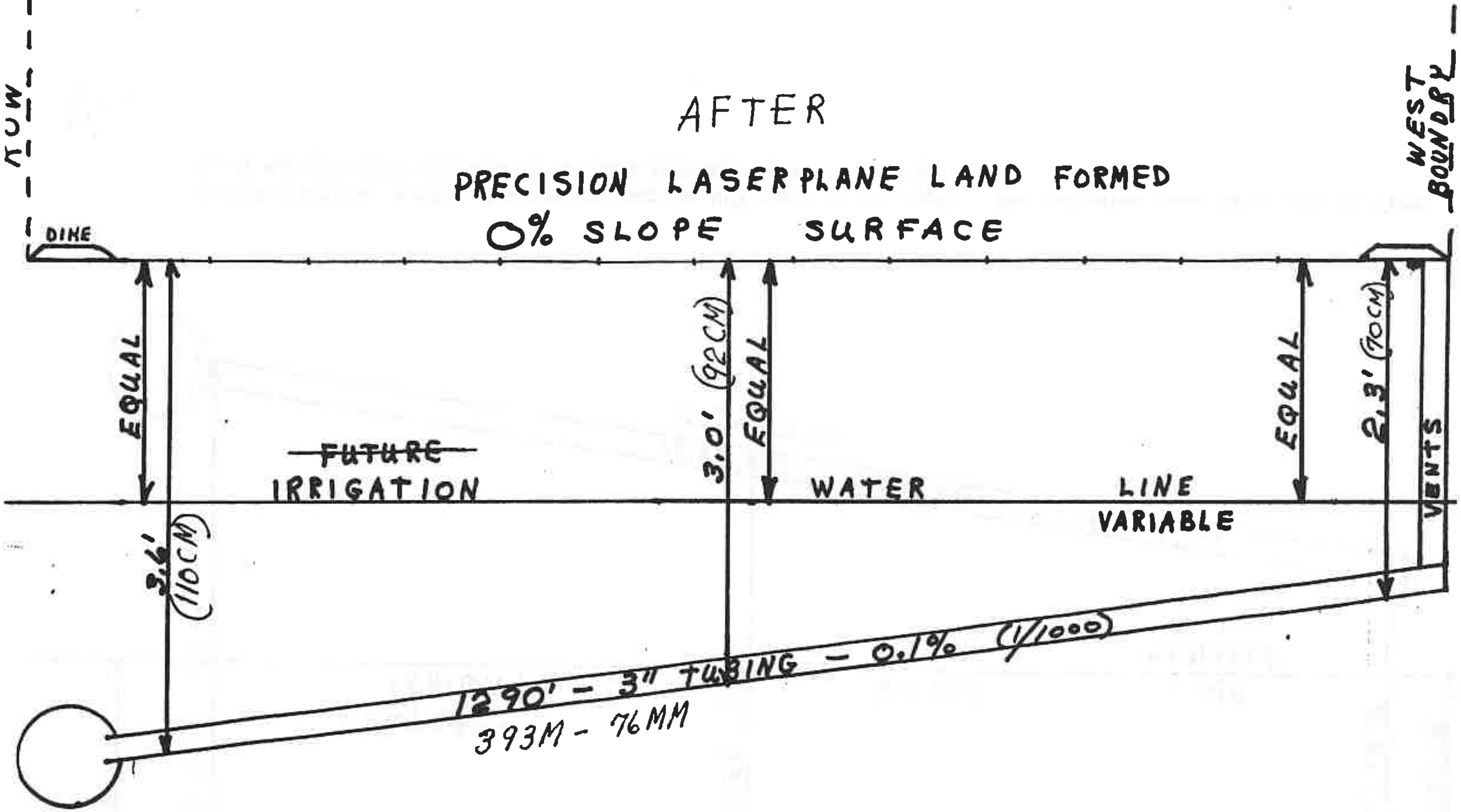


Attached are two profile sketches showing the difference in the depth to the irrigation water level with the farm as it was and after precision laser land forming, shown on next page.

V-1

AFTER

PRECISION LASERPLANE LAND FORMED
0% SLOPE SURFACE



V-2

Tappan Loam Soil 18

Michigan Management Group: 2.5c-c
Capability Unit: IIw-1

This is a poorly drained, nearly level soil. It has a very dark greyish brown loam surface layer about 13 inches thick, and a loam and silt loam subsoil with mottled colors. Water moves slowly through the soil. The ability of the soil to hold water for plant growth is high. Runoff is slow to ponded. The surface layer has 1.6 to 3.9 percent organic matter. It contains free lime, which may cause Manganese deficiency in sugar beets, oats and barley. This may also cause Zinc deficiency in corn and beans. This soil is highly productive for cropland and pasture with good management. Corn, sugar beets, soybeans, field beans, small grains, and hay are well adapted. Wetness and soil cloddiness are problems. Working the soil when wet results in a cloddy condition. Surface ditches, tile drainage, crop residues and cover crops will solve these problems.

Total annual precipitation averages 29.17 inches (74.1cm). A low annual total is 25.2 inches (64.0cm). A high annual total is 37.9 inches (96.3cm).

Average growing season precipitation April through September is 16.26 inches (41.3cm). A low growing season total is 9.7 inches (24.6cm) - 2 in 10 years. A high growing season total is 24.1 inches (61.2cm).

Depth	Clay (2mm	Moist bulk density	Permeability	Available water capacity	Soil reaction	Shrink-swell potential	Erosion factors K	Erosion factors T	Wind erodibility group	Organic matter
In	Pct	G/cm3	In/hr	In/in	pH					Pct
0-13	15-25	1.12-1.59	0.6-2.0	0.18-0.22	7.4-8.4	Low	0.28	5	5	1-4
13-31	18-30	1.48-1.80	0.2-2.0	0.14-0.19	7.9-8.4	Low	0.28			
31-60	15-28	1.46-1.95	0.06-0.2	0.15-0.19	7.9-8.4	Low	0.28			

Yield Data

Also included are our crop and yield data showing the benefits of subsurface drainage only, 1977 through 1982. Please note the 2.53 tons (46.4%) increase in corn yields after drainage only. No irrigation had been done until 1983.

Only the north 1/3 of the 1983 sugar beets were subirrigated. All from the one water management manhole at the NE corner of the farm. We plan to gather yield data differences for several years with part subsurface drainage only and part subsurface drainage and subirrigation.

In 1983, we had the east 1/2 of the farm idle because it was in PIK (Payment in Kind). We had a total of 15.5 hectares of sugar beets on the west half. Our CIDS irrigation for 1983 was on laterals 1 through 23 only. So the CIDS irrigated the idle PIK hectares as well as the north 4.81 hectares of the sugar beets. The south 10.65 hectares of the sugar beets were not irrigated. It is well tile drained and precision laserplane land formed. No surface drainage.

It was a moderately dry summer. 2.1" (5.3cm) of rain fell two days after irrigation started. The drained but unirrigated 10.65 hectares yielded a net 39.49 tons per hectare. 3.33 tons below the Michigan Sugar Company average of 42.82.

The CIDS irrigated 4.81 hectares yielded a net 54.98 tons per hectare. 15.49 tons per hectare more. 39.1% additional tonnage.

An interesting sight to observe was the response of the sugar beet leaf tops to receiving water after the irrigation pump was turned on. It had been very dry. The beet leaf tops were limp and drooping. First the tops stood erect

.....Continued

Yield Data (Continued)

over the tile drains on the east or lower (subsurface drain elevation) side of the field. Then gradually moved upstream over the drains toward the west. Then the tops began to spring up in the center at mid drain spacing beginning on the east side and gradually standing erect as the irrigation water spread westward.

Our extra expense for irrigation was the pump installation capital costs of less than $5,000.00. Electricity of $159.02 including $7.30 monthly ready to serve charges for 9 months, when no electricity was used. That is the cost for the idle PIK hectares too. $16.23 per hectare. According to our pumping records, we added approximately 15.4cm per hectare. $1.05cm cost per hectare for pumping. 62 cents if you deduct the ready to serve charge. No other type of irrigation comes close to that low cost.

It also cost us $3.25 per metric ton ($50.35 per hectare) to haul the extra sugar beet yield to the processing plant. We smiled all the way to the bank.

Increased Yields as a result of Precision Laserplane Land Forming with Subsurface Drainage only (No surface drainage and no subsurface irrigation)

Year	Crop	Yield - English System		Yield - Metric System
1980	Field Corn	Net 531,510 lbs.	Total	241,091kg
Moderate		Dry 127.4 bu. acre		7.98 metric tons hectare
to heavy		or 3.6 short tons acre		
fall rains		(74.5 acres)	Total	(30.2 hectares)
USDA - Agriculture Stabilization & Conservation Service Historical Field Corn Yield - this area		87 bu. acre		5,450kg hectare
		or 2.4 short tons acre		5.45 metric tons hectare
	INCREASE- quantity	40.4 bu. acre		2.53 metric tons hectare
	percentage	46.4%		46.4%
1981	Edible White	Clean 146,169 lbs.	Total	66,302kg
Very heavy	Navy Beans	Dry 32.7 bu. acre		2.2 metric tons hectare
fall rains		or 1,962 lbs. acre		2,195kg hectare
		(74.5 acres)	Total	(30.2 hectares)
1982	Edible White	Clean 123,054 lbs.	Total	55,817kg
Average	Navy Beans	Dry 27.5 bu. acre		1.85 metric tons hectare
seasonal		or 1,652 lbs.		1,848kg hectare
rainfall		(74.5 acres)	Total	(30.2 hectare)
Rainy during harvest (Sept.)				
Historical EWNB yields this farm				
1977 - very heavy fall rains				
	EWNB - unable to harvest - None			None
1978 - Moderate fall rains				
	EWNB	Clean 50,430 lbs.	Total	22,875kg
		Dry 11.6 bu. acre		.8 tons hectare
		or 696 lbs acre		778kg hectare
		(72.6 acres)		(29.4 hectare)
1981	INCREASE quantity	1,266 lbs. acre		1,417kg hectare
1982	INCREASE quantity	956 lbs. acre		1,069kg hectare
1981	INCREASE percentage	181.9%		181.9%
1982	INCREASE percentage	137.4%		137.4%

Increased Yields as a result of Precision Laserplane Land Forming with Subsurface Drainage and Irrigation only (No surface drainage)

Year	Crop	Yield - English System	Yield - Metric System
1983 Moderately dry summer Moderate fall rains	Sugar Beets 11.8987 acres or 4.8115 hectare	Net 24.9 short tons acre	Net 54.98 metric tons hectare
	PLLF w/SSD without Irrigation - (Control Plot)		
1983	26.3156 acres or 10.6493 hectare	Net 17.9 short tons acre	Net 39.49 metric tons hectare
1983	INCREASE quantity	7.0 short tons acre	15.49 metric ton hectare
1983	INCREASE percentage	39.1%	39.1%
1983	ADDITIONAL GROSS INCOME	$245.00 acre	$605.00 hectare
1983	Sugar Beets - overall (38.2 acres)	20.1 short tons acre	(15.5H) 44.36 metric ton hectare
1983	Michigan Sugar Co. average (92,000 acres)	19.4 short tons acre	(37,230H) 42.82 metric tons hectare
1983	PIK - Summer fallow 36.3 acres 14.7 hectares		
1983	Irrigation 24.2 acres 9.8 hectares	ELECTRICITY $6.57 acre	$159.02 $ 16.23 hectare
	Applied Irrigation	6.05 acre inches	15.4cm hectare
	Water cost per unit	$1.09 acre inch	$1.05cm hectare

1984 and later Yield Data

For 1984, the east half of the farm or the 1983 PIK field of 36.3 acres (14.7 hectares) was planted to winter wheat with subsurface drainage only. No irrigation. The wheat yielded 5.9 tons per hectare. During the 1984 spring thaw, water about 3cm deep could be seen the entire length of the 1/2 mile (.8km) field and no drowning occurred. Thanks to Precision Laserplane Land Forming. On June 18, 1984, the wheat and corn made it through a 4" (10cm) rain without damage.

The west half of the farm had corn in 1984. The northern two/thirds 25.2 acres (10.2 hectares) were subirrigated and yielded 9.47 tons per hectare. The southern one/third 5.28 hectares were subsurfaced drained only. This corn yielded 7.24 tons per hectare. 2.23 tons (30.8%) more per hectare. At $100.00 a ton, that is $223.00 gross dollars more per hectare.

Our irrigation pumping expense was $230.07 for electricity. That includes nine months of $7.30 per month ready to serve charge. We actually supplied water to 20.6 hectares because the wheat stubble field also received water. Per hectare costs were $11.17. We supplied 12.8cm per hectare of water during the season. It cost about 87 cents a centimeter. (62 cents again if you deduct the ready to serve charge). We would have pumped more had the Shebeon Ditch Drain provided more water. It almost dried up during 1984.

We did not receive any appreciable rain during the growing season. Unirrigated corn yielded .3 to .6 tons less than normal in the area due to a

.....Continued

1984 and later Yield Data (Continued)

dryer year. Had we had more water available, I believe yields would have been even higher on the irrigated corn.

Corn moisture at harvest was slightly lower on irrigated corn. Perhaps indicating a more mature crop.

1985 corn yield results were disappointing compared to 1984 when comparing irrigated versus non-irrigated as can be seen from the corn yield results page. In the spring of 1985, while the corn was only 4 to 8 cm high, we had two days of severe high winds which thinned the plant population causing the anticipated yield for the irrigated corn to be less than desired or expected.

The Shebeon Ditch yielded plenty of water in 1985 because of enough rainfall upstream in the ditch's watershed. When the pump was turned off in mid-September, we had water standing at the surface at our observation wells.

We plan to plant a higher population on the irrigated hectares than on the non-irrigated the next time corn is in our crop rotation. To date, the only variable has been the irrigation.

Increased Corn Yields as a result of Precision Laserplane Land Forming with Subsurface Drainage and Irrigation only (No surface drainage)

Year	Field	Acres/ Hectares	Sub Irrigated Yield Bu./Acre or Tons/Hectare	Non-Irrigated Yield Bu./Acre or Tons/Hectare	Average Yield Bu./Acre or Tons/Hectare
1979	Entire Farm	74.5 A 30.2 H	Construction year - No crop		
1980	Entire Farm	74.5 A 30.2 H		127.40 Bu. 7.98 T	127.40 Bu. 7.98 T
1981	Entire Farm		Edible white navy beans		
1982	Entire Farm		Edible white navy beans		
1983	East Field	36.3 A or 14.7 H	Fallow		(PIK)
1983	West Field	38.2 A or 15.5 H	Sugar Beets		
1984	East Field	36.3 A or 14.7 H	Winter Wheat		
1984	West Field	25.17A or 10.19H	150.89 Bu. 9.47 T		
	Dry summer	13.04A or 5.28H		115.44 Bu. 7.24 T	
	Moderate fall rains	38.2 A or 15.5 H			138.80 Bu. 8.69 T
1985	Entire Farm	48.51A or 19.64H	137.19 Bu. 8.61 T		
	Dry-windy spring	26.00A or 10.53H		128.57 Bu. 8.07 T	
	Very heavy fall rains	74.5 A or 30.2 H			134.21 Bu. 8.41 T
7 years - 3 Corn Crop averages			144.04 Bu. 9.04 T	123.80 Bu. 7.76 T	133.47 Bu. 8.36 T
Average Gross Income @ $ 2.50 Bu. or $100.00 T			$360.10A $904.00H	$309.50A $776.00H	$333.68A $836.00H
1984	Electricity costs		$ 4.52A $ 11.17H		
1985	Electricity costs		$ 8.24A $ 20.36H		

Conclusions

Crop results indicate that the combination of Precision Laserplane Land Forming and subsurface drainage only without surface drainage is viable in Huron County, Michigan. No surface water has left the farm since the project started. Only subsurface drainage water. The better water quality between subsurface and surface is well known.

In the six crop years, no late spring planting dates have been experienced. This in spite of the fact that Michigan among states has the second lowest percentage of daylight hours during which the sun shines to help the spring drying process.

Trafficability has never been a problem even during harvest in spite of some very heavy fall rains in 1981 and 1985. The yield of the edible white beans in 1982 was perhaps effected because of a prolonged continuing rainy time during the harvest period as were all beans in the area that year. The bean yield on this farm was still better than the bean yield on our farm across the road that is subsurface drained, but not Precision Laserplane Land Formed. Our second farm suffers drown out places, do to ponding. Perhaps more significantly the knolls dry out. In comparing the annual average yields of all crops, the improved farm has always been better in spite of the potential additional excess water risk taken by irrigating.

The prevention of surface water runoff and reduced pollution has been achieved. Subsurface tile drainage is a Best Management Practice. To do so on other farms, Precision Laserplane Land Forming to a single plane for

.....Continued

Conclusion (Continued)

the entire farm no doubt will not always be possible, practical or economical. However, farms can be PLLF to a number of reasonable sized benched planes. The planes on some soil types need not be zero slope for cultivated row crops. The row crop ridges will prevent the accumulation of ponded water. If your goal is to reduce pollution, the use of the proper combination of PLLF and subsurface drainage is encouraged.

Wildlife cover is provided with the tall grass on the dike around the 1.5 mile (2.4km) perimeter of the farm. Scotch pine were planted along the western farm boundry line and around the rear perimeter of the building site as windbreaks and for aesthetic value.

Farm details provided by:

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Pigeon, Michigan 48755
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(305) 736-7453 = Winter

WEATHER FORECASTS AS A SIMULATION MODEL INPUT FOR CONTROLLED-DRAINAGE/SUBIRRIGATION SYSTEMS. [1]

James L. Fouss and James R. Cooper, Baton Rouge, LA, USA [2]

Abstract

A method was developed to use daily rainfall forecast data to aid farmers in the operation of controlled-drainage/subirrigation systems for water table control. A computer simulation model was used to evaluate the method in terms of the reduced duration of excess soil water in the root zone during and following rainfall events.

1 Introduction

In humid and semi-humid areas, management of soil-water on cultivated lands is often complicated by erratic spatial and temporal occurrence of rainfall. In many humid areas, periods of excess and deficit soil-water occur within the same growing season. Proper water management for soils in such areas may require both drainage and irrigation. A water management system that is becoming popular in the United States uses the subsurface conduit system for both subsurface drainage and subirrigation.

A computer simulation model, DRAINMOD, was developed and validated by Skaggs (1980, 1982) to predict the performance of the dual purpose controlled-drainage/subirrigation systems over long periods of climatological record. Recorded weather data and site specific soil, crop, and system design parameters are required as inputs to the model to simulate the water management system. The computer program generates several operational and performance parameters during the

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[1] Contribution from USDA-ARS Soil and Water Research in cooperation with the Louisiana Agricultural Experiment Station.

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simulation which aid in evaluating various system designs. DRAINMOD has been widely adopted for design of subsurface water management systems. Engineers with the U. S. Dept. of Agriculture, Soil Conservation Service have used the model since 1981 to design drainage and subirrigation systems in the humid regions of the U. S. (SCS-USDA 1985).

A common method of water management during the growing season is to maintain a constant water level (elevation) at the outlet/inlet (O/I) of the subsurface conduits. When a heavy rainfall event occurs the water level at the outlet is lowered to allow the system to function in a conventional subsurface drainage mode. Another method involves lowering the controlled water table as the plant root system develops. With some minor modifications of the DRAINMOD computer programs, these control concepts can be accommodated in the system simulation process.

Several types of control parameters have been investigated for dual purpose systems. Warner (1972) used rainfall prediction as an input for a management-decision model that was coupled with a simplified controlled-drainage/subirrigation simulation model. A daily decision was made to raise, lower, or leave unchanged the O/I water level based upon the probability of rainfall over the next 24 hours. Smith et al. (1982) established operating criteria for subirrigation by regulating the O/I water level in response to minimum and maximum water table depths midway between drain lines. Smith (1983) also developed a sophisticated simulation model for this control method based upon a finite difference solution to the Boussinesq equation. Fouss (1985b) developed a subroutine for the model DRAINMOD to simulate automatic feedback control of the O/I water level, based upon the deviation of the midpoint water table from a desired depth.

Daily rainfall probability data can be used as a control input for computer simulations of water table management. When the rainfall probability "Index" (computed from daily forecasts) exceeds a threshold value, the O/I water level is lowered to allow the system to freely drain in advance of a predicted rainfall event.

A primary objective of this study was to evaluate the use of daily rainfall probability data as a control input for computer simulations of water table management systems. The goal of the system control is two-fold: (1) To provide adequate soil-water in the root zone via subirrigation during periods without rainfall; and (2) to minimize the duration of excess soil-water conditions in the root zone by controlling drainage before and during rainfall events.

2 Rainfall Forecast Data

The National Weather Service of the United States issues forecasts four times each day; 5:25 a.m., 10:45 a.m., 5:05 p.m., and 10:45 p.m. The early morning forecast (5:25 a.m.) is usually broadcast over radio and television about 6:00 a.m. This forecast was used in this study because of its greater potential use by farmers. The morning forecast includes the rainfall probability for three 12-hour time periods; today, tonight, and tomorrow.

For this and other studies (Fouss 1985a, and Fouss et al. 1985), the weather forecasts for the years 1979 through 1985 were obtained from the National Weather Service Station at Baton Rouge, Louisiana (USA). This location is central to the humid region of the Lower Mississippi Valley. Rainfall probabilities are stated in multiples of 10%, from 20 to 90%; the lowest percentage forecast is "less than 20%" (considered zero), and the highest probability forecast is "near 100%" (assumed equal to 100).

In many humid areas, rainfall events during the summer growing season frequently occur in the afternoon and early evening hours as convective storms. Such storm events may be assumed to be essentially independent (Warner 1972). If rainfall occurs due to a frontal storm pattern, then the events and forecast may not be independent. In such a case, a portion of the same weather data would be analyzed in determining the forecast. In this study, all storms, convective and frontal were assumed to be independent. This probably provided a positive bias in the computed value of the daily combined statistical probability for the occurrence of at least one rainfall event today, tonight or tomorrow. This was considered acceptable in this study because it provided additional assurance that simulated changes would be made in advance of any potential rainfall event to avoid the possibility of excess soil-water. For many crops, stress due to short-term excess water in the root zone can be more detrimental than short-term drought stress.

In this study a Rainfall Probability INDEX (RPI) was defined and computed using the following formula:

$$\mathrm{RPI}[E1\ U\ E2\ U\ E3] = 1 - [(1-P[E1]) * (1-P[E2]) * (1-P[E3])]. \qquad [1]$$

Where: "U" denotes the union (logical sum) of rainfall events, P[E1], P[E2], and P[E3] are the probability of rainfall for today, tonight, and tomorrow, and E1, E2, and E3 are events that are assumed to be statistically independent (Warner 1972). The term INDEX was used rather than combined probability because all storms were known not to be independent events, therefore the true combined probability could not be computed with this formula. Here, RPI represents the percent chance of at least one rainfall event today, tonight, or tomorrow. If the forecast probabilities of rainfall were 40, 40, and 45%, for today, tonight, and tomorrow, the RPI computed by Equation [1] would be 80%, the threshold value in this study.

3 Climatological and System Design Input Data

Maximum and minimum daily temperatures and hourly rainfall records for the period 1979 to 1985 were obtained for the Louisiana State University, Ben Hur Research Farm at Baton Rouge. Simulations were conducted for a Commerce clay loam which is a common soil type in the lower Mississippi Valley. DRAINMOD has been validated using field drainage research data for this soil type on the Ben Hur Research Farm (Fouss et al. 1984). The climatological data set has also been used in other drainage-irrigation simulation studies (Fouss 1985a, and Fouss et al. 1985). All input soil parameters for the DRAINMOD simulations have been previously reported by Fouss et al. (1984) for this site.

The following water management system-design parameters were used: drain diameter = 10cm, drain depth = 100cm, and drain spacing = 20m. Corn was the test crop for the simulations and a maximum rooting depth of 30cm was assumed. The variation of rooting depth throughout the growing season reported by Skaggs et al. (1981, 1983), was used in the simulations.

4 Simulation Procedures

The simulations utilize two different computer models; DRAINMOD with the feedback control subroutine that includes an option for input of rainfall probability data, and a special short-term simulation model, based upon a finite difference solution of the Boussinesq equation (after Smith, 1983). The Boussinesq-based model was used to conduct detailed simulations of water table response for selected single storm events and multiple storms within a period of one to two months.

The effectiveness of different operational modes for the controlled-drainage/subirrigation system, with and without the use of rainfall forecast information, was evaluated by comparing simulation results for selected daily or seasonal management schemes. DRAINMOD simulations were conducted for the complete period of climatological record (1979-1985) for each operational mode, but simulations with the Boussinesq-based model were made only for one-week to two-month periods of time selected by inspection of the DRAINMOD predictions.

The following operational/management modes were considered:

For DRAINMOD simulations ....

DM-1. Conventional subsurface drainage with O/I set at drain depth (100cm) for the entire year.

DM-2. Water table management during the growing season (Days-of-the-Year 100 to 230) by controlled-drainage and subirrigation, with the O/I water level held constant at a 55cm depth* below the soil surface.

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* Constant O/I depth of 55cm determined from previous simulations for optimum year-to-year relative corn yields (Fouss, 1985a).

DM-3. Same as DM-2, except O/I water level was dropped to drain depth on any day that RPI > 80% **; O/I water level was reset to 55cm depth whenever water table depth midway between drain lines dropped below 55cm.

DM-4. Same as DM-3, except the start of water table management was delayed until Day-of-the-Year 115 (i.e., control period Days-of-the-Year 115 to 230).

For Boussinesq-based model simulations ....

BQ-1. Validation simulation for DRAINMOD predictions, for control/management mode DM-3, during a one- or two-month period when excessive rainfall occurred.

BQ-2. Simulate and compare the start of water table management (subirrigation) on Days-of-the-Year 100 and 115 (same as DM-3 and DM-4) for a "wet" growing season (e.g. 1983).

BQ-3. Short-term (less than one-month) simulation when RPI was less than 80%, but significant rainfall occurred; simulate lowering O/I water level 24 hours in advance of the rainfall event.

BQ-4. Simulate lowering the O/I water level 48 hours in advance of a rainfall event that was predicted 24 hours in advance by the actual weather forecast.

Predicted overall relative yield, with crop yield impacts of drainage, irrigation, and spring planting delay (after Skaggs 1980) was used to evaluate the performance of the various simulated modes of system operation. Average controlled water table depth during the growing season and excess soil-water in the rooting zone (30cm depth) were also considered.

** RPI > 80% selected from multiple simulations using procedures presented by Fouss (1985a) and Fouss et al. (1985).

5 Simulation Results and Discussion

The DRAINMOD predicted performance parameters were evaluated to compare control modes over a seven-year simulation period (Table 1). The simulation results for year 1983 are also shown to represent a "wet" year. In wet years, control/management for dual purpose drainage/subirrigation systems often requires frequent changes from subirrigation to drainage. Thus, controllability of the water table management system during a wet season can be an important selection criterion.

Table 1. -- Summary of DRAINMOD Simulation Results For 1983 - A "Wet" Year, And The Seven-Year Averages And Standard Deviations [1979-1985].

Mode	Description of System Control	G.S[1] Avg. Water Table Depth (cm)	Excess Water; SEW-30 (cm-da)	Relative Yield (Drain) (%)	Relative Yield (Irrig.) (%)	Overall Relative Yield[2] (%)
		- - - - - - Year 1983 - - - - - - - - - - - [1979-85, Avg ± s.d.] - - - - - -				
DM-1	Conv.Drain[3] (all year)	99 [115±14]	61 [38±36]	94 [95±6]	100 [72±23]	94 [69±23]
DM-2	WT Mgmnt.[4] 0/I=55cm(const.) (Days 100-230)	57 [64±14]	201 [113±68]	76 [88±10]	100 [100±1]	76 [87±11]
DM-3	WT Mgmnt. 0/I=55cm,except when RPI > 80% (Days 100-230)	63 [70±5]	139 [74±46]	84 [92±7]	100 [99±1]	84 [91±8]
DM-4	WT Mgmnt. 0/I=55cm,except when RPI > 80% (Days 115-230)	65 [83±21]	115 [61±48]	90 [94±7]	100 [92±17]	90 [86±15]

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[1] G.S. = "growing season", approximately April 10 to August 8.

[2] Note: No planting delays were simulated for the 7-year period.

[3] Conventional drainage.

[4] Water table management

Conventional drainage (DM-1) and WT management with a constant O/I water level at 55cm depth (DM-2) during the growing season were simulated as the comparative standards for operation/control of the dual purpose system during the seven-year period. WT management (DM-2) improved performance over that of conventional drainage (DM-1) based on the 7-year average overall relative yield and standard deviation of yield. However, for the wet year (1983), the predicted overall relative yield with conventional drainage was significantly higher than where WT management with constant O/I water level control was used (see Table 1; DM-1 and DM-2). For the conventional drainage system, the principal cause of the reduction in relative yield over the 7-year period was the need for irrigation, as indicated by Relative Yield (Irrigation) = 72 ±23% (Table 1; DM-1). The irrigation demand was fully met by WT management with constant O/I water level control, but relative yield reductions did occur for some seasons of the 7-year period due to excess soil-water, as indicated by Relative Yield (Drainage) = 88 ±10% (Table 1; DM-2).

The simulated control of the WT management system was enhanced by the use of the Rainfall Probability Index (RPI) to lower the O/I water level to the drain depth (100cm) in advance of predicted significant rainfall events. The excess soil-water in the root zone (SEW-30) was reduced from an average of 113 ±68 cm-da for constant O/I water level control (DM-2) to 74 ±46 cm-da where the O/I water level was lowered when RPI > 80% (DM-3). Skaggs and Tabrizi (1983) have related that the SEW-30 of 100 cm-da is a dividing line (for many soils in the humid region) between an acceptable degree of drainage and excess soil-water conditions that begins to cause a reduction in corn yield. For the wet year 1983, a reduction in excess soil-water in the root zone from 201 to 139 cm-da was predicted when an RPI was used as an input (Table 1; DM-2 and DM-3). A maximum 7-year corn yield with minimum standard deviation (91 ±8%), was obtained with control Mode DM-3. The water table depth midway between the drain lines is shown in Figure 1 for year 1983 using control Mode DM-3. The broken line represents the depth to the water level at the O/I. Control of the O/I water level was begun on Day-of-the-Year 100 which was the simulated date for planting corn; no spring planting delay occurred due to excess soil-water.

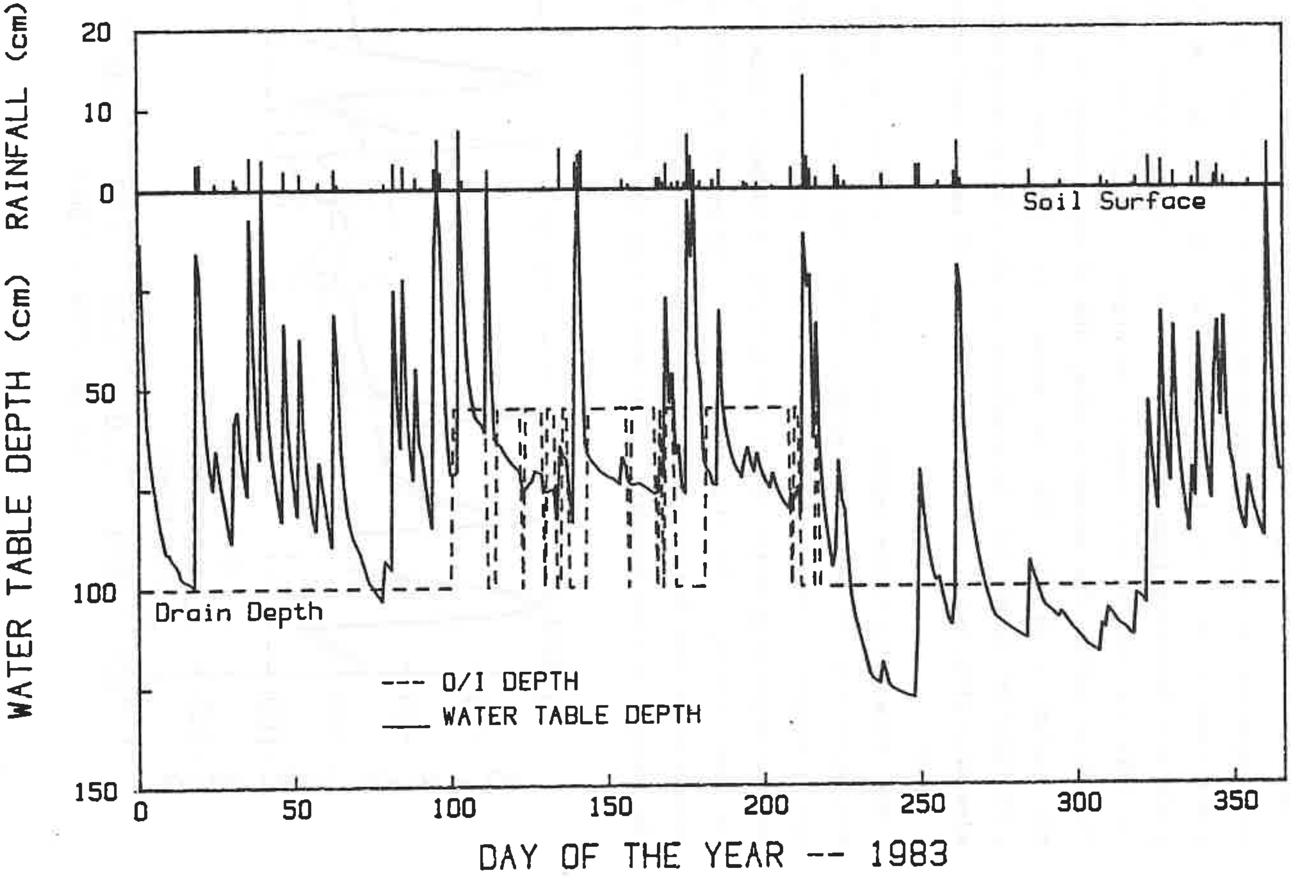

Figure 1. -- DRAINMOD simulated WT management with O/I=55cm depth, except when RPI > 80%, for "wet" year 1983.

Based on the 7-year averages, a 15-day delay in the start of subirrigation (beginning on Day-of-the-Year 115) reduced overall relative yield from 91 ±8 to 86 ±15 percent, but for 1983 the overall relative yield was increased from 84 to 90 percent. The predicted yield increase in 1983 was due to the reduced duration of excess soil-water in the root-zone during the spring months; SEW-30 was reduced by 24 cm-da for the period from Day 100 to about Day 120 (see Table 1). The subirrigation demand for the remainder of the 1983 growing season was not adversely affected by the delayed start of O/I water level control (Table 1; DM-4).

The Boussinesq-based model was used to conduct a more detailed simulation for the wet spring months of 1983 (Days-of-the-Year 91 through 151). Figure 2 presents the graphical comparison of the DRAINMOD (DM-3) and the Boussinesq model (BQ-1) predictions of midpoint water table depth for the period. The O/I water level changes indicated were those generated by the DRAINMOD simulation, and which were used as inputs for the changes in flow boundary conditions during the Boussinesq-based model

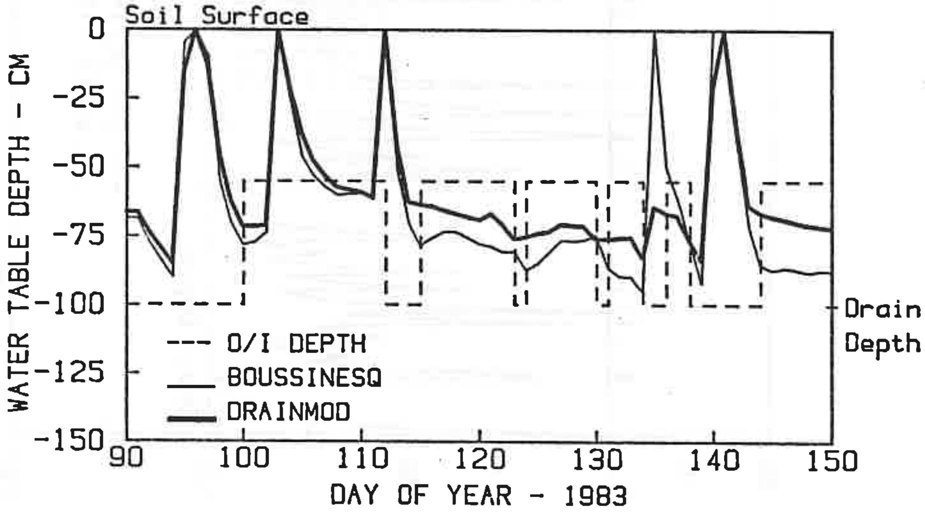

Figure 2. -- DRAINMOD and Boussinesq model predictions of "controlled" water table depth for the April-May period of 1983.

simulation. The WT depth predicted by the DRAINMOD (DM-3) and Boussinesq (BQ-1) models agree within acceptable limits, except for Day-of-the-Year 135 (Fig. 2). During the period of no rainfall from Day 112 to 134 (see Fig. 1), the DRAINMOD simulation predicted ET demand higher than what could be supplied by upward flux from the water table (tabular results not shown). A 10-cm deep "dry zone" (as defined by Skaggs, 1980) was developed in the root zone, which was refilled by the rainfall on Day 135, and only a slight rise was predicted in the water table. The Boussinesq model predicted that the WT would rise to the ground surface for the rainfall on Day 135. The surface runoff predicted was 22.0cm with DRAINMOD and 19.3cm with the Boussinesq model, from an accumulative rainfall amount of 39.6cm for the period (Day 91 through 151). The daily RPI values and the corresponding rainfall for the spring of 1983 are shown in Figure 3. The 5.1cm rainfall event on Day 103 provided no advance warning for lowering the water level at the O/I as the RPI was uncommonly low. However, the RPI of 80% was exceeded for the other significant rainfall events during the two-month period, allowing for advance lowering of the O/I water level before each rainfall event.

By delaying the start of the subirrigation period to Day 115 (BQ-2) for 1983, the impact of the large unpredicted storm on Day 103 is reduced (Fig.4). Although the simulated water table still rises to the ground surface, the duration in the root zone is decreased, thus reducing SEW-30. The success of this strategy over starting subirrigation on Day 100 is due to the poor correlation between RPI and the rainfall amount for this storm event. The delayed irrigation strategy would only have meaningful application for "wet" spring conditions, which are difficult to predict.

A special Boussinesq-based model simulation (BQ-3) was conducted where the O/I water level was lowered to drain depth on Day 102, one day before the 7.3cm rainfall on Day 103 (graphical results are not given here). The predicted WT still rose to the ground surface on Day 103, but the WT receded at nearly the same rate as that shown by the dashed line in Figure 4 for the delayed start subirrigation system. This demonstrates that for those cases where the RPI is less than the threshold but significant rainfall occurs, lowering the O/I water level when rainfall actually begins can be effective in reducing the duration of excess soil-water in the root-zone. The control of O/I water level based upon

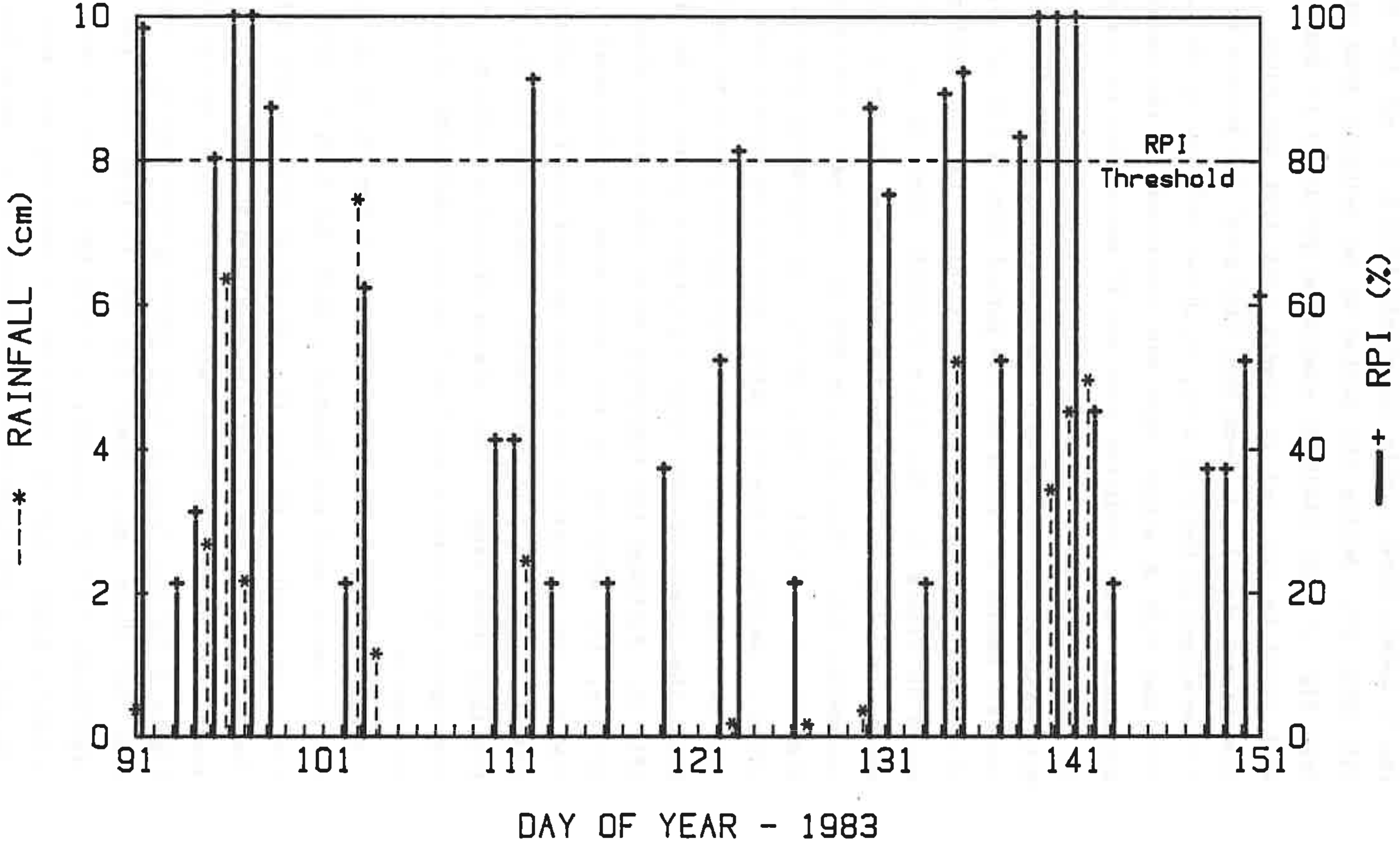

Figure 3. -- Rainfall and daily Rainfall Probability Index (RPI) for the April-May period of 1983.

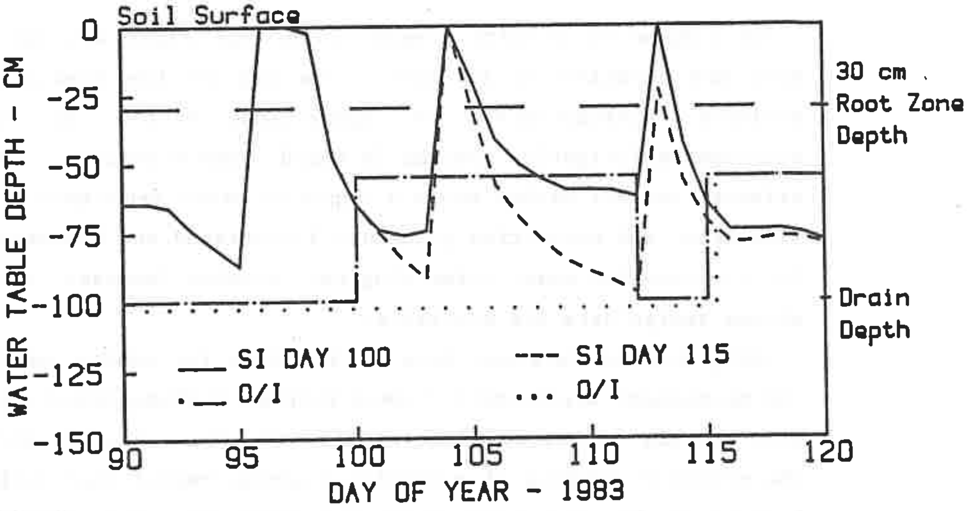

Figure 4. -- Boussinesq-based simulated water table depths for comparing the start of subirrigation on Days-of-the-Year 100 versus 115 in the "wet" spring of 1983.

rainfall amount and/or a minimum water table depth have been previously reported by Fouss (1985a and 1985b). Use of either one or both of these parameters can further enhance the system control with weather forecast information.

Finally, a Boussinesq-based simulation (BQ-4) was made to evaluate lowering the O/I water level to drain depth 48 hours in advance of a rainfall event that was predicted only 24 hours in advance by the weather forecast. The 5.1cm rainfall event which occurred on Day 135 of 1983 (see Figs. 1, 2, and 3) was used, assuming that subirrigation started on Day 100 (Fig. 4). The simulated water table still rose to the ground surface (graphical results not shown here), but the recession of the WT following the rainfall was slightly more rapid than when the O/I was lowered only 24 hours in advance of the rainfall, with a resulting reduction of about 5 cm-da in the excess soil-water within the root-zone (SEW-30) for this one storm. Thus, an additional 24 hours advance warning (forecast) of this rainfall event would have only slightly improved water table management.

6 Comments

The simulation results presented in this paper are for one specific soil and location to illustrate the use of the simulation method to evaluate alternatives for operational-control of dual purpose drainage/subirrigation systems in humid climate regions. The results and selected control method may not apply in other geographic areas, but the simulation and evaluation procedure illustrated and discussed can be used for any location where climatological, weather forecast, soils, crop, and system design data are available.

Using weather forecast data as an input for making daily operational and management decisions for dual purpose drainage/subirrigation systems also has the advantage of being able to adjust the O/I water level for the system in advance of a predicted storm, rather than during the storm. A reset of the O/I water level following the storm should control the outflow in order to avoid over drainage of the soil profile, thus eliminating the need to immediately resupply the soil-water by subirrigation. The simulation approach can also be used to optimize the O/I water level management by controlled-drainage to efficiently utilize the rainfall that is received (see Fouss et al. 1985).

7 Summary

A computer simulation study was conducted to evaluate various modes of controlling dual purpose drainage/subirrigation systems for humid climate and soil conditions in the Lower Mississippi Valley of the USA. A primary objective was to evaluate the use of daily rainfall probability data as a control input for computer simulations of water table management. When a Rainfall Probability "Index" (RPI), computed from data in the daily weather forecasts, exceeded a threshold value of 80% the outlet/inlet (O/I) water level for the subsurface drainage-irrigation system was lowered to allow the system to freely drain in advance of predicted rainfall events. The goal of the system control was twofold: (1) To provide adequate soil-water in the root zone via subirrigation during periods without rainfall; and (2) to minimize the duration of excess soil-water conditions in the root zone during and following rainfall events by controlling drainage.

Two computer models were used to simulate the operation of the water table management system over a 7-year period of climatological and forecast record. DRAINMOD with an O/I water level control subroutine and option for input of rainfall probability data was used to simulate the full 7-yr period. A special short-term simulation model, based upon the finite difference solution of the the Boussinesq drainage flow equation, was used to conduct detailed simulations of the "controlled" water table response for single storm events or multiple storms within a one or two month period.

Simulation results demonstrated the use of the Rainfall Probability Index (RPI) to decide when to lower the O/I water level to the drain depth. Lowering the O/I water level in advance of predicted significant rainfall events enhanced the control of the water table depth, decreased the duration of excess soil-water in the root-zone following rainfall, and increased relative corn yield while minimizing the variation in yield from year to year. Other on-site parameters, such as amount of rainfall received and minimum water table depth, can also be used as control inputs to further enhance the daily operation of the water table management system. Use of weather forecast data allows for advance adjustment of the O/I water level for a predicted rainfall event, rather than during or following the storm.

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SUBSURFACE DRAINAGE IN ALBERTA, CANADA

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Abstract

Approximately 4.5M ha of Alberta's agricultural land base is affected by excess water. Drainage of many of these areas is becoming a high priority and shallow subsurface drainage is expected to play a major role. The development of subsurface drainage guidelines and standards is currently taking place for the successful reclamation of all wetland types in Alberta.

1 Introduction and Background

Alberta is one of ten provinces and two territories which make up Canada. It is located in the western part of Canada between 110° - 120° longitude and 49° - 60° latitude. It is bordered at the west by British Columbia, to the east by Saskatchewan, to the north by the North West Territories and to the south by the state of Montana in the United States of America (Figure 1). The total land base of Alberta is approximately sixty-five million hectares of which approximately twenty-four million hectares is considered to make up the current agricultural land base (Figure 2). Approximately half of this twenty-four million hectares is presently cultivated.

Alberta, like most of the western provinces of Canada, has highly variable agro-climatic conditions as one moves from south to north, with the existing agricultural land base separated into zones 1, 2H, 2A and 3A (Figure 3). For the purposes of drainage, these zones can be combined to form three regions, with 2A and 3A forming Region 1; zones 1 and 2H in the central part of the province forming Region 2; and 2H in the northwestern part forming Region 3 (Figure 4). It is

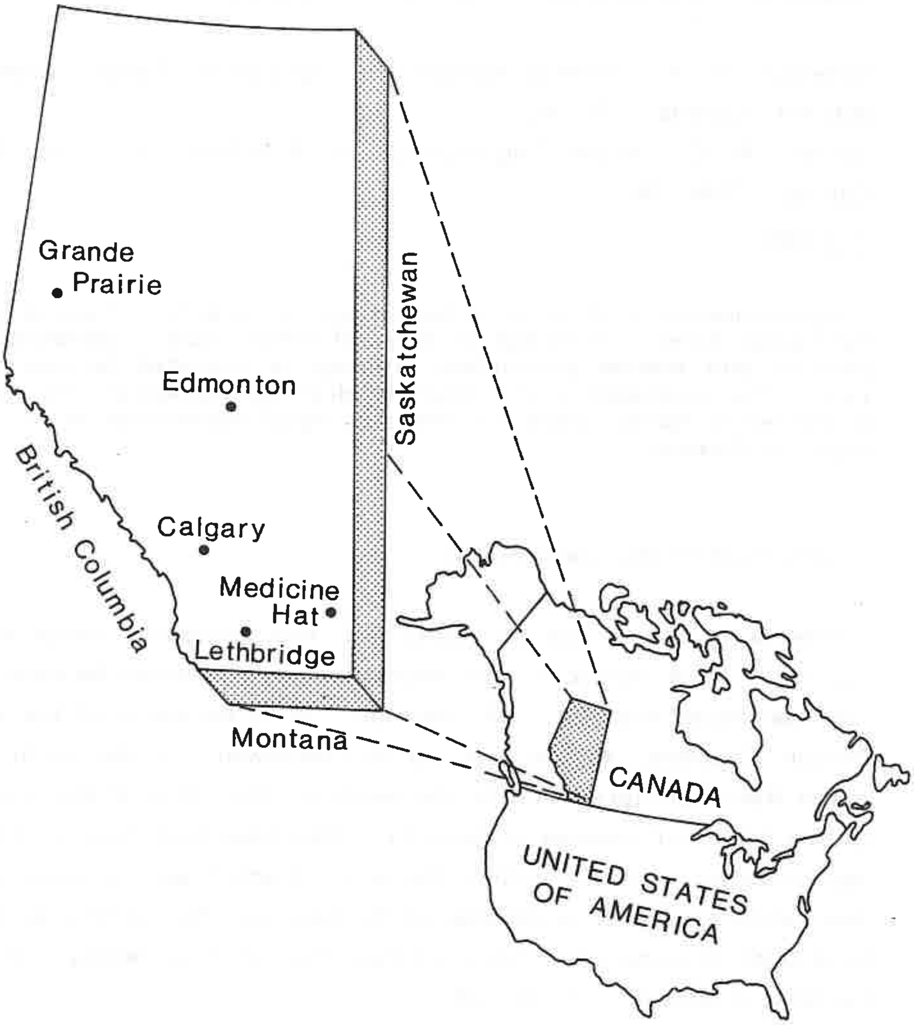

Grande Prairie
Edmonton
Calgary
Medicine Hat
Lethbridge
Saskatchewan
British Columbia
Montana
CANADA
UNITED STATES OF AMERICA

Figure 1

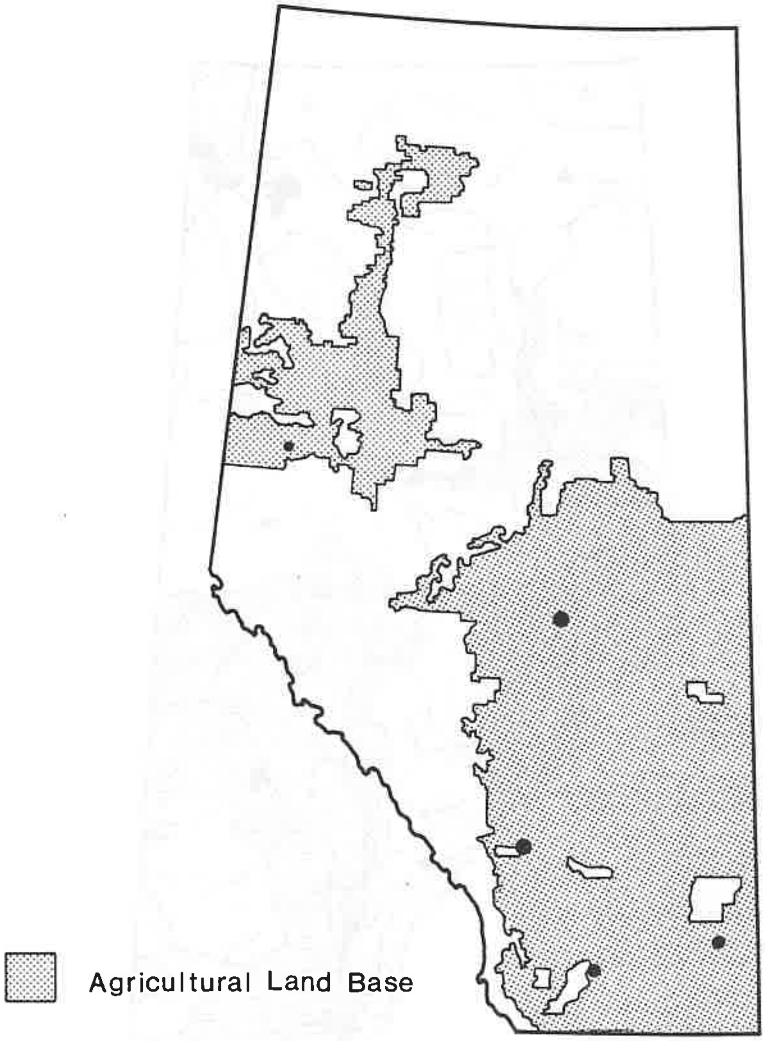
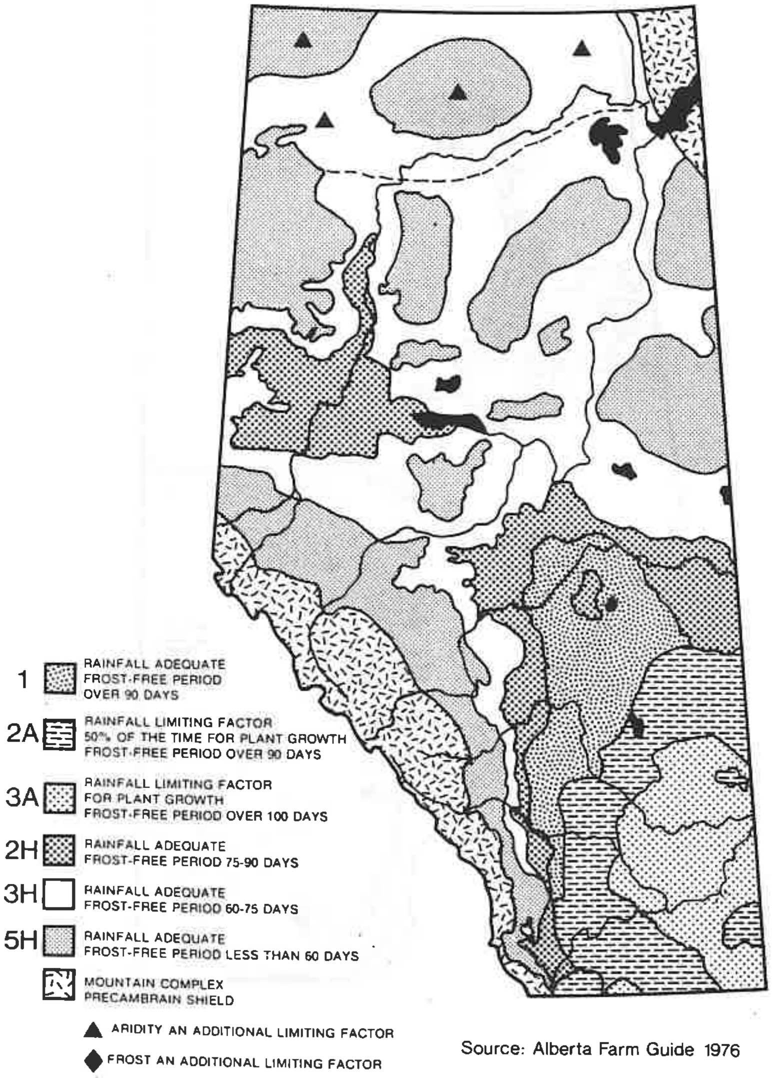


Figure 2



Source: Alberta Farm Guide 1976

Figure 3

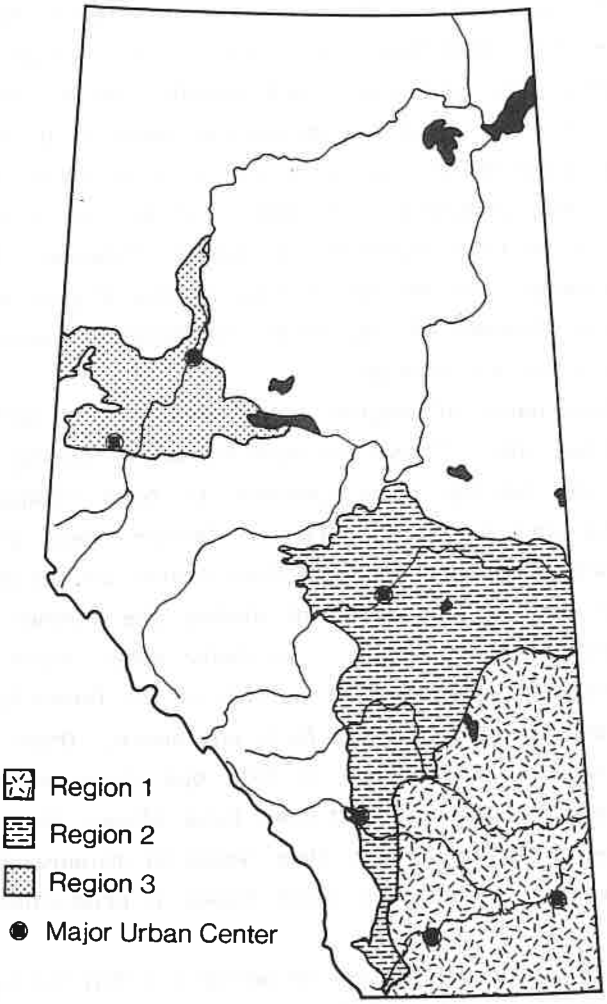


Figure 4

estimated that within the agricultural land base area approximately 4.4 - 4.5 M ha of land are affected to some degree by excess moisture. In Region 1 this accounts for less than 5% of the agricultural land base, while for Region 2 it constitutes 10 - 20% and for Region 3 approximately 30% (Birch et al., 1985).

Farms in all of these regions share concerns related to excess water problems. However, significant differences exist between regions regarding the secondary problems which result from the excess moisture. In Region 1 excess water from sources such as irrigation canal seepage, natural groundwater discharge and on-farm irrigation management result in salinity problems on 60 000 - 120 000 ha of the approximately 560 000 ha of land currently irrigated (Paterson, 1983). In addition, approximately 200 000 ha of land in this region are affected by dryland salinity (Vander Pluym, 1982). In Regions 2 and 3, salinity is not considered a serious problem.

In Region 2 and parts of Region 3 the existence of surface water bodies are a common site. These are most noticeable during the spring when snowmelt and spring rains combine to form shallow, usually temporary sloughs and marshes. To the farmer these are a major nuisance and financial problem because they cannot be seeded with the rest of the field and, upon drying up during the summer, become a haven for various types of weeds. In many cases these temporary slough/marshes make up a significant portion of the farmer's land base and with the trend towards larger farm equipment, these areas are looked upon as serious impediments to field operations such as cultivation, seeding and harvesting. Studies have shown that significant losses in fuel, seed, herbicides and time result in maneuvering around these water bodies, to say nothing about losses in production (Jensen, 1984).

In Region 3 the most prevalent type of wetland within the agricultural land base is bog/fen or peat. Of the approximately 1.5 M ha of wetlands in this region, over 80% are bog/fen, with the remainder made up of slough/marsh and sheetwater problems. Many of the smaller bog/fens are located within existing cultivated land and to a farmer, affect his field operations in a similar way as does a slough/marsh. The majority of bog/fen areas however, are large in size and usually border existing cultivated land holdings. More and more pressure on the agricultural development of these bog/fen areas is being brought to bear by each successive generation of farmers. At present only 0.2% of Alberta's 4 000 000 ha of bog/fen areas are developed. It is estimated that, with drainage and reasonable management, approximately half of the existing bog/fen areas located within the agricultural land base could be developed for agricultural production. In addition, significant areas of mainly bog/fen soils could be developed in areas adjacent to the agricultural land base in northwestern Alberta (Figure 5).

2 Drainage Development

Problems related to excess moisture have been a concern of Alberta's farmers since the early 1900's. However, because of the large agricultural land base coupled with a relatively small population, minimal pressure to reclaim and develop these wetland areas was felt until recently. It was easier and less expensive to simply farm around or replace those lands taken out of production because of excess water and/or salinity. This attitude has changed significantly over the past five to ten years. Higher land prices, larger farm equipment and the trend towards optimizing farm production has resulted in farmers becoming increasingly more interested in drainage and reclamation of their saline and wetland areas. The development of the subsurface drainage industry has in many respects paralleled this interest, beginning first with control and reclamation of saline and waterlogged lands in the irrigated areas of southern Alberta.

A Irrigation

Irrigation development began in Alberta during the late 1800's and has developed until today approximately 600,000 ha are currently irrigated. The majority of the irrigated land is located in the southern part of the province (Figure 6) and is considered somewhat unique in the world. Firstly, Alberta's irrigation season is relatively short with water applied for only three to four months (May - September).

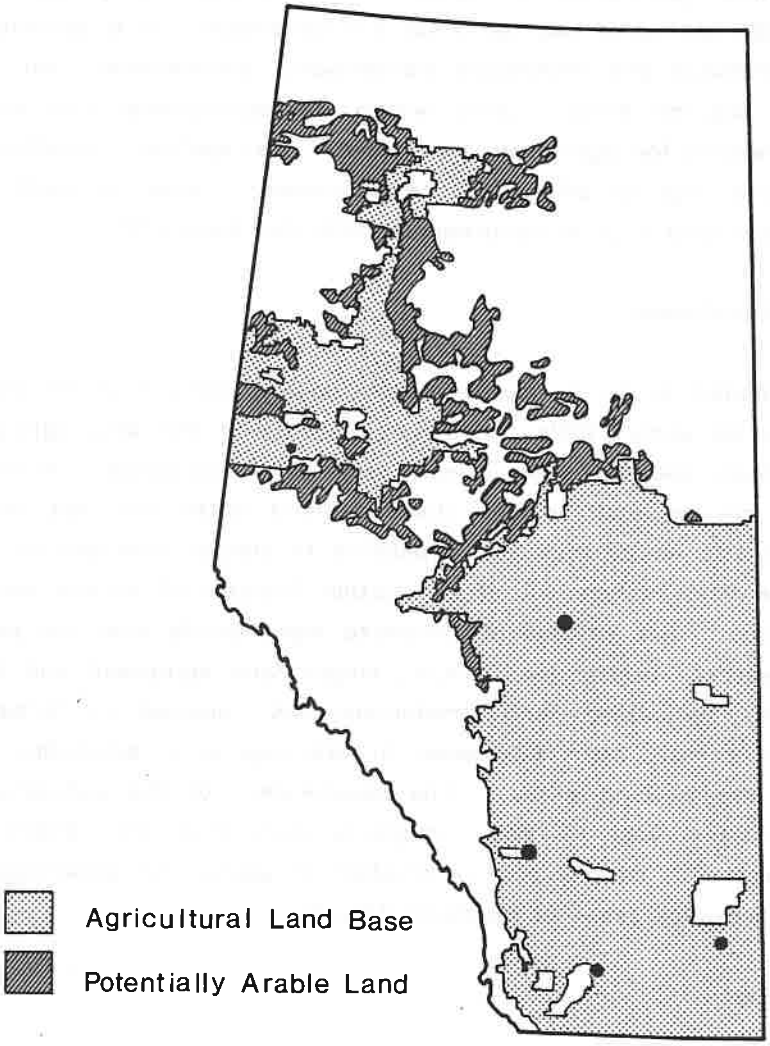


Figure 5

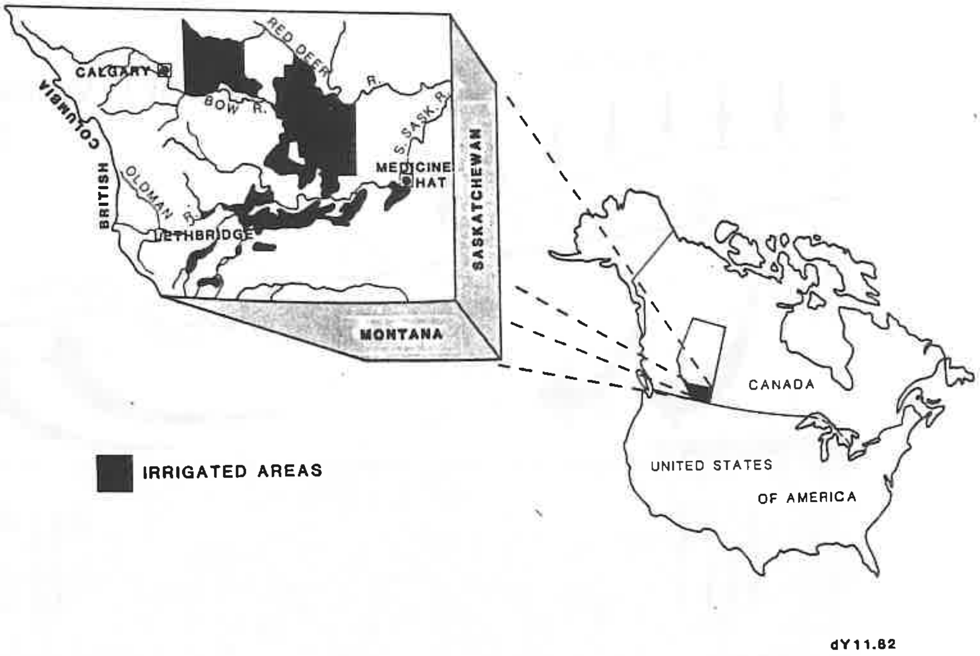


Figure 6

Secondly, essentially all of the irrigated area is underlain by glacial tills within 1 m of ground surface. These tills are generally medium to fine textured and are considered to have very low hydraulic conductivity rates ranging from 1×10^{-8} to 1×10^{-10} cm/s (Freeze and Cherry, 1979). These apparent low hydraulic conductivity values have caused concern by many regarding the long term irrigation potential of these soils. It was felt that the application of water, particularly by flood methods, would quickly result in a significant water table rise and subsequent salinity problems. However, recent work by Hendry (1982, 1983) has shown that hydraulic conductivities are considerably higher than initially thought because of fracturing in the upper weathered till layers. This combined with the short irrigation season and subsequent long drainout period has resulted in a surprisingly good soil water and salinity balance. The majority of the salinity problems which do occur are caused by excess water from canal seepage (75%) and/or natural groundwater discharge (20%) from dryland recharge areas above the

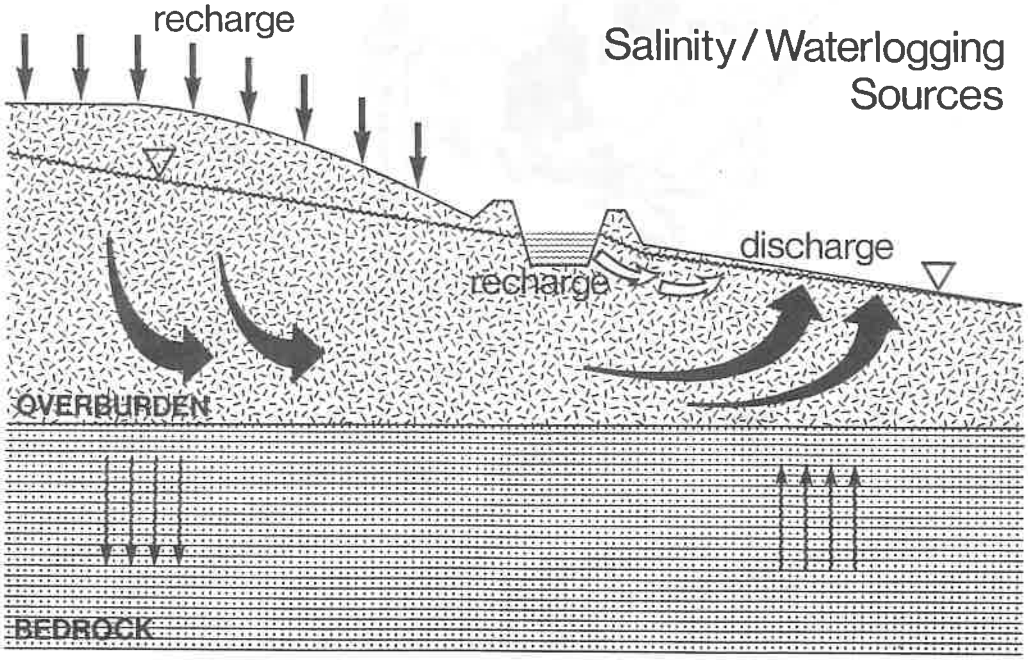


Figure 7

irrigation canals (Figure 7). Less than 10% of the existing salinity problems are the result of applying water to the soil.

Prior to 1975, reclamation of saline soils in the irrigated areas centered around canal seepage control measures such as concrete and plastic linings, replacement of existing canals with pipelines and installation of deep (> 2.5 m) interceptor drains adjacent to the seeping canals. While these measures have successfully controlled canal seepage, they have not proven successful in reclaiming those lands already affected by excess salinity. This is particularly true in those instances where natural groundwater discharge occurs in conjunction with canal seepage.

Shallow subsurface drainage (< 1.8 m depth), while popular in the more humid areas of eastern Canada, was not introduced to Alberta prior to 1975 for a variety of reasons. In addition to the general lack of demand by farmers for on-farm drainage, the general feeling by scientists was that shallow subsurface drainage would not control salinity problems (both irrigated and dryland) in the glacial till soils.

It was thought that drains must be installed at depths of 1.8 m or greater in order to prevent salinization of the root zone by capillary rise from the water table. In 1975, as a result of discussions between Alberta Agriculture and corrugated plastic drain tubing manufacturers in eastern Canada, a series of test projects were initiated within the irrigated areas of southern Alberta to evaluate the potential of using shallow subsurface drainage for control and reclamation of saline and waterlogged soils. The first of these projects was installed on approximately 72 ha of saline and waterlogged land caused by the application of excess water by pivot irrigation systems. The project consisted of 45 000 m of 100 mm and 150 mm drain tubing complete with polyester filter. The results of this and other test sites were excellent, with reclamation rates being relatively rapid and resalinization of the root zone not a problem provided sufficient irrigation water was applied. The success of these projects led to an increased interest by farmers in reclaiming salinity problems on their land. As a result, the subsurface drainage industry in Alberta expanded rapidly from 1975 - 1980, with two manufacturing companies actively producing a variety of sizes of corrugated polyethylene plastic drain tubing.

i) Investigation & Design

The key to the success of subsurface drainage within southern Alberta's till soils primarily depends on two requirements: a general understanding of the cause(s) of the soil salinity problems; and understanding of soil and groundwater flow characteristics for specific drainage sites. Since most of the salinity problems are due to groundwater flow from sources outside the affected area, most subsurface drains will act as both interceptor and relief systems. The depth and placement of these drains relative to the direction of groundwater flow then becomes critical.

The successful design of a drainage system is dependent upon the site-specific nature of the groundwater flow and geologic patterns. The extreme soil variability which exists throughout southern Alberta does not allow unilateral transfer of soil and groundwater data from site to site, even for sites located within a short distance of each other. A complete investigation must therefore be conducted for each potential drainage project to:

a) Identify the soil physical parameters including texture and horizon differentiation.

b) Instrument and monitor water table fluctuations and groundwater flow.

c) Analyze soil and groundwater chemistry including electrical conductivity (E.C.) and sodium/calcium relationships (SAR).

d) Estimate horizontal and vertical hydraulic conductivities.

Mobile auger drilling equipment is used extensively for site investigations which allows for rapid soil identification, sampling and groundwater instrumentation. Considerable discussion is ongoing regarding the correlation of traditional auger hole hydraulic conductivity values to actual field drainability. Recent work carried out by Buckland et al. (1985) shows a good relationship between the pump-out auger hole hydraulic conductivity results with drain spacings, assuming a drainage coefficient of 1 mm/d. The highly variable soils require that numerous hydraulic conductivity values be measured for each project in order to obtain soil differences.

Past experience with several hundred drainage investigations, including numerous research installations, has facilitated the design criteria necessary for successful subsurface drain installation on most saline and waterlogged lands throughout the irrigated areas of Alberta. Because of the horizontal groundwater flow component, most drainage systems are designed for installation within identifiable water bearing zones. These transmission zones are generally located within 1.8 m of ground surface, and found adjacent to or throughout the problem area. In some instances more than one aquifer or coarse textured layer may be transmitting excess groundwater into saline areas (Figure 8). In both instances it is important that the drains be installed within the water bearing strata.

The main function of Alberta's drainage systems is to control excess groundwater flow - not excess precipitation and/or intensive irrigation. Therefore drain spacings are often further apart than might otherwise

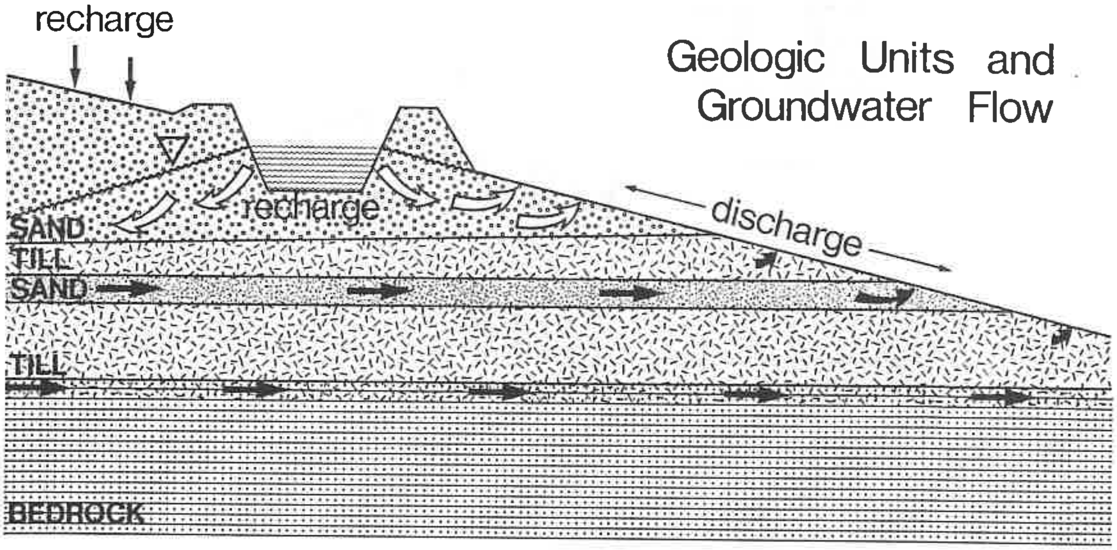


Figure 8

be acceptable. On initial research projects drains were installed at depths of 1.4 - 1.7 m and 15 m spacings, which tended to follow the humid region spacing criteria, but maintain maximum depths for salinity control. However, research has indicated that drain spacings of 30 m were equally successful in controlling the water table at or near the depth of the drain tubing (Bennett et al., 1982). At present the majority of drainage systems are installed at 25 - 30 m spacings. Installation depths vary with the location of water bearing strata, but generally average at 1.2 - 1.3 m.

ii) Equipment

A variety of drainage installation equipment was brought in from the more established drainage areas of eastern Canada. The first of these machines was the ladder or chain trencher (Figure 9), which has a maximum drain installation depth of approximately 1.8 m. The relatively deep installation depths for drains in the irrigated areas (ranging from 1.2 - 1.6 m), combined with the fine textured soils and rocks which are present in glacial tills, caused serious operational problems for these

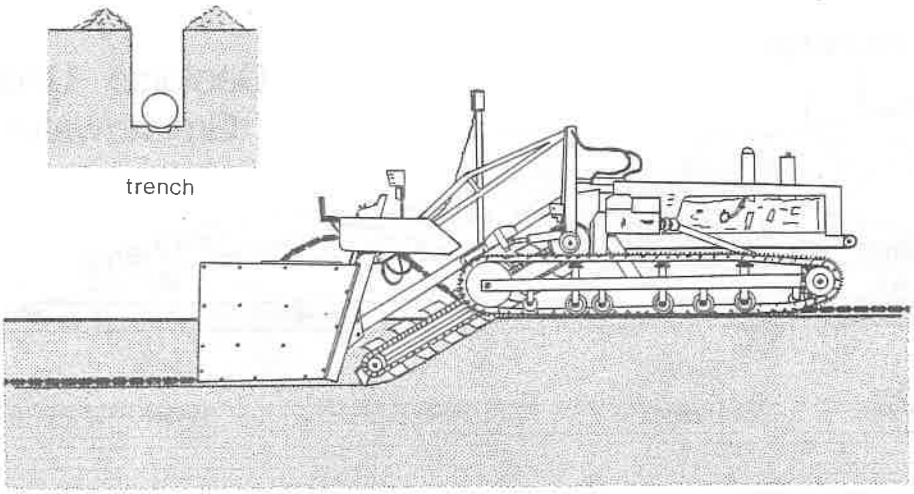


Figure 9

machines. In their place, a number of wheel trenchers (Figure 10) were introduced. The much slower rotation of the digging wheel enabled these units to handle the rocks and fine textured soils much better than the chain trenchers. Unfortunately the prolonged periods of installing drains at near maximum limits also resulted in high operation and maintenance costs and the use of this machine has declined significantly.

The most suitable drainage machine for use in Alberta is the trenchless plow (Figure 11). A number of different plow types have been utilized including the Badger, Krac, Wedge and Barth and all appear suited to the variable soil conditions, digging depths and drainage applications. Most contractors have found it necessary to employ a separate winch machine with the plow because its overall weight results in serious traction problems in the unstable soil conditions which are often found. A number of these plows have been successfully adapted to allow for concurrent installation of gravel or synthetic beads with the drain tubing (Figure 12). Some units have also been adapted to allow installation of plastic curtains to depths of 2.4 m (Figure 13) in order to control seepage from irrigation canals (Figure 14), surface drains and ponds. Adaptation of units for installation of larger drainage pipe (up to 300 mm) has also been carried out.

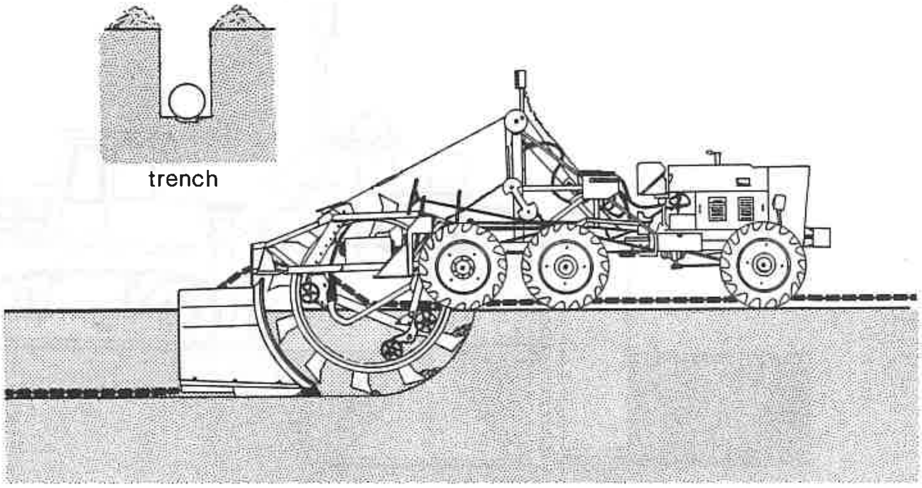


Figure 10

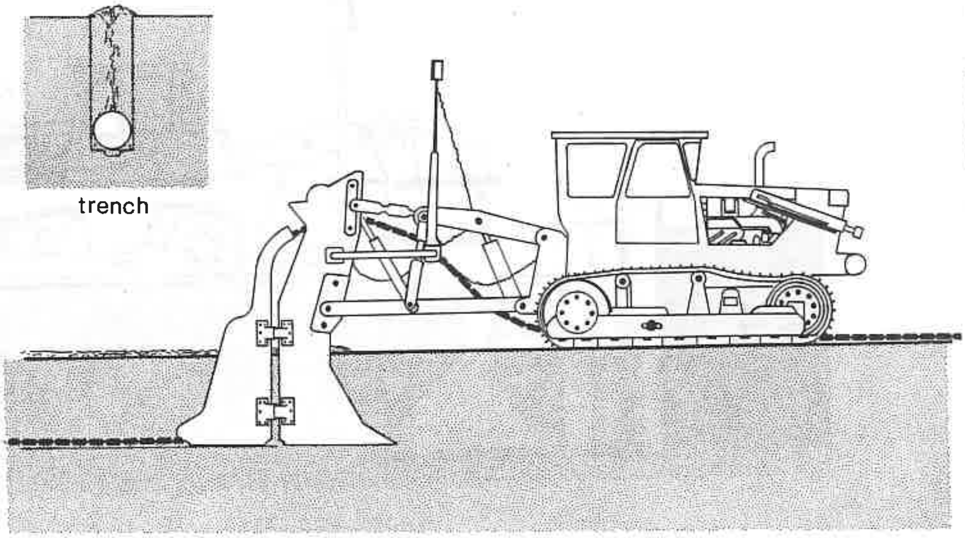


Figure 11

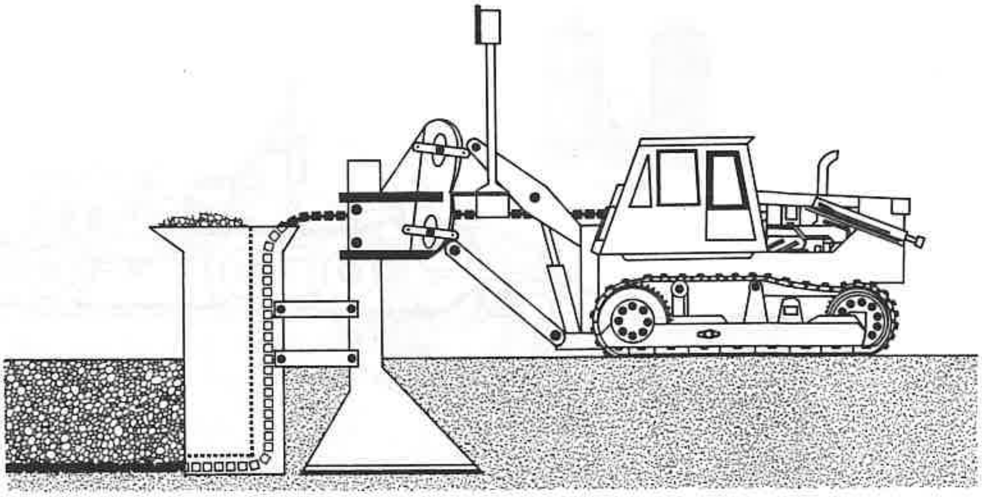


Figure 12

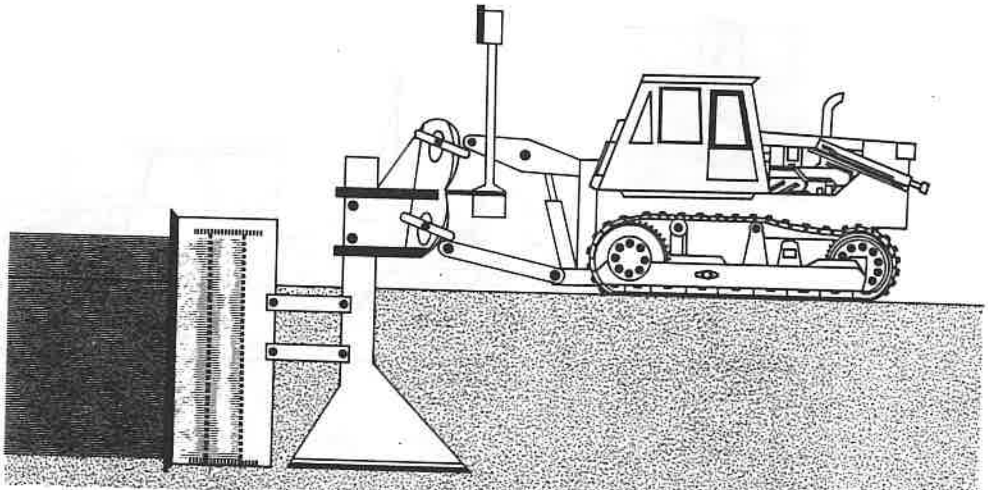


Figure 13

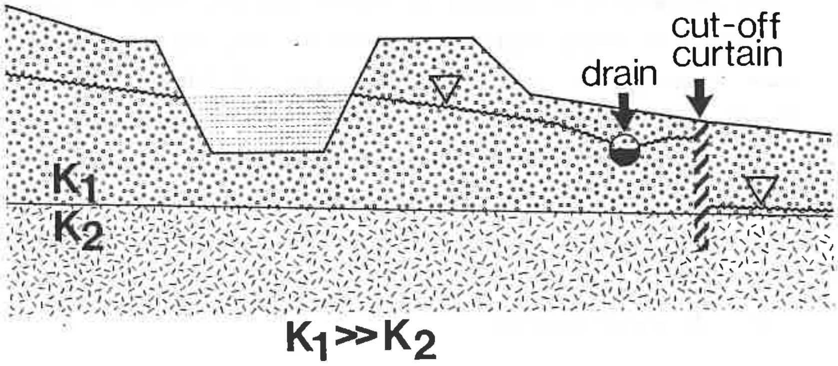


Figure 14

Regardless of the type of drainage machine, the use of automatic laser grade control equipment and power feeder is considered mandatory for any government assisted subsurface drainage project in Alberta. This is particularly important equipment for the high speed drainage plows where numerous instances of excessive drainage pipe stretch have been noted when power feeders are not utilized.

iii) Installation

To date, the majority of subsurface drainage in Alberta is in the irrigated areas with more than 400 projects identified. Over 50% of the drains installed in this area have the polyester knit filter sock enclosing the drain tubing to prevent entry of fine sands. While there continues to be considerable debate on the usefulness of these "sock" filters compared with gravel, they appear to perform well in Alberta. The significant cost savings in drainage installation when using the "sock" instead of gravel has also proven to be very important in determining the economic viability of many projects. Even with this saving, the cost of subsurface drainage remains relatively high, with costs of \$1 000 - \$1 300/ha (Cdn) or \$700 - \$900/ha (U.S.) to install 100 - 150 mm drain tubing to a depth of 1.2 m on a 30 m spacing. These costs are high because of the installation depths and difficult installation conditions. During the optimum installation period (spring and summer) the majority of the affected areas have high water table conditions and very unstable soils caused by water seeping from the canals.

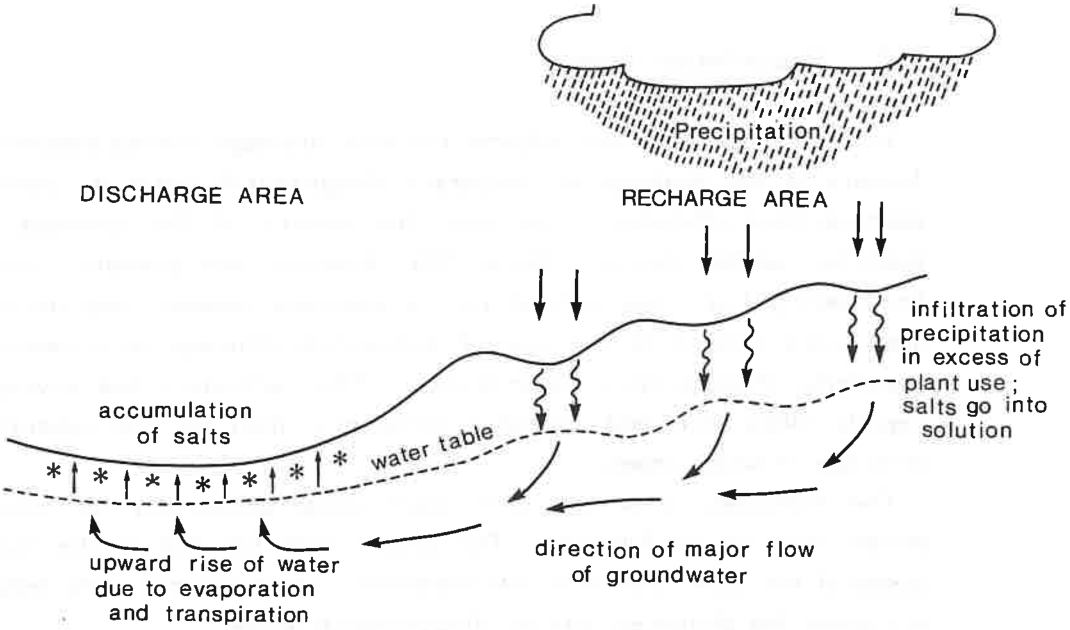
Even with these high costs however, studies have shown that subsurface drainage of the irrigated areas of Alberta is economic (Birch, 1983), particularly if soil salinity prior to drainage is not extremely high and good after-drainage management by the farmer is practiced. At present, on-farm drainage costs are borne entirely by the individual landowner, with very little in government subsidy available.

B Dryland Salinity

Natural groundwater discharge, which is a significant cause of irrigated salinity (Figure 7) is considered the prime cause of almost all dryland salinity problems. The exact mechanism is not yet well understood but the general process is thought to be similar to that shown in Figure 15. Because of the similarity of irrigated and dryland salinity problems, the successful development of shallow subsurface drainage as a control for irrigated related salinity quickly led to attempts to control and reclaim problems associated with dryland salinity. It is well accepted that the key to successful reclamation of irrigation salinity is the ability to apply large amounts of water to drained soils in order to leach the excess salts through the soil profile and into the drains. Under dryland conditions, where total annual precipitation may be less than 250 mm, this excess water is not as available and reclamation is somewhat slower. In spite of this, numerous projects have been installed throughout southern Alberta on dryland saline seep areas.

Subsurface drainage installation in dryland saline areas is similar to installation in the irrigated regions. Research is continuing to determine the overall effectiveness and economic practicality of using subsurface drainage to control dryland saline seepage. Reclamation of these projects have been variable and appear dependent on the seriousness of the salinity problem. The main benefit of the subsurface drainage in dryland saline seeps appears to be in simply controlling the water table, thus preventing the spread of the dryland saline areas and allowing farmers to carry out normal field operations without the danger

THE PROCESS OF SOIL SALINIZATION



From report by
Environment Council of Alberta
on Dryland Salinity

Figure 15

of getting their machinery bogged down. It is estimated that dryland salinity may increase by as much as 10% in a year (Vander Pluym, 1982) and controlling this increase is becoming a high priority. Because the source of excess water is groundwater and water levels tend to remain high through much of the summer, successful installations (both dryland and irrigated) require that winch machinery always be present on the site. Contractors have learned that at the first sign of the drainage plow becoming stuck, the winch machine is hooked up and the drainage plow pulled through the affected area. This not only reduces wear on the machinery but also ensures better grade control of the drain tubing and prevents excessive disturbance of the soil profile. Many of the saline soils in Alberta are in fact saline-sodic (E.C. > 4 m

S/cm and SAR > 15) and disturbance of the soil profile can cause serious soil structural problems resulting in reduced water movement.

C Slough/Marsh Areas

In central and northern Alberta the main drainage related concern by farmers is the drainage of temporary slough/marsh areas in order to improve field efficiency. To date, the majority of this drainage has been by surface means. Since 1975, however, one company (Jensen Engineering Ltd.) has carried out considerable research and development work related to the use of subsurface drainage as a means of reclaiming these surface water bodies. This technology has developed rapidly since then and somewhat differently than for the subsurface drainage of saline areas.

The trenchless plow has been used almost exclusively for slough/marsh drainage in Alberta. The main reason for this is the higher speed of the plow relative to the trenchers, which becomes very important given the distances between slough/marsh areas.

i) Investigation & Design

Aerial photographs, which are flown on a regular basis throughout Alberta by the Alberta Government, are used extensively for the design of slough/marsh drainage because these areas normally show up as distinct and well defined. In the past, the aerial photographs have been enlarged, reproduced and the slough/marsh areas measured by planimeter to determine rough volumes of water to be drained. A recent innovation is a microcomputer digitizing system which can rapidly enlarge plot and calculate the various wetland areas (Figure 16). With the slough/marsh areas located, a topographic survey is conducted very economically using a one-person laser surveying system. A reconnaissance survey is made to establish routing for the main drains and profile surveys carried out (using a hip-chain string-meter) to establish horizontal controls. Based on this data the depths of cut, slopes of

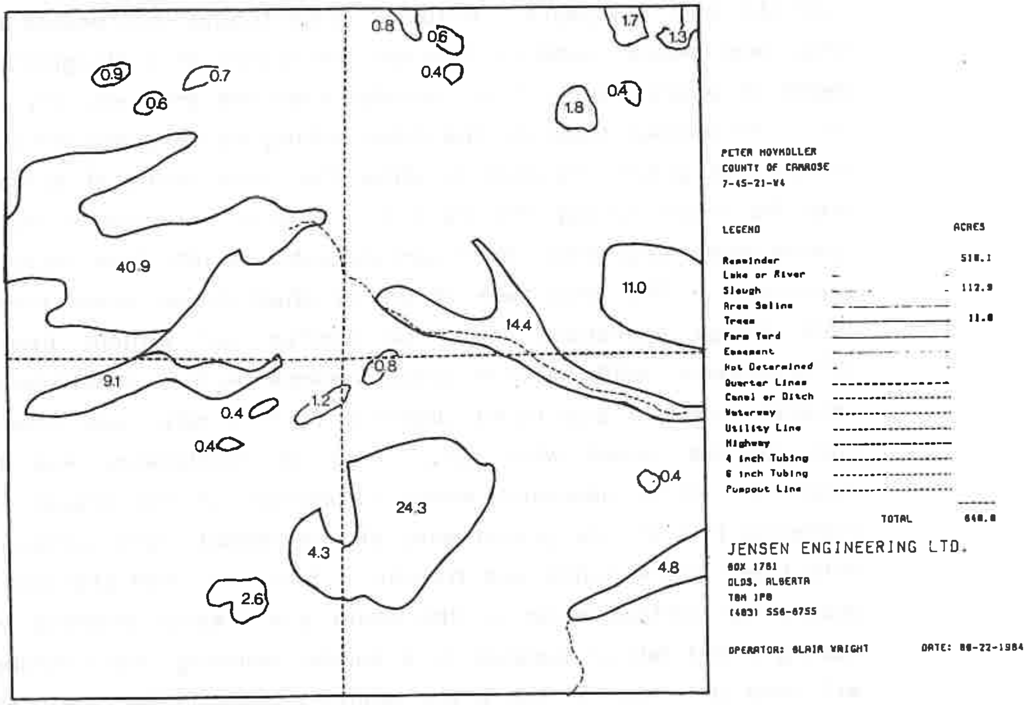


Figure 16

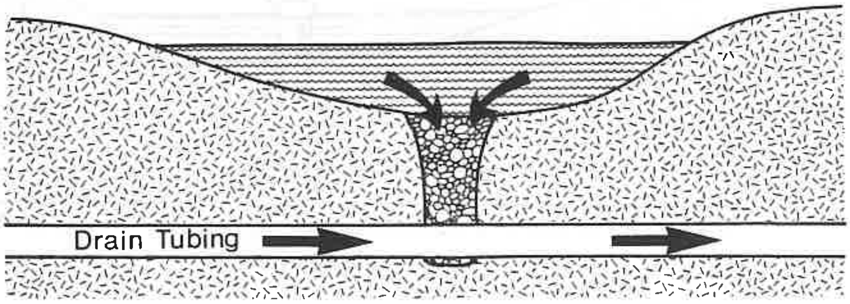
each drain and outlet locations can be quickly calculated. This information and the location plan of the drainage system can be put into the microcomputer and a permanent file established.

ii) Installation

While drainage plows have been modified in some instances to install drainage pipe to depths of 2.4 m, most contractors have learned that installing drains between slough/marsh areas, often in very dry soils, requires a great deal of power. In these instances, cuts of deeper than 1.4 m are usually excavated first to maintain a maximum installation depth of 1.4 m. In the long run this appears to not only save money but also streamlines the operation and reduces installation time.

The method of installing the drain tubing has evolved considerably over the past ten years. Initially, drain tubing (corrugated polyethylene) was simply installed through the middle of a slough/marsh at a depth of approximately 1 m, usually when the area was dry or nearly dry. At various locations the drain tubing was exposed through excavation and gravel installed to allow the rapid entry of surface water into the drain tubing (Figure 17). This is particularly important in spring when large amounts of surface water results from rapid snowmelt conditions. The advantage of the crushed gravel drain inlet is that field tillage operations could be carried out without interruption. Unfortunately, while most of these systems performed satisfactorily for several years, a significant decrease in flow rates was noted as the rock became mixed with soil. Regular maintenance was therefore required, which generally meant excavation of the gravel inlet and replacing it with new gravel material. A second, more serious problem with these gravel inlets was freezing. Since the inlet provides a direct access for surface water to the drain pipe, water entering very late during a wet fall or because of a sudden warming trend during winter will tend to freeze in the drain tubing when cold temperatures occur. In many parts of Alberta it is not uncommon for winter temperatures to change from -30°C to +10°C within twenty-four hours. These warm temperatures may remain for one to two weeks then quickly return to sub-zero temperatures. Experience has shown that once the water in the drain tubing freezes, thawing of the system may take until mid-June, rendering the drainage system virtually useless during the critical spring snowmelt period.

To better protect the subsurface drainage system from these freezing problems and ensure maintenance free inlets, Jensen Engineering Ltd. designed and field tested a PVC inlet (Figure 18). The main feature of this unit is the sliding valve which is placed in the down position (Figure 19) from late fall to early spring in order to prevent surface water from moving into the drain tubing. In spring, when accumulated snowmelt water rises above the valve, it flows into the drain through the upper slots. The occurrence of this "upper slot" flow is generally



Gravel Inlet

Figure 17

Figure 18

Jensen Inlet - Fall to Early Spring Position

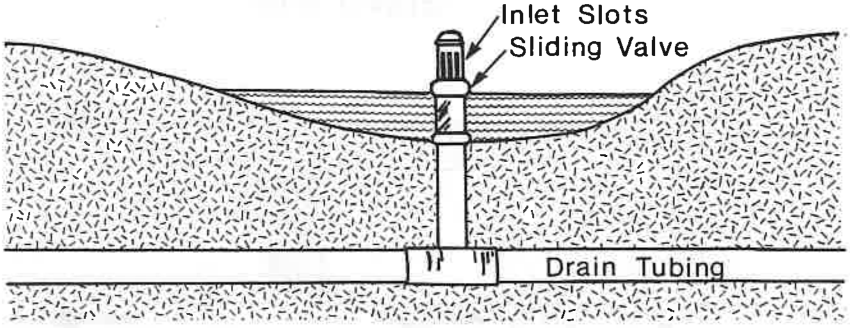


Figure 19

after any danger of prolonged periods of cold weather and coincident freezing in the drain tubing. Once the main runoff is removed, the valve is raised to its upper position (Figure 20) and the remainder of the surface water is removed. A further refinement to this valve is the installation of a flexible plastic seepage curtain around the inlet approximately 0.5 m below ground surface (Figure 21). This curtain effectively prevents surface water from moving down the outside of the PVC inlet during late fall or winter thaws and then freezing in the drains. This is particularly important when subsurface drains are installed late in the fall of a wet year. Figure 22 shows head discharge curves for the inlet in various modes of operation.

Several hundred of these inlets have been installed on subsurface drainage projects throughout central and northern Alberta. While farmers find each PVC inlet a minor inconvenience to work around, they generally agree that their effectiveness and maintenance requirements are much better than the gravel inlets and are therefore willing to work around them. Since each inlet has a greater flow capacity than a 200 mm corrugated plastic drain tube, one inlet is usually sufficient to drain each slough/marsh. In some instances, slough bottom variation dictates that inlets be installed in each localized depression within the slough. A recommended alternative is to carry out some shallow surface grading to bring the water to one or two strategic inlet locations.

While interest by farmers and local authorities for construction of on-farm drainage systems is increasing, so to is the concern by environmentalists. The wetland areas of central and northern Alberta are some

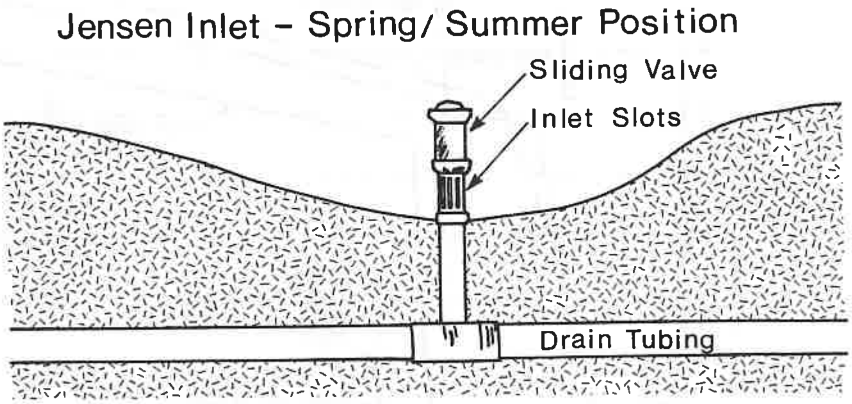


Figure 20

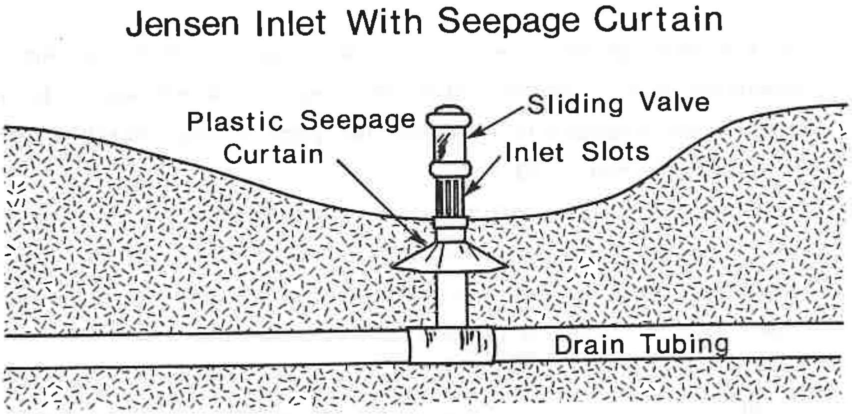


Figure 21

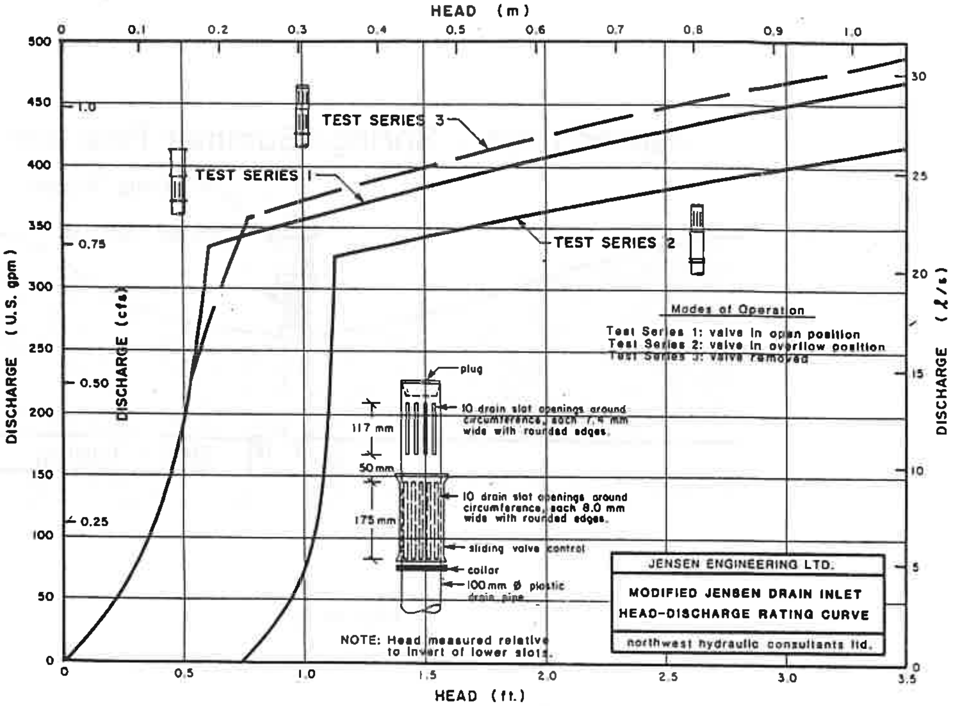


Figure 22

of the most productive regions for waterfowl in North America. Wildlife agencies are concerned that drainage of these wetlands may result in significant reductions in waterfowl populations (North America Waterfowl Management Plan, 1985).

Interdepartmental studies are currently being carried out to assess the impacts of drainage on wildlife population and evaluation of alternatives whereby on-farm drainage and wildlife concerns might be compatible. As a result, a number of research and demonstration projects are being initiated to further evaluate these alternatives. One such study involves both surface and subsurface drainage of numerous slough/marsh areas on a farmer's land (approximately 64 ha). The effluent from both drainage systems is pumped into a constructed consolidation pond (Figure 23), which was designed by wildlife biologists to allow for permanent fish rearing and nesting for various types of waterfowl. The relative effectiveness of the two drainage systems are being studied

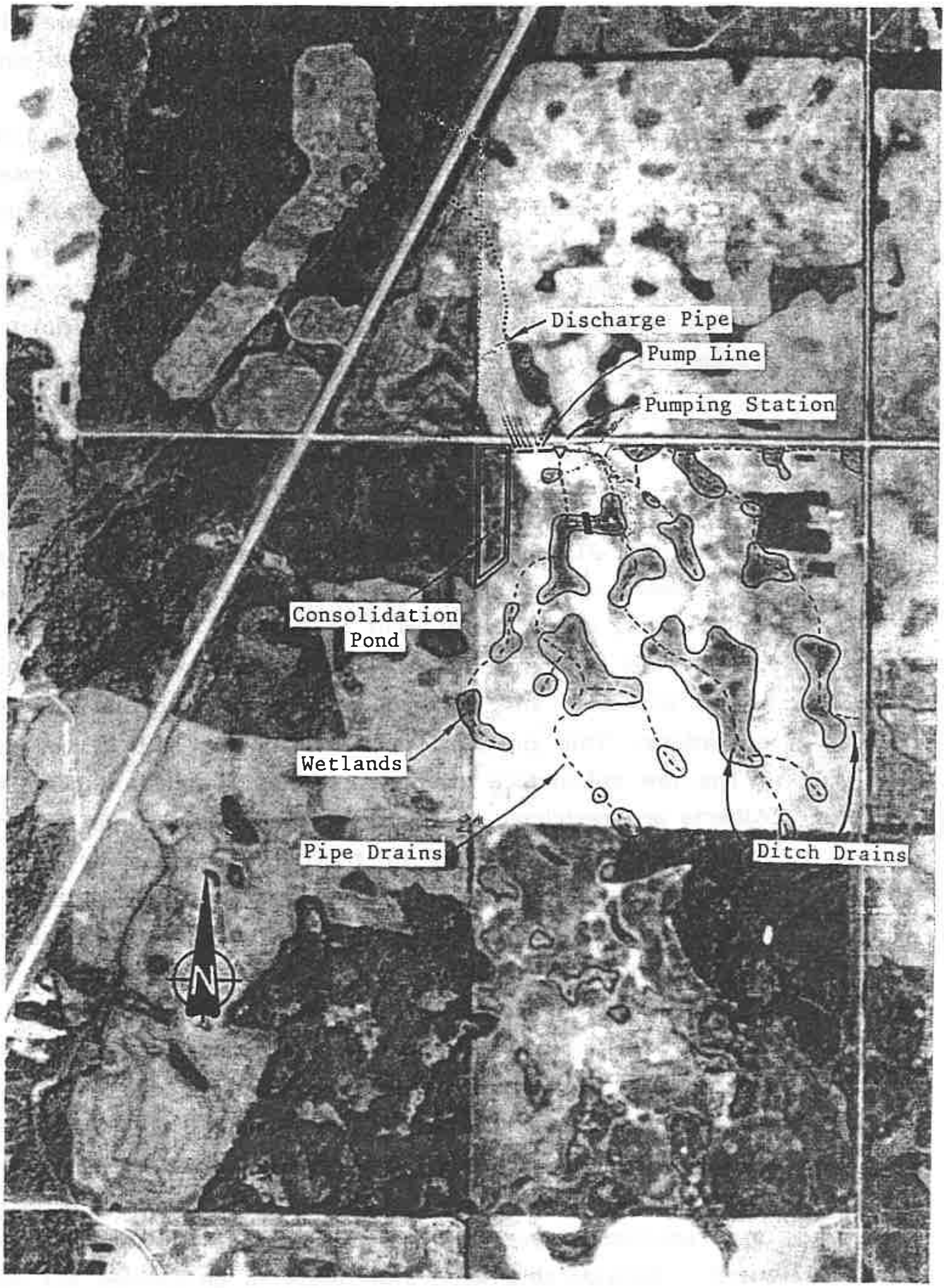

Discharge Pipe
Pump Line
Pumping Station
Consolidation Pond
Wetlands
Pipe Drains
Ditch Drains
N

Figure 23

as to improved field efficiency, erosion control, reclamation potential, and maintenance requirements. Preliminary estimates indicate that subsurface drainage may prove more cost-effective than surface ditches for draining surface sloughs and marshes.

The drainage/consolidation pond concept, in addition to mitigating the impacts of drainage on wildlife, is expected to provide excellent erosion control in regions with highly erodable soils and provide good water supplies for domestic and livestock purposes. Finally, significantly lower costs for off-farm surface drainage ditches are expected to result if consolidation and slow release of drainage effluent is proven successful.

D Bog/Fen (Peat) Drainage

Successful development of peat land areas depends first and foremost on drainage (Campbell, 1986). At present, only a minimal amount of development has taken place in the more than 2.2 M ha of peat land which exists within the current agricultural land base in Alberta. This is expected to change in the near future however as farming intensification increases and succeeding generations of farmers expand their operations. This pressure is already being felt in northern Alberta.

The few subsurface drainage systems installed in peat land areas in Alberta are restricted to relatively small areas within existing farmland. At present farmers tend to treat these areas as "solid sloughs", attempting to cultivate them during very dry years but usually farming around them. Subsurface drainage of these areas generally consists of single or dual 100 - 150 mm drain lines ploughed through the middle of the peat area. Depth of installation, where possible, is somewhat deeper than for slough areas to compensate for expected subsidence after one to two years. Regular monitoring of these drained peat soils indicates good performance of the drains and rapid and sustained control of the water table. Farmers are pleased with the drainage in that it allows farming of the entire field as a unit without the extra time required to go around these areas or the risk of getting stuck there. Considerable work still needs to be carried out in developing optimum drain depths which allows for subsidence but does not encourage over-draining of the peat. In addition, successful farming of these soils will require the adoption of special management practices.

Subsurface drainage of these peat soils will require further adaptation of existing drainage equipment or the development of new, more specialized equipment. One such machine was developed and tested in Alberta by Jensen Engineering under contract with Canada Agriculture. The unit (Figure 24) is adapted from the large rubber tracked carrier vehicles used to transport supplies into remote oil drilling areas in western Canada. Each of the tracks measured 1.4 m wide which provided excellent flotation and stability, an important consideration when using automatic laser grade control systems. The machine had a standard Badger plow mounted on the rear and was capable of speeds greater than 16 km/h. This not only saved significant return times from long drain lines but, compared with traditional tracked machines, resulted in less shock being transmitted to the sensitive laser grade control systems because of the rubber mounted track arrangement. The first prototype unit had all critical parts located or vented high on the frame which allowed it to work in water up to 1.2 m deep. Field testing of this machine was carried out on numerous projects having extremely unstable soil conditions. In all conditions the unit worked well, particularly in the one or two drainage projects involving bog/fen soils. The wide tracks, as predicted, resulted in excellent stability of this unit which significantly improved grade control of the drain tubing being installed, since the laser receiver on the machine always remained vertical. The major disadvantage of this machine was its overall length of 11 - 12 m, including plow. Further refinements were proposed to more fully integrate the plow and tractor but unfortunately additional funding was not approved. As subsurface drainage in the bog/fen areas increases however, it is likely that further development and use of this type of drainage plow will take place.

The drainage and development of bog/fen areas in central and northern Alberta requires considerable research and field demonstration before its full potential can be realized. Based on the few subsurface drainage projects in these areas, it appears that this form of drainage will form an integral part of the successful and sustained agricultural productivity of Alberta's bogs/fen regions.

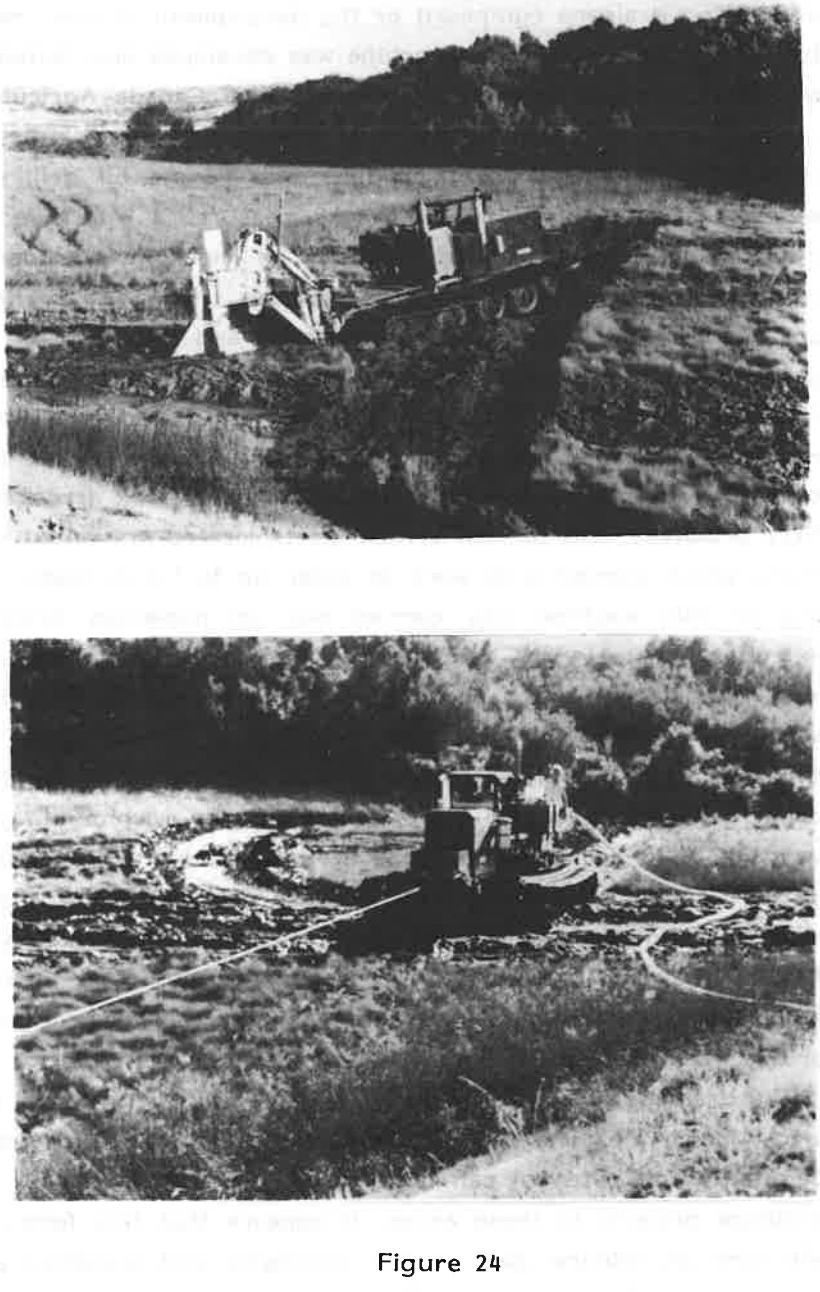


Figure 24

3 Future Development

In spite of the relatively poor agricultural economic climate in Alberta over the past ten years, the development of subsurface drainage as a viable practical means of controlling on-farm drainage problems has progressed. From a private industry position this development has been slow but from a technical position, the development has been rapid. The greatest immediate potential for this industry appears to be for salinity control in the irrigated areas of southern Alberta and for slough/marsh drainage in central Alberta. In the irrigated areas past research programs have shown conclusively that properly installed subsurface drainage is the most effective means of controlling and reclaiming saline lands.

It is expected that approximately 30 - 35% of the presently irrigated or adjacent lands will require subsurface drainage if they are to remain productive or, for those lands already salinized, be brought back into production. With that in mind the Alberta Government has initiated a project which will utilize shallow subsurface drainage to control irrigation canal seepage rather than the more traditional methods of canal lining or deep interceptor drainage. The project involves approximately 200 ha of saline and waterlogged land adjacent to a main irrigation supply canal which will require 90 000 - 100 000 m of 100 and 150 mm corrugated polyethylene drain tubing (with filter sock). This is the largest single project of its kind in Alberta and will likely be the first of many similar projects in the future.

Outside of the irrigated areas, the major concern by farmers is the removal of surface water from their land. The success of subsurface drainage in accomplishing this with virtually no disturbance to the land after installation has proven to be very popular with farmers. With over 1 000 000 ha of Alberta's agricultural land consisting of slough/marsh, the potential for subsurface drainage is high. As farmers continue to optimize farm production and increase operational efficiency, it is expected that subsurface drainage of temporary slough/marsh areas will increase significantly.

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FACTORS AFFECTING MASS TRANSPORT FROM FARMLAND

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Abstract

The paper deals with the problems concerning leaching and surface transport of nitrogen, phosphorus, and pesticides from farmland to rivers, lakes, and groundwater. Some fundamental results are presented from investigations at the Swedish University of Agricultural Sciences since 1976.

1 Introduction

Investigations on leaching of plant nutrients from farmland have been in progress since 1972 at the Division of Water Management of the Swedish University of Agricultural Sciences and of pesticides since 1979. The experiments are carried out on whole fields and on plots.

The investigation on whole fields was originally designed as a pure research project funded by the National Swedish Environment Protection Board (SNV) and the former Agricultural College of Sweden. The project was started in 1972 and in 1978 it was taken over by the Programme for Supervision of Environmental Quality (PMK) run by SNV.

The background to the project is as follows:

Changes in forms of management and more intense lines of production in agriculture made it a matter of urgent concern to establish a number of reference areas on arable land for studies of external effects of such conditions as intensive or even over-optimal use of fertilizers, monoculture production, use of organic manure or the cumulative effect of repeated application of fertilizers. The external effects were (a) groundwater contamination by, in particular, nitrate and organic matter; (b) surface water contamination with both eutrophicating plant nutrients (N and P) and nitrate leading to hygiene problems. The results of the studies were emphasized to be of considerable importance in assessing inconveniences to society as a whole as well as creating data for use in administrative measures.

The investigations on plots were established to complete the whole field experiments in order to eliminate the influence of climate, soil and cultivation conditions. Those experiments are suitable for differentiating in and amount of fertilizers as well as pesticides, crops, and cultivation measures.

For further information see Brink (1982) and Brink, Gustafson & Torstensson (1986).

2 Aims

The aim of the whole field experiments at the start was to provide data capable of being used in assessments of the risks of water pollution when applying fertilizers under normal agricultural conditions and also in recommendations on avoiding water pollution.

When PMK took over the project the aim was modified to supervise within selected agricultural areas the effects of cultivation on the quality of the groundwater and surface water.

The aim of the plot experiments is to find measures to prevent the pollution of rivers, lakes, and groundwater from farmland.

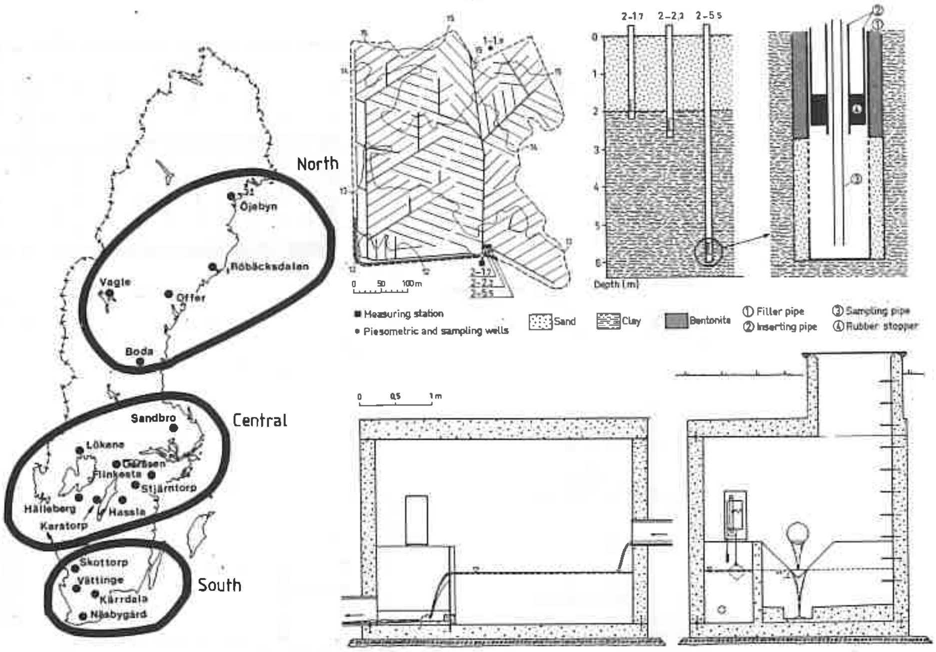

Fig. 1. Locations of the experimental fields. Tile-drained field, soil profile, sampling pipe and an underground measuring station with a triangular weir.

3 Material and methods

Whole field experiments

Until 1976 sixteen stations had been established. In 1982 Geråsen station was built, the only one on a mull soil. The measurements at the northern stations (Öjebyn, Röbäcksdalen, Offer, and Boda) ceased in 1981 owing to lack of funding. (Fig. 1.)

Surface runoff and drainage discharge from tile systems are collected in underground concrete cisterns continuously registered with triangular weirs and water-level recorders. The size of the fields varies between 4.5 and 36 ha. The fields represent many kinds of soils.

At one or more sites on the experimental fields piezometric and sampling wells are placed at different depths. The inserting pipe with the thin sampling pipe is designed to reduce the sampling volume, avoiding stagnant water higher up in the well. Sometimes combined piezometric and sampling wells are used.

The precipitation is taken from nearby meteorological stations. Data on fertilization, crop, and agricultural practices are compiled. Water samples from the measuring stations are collected 2-4 times a month

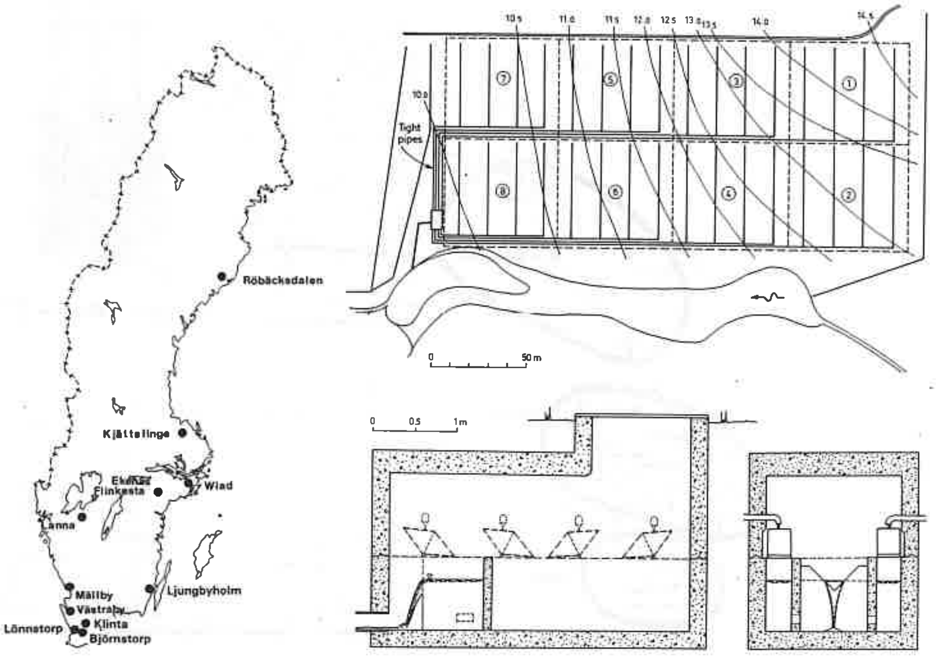

Fig. 2. Location of experimental fields with separately drained plots. Measuring station with tilting-vessels and a triangular weir.

and from the groundwater four times a year. The samples are sent by express mail to our own laboratory and are analysed for numerous elements.

Plot experiments

Special experiments are made at twelve places for comparative studies of various factors, and for investigations regarding counter measures.

The plots are usually seven to ten in number. They vary between 0.16 and 0.40 ha. A separate drainage system runs from each plot to an underground flow meter for continual registration of the discharge. The groundwater is checked (Fig. 2).

In three cases arrangements are made to collect surface runoff in watertight furrows along the lowest edges of the plots.

Measurements are made of the leaching with increased use of fertilizer and liquid and solid manure. Furthermore, the surface runoff of plant nutrients after spreading of farmyard manure on frozen ground is studied as well as the erosion of phosphorus from bare and cropped

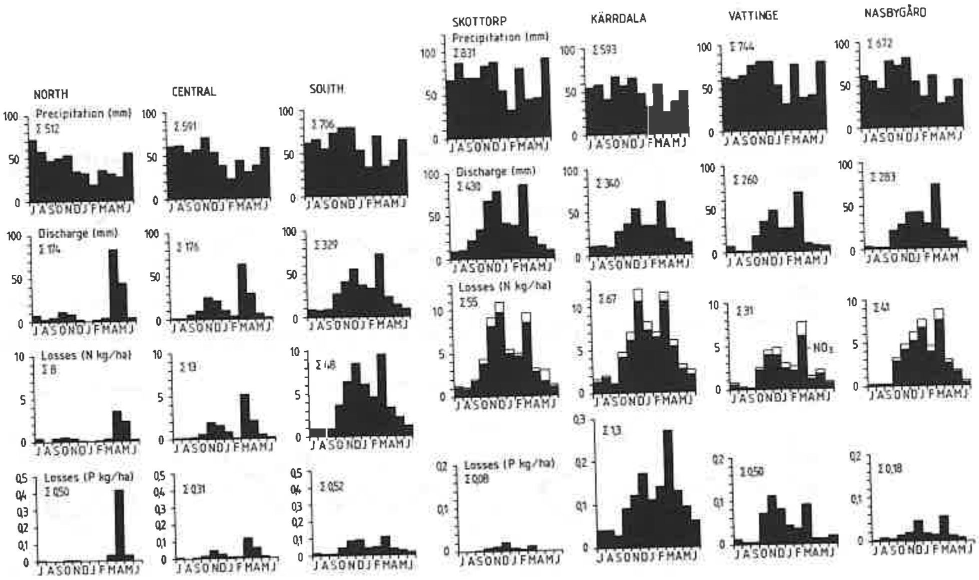

Fig. 3. Precipitation, water discharge, and losses of nutrients from different parts and sites of Sweden in 1976-83. Skottorp and Kärrdala are sandy soils, Vättinge heavy clay, and Näsbygård clay till.

plots. Finally, plot experiments are undertaken for the purpose of reducing the leaching of nitrogen in potato and barley cultivation.

Some of the experiments are utilised for measurement of pesticide leakage.

4 Results and discussion

Leaching of nitrogen

The *climate* is crucial for the leaching, as indicated by Fig. 3. The long winter in northern Sweden effectively limits the N loss since the majority of the melt water runs off on the surface. The nitrogen (and potassium losses) are by far the largest in southern Sweden. As is to be expected, Middle Sweden has an intermediate position.

The importance of the *soil type* can be seen from Fig. 3. The differences between light (sandy) and heavy (clayey) soils may be considerable. One explanation of the heavy leaching of nitrogen from a light soil is that the root depth of the plants in such soils rarely exceeds 40-60 cm. As soon as the nitrogen has moved further down in the soil it becomes lost to the plants. In a clay soil, on the other hand, the roots can easily penetrate to depths of one meter or more, which results in a more reliable nitrogen uptake.

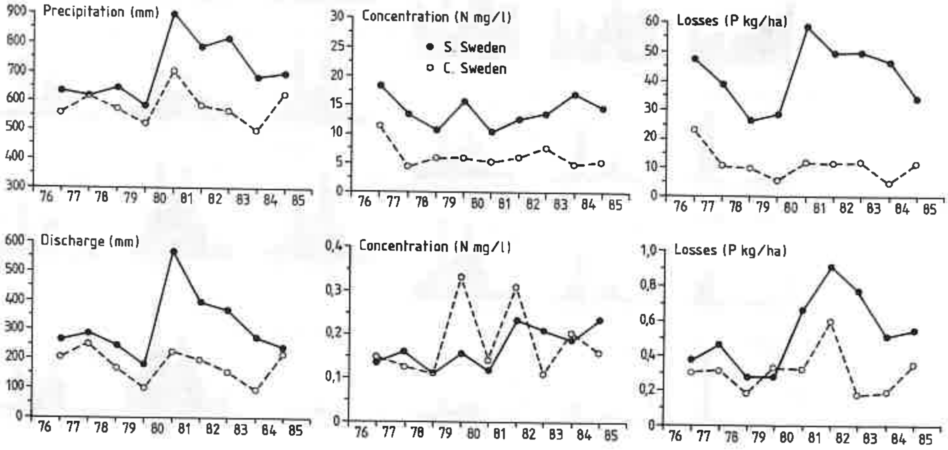

Fig. 4. Long-term changes of precipitation and discharge as well as concentrations and losses of nitrogen and phosphorus in South and Central Sweden.

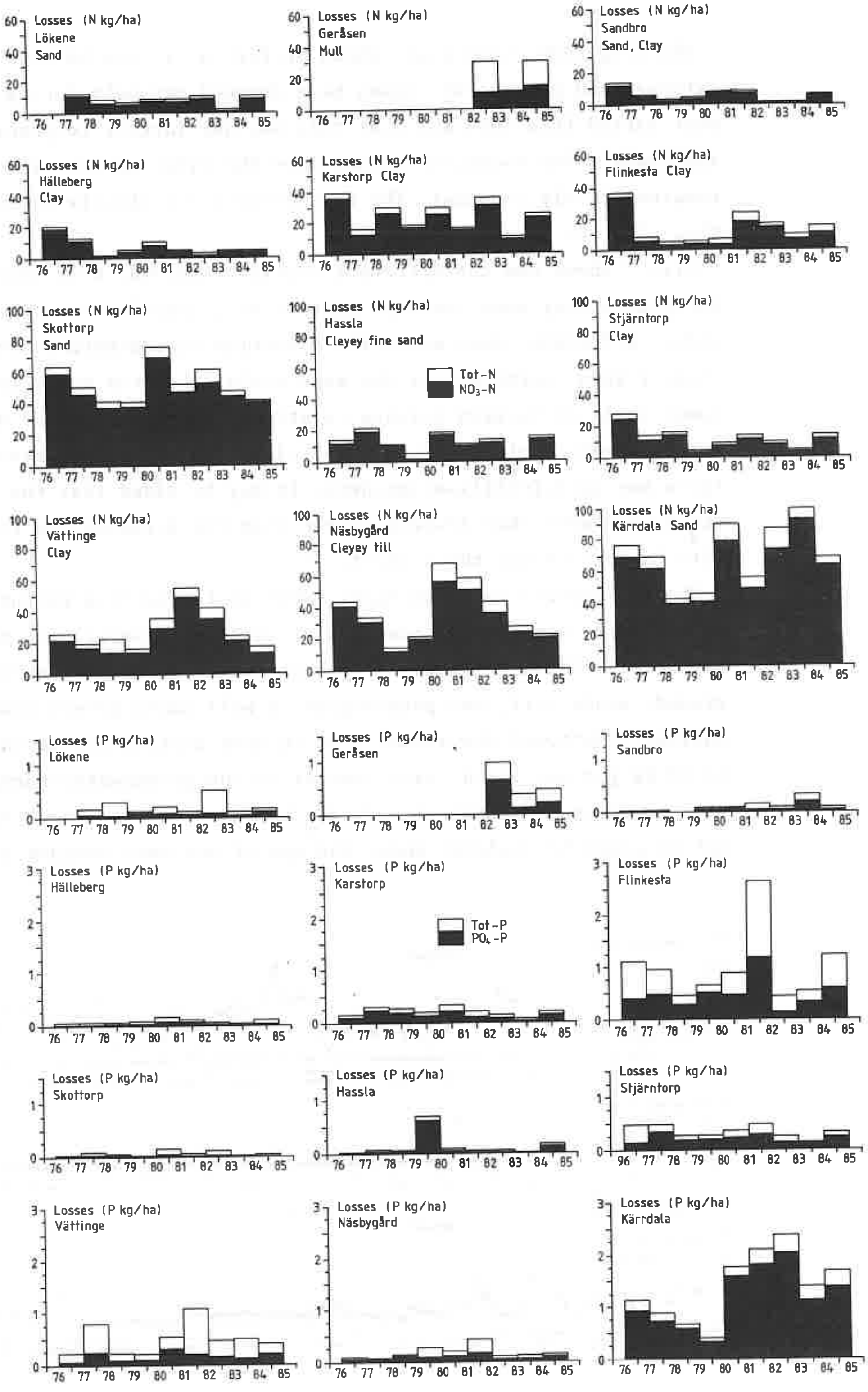

Fig. 5. Losses of nitrogen (N) and phosphorus (P) from the PMK fields 1976–85.

The long-term changes are shown in Fig. 4. It can be seen that both nitrogen and phosphorus losses have changed strongly during the nine year period from 1976 and that this was due largely to precipitation and runoff. The N-concentrations were the first to decrease and then remained fairly constant. The P-concentrations clearly increased and thus also the losses.

Fig. 5 shows how the different stations behaved. With hardly any exceptions they show the same pattern of losses but the levels are widely different. Once again the situation in southern Sweden is clearly seen, particularly the sand soils. Also the newly reclaimed humus soils at Geråsen release relatively large amounts of nitrogen, which depends exclusively on the oxidization of organic matter since there was no N-fertilisation here. It may be added that the losses of SO_4-S were more than 10-fold larger than the N-losses and together with Ca were by far the highest.

The *groundwater* is often fairly well protected from pollution by agriculture. Certain combinations of factors, however, are highly unfavourable. Thus, an excess of precipitation in winter, unfrozen ground, sandy soil, and potato-growing will cause severe leakage. In Halland (Skottorp) the annual loss in such cultivation amounts to 40 to 60 kg per ha. The nitrate content in the groundwater-forming water often becomes more than 10 mg/l NO_3-N. Water so rich in nitrate must not be given to children under the age of one year because of the risk

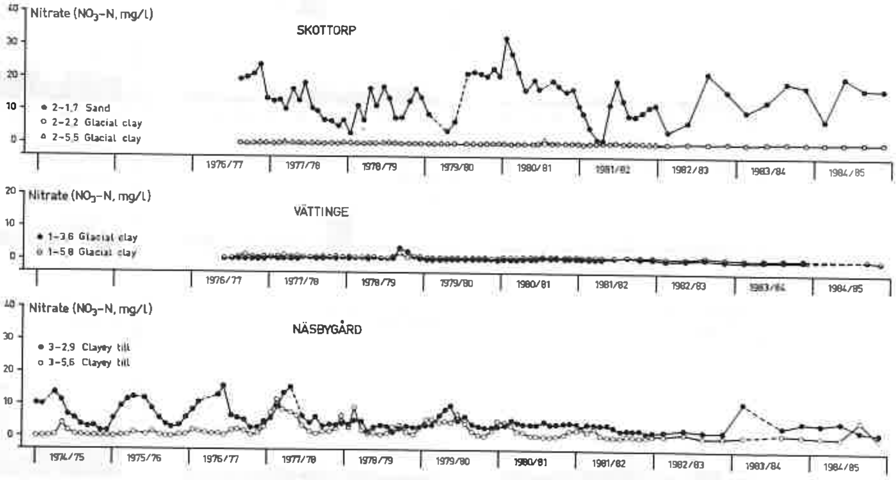

Fig. 6. Nitrate in groundwater at some of the PMK-fields. 2-1.7 means site 2, depth 1.7 etc.

of a methemoglobin disease. On clay soils the concentrations are frequently much lower. (Fig. 6.)

The leaching of nitrogen depends on the *amount supplied in fertilizer*. This has been demonstrated by, for example, plot trials with cereals at Lanna (Fig. 7). The figure shows how the yield q(N) and the protein content c(N) increased considerably at low nitrogen doses and levelled out at high doses. The yield increase was minimal after an application of 100 kg/ha N for oats and barley and after about 140 kg/ha for winter wheat. The additional protein was largest up to a dose of 100 kg/ha for all three and thereafter the increase was negligible. An unjustifiably high protein level at 200 kg/ha N slightly distorts the picture for barley.

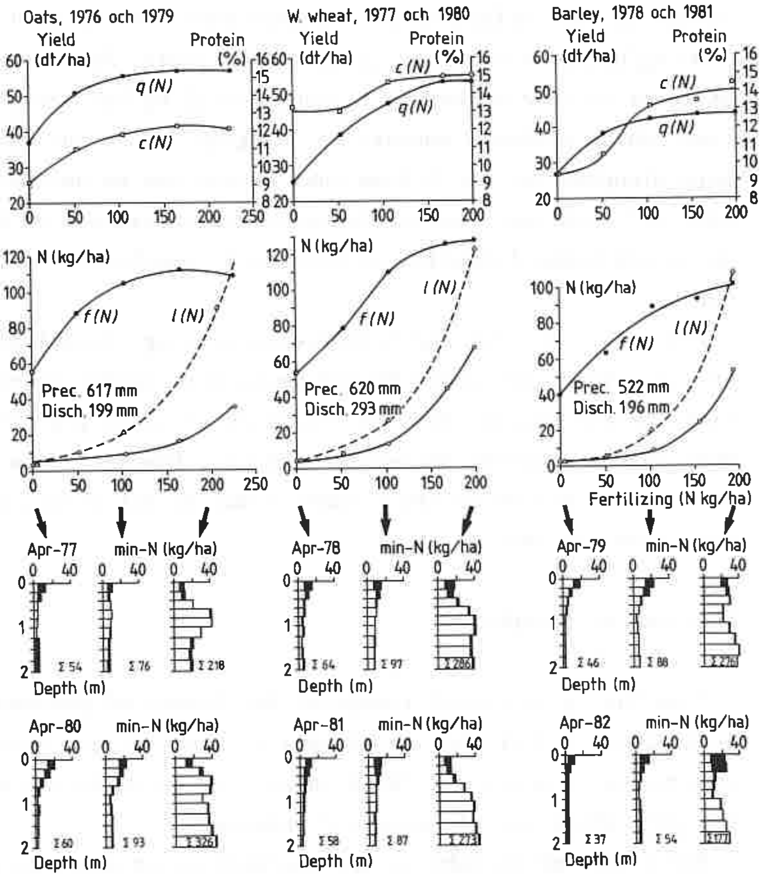

Fig. 7. Results from the Lanna experiment. q(N) yield; c(N) protein concentration; l(N) leaching losses; f(N) harvested protein; min-N mineral N in the soil.

The harvested nitrogen f(N) in the grain and the leached amount l(N) are to some extent images of each other. At doses where the yield increased strongly the leaching was low but strongly increased when the yield increase was smaller or failed to appear. The figure also shows the accumulation of mineral-N (min-N) down to a depth of 2 m. The lower unbroken curves give the measured amounts in runoff water from the covered drains. The upper dashed curves have been calculated on the basis of leached min-N to a depth of 1.2-3 m up to the second harvest of barley in December 1981:

In fertilizer (kg/ha per year) ...	0	100	200
In leachate (kg/ha)	0,0	85	380

If the amount of N taken up in the grain is summed together with the losses to the surface water and groundwater there will be a deficit of 0-60 kg/ha, mostly in the unfertilized plots. This deficit is covered at least to some extent by fallout (10-20 kg/ha) and nitrogen fixation, which probably amounts to 30 kg/ha. Since the harvest residues were ploughed in, the N from that source can be omitted from the balance calculations. Denitrification, mineralisation of humus at low doses and humus formation at high doses complicate the picture further.

From environmental and resource-conserving viewpoints, the fertilizer rates that were above 80-100 kg/ha were hardly justified. The extra yield became smaller and the increased yield of protein levelled out whereas the leaching increased strongly. However, from the viewpoint of business economics the situation may be different, but this will be discussed elsewhere.

Leaching of phosphorus

From the agricultural viewpoint the losses of phosphorus are small, being about 2 % of the amount applied, on average. This amount of phosphorus, however, is fully capable of contributing considerably to the eutrophication of lakes and waterways.

The losses of phosphorus are controlled, at least to some extent, by the same factors as those governing the losses of nitrogen. For example, the amount of *precipitation* is important for the magnitude of the losses (Fig. 4). In addition, the different *climatic* conditions in the different parts of Sweden are reflected clearly in the variation of the losses throughout the year (Fig. 3). The total amount of P lost per year, however, does not differ to any great extent from north to south, possibly since P is much less mobile than N in the soil. Phosphorus largely remains in the upper layers of the soil and some of it may be removed by the *erosion* caused by precipitation or meltwater running off the soil surface. The extent of the erosion is not only strongly linked with the precipitation but also to the *soil type* and the fertilizer status. Erosion losses of P are much larger from clay soils than from light soils (Figs. 5 and 8) and particularly sloping fields supplied with farmyard manure can lose fairly large amounts of P.

Even on level ground considerable P losses occur following application of *farmyard manure*. This is found on pure sand soils but here it is not a question of erosion but leaching down to drainage depths (Figs. 5 and 8). Studies in plot experiments have revealed that solid manure causes more P leaching than slurry, particularly at higher rates of application, owing to the larger amount of free P (i.e. phosphate) in solid manure.

In a surface runoff trial comparisons were made of erosion of soil and phosphorus for four years from a long-term clover-grass ley and a ploughed field of stubble. The soil was a clay and the experimental plots were located on a slope with a 10 % gradient. The field was ploughed immediately after harvest and was allowed to remain untouched until the following year when it was again sown. The result is given

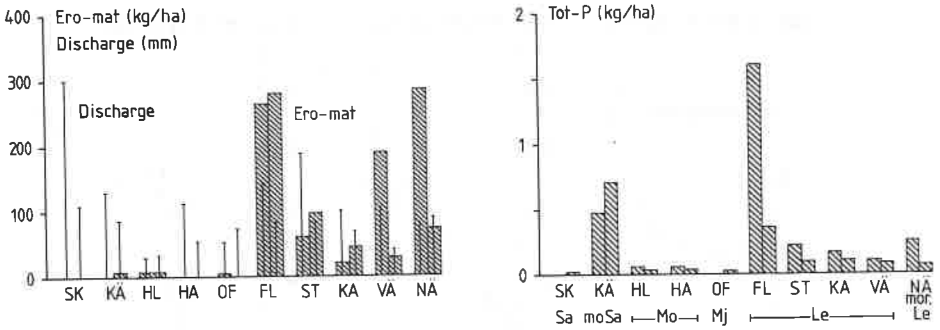

Fig. 8. Erosion soil material and losses of phosphorus from the PMK fields. Sa, sand; moSa, silty sand; Mo, fine sand; Mj, silt; Le, caly; morLe, clayey till.

in Fig. 9. Soil erosion grew exponentially with the runoff of water whereas P-erosion was linear. This may be interpreted as indicating that only P-rich soil was eroded in situations of low runoff whereas also P-deficient soil eroded when the runoff was high. The relationship between eroded soil and eroded phosphorus gives a clear expression of this.

There were no differences in the transport of P on vegetation-covered or uncovered soil. The amount of the runoff governed the process and here the runoff from the ley was lowest probably because of the frozen soil being more porous. Frozen soil is namely of great importance for the amount of water that runs off on the surface and how much finds its way through the soil. The picture is complicated further since phosphorus might have been frozen out of the plant residues lying on the ley plot.

Leaching of pesticides

The use of pesticides in Sweden is presented in Figure 10. Herbicides have increased with time and have dominated many years. Among them we find that the phenoxy acids MCPA and dichlorprop together with trichloroacetic acid (TCA) have been used most. On the other hand, plant protectants (against fungi and insects and for dressing seed) have decreased. New compounds often arrive and others disappear. As an example of the former, the highly effective herbicide Glean (chlorsulphuron) can be mentioned and as regards the latter the banned mercuric seed dressings and the insecticide DDT. Consequently, the comparisons

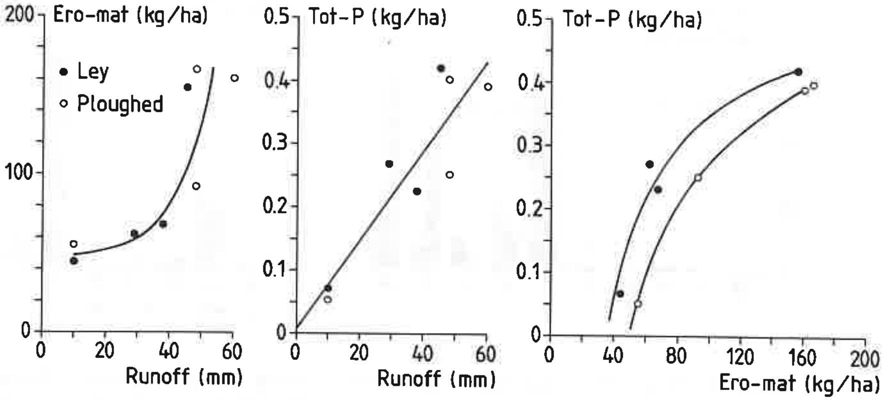

Fig. 9. Erosion of soil matter and phosphorus in a plot experiment.

in Figure 10 are not fully correct. For example, a normal dose of TCA is 20 kg/ha, that of MCPA is 2 kg/ha and of Glean 0.002 kg/ha. In such a situation it is of little use stating the quantity of active ingredient instead of the amount of commercial product as in the figure. Some kind of efficiency factor should be introduced, in other words details of the sprayed area when used under normal conditions.

Pesticides are used with the intention of killing such plants and animals which are considered undesirable as a result of unsuitable inputs. The unsuitable inputs are of many different kinds: monocultures, excessive fertilizer applications, impurities in seed, and reduced soil tillage. The *secondary effects* have not been long in appearing. They can be grouped as follows:

(1) Enrichment in nutrient chains. (2) Residues in foodstuffs. (3) Eradication of the "wrong" organisms.

The above list does not imply any order of merit. We know that the consequences of mercuric seed dressings and the use of DDT implied enormous ecological problems. But it is not known what pesticides in foodstuffs and the eradication or inhibition of plants and animals imply in the long term. This may arrive in different ways. An important such route is water.

Erne, 1970, found in *surface water* (153 localities) and *groundwater* (58 localities), detectable concentrations of phenoxy acids in the following number of the total number of samples analysed:

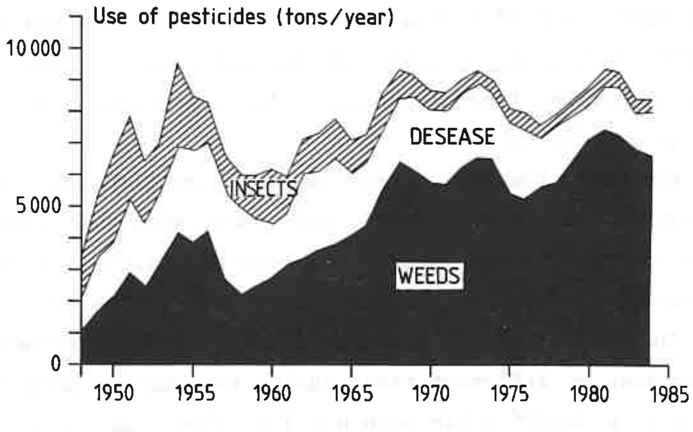

Fig. 10. Use of pesticides in Sweden.

Table 1. Leaching of pesticides from arable land.

Pesticide[a]	Application	Runoff (mm)	Dose (kg/ha)	Conc. (µg/l)	Loss (%)
Surface water, clay soil					
Cyanazine	Nov	85 Nov-Apr	0.16	3-34	4
Drainage water, clay soil					
MCPA	Oct	77 Oct-Feb	2	0.3	0
Dichlorprop	Oct	69 Oct-Feb	2	2.5	0.06
Fenvalerat	Jun	0 Jun-Oct	0.1	0	0
TCA	Apr	13 Apr-Sep	21	60	0.01
Drainage water, sand soil					
TBA	Oct	196 Oct-Jun	0.2-0.6	2-78	10
MCPA	Nov	218 Nov-Mar	2	0.1-15	0.4
Dichlorprop	Nov	242 Nov-Mar	2	0.1-23	0.9
TCA	Apr	47 Apr-Aug	20	100-900	1.1
MCPA	Jun	3 Jun-Jul	1.5	0.3	-
Dichlorprop	Jun	3 Jun-Jul	1.5	0.3	-

[a] Fenvalerat is an insecticide, all the others are herbicides.

Concentration (µg/l)..	2-10	11-100	110-1000	1100-10,000	>10,000	Total
Surface water	16	9	6	2	1	383
Groundwater	30	5	0	3	3	93

Samples of surface water were taken in ditches, ponds, streams, small rivers, large rivers, and lakes, whereas groundwater samples were taken in wells, springs, and covered drains. All high values and also some of the low values are said to be caused by known discharges or have occurred following the emptying and rinsing of sprayers. Weed control on arable land is not mentioned as the cause but is probably certainly involved since such a large proportion of the groundwater samples were polluted.

The investigations at our own division (Jernlås & Klingspor 1981, Jernlås 1983, Kreuger 1985, Ulén 1985) show that some pesticides run off on the surface, others are adsorbed in the topsoil or transported through the soil to the drainage system (Table 1).

The investigations were conducted in plot experiments. The spraying was done at different times during the year in normal doses. The contents in *runoff water* were usually below 5 µg/l and the total loss generally amounted to less than 1 % of the amount sprayed. However, it should be noted that the loss of cyanazine with surface runoff was 4 % and that of TBA with drainage water was 10 %. Consequently, the variations are very large both as regards concentrations and the amount leached.

It is interesting to see that the *discharge through the covered drains* is not entirely decisive for the mobility. After the spraying of MCPA and dichlorprop on June 8 there were detectable concentrations despite a very small discharge. Soil samples confirmed that the compounds moved rapidly through the profile on the same day as the spraying took place (Fig. 11 uppermost). The herbicides may have been transported deeper owing to negative pressure there. Or is it a question of transports from the leaf of the plant through the stem and root? After slightly more than one month there were no detectable amounts remaining in the soil. The soil in this case was a sandy soil.

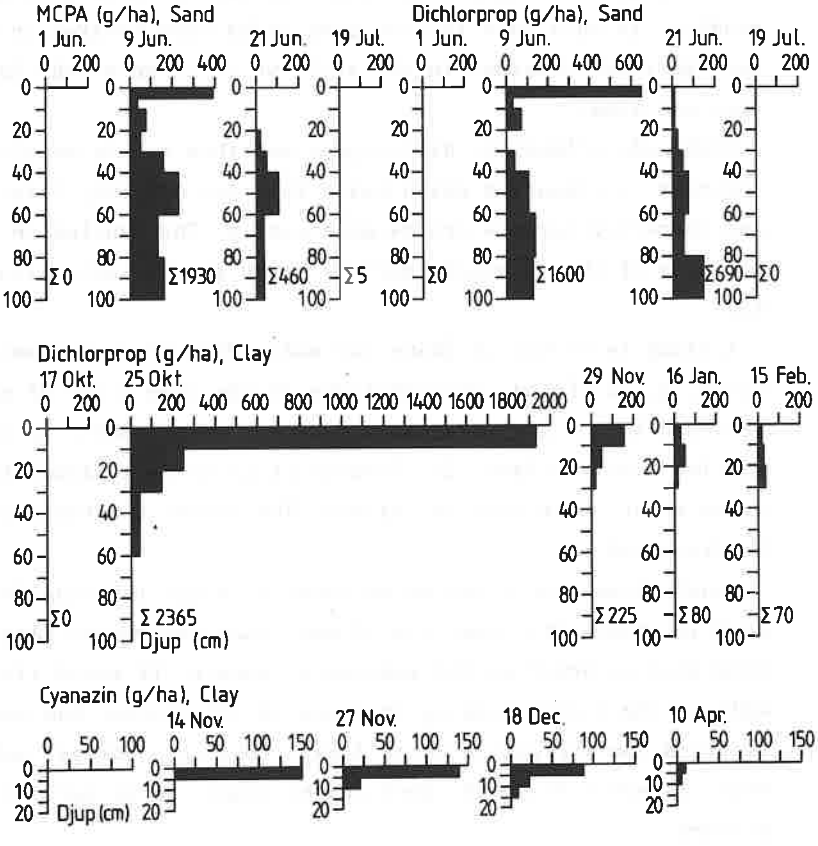

Fig. 11. Pesticides move at different rates in the soil.

Table 2. Pesticides in the rivers Fyrisån, Smedjeån, Vegeån, Råån, Höjeån, Snogerödsbäcken, and Lybybäcken.

Pesticide	Water	Conc. (µg/l)	Longest persistence
Herbicide			
MCPA	All	0.1-8	2 months
Dichlorprop	All	0.1-16	2 months
Atrazine	Råån, Lybybäcken	0.4-3	2 months
Cyanazine	Råån	0.7	1 month
2,4-D	Vegeån, Lybybäcken	0.4-0.6	1 month
Mecoprop	Vegeån	2	1 month
Insecticide			
Fenitrotion	Vegeån	0.1	1 month
Fungicide			
Metalaxyl	Lybybäcken	0.8	1 month

On a clay soil the process was considerably more prolonged (Fig. 11 middle). In this case the two pesticides were sprayed in early November. Residues remained in the soil two or three months later. Degradation was slow.

MCPA and, primarily, dichlorprop are thus easily mobile compounds in contrast to cyanazine which has a very low mobility (Fig. 11 lowest) and therefore perhaps erodes more easily. The conclusion is that the mobility of the chemicals must be given greater attention than hitherto.

A study in *rivers* in Skåne was made 1983. Öresundskommissionen (1984, p. 32) found concentrations of the same order of magnitude as we found in our drainage water. Our own measurements in 1985 gave similar results (Table 2). Clearly it is no coincidence that pesticides occur in streams and rivers. The reason for their occurrence may be discussed.

Nonetheless, there can be no doubt that the leaching from arable land is important. Durations of more than two months cannot depend on something so brief as the washing of sprays. It would also be remarkable if there were leaking storages in all rivers. And such concentrations in the irrigation water damage tomatoes, onions, and lentils. There is every reason to keep an observant eye on agricultural streams.

Table 3. LC50 for a number of pesticides in plants and animals.

Pesticide	Plant Animal	LC50 (µg/l)	Time	Author
Herbicide				
Diuron, atrazine	Algae	10-200	10 d	Walsh 1972
Trifluralin, 2,4-D	Perch[a]	11-1100	48 h	Edwards 1977
Trifluralin, 2,4-D	Crustaceans	100- 10 000	48 h	Sanders 1970
2,4-D, MCPA	Oysters	740-31 300		Davis & Hidu 1969
MCPA, dichlorprop	Protozoa	100- 100 000	9 h	Loeper 1985
Insecticide				
Metoxychlor, lindan, malation	Neuroptera	1.4-10		Sanders & Cope 1968
Metoxychlor, malation	Crustaceans	0.8-3.8		Sanders 1969
Metoxychlor, lindan	Pearch[a]	20-60	96 h	Edwards 1977
Sumicidin	Protozoa	6000- 100 000	9 h	Loeper 1985

[a] Perch and rainbow trout

One way of expressing the damage to aquatic organisms is to state a LC50-value (Lethal Concentration) which is the concentration at which 50 % of the plants or animals die after a certain period. Usually this is a matter of 24, 48, and 96 hours or 10 days.

Table 3 shows that the concentrations may be of similar magnitude as those we have found in rivers and in the groundwater. Naturally, animals are generally the most susceptible to insecticides. It may be added that the table only includes pesticides which are approved for marketing in Sweden. Considereably lower values are present for pesticides which have previously been used but have now disappeared from the Swedish market.

It should be observed that the concentrations of pesticides in discharge water are 100-1000 times weaker than in the spray liquid. Unicellular animals in soil layers close to the surface therefore live in a much more dangerous environment than animals in streams and rivers. Since some species are susceptible and are eradicated whereas others are very resistant and become dominant this may imply a total imbalance in the soil fauna. Such imbalances may disturb, for example, nitrogen metabolism.

What concentrations should then be allowed in fresh water, salt water, and drinking water? The US Environmental Protection Agency

(EPA) has suggested the following *criteria* in µg/l:

	Lowest	Criteria	
	LC50	Fresh - salt water	Drinking water
Herbicides	-	-	10-100
Insecticides	0.11	0.001-0.1	0.2-100

In the calculations a safety factor of 0.1-0.01 of 96h LC50 has been used. It is clear that fresh and salt water are subjected to considerably more severe criteria than drinking water. This is a result of body sizes. In Denmark as in other EG countries the requirement for pure drinking water is very severe. The highest permissible content of pesticides is 0.5 µg/l and that of one individual pesticide is 0.1 µg/l (Helweg 1984). Nonetheless, the values given above for different pesticides in rivers and groundwater are within or above the EPA criteria.

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STUDY ON POORLY FUNCTIONING DRAINAGE SYSTEMS TO REVEAL THE CRITICAL POINTS OF A REGIONAL DRAINAGE PROJECT

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Abstract

An extended drainage project has been envisaged for the hillfoot-near alluvial plane of Sárköz, where high watertable and pounding water was aften damaging the crops. The paper summes up the final results of the monitoring study of the hydrological situation and of some poorly functioning drainage systems, emphasizing the critical points of the drainage works.

1 Introduction

In 1984 for the region of Sárköz (25 000 ha) a land drainage project has been started. On the relatively low plots of this alluvial plane field crops have been aften locally damaged by water logging and water pounding. Even more serious problems have been experienced at the western hillfoot boundary of the plane. The long-term groundwater observations have shown higher elevation of the watertable along this belt of the plane area. For correct drainage prediction hydrological observations were needed in order to obtain quantitative description of the subsurface seepage recharge. Therefore an observation field has been established at the hillfoot belt. This field included also two existing drainage systems, the poor functioning of which might be ascribed to groundwater seepage.

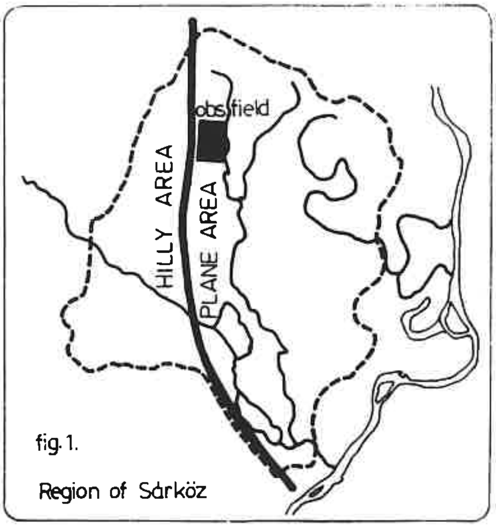

fig.1.
Region of Sárköz

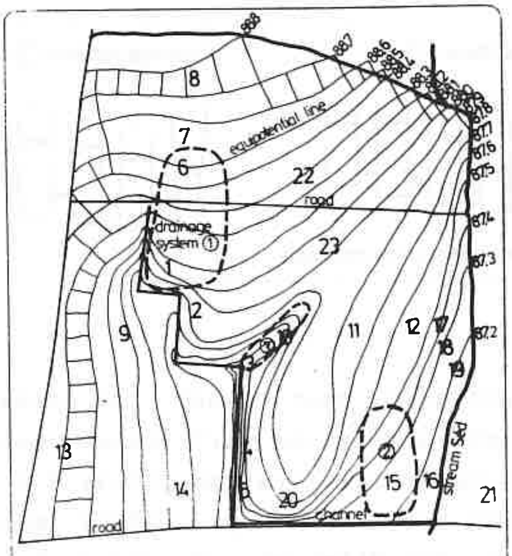

fig 2 Equipotential surface map

2 Methods and results

To describe the subsurface seepage recharge, by 23 groundwater observation wells the changes in the watertable have been determined during spring 1985 on 400 ha of a characteristic observation field. Equipotential surface maps have been drawn. By flow net method the amount of seepage water has been estimated, using the following equation (see also Fig.2):

$$Q = n \cdot \Delta h \cdot K \cdot D = 30 \cdot 0{,}1 \cdot 1 \cdot 30 = 90 \text{ m}^3/\text{day}$$

that is 0.02 mm/day considering 400 ha, where

Q: amount of seepage water m^3/day
K: hydraulic conductivity, m/day
D: depth down to the impending layer, m
n: number of squares
Δh: change in elevation between equipotential lines, m

No significant changes in the seepage recharge have been found during the test period. The presented example of May 3 gives a good approximation of the average situation.

Monitoring the functioning of two drainage system the water levels in the manholes have been observed during the same period.By coloring the water along the collectors' manholes,the velocity of the water has been also observed. By these means it has been proved, that the systems are poorly functioning because of (see also Fig.3):

system 1.: clogging of failured between manhole 3 and 4; no free outfall at the pumping pit of the collector;
system 2.: collector connected to open ditch has submerged outfall during high discharge periods at springtime.

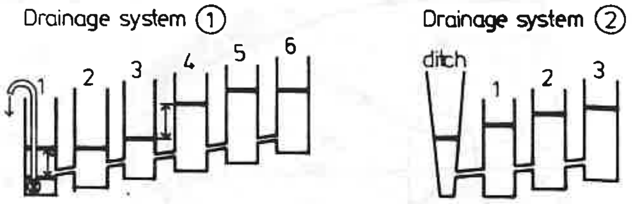

fig.3. Water levels in the manholes

Some laterals have also been opened for observations on the drain pipe, ditch and filter performance. Because of low velocity of drain water some siltation (10-15 % of cross section of the pipe) has been found 2 year after implementation. The soil structure in the ditch showed good quality, the more even further improvement due to high earthworm activity. The uncovered compact textile fabric filter material was saturated with soil particles.

Previous and actual soil survey studies have shown the groundwater to be under pressure, thus the presence of some shallow impending layer has been supposed, yet not indicated by the auger-hole method. Vertical and horizontal core sample investigations have proved the anizotropic properties of the soil at shallow depth (Table 1).

Table 1. Hydraulic conductivity values (K)

Measured by auger-hole method											
Measurements	1	2	3	4	5	6	7	8	9	10	average
K (cm/day)	48	200	23	360	12	161	37	58	17	40	96
Measured by core samples, taken from observation point number 23, at depth of 100-140 cm											
$K_{hor.}$ (cm/day)	36	9	45	30	8	50	10	55	-	-	30
$K_{vert.}$ (cm/day)	0.2	0.7	1.1	0.4	1.1	2.7	0.4	1.9	-	-	1

3 Conclusions

The subsurface seepage recharge observed at the hillfoot belt has been found to be negligeable. However it has been proved, that at hillfoot belt the land has to be drained at higher surface elevation, as compared to the average drainable elevation within the total region. Lowering the watertable by the interception of the subsurface seepage seems not feasible (see Fig.2).

The monitored drainage systems have not been overcharged by subsurface seepage, but failured because of technical defects. Of their observation the following usefull information has been obtained for drainage works:

- free outfall has to be provided for each collector,
- some collectors and the laterals have to be cleaned or repared,
- the compact textile fabric as filter material is not of good use for the heavily textured soil,
- the anizotropic layer has to be broken up by deep loosening.

For better drainage prediction further studies on observation fields are recommended for other parts of the region. Such practical investigations may provide a live picture of the drainage situation of a given territory and increase the interpretability of the results of rutin field surveys.

CALCULATION OF SOIL MOISTURE BUDGET

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Abstract

The soil moisture content is one of the most important factors of the agricultural water management. A lot of effort has been devoted to develop models to simulate and to forecast the soil moisture content since the computer is available for sophisticated calculation. Knowing the actual forecasted soil moisture content the crop production, the necessary cultivation, irrigation or drainage need can be predicted.

The purpuse of this paper is to describe a soil moisture simulation model.

On the basis of the developed calculation method - varied by the properties of the soil - the evapotranspiration, the surface and subsurface runoff, can be calculated and the questions can be answered whether the soil is too wet or dry, whether it is necessary to irrigate or drain the soil. It is even possible to calculate the driest and the most wet time periods as well as the optimal cultivation time.

1. The model

1.1. Model development

There are a lot of different computer programs and models to calculate the moisture (or water) content of the soils to solve the regional agricultural management problems. These methods are very different but from the in/output parameter's point of view they seem to be quitly similar. The biggest problem is with this - usually not for Hungary developed - models, that they require too much data to operate with. Therefore our goal was to develope a model using data available for every region in Hungary, and the calculated results can be used in the everyday practice.

To run the model the following data are required:

- the time period
- for every ten days the:
  - precipitation
  - average air temperature
  - relative humidity
- the soil - layer data, as:
  - thickness
  - unavailable soil moisture
  - disposable water content
  - temperature at the beginning
  - storage and infiltration coefficient
- the initial soil moisture content in the layers
- "b" constant depending on the vegetation
- rooting depth

As it is shown, the program does not requires much data and at the same time there are only a few constraints built in the mathematical model, nevertheless the results are reasonable correct.

The most important results at the different vegetations are:

- the soil moisture content in the layers
- the actual and potential evapotranspiration
- the surface and the subsurface runoff.

1.2. Basic concepts

The motion of the soil moisture in the soil is a complex process, which has been studied intensively in the past few years. There are a lot of theoreticaly different ways to calculate the infiltration process. The storage equation has been used to calculate the soil moisture in our study.The soil storage capacity is based on the water capacity of the layers, and the infiltration is meant as the outlet of an elementary reservoir. The evapotranspration comes from the above described elementary reservoir and from the outlet. It is zero if the reservoir content is the unavailable moisture content.

The Childs and Collis - George equation is used in the model to characterize the storage capacity:

$$\frac{dW}{dt} = -m\ B\ W^{n+1} \qquad (1)$$

where

W is the gravitational water content

m a constant which depends on the ν kinematic viscosity and on the soil texture

t the time

$B = \frac{\pi^2}{4L^2}$ where L is the thickness of the layer

n constant with a usual value -1 / It expresses that the soil moisture change in time is a quadratic function of the actual water content./

This equation describes an emptying process of a reservoir, with no input into it. This equation was used in Glugla's model where he described the water movements driven by gravity forces in unsaturated, multilayered soils as,

$$\frac{dW}{dt} = i(t) - p(t) - \lambda W^2 \qquad (2)$$

where

$i(t)$ the precipitation

$p(t)$ the evapotranspiration.

Glugla has carried on laboratory measurrements to get the value of the coefficient and checked them with field tests.

The detailed equations of the soil moisture content calculation are given in Glugla's /9.,10./ papers.

The upper, 1.2m thick part of the covering layer devided into a 50cm thick upper and a 70cm thick lower layer is examined in our paper.

The input data of the model refers to ten days, but to get the most correct results, the time increment dt was chosen 1 day.

The water infiltrated into the upper layer is the effective precipitation. The amount of water percolated into the deeper layer can be calculated from the upper layer's outlet and the deeper layer's evapotranspiration.

2. Model components and their computation

The less data is used in a model the more assumptions have to be accepted.

2.1 The soil

For purpuses of the soil description from the view of plant cultivation we considered two soil factors,

- the disposable water content

- hydraulic conductivity.

Examinig the soil moisture budget the first is the most important factor. The hydraulic conductivity is being taken into account when the moisture content exceeds the water capacity.

The equation to calculate the λ factor can be written as,

$$\lambda = \frac{m\pi^2}{4} \frac{1}{L^2} \qquad (3)$$

where

L - thickness of the soil layer

m - constant depending on the water kinematic viscosity and the soil texture.

Depending on the soil texture the factor m is taken into account in two different ways:

- first is when the upper 50cm layer is heavily cultivated. In this case its hydraulic conductivity exceeds that of the lower layer and it is loam,

- second is when the lower layer is in natural state, and it is clay.

2.2. The crops

Taking into account the roots of the plants - to distribute the evapotranspiration in the layers - is fundamental. The roots of the plants link the soil layer into one, together operating system. So the distribution of the calculated evapotranspiration is taken into account as it was published by Haalaire/11./.

2.3. The hydrometeorological data

The fundamental evapotranspiration was taken according to Antal/2.,3./. This method fits into our model very well, because apart from the plant descriptors, the temperature and humidity are necessary to be able to calculate the soil moisture content and they are used by the method.

3. Calculated results and conclusions

Computations for 3 different soils and for 4 different crop (wheat, maize, onion, grass) have been carried on. As the results of our study about 200 thousands figures were got.

To check the computed results several field measurements were used and they are reasonable correct.

Because of result evaluating difficulties a new version of the model was developed on a micro computer. It gives the users more freedom in analysing the results. Not only numerical but graphical interpretations are available as well. The user friendly, menu driven microcomputer program enables the user to study the modelled processes and to see the effect of the different parameters. Several results can bee seen in figure 1.,2.

Final conclusions:

- the results of the model are good enough to calculate drain spacing though it needs further development

- the agricultural experts somehow relact to apply the program because of the lack of their familiarity with the computers.

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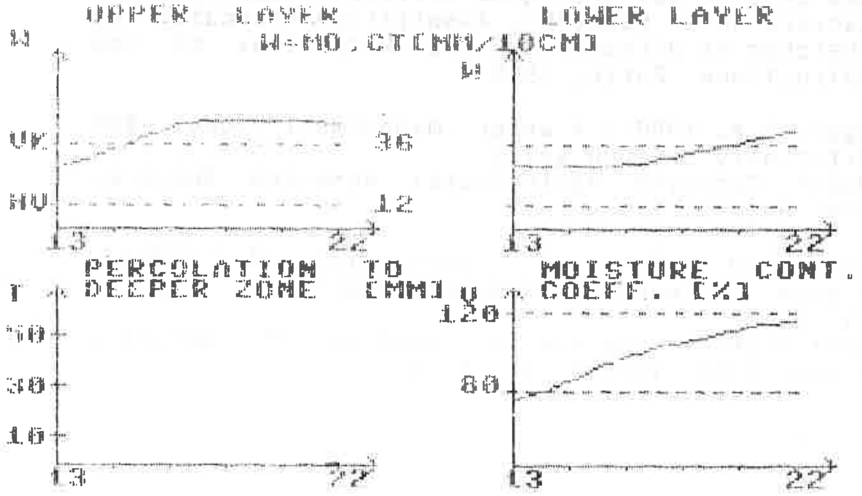
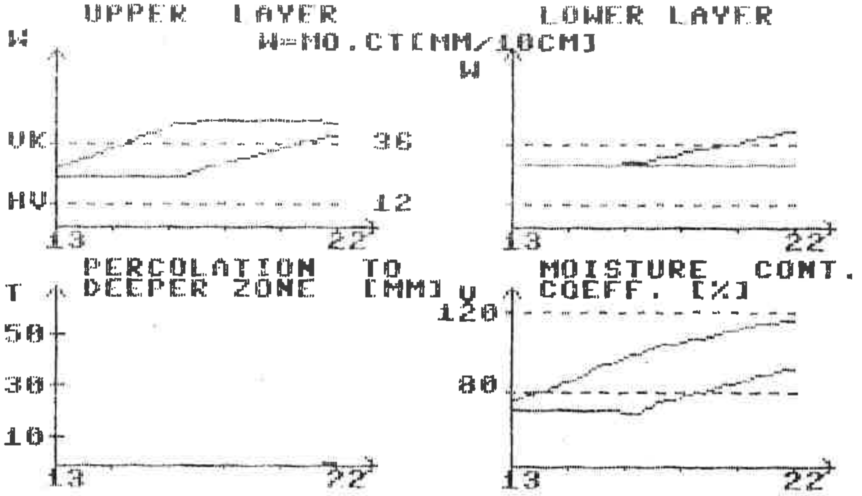


F I G U R E 1



F I G U R E 2

TECHNICAL AND ECONOMIC CALCULATION OF OPTIMAL DRAIN SPACING

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Abstract

Economic aspects of drainage system are very important due to the relatively high investment costs. The study describes the calculation method of a drain spacing providing the highest not profit and the shortest time of return. It was found that these two conditions cannot be met by the same drain spacing.

1. Introduction

Investigation on the economic quastions of drainage is a rather complicated job since a significant part of the related land reclamation works is of infrastructural character. E.g. very often new roads, new field shaping, restructuring have to be done together with the drainage. These additional works, however, do not directly increase the yields. On the other hand, the drainage work does. The effect of these infrastructural interventions cannot be separated from that of the drainage therefore the cost-effectiveness of the drainage can only be studied in relation to the infrastructure.

Determination of the optimal drain spacing is one of the main tasks of drainage design. Experience shows, however, that calculation of drain spacing is uncertain as in some interval the change of drain spacing hardly has effect on the profitability of agriculture. For example, similar results can be obtained on the same land with either 15 or 25 meter drain spacing.

2. Cost-effectiveness of subsurface drainage

Methods for calculating profitability and effecacy are very different in the various countries. To describe these proterties indices of the economic efficiency, profitability and social effecacy are the most often used. In this study two basic properties will be investigated, from the many possible indices, to determine cost-effectiveness of drainage. These two factors are annual extra income and the time of return.

The annual extra income of the investment (with other words the annual net income):

$$J = H - R \qquad (1)$$

where

H = the extra yield, which is purely the result of the drainage (land reclamation)

R = annual expenses of drainage (land reclamation) (depreciation, maintenance, expenses on the extra yield)

The value of J is generally discounted as a function of the duration of the investment (establishment), but in this case it will not be taken into consideration.

The time of return of the investment (with other words "the absolute time of return"):

$$M = \frac{B}{J} \qquad (2)$$

where

B = single input cost of land reclamation;

J = annual extra income.

Cost-effectiveness of the land reclamation can be determined by the extent of the annual net income and by the time of return. In this study optimalisation is shown for two cases. It means that two solutions are looked for:

a) investment resulting in the highest net income;
b) investment with the shortest time of return.

In the case a) the investment cost is not limited. The aim is to find a solution where the investment will result in the highest net income. In the case b) the investment cost is limited, therefore the objective is to invest with the shortest possible time of return. The advantage of such solutions is that they provide easy methods for the practice, but their disadvantage is that they use relatively few factors for the optimalisation.

Optimalisation could be shown with other economic indices too, but there is no place here to describe them in this study.

3. Conditions used for optimalisation

3.1. Cultural conditions and plant production

Wetting of the field can cause yield decrease for three reasons:

a) the field is wet at spring, therefore sowing is delayed;
b) the field is overwaterd during the growing period, therefore the crops are damaged;
c) the field is mudy in autumn, and the harvest is delayed.

At the investigations it is presumed that b) is determining for the drainage. It is presumed that if a drainage system is built on an area damages a) and b) will not occur.

Crop damages are caused by the higher water supply in the root zone. It will occur if there are surface flooding. The yield loss is therefore determined by the flooding time.

Yield loss caused by flooding or by delayed removal of excess water can be obtained with Guyon's eyuation (1975)

$$Y(t) = A\ t^n \qquad (3)$$

where

$Y(t)$ = total yield loss, %

A = factor of the daily yield loss, %

t = period of flooding or overwatering, d,

n = power index depending on the t.

Equation (3) can be well used for flooding of 1 to 3 days, since in this case $\underline{n} = 1$. Table 1 shows factor A of yield loss, determined by Guyon on the basis of Hungarain results (Cziráki, Salamin, Petrasovits).

Table 1

Growth stage	Values of factor A, %				
	cereal	maize	potato	lucerne	meadow
beginning of growing period	3 - 5	-	-	1,5 - 2	1 - 1,5
sowing time	2 - 3	1 - 2	2- 3	-	-
beginning of stooling	5 - 7	2 - 4	10-12	3 - 5	1,5-2
beginning of flowering	5 - 7	1 - 4	13-17	5 - 7	3 - 5
summer harvest	1,5-2	1 - 3	13-17	4 - 6	1 - 2
autumn harvest	-	0 - 1	3- 5	3 - 5	1 - 1,5

3.2. Methods used for the calculation of investment costs

The following conditions are observed at the determination of equation used for the optimalization of drainage (land reclamation):

a) costs of different investments depend basically on the total length of the drain pipes, the length is being expressed by the average drain spacing ($\underline{L}$);

b) the change of drain depth ($\underline{H}$) has no significant effect on the input costs;

c) the annual operational costs (cultural, plant production and maintenance costs) are constant, the extra yield is not charged by operational cost, it is the result of land reclamation only;

d) the annual depreciation is constant.

Costs of different investments are estimated with the following empiric equation, taking the conditions a) and b) into consideration:

$$B = C \quad L^{-m} \tag{4}$$

where

B = cost of investment/hectare,

L = average drain spacing, m,

C = constant depending on the drainage solution (diameter, filters and envelops),

m = constant of costs directly not depending on drainage (preparatory costs of the contractor, insurance of the reciever, etc).

The value of C will change as a function of the means of payment used for the calculation, while this latter has no effect on the value of m. Under Hungarian conditions the average value of m is 0,556.

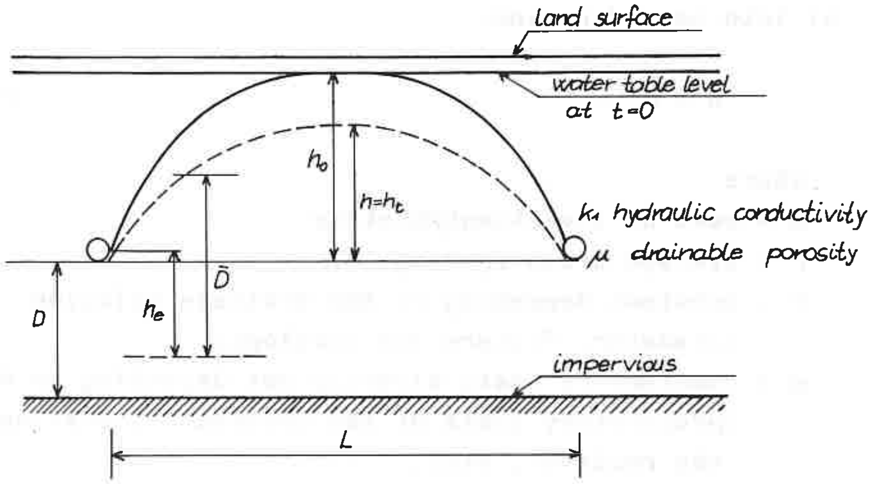
3.3. Hydrologic and hydraulic conditions

The following conditions were used for the determination of the various parameters of drainage system:

a) removal of excess water can be calculated by using steady drainage formulae during the period end of winter and spring, and by non-steady drainage formulae in other periods (the equations (5) and (6) are shown in figure 1);

b) in case of steady measurement method, if the soil is water logged the average discharge rate (q) is equivalent to the average intessity of several days' rainfall, and possible damages of the crops is in proportion with the time t of the design rainfall;

c) in case of non-steady design method the possible damage of the crops is in proportion with the water removal time, t;



Non-steady state drainage equation:

$$L=\sqrt{\frac{10k\bar{D}\cdot t}{\mu \ln 1{,}16\, h_0/h_t}}$$

Steady state drainage equation:

$$q=\sqrt{\frac{8k_1h_eh}{L}+\frac{4k_2h^2}{L}}$$

Fig. 1.

A conventianal method of the rainfall calculation under b) is the function of rainfall maximum with the following general form:

$$i = q = a\, t^{-b} \tag{7}$$

where

i = average intensity of several days' rainfall, m/d;
q = average discharge rate of drainage, m/d;
t = duration of rainfall, d;
a,b = constants of the function.

4. Determination of the optimal drain spacings

Equations (Klimkó, Kanciber, Ermolin, 1979) of investments determined under 2) can be written down in the following forms, taking the conditions of 3) into consideration:

$$J = \eta H_p - Y(t)H_p - \xi B - C_c \quad \longrightarrow \max \qquad (8)$$

$$M = \frac{B}{J} \quad \longrightarrow \min \qquad (9)$$

where

J = annual net income/hectare;
M = the time of return of the investment, year;
B = real cost of investment/hectare;
C_c= annual costs of operations, i.e. the production cost;
H_p= potential yield on a given area, ton;
Y(t)= yield loss due to flooding or delayed removal of excess water of period <u>t</u> (expressed as quotient and not in %);
η = marketing price of yield/ton;
ξ = depretiation/year.

Using relations (3) and (4), the equations (8) and (9) will be as follows:

$$J = \eta H_p(1-At) - \xi CL^{-m} - C_c \quad \max \qquad (10)$$

$$M = \frac{CL^{-m}}{\eta H_p(1-At) - \xi CL^{-m} - C_c} \quad \min \qquad (11)$$

3.1. Steady design method

For the estimation of the optimal drain spacing the period of design rainfall causing flooding or harmful watering is expressed from equation (7):

$$t = \left(\frac{a}{q}\right)^{-b} \qquad (12)$$

By replacing equation (12) into equation (10), and using equation (5) from figure 1, a function will be obtained with extreme value expressing drain spacing providing maximal net income. The maximum value of the function can be expresses from the presumption $\frac{dJ(L)}{dL} = 0$.

From this:

$$L_t = \left[\frac{m \lambda Cb}{2H_p \eta Aa^{-b}} (8k_1 h_e h + 4k_2 h^2)^{-b}\right]^{\frac{b}{2+mb}} \tag{13}$$

The average drain spacing for the shortest time of return is obtained from equation (11), by using equations (12) and (5). The maximum value of the function can be expressed from

$\frac{dM(L)}{dL} = 0$, and result will be:

$$L_m = \left[\frac{mb(\eta H_p - C_c)}{\eta H_p \; A \; a^{-b}(mb+2)} \quad (8k_1 h_e h + 4k_2 \cdot h^2)^{-b}\right]^{\frac{b}{2}} \tag{14}$$

4.2. Non-steady design method

For the calculation of optimum the water removal time $\underline{t}$ is expressed from equation (6) of figure 1:

$$t = L^2 \; \frac{\mu \ln 1{,}16 \; h_o/h_t}{10 \; k \; \overline{D}} \tag{15}$$

The water removal time, $\underline{t}$ is replaced into equations (10) and (11). Maxima of the functions are again obtained by differential calculation. The drain spacing providing maximum net income can be calculated from the presumption $\frac{dJ(L)}{dL} = 0$.

From this:

$$L_t = \left(\frac{C\ m\ \xi}{2\ \eta\ H_p A} \cdot \frac{10\ k\ \overline{D}}{\mu\ \ln 1{,}16\ h_o/h_t} \right)^{\frac{1}{2+m}} \qquad (16)$$

The average drain spacing of the shortest time of return can be obtained from the presumption $\frac{dM(L)}{dL} = 0$, where the result will be:

$$L_m = \left[\frac{m\ (\eta H_p - C_c)}{\eta\ H_p(\ m + 2\ )A} \cdot \frac{10\ k\ \overline{D}}{\mu\ \ln 1{,}16\ h_o/h_t} \right]^{\frac{1}{2}} \qquad (17)$$

5. Experiences of the use of optimum calculation methods

Several examples prove that under Hungarian conditions good results can be obtained by using 20 m and even 30 m of drain spacings on the same land, and in some cases, the partial drainage can also provide good results. Of course, the lower and higher limit of the effective drain spacing depends on the environmental conditions (Thyll, Fehér, Madarassy, 1983.)

These partical experiences are reflected also in the above equations. It can generally be concluded that, under Hungarian conditions, the highest net income/year is provided by 15-25 m drain spacings, and the shortest time of return is obtained with 30-60 m drain spacings. The two design objectives can not, therefore, be met by using the same drain spacing. It was found with the single optimum calculation methods in this study, that the optimal drain spacing depends on the design objective. There is no great difference between the extra incomes of the two solutions, thus the functions in the studied interval are low.

On a given area the steady design provides greater and the non-steady design smaller drain spacing.

If the project objective is to complete the investment with the shortest time of return, it is found from equations (14) and (17) that the extent of the optimal drain spacing is in proportion with the potential yield and with the price of the product and inversely proportional with the production cost, i.e. the drain spacing is in proportion with the realisable income. If the objective of the investment is to produce the highest net income, it can be found from equations (13) and (16) that the drain spacing is inversely proportional with the possible yield loss ($\eta H_p A$), i.e. it is inversely proportional with the potential yield.

The question is: wich technical/economic calculations will be chosen by the designer. This is rather simple, if the sum available for the investment is low. In this case the average drain spacing producing the shortest time of return should be applied. The choice is little more complicated if the economic efficiency is at a high level in the agricultural farm, and the farm makes the investment to increase its income. In this case the aim may be to use a drain spacing which gives the highest net income.

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July 9 - 11, 1986

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ISLD PROGRAMME

	WEDNESDAY 9th	THURSDAY 10 th	FRIDAY 11 th
	Chairman: Prof. Schwab	Chairman: Prof. Vakkilainen	Chairman: Prof. Palmer
8.30	Seminar Opening Ceremony Mr. J. Saavalainen: " Finnish Drainage Construction Practices"	Dr. R.A. Feddes: " Simulating Effects of Soil Type and Drainage on Arable Crop Yield"	Prof. B. Nolte: "Design Documentation for DRAINMOD in North Central Region of U.S."
9.00-9.30	Dr. D.W. Rycroft: " Pathways of Water Movement during Flood Irrigation on Saline Clay Soils"	Prof. P. Kowalik: " A Model to the Evaluation of Water Management and Crop Yield of Selected Polder"	Dr. B. Schmidt: " Technology Transfer Systems for Tillage and Soil Management Practices on Poorly Drained Soils"
9.30-10.00	Prof. P. Vakkilainen: " Applicability of Drainage Design Equations in Finnish Conditions"	Prof. R.W. Skaggs: " Application of a Water Management Model in Research and Design"	Mr. J. Lundegrén: " Land Drainage Quality and Durability with Regard to Methods of Planning and Techniques of Installation"
10.00-10.30	COFFEE BREAK		

	WEDNESDAY 9th	THURSDAY 10th	FRIDAY 11th
10.30-11.00	Prof. J. Eriksson: " Influence of Compaction on the Drainability of Soils"	Dr. G. Merva: " Computer Analysis of Water Table Observation Wells for Water Management"	Mr. T. Karvonen: " Infiltration into a Seasonal Frozen Soil"
11.00-11.30	Dr. N. Fausey: "Managing Permeability in Fine Textured Soil in Cool Climates"	Dr. P. B. Leeds-Harrison: " A Computer Model for Water Movement in Drained Clay Soils"	Mrs. Ruth Olsen Grant: " Experiments with Drainage Materials and Submerged Drains on Ochreous Sites"
11.30-12.00	Prof. E. Elonen: " Soil Compaction in Finnish Agriculture"	Mr. Cy Schwieterman: " Drainage Construction Practices and Techniques"	Mr. R. Peltomaa: " Ochre and Subsurface Drainage in Finland"
12.00-13.30	LUNCH		
	Chairman: Mr. J. Saavalainen	Chairman: Prof. B. Nolte	Chairman: Mr. T. Luoma
13.30-14.00	Dr. W. Dierickx: " Field Experience and Laboratory Research on Drainage Envelopes"	Mr. R. Wenberg: " Computer Aided Drainage Design and Application of Water Table Control Systems"	Dr. R. Bengtson: " Improving Surface Water Quality with Subsurface Drains"
14.00-14.30	Prof. G. Schwab: " Sediment Inflow into Pipe Drains through Synthetic Envelopes and Pinholes"	Mr. T. Karvonen: " Computers in Surveying and Drainage Design"	Dr. R. Kanwar: " Agricultural Chemical Losses Through Subsurface Drains from Agricultural Watersheds and Their Impacts on Water Quality"

	WEDNESDAY 9th	THURSDAY 10th	FRIDAY 11th
14.30-15.00	Mr. B. Jonsson: " Organic and Synthetic Fibres as Drainage Filters"	Prof. T. Steenhuis: " Use of Micro Computers in Drainage Design"	Mr. L. Kraft: " Subsurface Drainage and Land Forming for Pollution Control"
15.00-15.30	COFFEE BREAK		
15.30-16.00	Mr. P. Hove: " Drainage Intensity and Timelyness of Arable Land"	Dr. H. Zaradny: " A Method for Dimensioning of Surface Drainage in Heavy Soils considering the Reduction in Potential Transpiration"	Dr. J. Fouss: " Weather Forecasts as a Simulation Model Input for Controlled-Drainage/Subirrigation Systems"
16.00-16.30	Dr. L. Stuyt: " A Non-Destructive Morphological Study of Mineral Clogging of Drains"	Prof. A. Pehkonen: " The Malfunctions of Finnish Subsurface Drainage"	Mr. B. Paterson: " Subsurface Drainage in Alberta, Canada"
16.30-17.00	Mr. C. Carter: " Oxidation Reduction due to a High Water Table"	Mr. T. Luoma: " The Reasons Behind Inadeguate Drainage and Some Methods of Solving Them"	Prof. N. Brink: " Factors affecting Mass Transport from Farmland"
19.00	Welcoming Reception hosted by Finnish Ministry of Agriculture	Free time	Seminar Closing Dinner