USING A COMBINATION OF BIOCIDE AND INLET HOLE CONFIGURATION IN DRAIN TUBING TO MINIMIZE BIOLOGICAL CLOGGING

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Biological clogging of drains is most frequently associated with iron deposits (ochre). Black manganese, white elemental sulfur slime, and black odoriferous iron sulfide also are associated with biological clogging. A more detailed description of ochre and biological clogging can be found in other publications.[1]

Clogging of corrugated tubing has been most severe in slits of tubing without envelopes installed in muck soils. Clogging has also been severe in the valleys and slits of tubing with synthetic envelopes which have been installed in ochre-prone or sandy soils.

Usually the higher the organic carbon content of ochre, the more tenaciously ochre will attach itself to the drain wall. Surveys and analyses indicate that ochres from arid regions, such as the Southeastern United States, have less organic matter. Ochres from arid regions have been easier to remove with acids and jet rinsing. Attempts to use these methods for removing ochres from tubing in humid regions of the Midwest and Eastern United States have been less successful (Lidster and Ford 1981).

Certain bacteria must be present for ochre to stick to surfaces of tubing. Sticking seems to be associated with bioslime-forming organisms that contain complex polysaccharide lipid compounds (Romano and Peloquin 1983).

Efforts to kill bacteria with pesticides have been considered unsatisfactory because of potential labeling requirements and pollution hazards. Natural substances placed in envelopes to complex the iron and inhibit bacteria have encountered pollution limitations. Attempts to change the pH of the drain influent to limit bacterial growths or prevent ferrous soluble iron from entering the drain have not been economically successful (Ford 1985).

A bioslime inhibitor must have stable residual properties with slow release. The amount of inhibitor discharged in the drain water must be below limits set by various environmental regulatory agencies.

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[1] H. W. FORD, W. E. ALTERMATT, and N. F. HAMILTON, "Inhibiting Bioslimes on Surfaces of Polyethylene Tubing," Proceedings of the ASAE Fifth International Drainage Symposium, Chicago, IL, December, 1987.

SUMMARY

An antimicrobial active compound, known by the chemical name of OBPA, in combination with a pipe design utilizing a specific hole configuration (Bio-Flow) has shown promise as an aid in the control of iron ochre. Effectiveness appears limited to a thin layer of bioslime attempting to stick to the pipe surface. The bioslime inhibition at the tube wall surface and around the peripheries of the drain holes has been shown to delay ochre deposition, which is sufficient to make it possible for self-flushing of drains.

Additional research is underway attempting to evaluate improved placement of the antimicrobial compound in the tube wall.

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Commercial spray field installation in Florida: Bio-Flow drains were installed on a site that was developed to accept surface-applied commercial waste, a 303.5 hectare project. Bio-Flow drains had both holes and an antimicrobial compound. The site was rated moderate to severe for ochre potential, based on the ground water ferrous iron content of 3 ppm. The site received organic carbon from surface-applied processing effluent. Organic carbon in the subsoil can increase ochre potential by increasing ferrous soluble iron entering the drains. Holes were not clogged after one summer of rainfall and three months of effluent application. Some precipitation of ochre and slime formed in the water and settled out on the bottom of the drains, but there were no clogged holes found in four excavations.

It should also be noted that a sock envelope was used which did not compress against the holes or experience clogging problems. Standard slitted pipe, installed in a similar project with like soil type, encountered clogging problems within two years.

DISCUSSION

The use of OBPA antimicrobial compound delayed ochre deposition on the first layer of bioslime within the pipe. The reaction was best observed using plexiglass boxes and test coupons resembling slides.[3] There was no further inhibition once the layer became coated with additional ochre. The level 4.0 compound, which is within approved EPA limits, is effective in inhibiting ochre growths on the tube wall surface and around the peripheries of holes.

An encouraging observation was ochre removal through self-flushing of the level 4.0 drain tube following a substantial rainfall event. A one-pass, low pressure, jet rinsing operation would appear to be a suitable maintenance procedure because of the reduced sticking properties of the ochre. Jet rinsing will expose holes covered by heavy deposits of amorphous or crystalline material should sufficient, periodic self-flushing not occur. A major problem with long-term ochre, if not removed, is that it gradually changes from a gelatinous, amorphous structure to a crystalline formation. Crystalline ochre, which may be detected within two years after ochre deposition, is hard and chunky and can have the consistency of sandstone. It is more difficult to remove if attached to the surface of drains.

It is anticipated that sufficient antimicrobial compound, in combination with holes rather than standard slits, will delay serious ochre problems for several years in short-term sites until there is no longer a significant ochre potential. Severe sites, where drains would normally last for only a few years, may require modifications in drain design and maintenance. The effective life of the active compound in Bio-Flow drains is not yet known. Data regarding residual concentration in the drain tube wall has been collected; projections are expected to be made.[4]

The use of standard slits with an antimicrobial compound has not been a satisfactory solution. Design and placement of the active compound are important for Bio-Flow pipe. For evaluation purposes, the next generation pipe design has been prepared by Hancor and is being field tested.

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*A knitted polyester synthetic envelope

[3] Ford, Altermatt, and Hamilton, p. 3.

[4] Ford, Altermatt, and Hamilton, p. 4 & 5.

Michigan muck site: Experimental tubing at this site had been installed on 0.1% grade. Drains contained standard slits and holes and were installed without synthetic envelopes. The ferrous soluble iron content of the ground water was as high as 30 ppm in certain samples. The vegetable farm was located on a permanent, long-term ochre site where drains have failed quickly from iron ochre clogging.

Within one year, stalactites of ochre were found hanging from standard slits in the top halves of the pipes with or without an antimicrobial compound. Approximately 80% of the standard slits were clogged in the treated drains. 100% of the holes in the bottom halves of pipes with level 4.0 were open and functional. The holes were covered with precipitated non-crystalline ochre. The installed slope of the drains coupled with moderate drainflow did not provide sufficient energy, derived from flow velocity, to remove the precipitated ochre. After two years, the drains were excavated following a period of significant rainfall. Accumulated ochre had washed free from the level 4.0 drains. 100% of the holes and 50% of the slits were open. After two and a half years, amorphous ochre was forming in the drain effluent. Drain discharge through the winter had been too low for self-flushing to occur. Ochre that had formed in the water was precipitating on the walls and bottoms of the level 4.0 treated drains. Although 80% of the holes were open, 32% had ochre growing on the muck in the holes. Under field conditions, it was not determined whether the remaining 20% of the holes were actually clogged by ochre deposits or muck conditions in the native soil.

When pipe segments from level 4.0 were rinsed with a low pressure, finger-pumped jet spray (a common household detergent cleaner bottle), ochre washed free from the polyethylene surfaces and 100% of the holes. The polyethylene tube wall was exposed around the holes. In contrast, ochre could not be rinsed free from the untreated control segments of tubing in sufficient amounts to expose the polyethylene tube wall by using the jet spray.

Michigan (sandy soil) site with synthetic sock envelopes: This site had a muck profile to a depth of 60 cm underlaid with fine, sandy soil. Drain depths were about 115 cm. Drains were over 600 meters in length, on 0.3% grades, and spaced 29 meters apart. There were three equally spaced 19 mm diameter holes at 20 cm intervals. Standard slits were also cut into the pipe between the hole spacings. Levels 0.0, 2.0, and 4.0 treated drains were tested.

The drain installation with antimicrobial compound, holes, and synthetic sock* envelope was functioning normally and running full after two years. The sock envelope was not clogged with ochre. There was a moderate ochre coating in the valleys of the corrugations of the drain between the drainwall and the sock envelope. Limited amounts of voluminous ochre sticking in the level 4.0 drains were partially crystallized - a condition that cannot be removed easily under normal drain flow. 100% of the holes in the treated drain lines were open, but there was an added difference. Ochre in excavated pieces of drain tube at level 4.0, washed free using only a low pressure, finger-pump jet spray. The perimeter of the holes exposed a clean polyethylene surface, indicating that ochre was not sticking. The level 2.0 treated drain lines retained a thin ochre coating on the tube. Within the untreated drains, ochre remained in clumps and demonstrated strong adhesion properties when sprayed by the hand pump spray.

A visual inspection of drains with slits and sock was performed outside the experimental area on the same site. Reduced outflows and high water tables indicated likely clogging problems. Drain lines were not excavated.

An organic arsenical formulation known as OBPA (10, 10' osybisphenoxarsine) appeared to meet stability and environmental hazard limitations. The compound was first added to high density polyethylene (HDPE) test coupons, which resembled slides. These test coupons were slitted to simulate standard drain inlets. Phase contrast microscopy was used to study the coupons for bioslime deposits. The work was conducted using plexiglass boxes installed at drain outlets in Florida in 1983.[2]

Field trials were initiated in four locations following successful completion of plexiglass box tests. Field trial locations included two sites in Michigan and one in Ohio. The fourth location, a large commercial spray field installation in Florida, was installed using Bio-Flow®* in 1985-1986, a 303.5 hectare project. Commercial Bio-Flow, containing OBPA, was introduced to the marketplace in 1985. Bio-Flow tubing utilizes an active antimicrobial compound and holes rather than standard slits.

METHODS AND RESULTS

Research was conducted in Florida in sandy soils. Tubing lines with 7 mm holes and synthetic envelopes were installed and compared to tubing lines with standard slits. Ochre accumulated in the valleys of the corrugations between the inlets and synthetic envelopes. The lines with holes were successfully cleaned with low pressure jet rinsing. Ochre residue remained in the valleys of the corrugations of the standard slit tubing after cleaning with low pressure jet rinsing. Kuntze (1982) also found that larger openings did not clog as quickly as smaller inlets.

Pipe perforation design for the Ohio and Michigan field trial locations involved both standard slits and holes in the same foot of test pipe. The holes were 13 mm and 19 mm in diameter. The objective was to determine the performance of slits vs. holes in relation to rate and degree of clogging in sites with severe, long-term ochre potential when a surface-acting antimicrobial compound was used.

The two installations in muck soils, one in Ohio and one in Michigan, did not require synthetic envelopes. Both sites had severe, long-term ochre potential as measured from ground water by a test kit (Ford 1982). Two concentrations of OBPA were tested, levels** 2.0 and 4.0. In addition, an untreated, control drain line (level 0.0) was installed.

Ohio muck site: Within six months, ochre had clogged about 70% of the standard slits while 100% of the holes were open. Approximately 35% of the holes of level 4.0 had a visible polyethylene (PE) surface around the perimeter of the holes, indicating good inhibition to bacterial growth and resulting in poor ochre-sticking properties. Holes of level 0.0 and level 2.0 had ochre adhering to the surface around the perimeter of the holes.

After one and one-half years, there was visible evidence that non-crystalline ochre had washed out of drains containing level 4.0, presumably when the sump pump was activated in the spring. 100% of the holes were open. The drains with level 2.0 and holes were also functional after two years. Previously installed drains with standard slitted pipe had failed within one year.

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[2] Ford, Altermatt, and Hamilton, p. 3.

*Bio-Flow is a registered trademark of Hancor, Inc. Hancor sponsored the simulated drain tests and field trials.

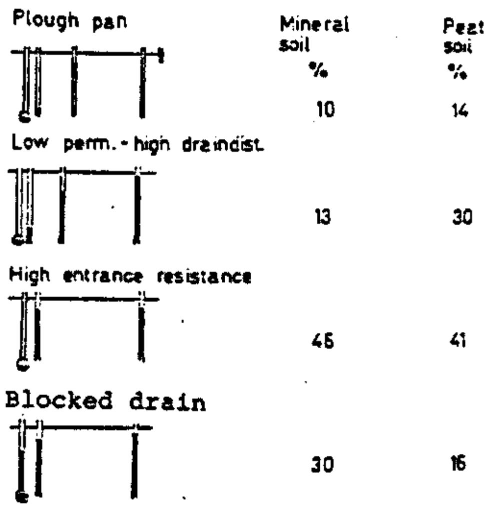
**Proprietary Code

ORGANIC MATERIALS FOR ENVELOPES FOR DRAIN LINES

Peder Hove*

An investigation into the reason for faulty drainage systems revealed that about 50 % of the cases could be traced to fault in filter/envelope.

Reason for malfunction of drain systems in Norway as investigated by IHT.



Organic materials such as moss, peat and saw-dust have been used as envelope materials for drains in Norway for at least a century. Organised experiments with drainage materials were first carried out after 1955, and this paper refers to an examination of drains with various filters installed in 1955-57.

Faulty filters (envelopes) may lead to

A. Clogging of filter and reduced drain runoff or
B. Excessive migration of materials into drain-pipes, leading to clogging of drain lines and excessive pollution of water courses.

In the past envelopes have been designed to let particles finer than medium silt through. A substantial part of the nutrients, in particular phosphorus, is attached to particles of that size, and is thereby depleted from the soil.

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The pollution that consequently occurs has been looked upon as unavoidable. In a number of cases this transport of matter makes up the major part of the total loss of nutrients.

It has been claimed that an organic filter or envelope material will trap more of the finer particles without becoming clogged due to the desintegration of the organic materials. Laboratory tests over a short period of time show that a great part of the actual particles are trapped in the filter. Investigations of organic filters after 30 years service show, however, that the practical importance of this process is limited to the amount of matter stored in the space left by the desintegrated filter. Under Norwegian conditions that space can be approximately evaluated to 50 % of the filter volume after 10 - 20 years. Where the filter is exposed to oxygen (not submerged) no sign of clogging has been observed.

Experimental sites.

Jarlsberg, Tønsberg 59.2°N. Elevation O.S.L. 1 m.
Soil: Silty clay. Drained 1957, investigated 1987.
130-150 m long laterals. Slope approx. 0,5 %.
The following materials where tried:

1. Gravel
2. Glaswool
3. Rockwool
4. Barley straw
5. Moss peat
6. Saw-dust
7. Wood shavings
8. Paper

Each with 2 replications.
Organic material approx. 75 % desintegrated.

Haugrem. 60.1°N. Elevation O.S.L. 120 m.
Soil: 0.6 m layer of silt over clay. Drained 1955, investigated 1987.
60 m long laterals. Slope approx. 0,5 %.
The following materials where tried:

1. Turf
2. Gravel around pipe
3. Gravel over pipe
4. Peat
5. Moss peat
6. Wool shavings
7. Saw-dust
8. Chopped straw
9. Straw
10. Paper
11. Rockwool
12. Glasswool

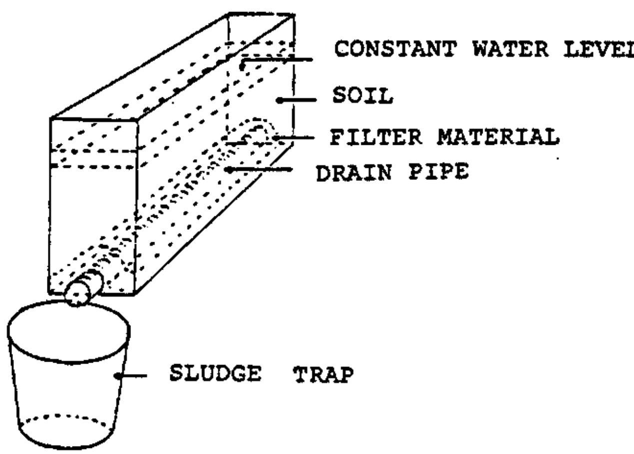
Each with 2 replications.
Organic materials approx. 60 % desintegrated.

Samples from the drainage drainflow showed the following content of solids:

Filter	Solids, p.p.m. Average	High	Low
Gravel	32	75	14
Saw-dust	7	20	4
Moss peat	22	45	17
Paper	52	86	31

Intake resistances were measured by means of pizometers placed ,1 m to the side of drain. In none of the measured places were excessive values measured.

Laboratory investigations.



A box, 1.0 by 0.2 m, 0.6 m deep was used as a 1.0 m drain section (flow to drain from above trough trench only) various filters and soils used (Table 1).

Soil	Filter	Filter thickness, m	Solids in drain water Water average 2 days, p.p.m.
Silt	Saw-dust	0.02	Trace
Silt	Saw-dust	0.2	Trace
Silt	Moss peat	0.02	350
Silt	Moss peat	0.2	30

Conclusions.

Organic filter (envelope) materials are extensively used in Norway. In areas with logging and sawmill industry saw-dust is a cheap and practical material. In soils with high to medium tendency to siltation, an approximately 20 cm layer of saw-dust over and around the drain-pipe has kept the drains working for 30 years. The transport of solids in drain water are reduced to 1/3 of the value in drains covered with moss peat, to 1/5 of drains covered with gravel and to 1/7 of the value in drains without cover. The functioning of drains with no cover are severely reduced due to siltation.

At the start of a drainage system, the differences are greater. A number of cases with excessive entrance resistance are reported where organic filters are used under submerged conditions

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THE IMPROVEMENT OF THE DECOMPOSITION RESISTANCE

OF COCONUT-FIBRE-FILTER

H. Kuntze*

Filters are used to protect and improve the functions of tile drains. Therefore, in FRG 40% of drain pipes produced are totally wrapped, since 1970 mainly with coconut-fibre-filter.

Consequently totally wrapped plastic pipes with coconut-fibres became as important as formerly the fibrous peat for the clay drain tiles. Both fibrous materials have a wide pores spectrum due to the diversity of natural fibres. Natural fibre filters therefore are better suited for the different pores systems of nearly all soils, contrary to the artificial fibre filters with their uniform porosity (Burghardt, 1976). The most important attributes of three most common filter materials (coconut-fibres (coco), peat fibres(Filtan)and polypropylen fibres (Vlynt) are summarized in table 1:

Table 1. Attributes of some Filter Materials

Qualities	Coco[R]	Filtan[R]	Vlynt[R]
Bulk density (g/l)	107	66	118
Density (g/cm³)	1.52	1.56	0.91
Pore volume (vol.%)	93	94	87
with >2 mm	7	15	17
2-1 mm	18	22	3
1-0.6 mm	39	22	4
0.6-0.2 mm	17	26	61
<0.2 mm	12	9	2
Permability (m/d)	129.6	0.6	n.i.
Lignin (weight %)	35	42	-

Natural filter materials are preferred where a temporally limited primary silting is expected due to the digging. New pores are opened instead of blocked ones by the fast biochemical decomposition of the cellulose and hemicellulose. Only fibres rich in lignin (vascular bundles) remain, hardly to be decomposed which give good continuous protection against secondary silting (Kuntze, 1974). But the decomposition if favoured by intensive land use (semi liquid manure!)(Burghardt et al. 1978). An average annual loss of 1 mm filter thickness must be expected. Supposing a filter 1 cm thick, totally wrapped pipes will only be protected for 10 years. This is sometimes a too short filter period. Therefore the question arises: How to preserve the worthy filter attributes for a longer time?

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E.g. it is observed that timber piles decay preeminently in the upper humic soil layer. This is the biological most active part of the soil profile. Therefore timber is impregnated with liquids containing bactericides and fungicides when used for soil engeneering. Formerly tar products were used for this purpose. Modern impregnation products for wood take advantage of the bactericide/fungicide effect of certain heavy metals, e.g. Cu^{++} and Cr^{3+}. Antheunisse (1979) noticed an internal fungus decay of the coco fibres and an external microbiological decay by contact with the soil. A biochemical inhibiting effect of the cellulose-lignin decay by basidiomyzetae fungi (white root decay) by Cu^{++} and Zn^{++} was found out later (Antheunisse et al. 1983).

TEST PROGRAM

Laboratory experiments

Therefore in a laboratory test coco filter were impregnated with a timber conservation agent by wet treatment for 15 minutes in a 2 and 5% solution of Baselit CCB^{R} and then dried in the air.

According to the producer, Desowag-Bayer Holzschutz GmbH, Düsseldorf, FRG, Baselit is a high soluble and highly fixing timber conservation salt/agent. The active ingredients are chromium, copper and boron. Table 2 shows more details.

Table 2. Description of Baselit CCB (partially according to the producer Desowag-Bayer Timber Conservation Ltd., Düsseldorf, FRG)

- High soluble and highly fixing timber conservation salt
- Active ingredients: chromium (13,8%), copper (5.7%), boron (form) (potassiumbichromate) (copper sulphate) (sodium sulphate
- Water solubility (20°C) 18% of total agent
  28% of copper
  35% of chromium
- pH of Baselit-CCB solutions: 3 - 4
- Irritates eyes, respiratory organs and skin
- Fixation period: 30 days (kept away from rain)
- Not to be declared according to the German decree on commerce with poisons
- No distinguishing marks according to the German decree concerning dangerous agents
- When stored and treated salts and solutions may not come in contact with soil and surface water
- Treated timber is acutely non-toxic

The following quantities of heavy metals were fixed by the coco fibres when treated with Baselit:

Coco fibres, untreated	44 ppm Cu	- ppm Cr
Coco fibres + 2% Baselit solution	3234 ppm Cu	5500 ppm Cr
Coco fibres + 5% Baselit solution	4109 ppm Cu	13514 ppm Cr

5 g of these differently treated coco fibres were soaked 16 hours with 50 ccm of the extraction agents shown below, then 3 hours shaked and filtered. 5 hours after the filtration this procedure was repeated. altogether 15 of such intermittant extractions followed. The extraction agents were:

1. aqua dest, pH 5,7
2. 0.01 mol/l HCl, pH 2
3. 0.1 mol/l CH3COOH, pH 3
4. 0.1 mol/l acetate buffer, pH 5

By a second continuous extraction 10 g of the three coco fibre variants were percolated with 100 ccm of the extraction agent 1., 3. and 4. during 7 hours in a percolation cylinder (≙14,5 ccm/h). After 17 hours 100 ccm were percolated again for 7 hours. Altogether 16 times 100 ccm were percolated.

Field trials

In autumn 1984, near Bad Zwischenahn (TK 2813), a very humic till peaty gley-soil based on glacial sand above glacial loam was drained with the following 4 variants with three replications each (150 m strings of tiles, distance 12 m, average depth 0,6 m):

Corrugated pvc-pipe without filter, 65 mm diameter
Corrugated pvc-pipe with coco filter, 65 mm diameter
Corrugated pvc-pipe with super coco filter, 65 mm diameter
Corrugated pvc-pipe with super coco filter + 0.3 g/m copper wire, 65 mm diameter

Super coco[R] is the commercial name of the coco filter material impregnated with Baselit CCB (3%). Super coco with copper wire inlaid shall support persistently the bactericide/fungicide effect of the impregnated copper salt which remains easily soluble. This filter type is protected by the German patent no. P 3230323.

During winter discharge periods water samples were taken repeatedly for analysing on heavy metal load. After 3 years, in April 1987 out of each plot pieces of 1 m plastic pipe including filter were digged up in the same distance (30 m) from the outlet. Silting degree, state of filter and pipes as well as chemical alterations of the soil round about the pipes were analysed in the laboratory.

Table 3a. Cu(%) extracted (15 x intermittently) from impregnated coco fibres

Extraction agent	Control	Impregnated with Baselit CCB 2%	5%
aqua dest	3.7	2.1	0,9
HCl	33.0	100,0	100.0
CH_3 COOH	28.0	97,0	98.0
acetate buffer	4.3	51,0	53.0

Table 3b. Cr(%) extracted (15 x intermittently) from impregnated coco fibres

Extraction agent	Control	Impregnated with Baselit CCB 2%	5%
aqua dest	0,5	0.4	1,4
HCl	1,6	8,1	7,5
CH3 COOH	0,4	12,2	13,1
acetate buffer	2,0	4,4	6,1

RESULTS

Laboratory experiments (Lambers, 1984):

Based on the increases of heavy metal contents obtained by the impregnation with Baselit acc. Test Program (lab. experiments), different quantities of Cu^{++} and Cr^{3+} were leached by intermittent extraction with the 4 solvents (see Table 3a. + 3b.). Copper was extremely more leached than chromium. The more acidic the extraction agent the more copper was leached. Acidic acid leached more Cr than hydrochloric acid. These results show that preferably an adsorption of heavy metal ions is caused by impregnation. The heavy metals remain exchangeable, depending on pH but Cr^{3+} much less than Cu^{2+}.

Compared with the intermittent extractions equilibrium conditions of the continuous extraction corresponded somewhat more to the leaching with discharges from the soil round about the pipes. But the leached parts of heavy metals obtained in this experiment are nearly the same when extracted intermittently.

Table 4a. Cu(%) extracted (16 x continuously) from impregnated coco fibres

Extraction agent	Control	Impregnated with Baselit CCB 2%	5%
aqua dest	1.8	0.7	0.6
CH3 COOH	1.5	100.0	100.0
acetate buffer	0.0	71.9	76.3

Table 4b. Cr(%) extracted (16 x continuously) from impregnated coco fibres

Extraction agent	Control	Impregnated with Baselit CCB 2%	5%
aqua dest	0.4	0.2	0.9
CH3 COOH	0.3	13.1	16.7
acetate buffer	0.2	4.7	6.6

Field trials

The relative small amounts of leached heavy metals except Cu by the heavy acid extraction agents gave encouragement for a field trial started in 1984. Lasting filter resistance and ecological side effects may be find out only by this procedure. Diggings up in 1987 confirmed first the good filter effect of coco (Table 5.). When coco filters are used the average silting amounts to 38 g/m = 20% compared with the non-wrapped pipes. But 2 to 3 times higher C-contents were found in the siltings of pipes wrapped with coco. This drain sludge was enriched with Cu and Cr.

Table 5. Quantity and composition of drain sludge

Filter type	g/m	%C	%N	C/N	ppm Cr	ppm Cu
without	185	4,8	0,4	13	24	24
super coco	31	7,8	0,5	15	255	163
super coco + Cu wire	46	7,9	0,5	16	384	341
coco	38	13,0	0,8	17	38	34

After 3 years in the soil the impregnated coco filters have an ash content approximately 50% less compared with the non-treated control (see Table 6.). The increases of the r-value (= relative lignin enrichment) are proportionally reduced. Both observations signify an inhibition of decomposition due to the impregnation with Baselit.

After 3 winter discharge periods higher Cu- und Cr-amounts are leached from the impregnated filters analogous to the laboratory experiments: 92-94% Cu and 50-70% Cr of the original enrichment disappeared (see Table 6.).

Table 6. Parameter of the coco filters

a) new and b) after 3 years in the soil

Type of filter		ash weight%	r-value weight%	ppm Cr	ppm Cu
coco	a)	3.1	35.8	n.i.	44.0
	b)	12.8	40.1	1.5	9.2
super coco	a)	3.6	35.6	3038(100)	1890(100)
	b)	7.1	37.0	1535(50)	157(8)
super coco + Cu wire	a)	3.9	35.9	5500(100)	2190(100)
	b)	6,2	38.5	1606(29)	216(6)

Where did these heavy metals go? Only at the beginning of this field experiment higher amounts of heavy metals were leached with discharge water of pH 5.5-6.7 from the treated variants compared with the non-treated coco filters. In the third discharge period the Cu- and Cr-contents of the drainage waters of the three variants are very similar. Only the first year (1984/85) the Cu-content of the discharge water was above the EC-guide lines (1980) for surface water, fish toxidity and drinking water. The quality demand for the Cu content of irrigation water acc. to RIJTEMA, 1981, respectively German Chemists Society, 1971, was only infringed in the first year of the trial (see Fig. 1 and 2). Just after the beginning of discharge Cr-contents about 100 ppb lie distinctly above the EC-guide line for drinking water (50 ppb). But after 2 months already these contents dropped down to a least 10-20 ppb.

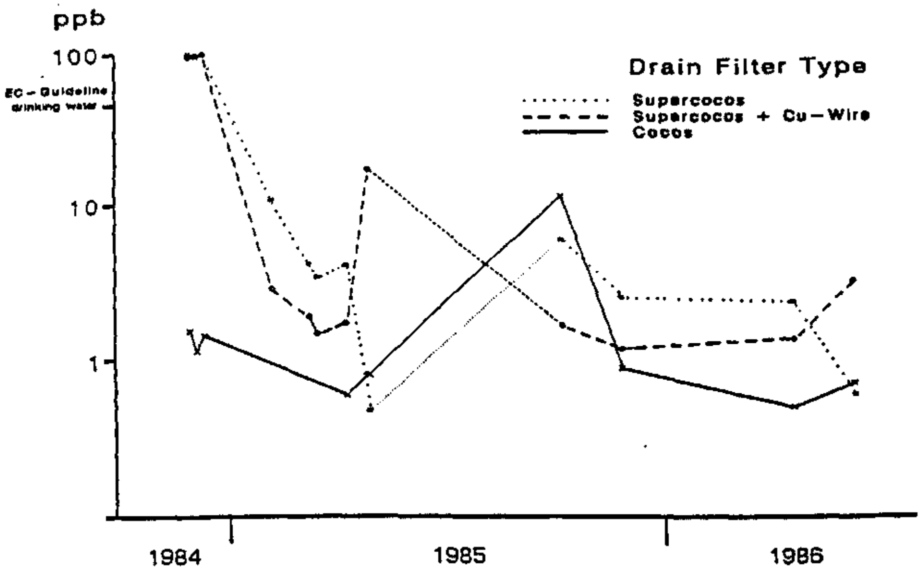

Fig. 1 Cr - Contents of Discharge Water

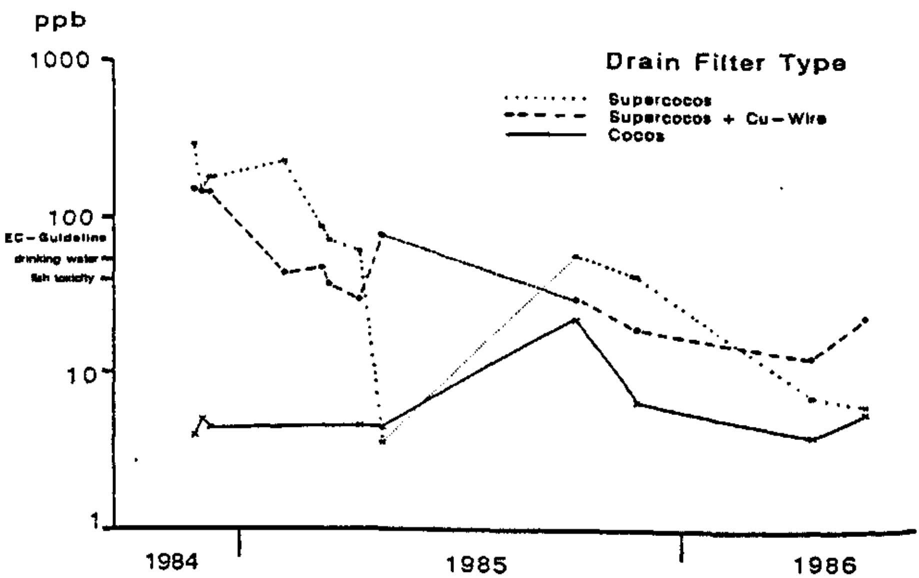

Fig. 2 Cu - Contents of Discharge Water

In the first year approximately 0.35 g Cu and 0.2 g Cr are leached per ha supposing an annual discharge of 200 mm. In the third discharge period these rates dropped down to an average of only 0.04 g/ha and 0.006 g/ha Cr.

If a bulk density of the coco filter of 107 g/l (see Table 1.) and a filter thickness of 1 cm is given, 4.4 l or 469 g coco material was needed per running meter drain pipe 65 mm diameter. For single subsoil drain pipes, 12 m distance the following calculation is made: 830 m running m/ha x 0.469 kg/m = 370.7 kg/ha coco material with 1126.2 g Cr for super coco and 2038.9 g Cr for super coco plus copper wire, respectively 690.6 g Cu for super coco and 811 g Cu/ha for super coco plus copper wire.

Assuming the same small degree of silting (38 g/m) all over the drain pipes wrapped with coco filters a Cr-content of 255-384 ppm and a Cu-content of 163-341 ppm of the drain sludge correspond per ha 8.1-15.1 g Cr and 5.1-10.8 g Cu respectively.

A loss of approximately 0.5 g copper with the discharge water and 5-11 g Cu accumulated in the drain sludge is not enough to give evidence for the higher loss of copper from the filter (640 respectively 760 g). The same applies to 0.2 g Cr in the drainage water and 8-15 g in the drain sludge considering the high loss of Cr (550 g/ha respectively 1400 g/ha).

Therefore, the surrounding soil (till a 2 cm distance from the pipe) was analysed. Table 7. shows that considering the control more than twice of Cr and nearly four time of Cu was accumulated in the nearest soil environment of the pipes. In comparison to the undisturbed, natural soil poor in C, 25 cm close to the drain, the heavy metal contents of the backfill soil 2 cm to the drain are remarkably higher, especially the easily extractable copper.

Table 7. Ct and heavy metal contents (ppm) in the soil

Type of filter	At the drain 2 cm Ct (%)	Cr ppm	Cu	25 cm besides the drain (undisturbed soil) Ct (%)	Cr ppm	Cu
without	1.7	9.5	4.1	0.2	8.4	1.3
coco	1.3	14.9	7.8	0.3	11.5	6.0
super coco	0.6	14.6	11.0	0.3	12.4	1.8
super coco + Cu wire	1.1	21.7	18.6	0.4	16.0	5.8

In the backfill soil at a distance of 2 cm around the pipe and a soil bulk density of 1.5 g/ccm for a length of 833 m/ha drain pipes 25.3 tons are calculated. An increase of only 1 ppm in this volume or weight correspond already to 25.3 g. The increase of heavy metals around the pipe amounts to 7-15 ppm Cu and 5-12 ppm Cr. Consequently the soil around the pipe is a sink for the heavy metals leached from the impregnated filter.

FINAL REMARKS

Within 3 years the biochemical decay of the coco filter installed in a very humic/peaty gley-soil was limited by impregnation of the coco fibres with the timber conservation salt Baselit CCB, that means by adding bactericide/fungicide effective heavy metals. The lasting filter stabilizing effect is to be waited for.

This advantage aspired includes disadvantages for the waters. Only the chromium loads of the drain waters became remarkably below the legal guide lines for surface water, fish water, drinking and irrigation water, 2 months after the drain pipes were installed. The Cu-contents remained above the corresponding limits during the first two years. The Cu-enrichment of the coco filter material with the timber conservation agent Baselit has already been recognized as slightly leachable in laboratory experiments. After three discharging periods, in field trials 95% Cu and 50-70% Cr have disappeared from the impregnated coco filter and have been adsorbed predominantly by the soil around the pipe. Therefore, in addition a thin Cu-wire (0.3 g/m) was put in the filter wrap. This is an additional slowly leachable Cu-source. The relative low Cr-leaching expects a lasting Cr-effect after impregnation. The increase of the soil Cu- and Cr-content near the drain pipes must be investigated for their filter stabilizing and iron clogging continuous effects too.

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SILTATION OF PIPE DRAINAGE SYSTEMS IN NEW ZEALAND SOILS

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Soils lacking structural stability may make it necessary for a filter to be used if subsurface drainage is attempted.

Unfortunately the likelihood of pipe sedimentation problems is not always easy to predict. Although no survey has been carried out in New Zealand, feedback would suggest that many past installations are functioning far below their design capability, as a result of blockage through sedimentation.

It would undoubtedly be of advantage to our drainage designers if guidelines and field tests were available to aid in assessment, instead of local experience being the solitary guide.

Particle size analysis of the soil is often considered to be the best indicator of the need for filtration (Dierickx 1982). Soils with a high proportion of fine sand-sized particles are of greatest concern, with the most troublesome soil fraction being the 0.05 - 0.10 mm range (Broughton et al. 1976; Irwin and Hore 1979; Stuyt 1981; Trafford 1972). Soils with a predominance of particles less than 0.05 mm are unlikely to need a filter because of stable ped formation (Nelson 1960).

A wide variety of materials has been used as drain pipe filters, ranging from voluminous materials such as peat, straw, flax, and coconut fibre, to numerous forms of thin synthetic materials. A variety of new products have recently come on the market, as a result of the rapid expansion of the geotextile industry. Evaluating the relative performance of different filter materials has been the basis of much research (Overholt 1959; McKyes and Broughton 1974; Rapp and Riaz 1975; Willardson 1979; Stuyt 1981;). Although results have often provided contrasting opinions, a clearer understanding of filter functioning has emerged.

Bearing in mind the limited information available on New Zealand soils, and the need to understand how a filter functions, a research project was initiated at Massey University to investigate the pipe sedimentation problem. The project had the following objectives:-

(1) To ascertain which soil types would need a filter if subsurface drained.

(2) To determine what soil properties would offer the best guide to predicting pipe sedimentation.

(3) To derive a simple practical test for assessing pipe siltation risk.

(4) To examine the effectiveness and mode of operation of commercially-available drain pipe filter materials.

EXPERIMENTAL PROCEDURE

Lysimeters

Twelve drainage lysimeters, each 1.2 m long, 0.5 m wide and 0.6 m deep, were used (Fig. 1). Subsoils from selected sites were repacked to a depth of approximately 0.4 m, following the placement of a drainage treatment near the base of the lysimeter bin.

The drainage treatments included: standard 100 mm diameter perforated corrugated plastic tubing (with slots 2 mm in width), a pipe plus synthetic woven filter stocking material (Filtersok) as an envelope, and a non-woven geotextile drain material (Stripdrain). Three replicates were used per treatment.

Testing involved sprinkler irrigating the equivalent of a 10 mm rainfall event onto each bin twice weekly. Then every 10 days the bins were ponded to a depth of 100 mm, and the pipe flow rate recorded by measuring the infiltration rate once steady state conditions had been reached. The amount of sediment washed through the pipe after each water application was collected, oven-dried, and weighed.

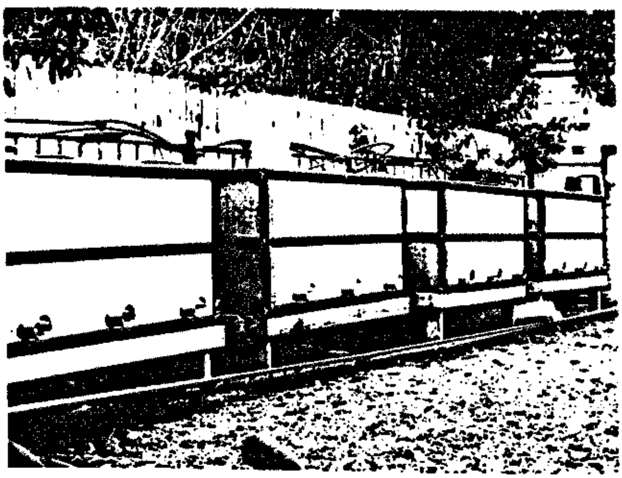

Fig. 1. The drainage lysimeters

Laboratory Columns

A laboratory column study was carried out in the hope of deriving a simple test for predicting pipe drain filter needs. The technique involved packing moistened soil samples into 75 mm diameter by 150 mm length tubing. The base of the tubing was sealed except for several slots, 2 mm wide x 10 mm in length, which were designed to simulate the aperture of the standard drain pipe. Water was ponded on the surface of the column to a depth of approximately 100 mm and the flow rate and sediment discharge recorded.

Soils used in both the lysimeter and column study were soil types considered of high sedimentation risk. All samples were weakly-structured, sandy-textured soils from sites where a rising water table problem was anticipated. Particle size analysis of each sample was determined by air-drying and sieving. Particle density and predominant particle shape were also assessed.

Field Trials

Field experiments were set up at 3 separate sites. At each site trial lines of standard 100 mm corrugated drain pipe, drain pipe plus filtersok and strip drain were installed. The long term performance of these treatments has been, and will continue to be, evaluated through a combination of flow measurement, endoscope observation of any sediment or iron ochre accumulation, and by recording permeability of the drain material and soil surround.

RESULTS

Soil Description

An evaluation of the soils used in the lysimeter and column study is presented in Table 1. The field trial sites include the Puke Puke black sand and Omanuka peat soil.

Table 1 Particle size analysis (%), particle density (kg m^{-3}), and particle shape of samples tested.

Name of soil from where samples were collected[1]	Particle size (mm)							Particle density	Predominant particle shape (Shepherd & Young 1961)
	>2 mm	2-1	1-0.5	0.5-0.15	0.15-0.125	0.125-0.075	.075<		
Puke Puke black sand	9	4	3	69	10	5	1	2 700	mainly sub-rounded
Himatangi sand	-	-	-	93	6	1	-	2 800	sub-rounded
Kumenga mottled sand	7	2	3	27	19	32	10	2 700	mainly rounded
Meeanee fine sandy loam	21	5	3	10	18	33	10	2 700	sub-angular
Owaiti coarse sand	-	1	3	81	4	8	3	2 500	sub-angular
Manawatu fine sandy loam	-	9	5	41	15	19	11	2 700	mainly sub-rounded
Te Arakura fine sandy loam	15	3	5	67	6	4	-	2 700	mainly sub-angular
Matuku silt loam	37	20	28	10	4	1	-	2 800	variable
Kaharoa ash	11	17	34	35	1	1	1	2 500	sub-angular
Wairakei pumicey sand	-	1	-	18	15	40	26	2 700	very angular
Eltham loamy sand	4	2	4	30	15	26	18	2 600	angular/sub-angular
Omanuka peat	-	1	4	84	7	4	-	3 000	rounded/sub-rounded

[1]Samples for the study were collected about drain position depth, hence their textural classification is likely to differ from that indicated by the soil type.

Drainage Lysimeter Study

Figs. 2 to 6 illustrate the changes in pipe flow rate and sediment discharge from the drainage lysimeters over time for 5 of the soils investigated. Graphs show the data points for each replicate and the replicate mean.

Results show variation in behaviour between the soil types. The permeability of both the Kumenga mottled sand and Meeanee fine sandy loam was relatively low initially, and declined further over the period of study. In comparison, the Himatangi sand and Owaiti coarse sand remained highly permeable throughout the study. For all soils the flow rate had reached a relatively constant value by the end of the experiment, so it was assumed that long-term predictions could be made from these data.

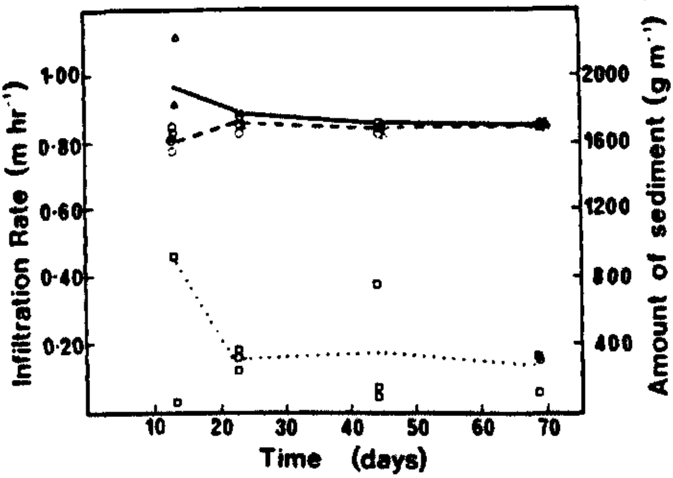

Fig. 2 Change in lysimeter infiltration rate over time with (○ – –) and without Filtersok (▵ —) for Himatangi sand. Also shown is the sediment discharge per unit length of pipe without Filtersok (□ ···) per drainage event.

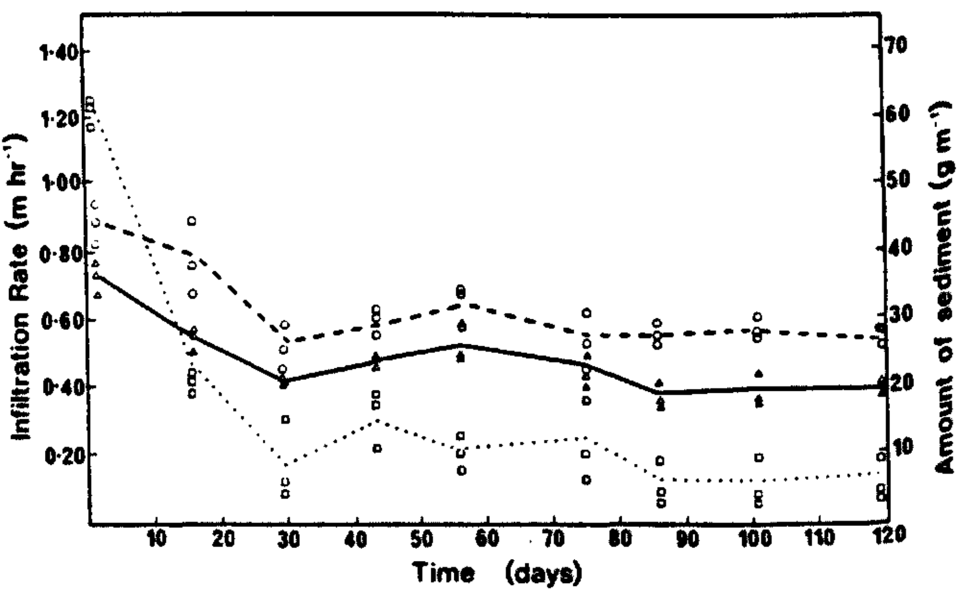

Fig. 3 Change in lysimeter infiltration rate over time with (○ – –) and without Filtersok (▵ —) for an Owaiti coarse sand. Also shown is the sediment discharge per unit length of pipe without Filtersok (□ ···) per drainage event.

For the Himatangi sand, the Meeanee fine sandy loam, Owaiti coarse sand, and Puke Puke black sand there was no indication that the drain filter became clogged during the course of the study. The flow rate decline over time with the Kumenga mottled sand and the Meeanee fine sandy loam occurred with both treatments, and appeared to be the result of sealing at the surface of the drainage lysimeter caused by microjet droplet impact, since readings from installed piezometer tubes showed that the surface few cms provided the greatest hydraulic resistance.

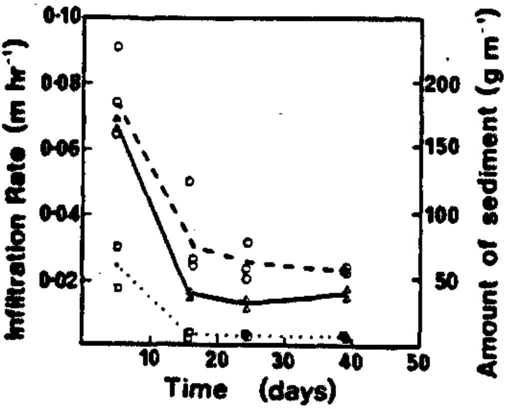

Fig.4 Change in lysimeter infiltration rate over time with (o - -) and without Filtersok (Δ —) for a Meeanee fine sandy loam. Also shown is the sediment discharge per unit length of pipe with Filtersok (□···) per drainage event.

The quantity of sediment passing through into the unfiltered pipe varied markedly with soil type. Whereas only 4 g of sand passed through the 1 m length of pipe during the first flooding on a Kumenga mottled sand, more than 900 g was measured when a Himatangi sand was used (Fig. 2 and 6).

In all instances the greatest quantity of sediment was measured following the first flooding. The sediment discharge rate appeared to taper off to a constant level during subsequent flood events.

For all soils in which a filter was used the sediment discharge from the pipe was negligible. Excavation of the pipes upon completion of the experiment showed that pipes using a filter remained clean. In contrast, unfiltered pipes were partially blocked.

Laboratory column study

Table 2 shows the amount of sediment moving through the column drain slot following application of 45 mm of water to different soil types.

Table 2. The quantity of sediment collected from laboratory columns following application of 45 mm water

Soil	Mean quantity of sediment (g per 100 cm^2 of pipe surface area)
Puke Puke black sand	14.3
Himatangi sand	80.1
Kumenga mottled sand	6.5
Meeanee fine sandy loam	2.2
Owaiti coarse sand	14.8
Manawatu fine sandy loam	0.9
Te Arakura fine sandy loam	11.7
Matuku silt loam	0.2
Kaharoa ash	1.5
Wairakei pumicey sand	5.3
Eltham loamy sand	0.9
Omanuka peat	13.9

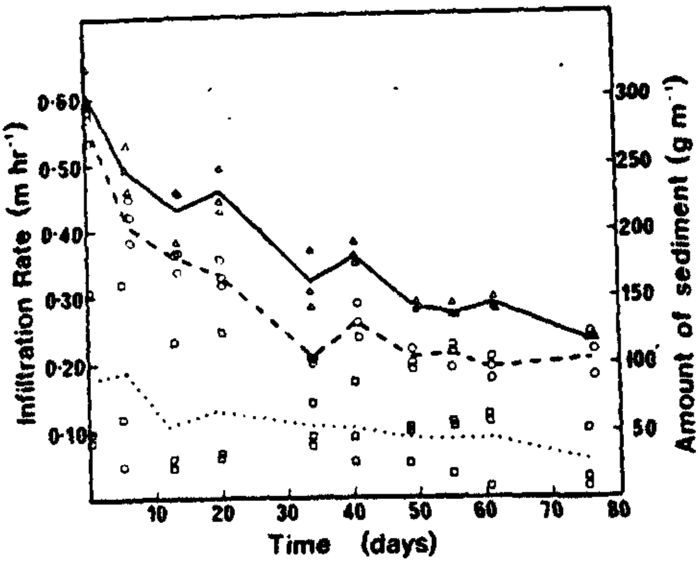

Fig. 5 Change in lysimeter infiltration rate over time with (○ – –) and without Filtersok (△ —) for a Puke Puke black sand. Also shown is the sediment discharge per unit length of pipe without Filtersok (□ ···) per drainage event.

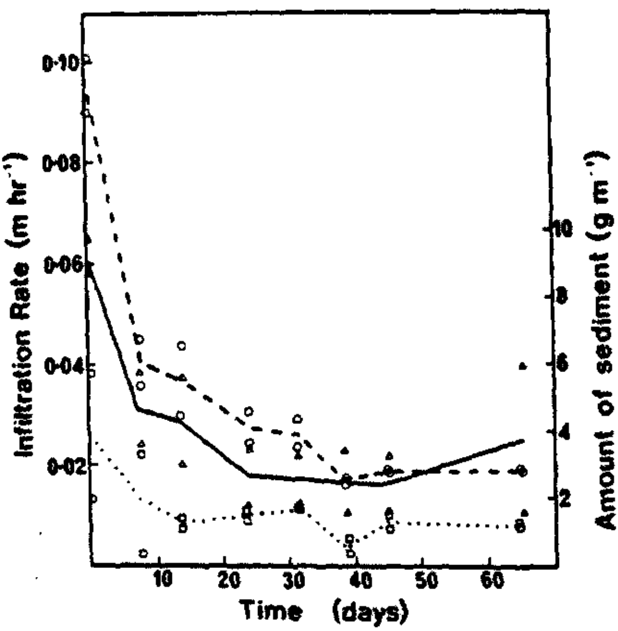

Fig. 6 Change in lysimeter infiltration rate over time with (○ – –) and without Filtersok (△ —), for a Kumenga mottled sand. Also shown is the sediment discharge per unit length of pipe without Filtersok (□ ···) per drainage event.

The trends apparent from the laboratory column study matched the findings from the drainage lysimeters, with soils producing high sediment discharge in the lysimeters also yielding the highest discharges in the columns. A simple laboratory column experiment may therefore provide the drainage designer with at least some indication of the siltation risk for a particular soil.

Field Trial Study

An investigation of the 3 field trial sites was carried out approximately 2 years after installation.

At each of the sites all trial drain lines were found to be functioning effectively with respect to flow rate.

Excavation and inspection at two of the sites revealed iron ochre build up on the pipe filter material and adjacent soil surround. This build up was found to have caused a significant decline in permeability at one site (the Omanuka peat site), and it could be expected that the problem will worsen with time (Table 3).

At all 3 sites the unfiltered drain lines were found to be relatively free of sediment. This was a somewhat surprising observation with respect to the Puke Puke black sand and Omanuka peat sites, since they were deemed to be high sedimentation risk soils from the lysimeter studies. It would appear that sand particles immediately adjacent to the pipe drain had become partially cemented and stabilised by iron and manganese precipitation.

Table 3. Measurement of permeability at the Omanuka peat site

	Permeability (mm hr^{-1})
subsoil sand	250-400
pipe-backfill interface	20- 90
clean stripdrain*	3600
iron ochre-coated strip drain*	700

*Measured using 1 KPa hydraulic head.

DISCUSSION

From our studies it is apparent that numerous parameters are likely to have a bearing on the pipe sedimentation risk, including: particle size distribution, soil structure, particle shape, particle density, flow velocity and soil mineralogy.

Soils found to have uniform particle size distribution with a predominance of particles in the 0.1-0.5 mm range, such as the Owaiti coarse sand, Puke Puke black sand, Omanuka peat, and Himatangi sand, appear to be in greatest need of a filter. Samples containing a significant silt or clay component, such as the Manawatu fine sandy loam and Eltham loamy sand, appear unlikely to cause problems, because soil ped formation promotes stability (provided sufficient time between backfill return and drain flow). Any evidence of stable soil ped formation in the subsoil could indicate that sediment entry which does occur may be of a temporary nature only, until the backfill material consolidates and stabilizes.

A comparison of the Owaiti coarse sand and Himatangi sand indicates that particle shape may have an important bearing on soil stability. Rounded sand particles, as found in the wind-deposited Himatangi sand (Table 1), appear to be less stable than angular sand particles, such as those in the Owaiti soil.

The soil mineralogy may also influence pipe siltation risk. Himatangi sand and Omanuka peat samples have a similar particle size distribution, but markedly different sedimentation behaviour. This difference is likely to be due to the high magnetite level (as indicated by the high particle density) in the Omanuka peat sample. In addition, the high iron content in the Omanuka peat sample would appear to help cement together soil particles, provided sufficient time was allowed between backfill return and subsequent drain flow.

The particle density is also likely to influence the flushing potential once particles have entered the pipe. For example, drains installed in pumice soils of low particle density (e.g. the Kaharoa ash) are seldom blocked by sediment, even though particle size analysis may suggest otherwise.

Hydraulic conductivity and hydraulic gradient both have a bearing on pipe sedimentation, since they determine the velocity and thus energy of the flowing water (the erosive force). A soil with high hydraulic conductivity, such as the uniformly graded Himatangi sand, may pose a greater sedimentation risk than a less permeable soil.

Where a filter was used in the drainage lysimeters it proved effective at preventing entry of soil into the pipe. There was no indication that the filter became significantly clogged over time.

The traditional viewpoint of pipe envelope functioning is that it must selectively filter drainage water, allowing fine silt and clay-sized particles to pass into the pipe yet retaining the potentially harmful fine sand. But perhaps a more apt way of describing how a filter works is to consider it as a soil stabiliser, physically supporting the soil immediately around the pipe, and preventing collapse of soil particles into the drain slots. Microscope studies show that sand particles appear to bridge filter pores, rather than lodge within the pores. The soil particles retained may in fact be much smaller than the effective pore size of the filter.

The lysimeter trial illustrated that the rate of any sediment entry into a pipe is likely to be most rapid during the first flow events and taper off over time as the soil immediately around the pipe stabilises.

That minimal sediment build up had occurred within the unfiltered drain lines at field trial sites contrasts with the results obtained from the lysimeter study. The trial drainage lines were installed several months in advance of the drainage season, thus providing sufficient time and opportunity for some degree of soil backfill stabilisation. This stabilisation period was not allowed for in the lysimeter study. Further, the hydraulic head used in the lysimeter experiment, a saturated profile with 100 mm of ponding, was much greater than that experienced to date at any of the trial sites. This disparity illustrates the difficulties in extrapolating laboratory or lysimetry results to the field situation.

SUMMARY

Many soils throughout the world require a pipe filter to be used when subsurface drainage is attempted. In New Zealand little information is available to help predict when a pipe drain filter is required, and local experience is the solitary guide. To gain more information on pipe siltation

an experiment was carried out using drainage lysimeters, laboratory columns and field trials to study the behaviour of pipe drainage materials in a range of "suspect" soil types.

The lysimeter and laboratory column test results suggests that several soil types will require a filter to be used if subsurface-drained. Soil types of greatest risk appear to be cohesionless, fine sandy soils with a rising watertable. Not only should particle size analysis be used to indicate possible siltation risk, but also soil structure, particle shape, particle density, soil mineralogy, hydraulic gradient and hydraulic conductivity.

The two synthetic filter materials tested proved to be effective at preventing siltation without becoming significantly clogged. It would appear the filter functions by physically supporting and stabilising the soil surrounding the drain aperture.

Results from the field trials suggest that even seemingly cohesionless, unstable soils may naturally stabilise through chemical cementation or ped formation if given the opportunity.

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EXPERIMENTS TO IMPROVE THE EFFICIENCY OF DRAINAGE

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Modern mechanized agriculture places ever greater demands on subsurface drainage in regard to the drying of fields. Big and heavy machines are now used in agriculture and drainage must be efficient so that the trafficability of fields is sufficient to allow the machines to work. Finland's short summer sets demands of its own. It is important to get into fields as early as possible in spring so that the best possible use of the short growing periods of plants can be made. The heavy machinery and the one-sided choice of plants and modern farming causes deterioration in the drainage of fields. Working with heavy machines on wet fields compresses the land and reduces most the amount of great porosity in the soil and thus causes the formation of layers with bad hydraulic conductivity above the subsurface drains.

Due to the above mentioned facts particularly clay and peat soils suffer from a lack of hydraulic conductivity and drainage becomes less effective. In cultivation wet clay soil loses its porosity and becomes compact with bad hydraulic conductivity. Because of cultivation carried out in wet circumstances a subsoil of bad hydraulic conductivity is formed under the plow layer and also the cultivation layer might become compact. Modern agriculture is often also specialized. For example one-sided grassless cultivation is charasteristic of southern clay fields. As a result of this the field has to be cultivated every year and the porosity created by the roots of the grass is lacking. Nowadays in addition it is aimed to cultivate varities which provide a good yield which demand a long growing period, for which reason spring crop work has to be started earlier than before in the spring. This might be lead to a vicious circle in which the cultivation of land in moist conditions weakens the drainage of the field and because of this cultivation the following year has to be done in even damper circumstances. On the other hand in peat land the deterioration of the structure and the compaction of the soil takes place almost entirely in the cultivation layer.

Clay soils sensitive to compaction are found in Finland particularly in Western and Southern Finland. The share of peat soil of arable land on the other hand increases rapidly mowing from south to north. The maps in Fig. 1 depict the proportional share of clay and peat land both in cultivation layers and in groundsoil of arable land in Finland.

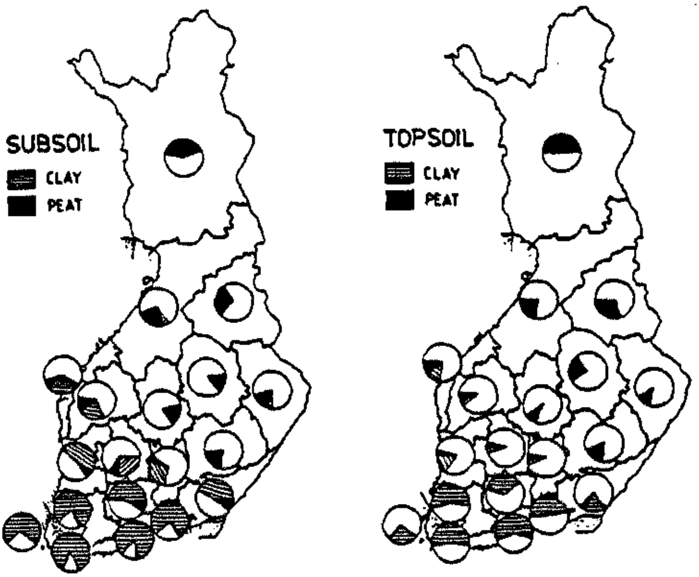


Fig. 1. The proportion of soil types in the cultivation layers and groundsoil by regions in Finland.

The drainage of fields in Finland has been carried out by either surface drainage or subsurface drainage. Modern farming demands subsurface drainage. Through subsurface drainage the level of ground water can be lowered so that the marginal drainage effect required by agriculture is reached. In the fields in which the soil types become poorly permeable due to cultivation and hydraulic conductivity becomes low, however, it might be that a new ground water surface is formed on the surface or close to the surface and thus the desired drainage effect is not reached.

In unpermeable clay soil also a subsurface drainage trench which, after the subsurface drainage, is of its structure loose and well permeable soil, becomes compact with time and resembles the surrounding soil. The compaction of the subsurface drain trench, it has been verified, becomes harmful to drainage already 4-5 years after carrying out subsurface drainage. In this kind of soil the draining reached by subsurface drainage has to be made more efficient in order to attain adequate drainage effect.

Methods to improve subsurface drainage depend on the quality and location of the impermeable layer which in turn depends on the type of soil. In the compaction of peat soil the problem is the accumulation of surface water on fields, while in clay soil the consequence of compaction causes "double ground water" fenomen. In both clay soil and peat soil it has been aimed to improve drainage by increasing the number of subsurface drains, the blind inlets or by changing the backfill material in the trench to material which conducts water well. In peat soil where the surface water causes problems there have been attempts to make drainage more effective by cambered bedding. Under testing there is also the mixing of a thin peat layer on the mineral soil below it. These tests aim at increasing the hydraulic conductivity of the surface soil. In addition to the changing of existing subsurface drainage structure and as well as measures aimed at the soil, experimental areas have been created in compact clay soil in which the improvement of drainage is tested by methods supplementing subsurface drainage.

and by filling the ditch with either gravel or woodchips. The impact of woodchips and gravel on the improvement of drainage is being compared, because woodchips is light and thus drainage construction causes no dangers to the compaction of land. An advantage of woodchips is also its price if it is made of a farm's own raw materials. An advantage of gravel is its good hydraulic conductivity and its preservation in the soil. In the test fields one of the factors to be followed up is the decomposition of woodchips and the age of shallow drains.

The installation of shallow drains can be done with different machines. By developing new methods to improve drainage, one of the aims was that it can be carried out by the farm itself. To attain this goal a digger which could be pulled by the farm's own tractor was sought for. A comparison has been made between two such diggers. One of the machines is a small chain digger and the other is a cutting digger. The advantage of a small chain digger is that the depth of the trench can be regulated from the surface to the depth of the subsurface drain, but it produces a wider trench than that made by a cutting digger, which is 10 cm. In cutting digger the variation of the depth of the trench is only 15 cm of the maximum depth of trench.

The Finnish Field Drainage Centre has established test areas in two clay fields in southern Finland in order to investigate shallow drains filled with chips of wood. The first test areas were established in the summer of 1986. Shallow drains were made in the test areas which were dug to a depth of 60-70 cm in such a way that the trenches reached down to almost the gravel layer on the subsurface drains. The ditches were dug by a drainage machine and the width of the trench was 19 cm. They were dug perpendicularly towards the subsurface drains and the ditch was filled with woodchips up to the surface. The woodchips drains were made by using drain spacing of 15 and 30 metres. In the autumn of 1987 experimental areas were created in the test fields using a small chain-type drainage machine and a cutting digger and by filling the trenches with woodchips and gravel. A pipe was installed in some of the shallow drains and some of them were filled with gravel and some with woodchips.

There are as yet few results from the test areas. There are, however, preliminary results from the test fields established in 1986 on woodchips drains. The functioning and efficiency of the woodchips ditches have been followed up by interviewing the farmers about the drainage of the fields and about the condition of growing units and by measuring the moisture in areas where woodchips drains had been made as well as observing the differences in the fields trafficability from the wheel tracks of tractors. Also the decomposition of the woodchips is being followed as well as the impact on the quality of water coming out of the drains. While establishing the testing areas questions relating to expenditures and working methods have been studied. In the test areas cultivation has started at the normal time and the surface water has not accumulated as in previous years.

Methods to improve subsurface drainage will be further developed and new test fields will be established. The methods developed until now have been mainly designed to improve drainage in clay soil. In the future, attempts will be made to develope new methods for peat soil too.

In Finland while making subsurface drains blind inlets are made in places where open surface drainage has been filled. If drainage, for example due to the compaction of soil proves to be inadequate more blind inlets have been put in the wettest places to improve drainage. Blind inlets made by big excavators improve drainage more than small drilled blind inlets. Experimental fields have been established to study the effect of distances between blind inlets. Research has also been directed at the way of filling subsurface trenches and at alternative envelope materials. In clay soil research is directed among other things at how well subsurface drainage trenches remain hydraulic conductive when the dug clay land is left to dry before putting it back into the trench. There have been tests both in peat and clay soils to fill entirely the subsurface drainage trenches for example with gravel or sawdust which allow good permeability. In the experiment subsurface drainage has been complemented by making new subsurface drains between every lateral drain. By dense drain spacing and by gravelling ditches right to the surface drainage has been improved, but due to the great consumption of gravel and the number of ditches, expenditures have become great. In the experimental areas the placing of supplementary drains into every second absorbing drain has been investigated but the results have been that the drainage of the field has been uneven.

In clay soils, into which a unpermeable subsoil is formed due to the compaction of the soil and which prevents the rapid flow of water into subsurface drain pipes, experiments have been carried out to improve drainage with methods complementing subsurface drainage. With these methods a shallow drainage is made in the field which leads the surface water accumulated on the subsoil either into the field boundary ditches or to subsurface drains. In Finland mole ditching was experimented with in the 1950's. Mole ditching did not succeed, however, in Finland in the improvement of draining clay land because the length of its lifetime, 3-5 years, was considered too short. Subsequently other methods have been developed to improve subsurface drainage. The draining of poorly permeable clay land has been improved by digging narrow trenches which are filled with sawdust or woodchips on the subsurface drainage. This originally Estonian method has been further improved in Finland.

In Finland a goal was set in regard to improved methods of drainage, that they should drain surface water away quickly, be economic, to be carried out by the farmer itself, as well as to have long lifetime. The principle behind these methods is to drain both the surface water and the water accumulated in subsoil along a shallow drainage system away from fields either to subsurface drains (Fig. 2) or to field boundary ditches, or to both. In these methods the shallow drains are made in a way that they are perpendicular to the subsurface drainage thus crossing the subsurface drains as often as possible. In the field the low ditches and the subsurface drains form a net of squares (Fig. 3) and at the point where the low ditches meet the subsurface drains the water flows into the subsurface drains. In the fields in which the soil has poor hydraulic conductivity all the way to the subsurface drain the shallow drains always reach down to the gravel layer on the subsurface drain. Prerequisite to this is, however, that maps of the old subsurface drain system exist as is the case most often in Finland. If the ground below the subsoil is not unpermeable and allows easy water percolation, a method with which the water can easily penetrate through the subsoil to soil which drains more readily is enough for the improvement of drainage. A third alternative is to make shallow drains in such a way that they end at the edge of the field.

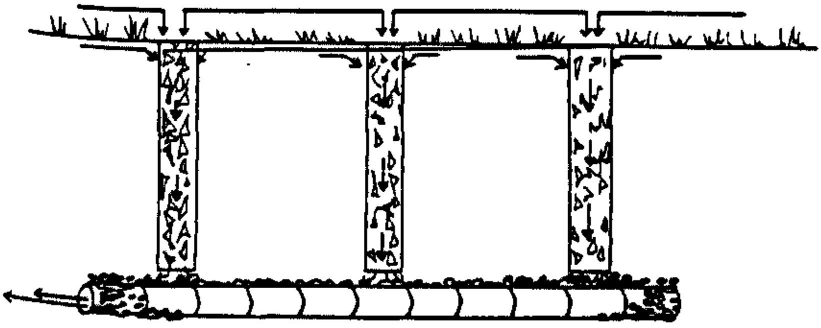


Fig. 2. The functioning of a shallow drain.

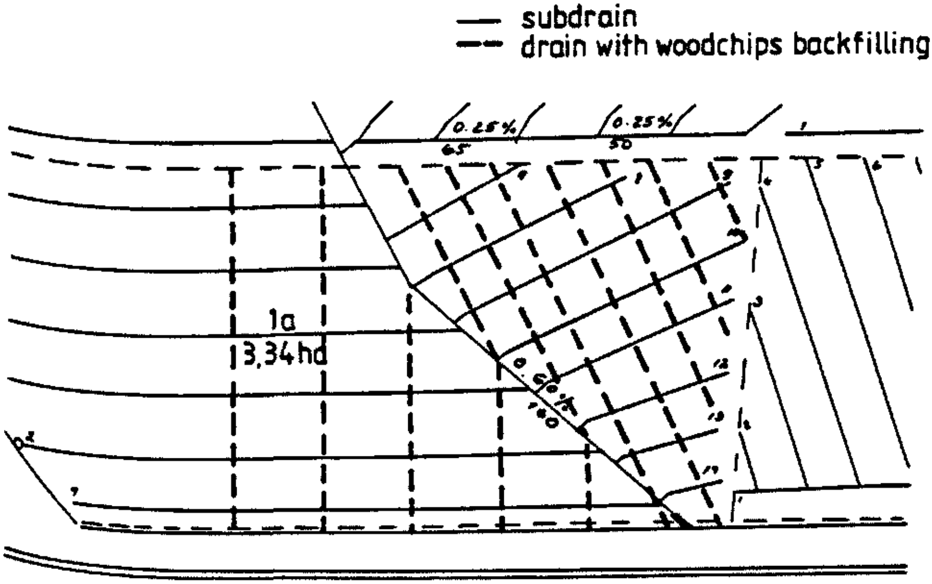
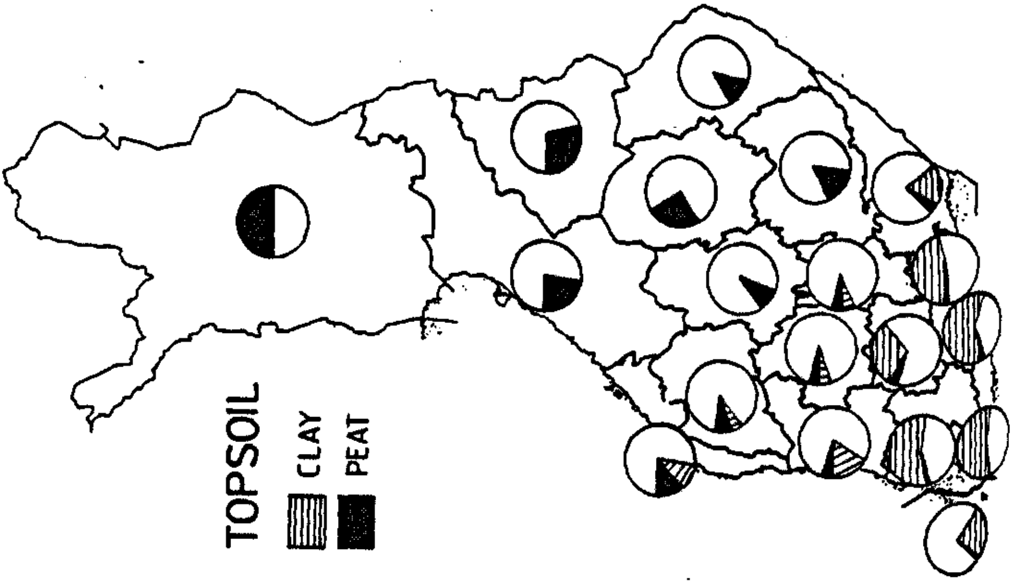
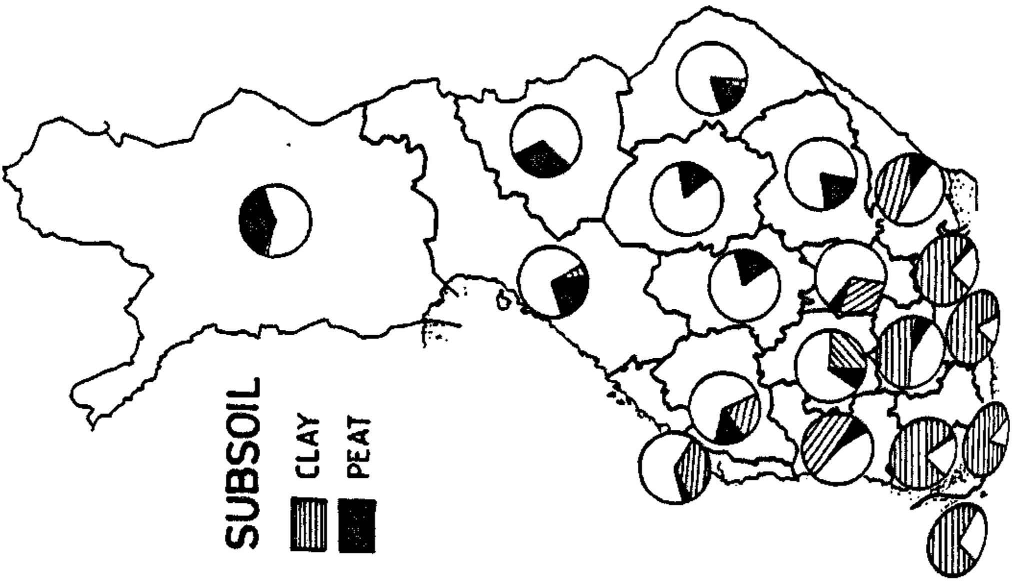
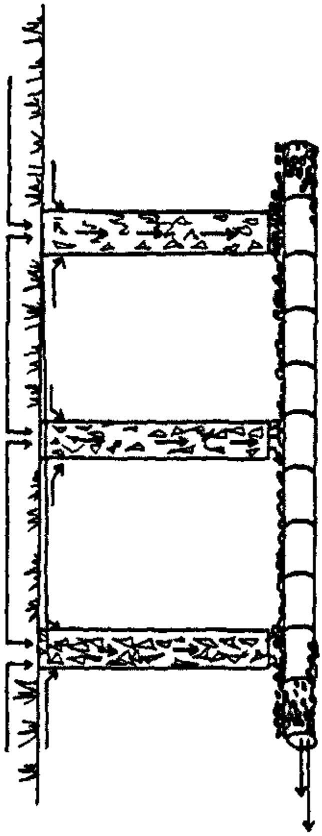


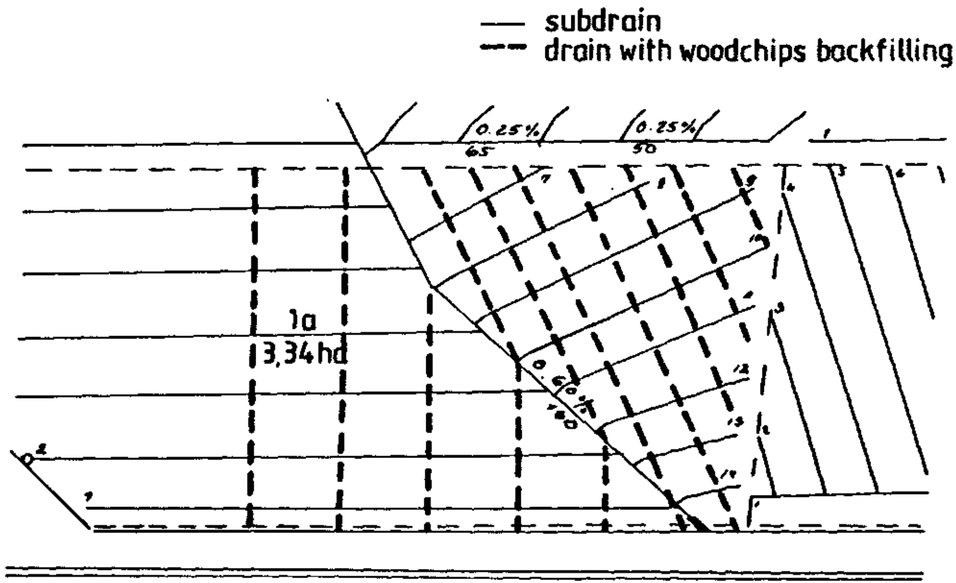
Fig. 3. Shallow drains are made perpendicular to the subsurface drains when they cross the subsurface drain as often as possible.

Shallow drains are made by digging narrow trenches which can be filled with different materials of high hydraulic conductivity. In Finland the filling of a shallow drain in test areas either with chips of wood, gravel or by installing at the bottom of the ditch a small pipe with a diameter of 32 mm


TOPSOIL
CLAY
PEAT


SUBSOIL
CLAY
PEAT





— subdrain
-- drain with woodchips backfilling
0.25%
65
0.25%
50
0.60%
180
1a
3,34ha

Figure 3.

Asphalt and Polyacrylamide Stabilization of Soil for Drain Envelopes[1]

by

L.S. Willardson and C.A. Milano[1]

INTRODUCTION

One of the important soil physical properties related to agricultural drainage is soil structure (4). Soil structure is related to permeability and, therefore, plays an important role in drainage efficiency. A strong well aggregated soil is also unlikely to cause drain sedimentation problems.

In the recent years, the application of chemical soil conditioners has increased in an attempt to improve soil aggregation. In 1952, the Monsanto Chemical Company marketed a patented chemical compound named "Krilium" that was said to be effective in increasing the structural stability of soil. Krilium was considered to be too expensive to use in general agriculture (5). Polyacrylamide (PAM) and hydrophobic asphalt emulsion are currently two of the more promising soil structure stabilizers because of their relatively low cost, effectiveness, and long life (3). Use of a soil stabilizer on backfill material may be an effective way to reduce the cost of providing artificial envelopes used in subsurface drainage.

Spraying soil, excavated from the trench for installation of a subsurface drainage system, with a polyacrylamide solution or an hydrophobic asphalt emulsion can potentially increase the stability of the soil aggregates of the trench backfill material. The treated soil might even be used as an envelope material, having higher hydraulic conductivity and higher stability than the surrounding natural soil. The hydraulic failure gradient of the original soil and treated soil can be tested in the laboratory and the results used as a guide for use of the stabilized soil as drain envelope material.

Hydraulic failure gradient, according to Walker (6), is the gradient at which the structure of a soil-envelope interface begins to fail. The characteristic hydraulic failure gradient can be determined for different soils and the information can be used to design an adequate soil-envelope interface. Hydraulic exit gradients can be regulated to values equal to or lower than the hydraulic failure gradient of the soil being drained in order to prevent sediment inflow to drains.

Soil structure strength is the important defining factor affecting the hydraulic failure gradient of a given soil. Hydraulic failure gradient can therefore be used to determine the need for envelope material around drain pipes. Combining these concepts with the use of a soil conditioner to increase soil stability, it was concluded that using a suitable soil conditioner to stabilize the soil around a drain pipe has promise as a substitute for other envelope materials, especially in areas lacking suitable gravel material.

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One question that arises is, how long will the effect last? It is known that the degradation of soil stabilizer products is a function of the micro- biological activity in the soil. Since at drainage depth microbiological activity is limited, chemically stabilized soil should continue to be effective for a long period of time.

At Utah State University, a laboratory study (1) was conducted to determine the influence of asphalt emulsion and polyacrylamide (PAM) on the hydraulic failure gradient of treated soil used as drain envelope material. The cost of applying the soil stabilizers to the soil from a subsurface drainage trench was also calculated.

METHOD AND PROCEDURE

The soil stabilization study was conducted using soil samples obtained from the subsoil close to drain depth (50-100 cm from the soil surface). Layton (loamy sand), Collet (silt loam), and Cardon (clay) soils found in the Cache Valley of Utah were used for the tests. The particle size distribution curves of the soils used in the tests are shown in Figure 1. The soil conditioners used were a polyacrylamide granulate (PAM) with a molecular weight of 5-6 million Daltons produced by Polisciences, Inc., Warrington, Pennsylvania, and an asphalt emulsion produced by American Tar Company, Seattle, Washington.

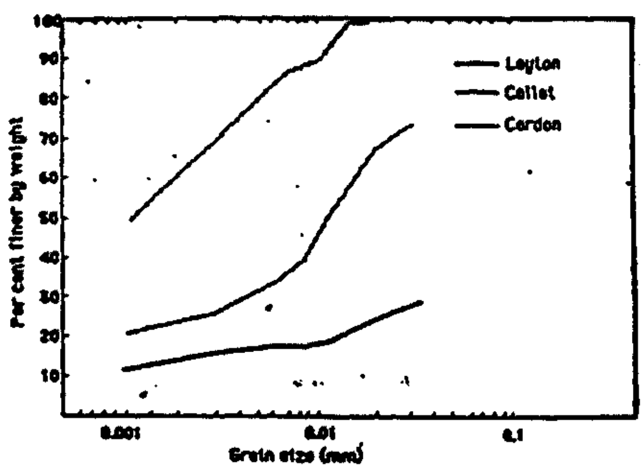

FIG. 1--Soil Particle Size Distributions for the Soils Used

Two solutions of polyacrylamide (0.01% and 0.1% by weight) were prepared for soil sample treatment as was a solution of asphalt emulsion (12.5% by weight).

Soil Sample Preparation

The soil samples were dried and passed through a 4-mm sieve. Water was added with a spray bottle to bring the water content of the soil close to field capacity and then the moist soil was again passed through a 4-mm sieve. The wetted untreated soil was covered and allowed to equilibrate in the laboratory at least 3 days before packing in the test permeameter.

Treated Soil Preparation

Four different concentrations of polyacrylamide were applied to subsamples of each soil. The polyacrylamide was sprayed on different treatment soil samples as a 0.01% dilution in water at a rate of 0.0001%, 0.0004%, and 0.0016% by soil dry weight, and as a 0.1% dilution in water at a rate of 0.016% by weight.

Three different concentrations of asphalt emulsion were used on each soil type. The asphalt emulsion was sprayed on the soil sample as a 12.5% dilution in water at a rate of 0.625%, 1.25%, and 2.50% by the dry weight of the soil.

The conditioners were applied as fine stream spray and carefully mixed with the soil using a rubber spatula. The treated soils were allowed to age in the laboratory with a plastic cover at least 3 days before packing in the permeameter. Most of the samples were kept continuously moist. A limited number of samples treated with 2.5% asphalt emulsion and 0.016% PAM were tested after drying following application of the chemical treatment.

Sample Placement in the Permeameter

The treated soil was placed in a 10 cm diameter inverted permeameter, which was filled up to half of its capacity with treated soil in layers approximately 3 cms thick. Each layer was compacted with a load of 29.66/m2to simulate the magnitude of the loading that might be expected around a newly installed subsurface drainpipe. The other half of the permeameter was filled with the untreated soil following the same procedure used for the treated soil. The cross section of the permeameter and soil is shown in Figure 2.

A continuous flow of carbon dioxide was directed into the permeameter during packing to displace the air within the soil samples and help to obtain complete saturation of the samples when they were wetted.

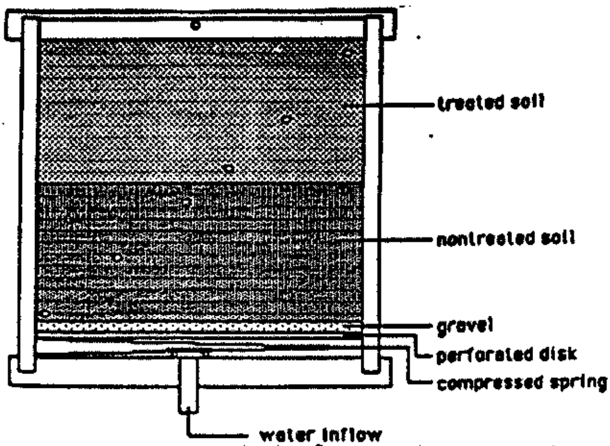

FIG. 2--Cross Section of the Permeameter and Soil Sample

Conducting the Tests

The soil sample was saturated from the bottom with deaerated water and was held for approximately 18 hours with a small water flow passing through it (the gradient in the sample was much less than 1.0). The schematic of the test apparatus is shown in Figure 3. The test was started by slightly increasing the flow rate at equal intervals of time (every 15 minutes).

The flow, the gradient, and hydraulic conductivity were measured at short time intervals. The point in time at which failure occurred was recorded along with the hydraulic data.

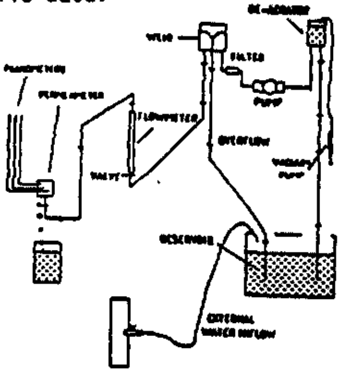

FIG. 3--Schematic of the Test Apparatus

RESULTS AND DISCUSSION

During the experimental tests, the head (hydraulic potential) was measured at three levels within both the treated and untreated soil. These data were used to calculate the gradients in the non-treated soil, near both sides of the interface and in the treated soil.

Using Miller's conclusion (2), to calculate the hydraulic conductivity, and to eliminate the effect of excess energy loss for water entering and leaving the soil, only the internal gradients in the non-treated or treated soil were used to evaluate the treatments.

The Cardon clay did not show any apparent effect of soil stabilizer treatments. For this clay soil only the tests with the highest application of the chemicals combined with drying before packing showed an increase in the hydraulic conductivity (less than 0.002 cm/min.).

Hydraulic Failure Gradient

The observed soil sample hydraulic failure gradients are shown in Figures 4 and 5 for the different treatments. Three modes of hydraulic failure were observed. The first, called piping, began when soil appeared in the flow of water at the top of the permeameter. This failure occurs because the drag force for high gradients exceeds the cohesive forces of the individual soil aggregates. This mode of failure was observed especially in loamy sand.

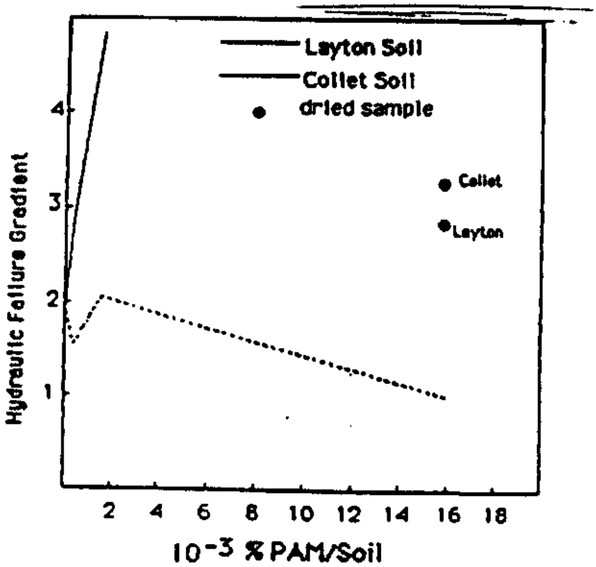

FIG. 4--The Effect of Different Concentrations of Polyacrylamide on the Hydraulic Failure Gradient of the Treated Soil.

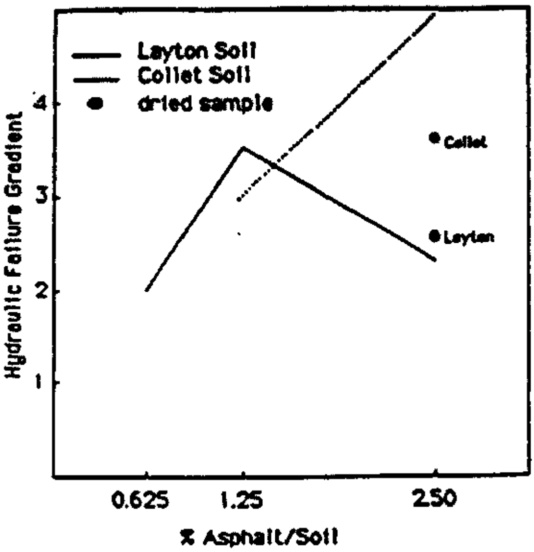

FIG. 5--The Effect of Different Concentrations of Asphalt Emulsion on the Hydraulic Failure Gradient in the Treated Soil

The second mode of hydraulic failure is called consolidation. Consolidation occurs when the drag forces reduce the internal pore sizes of the aggregates with a reduction in permeability and an increased gradient for the same flow rate. This model failure was observed in silt loam (cohesive soil).

The third mode of hydraulic failure is internal erosion, which occurs at the interface between non-treated soil and treated soil. It occurs when a change in the expected pattern of the gradients (higher in the non-treated soil than the treated soil) indicated movement of soil particles from the non-treated soil to the treated soil. Movement of soil particles at the interface causes formation of some channels in the non-treated soil reducing the gradient (increased hydraulic conductivity), and clogging of the pores in the treated soil, increasing the gradient (decreased hydraulic conductivity). This mode of failure was observed in both loamy sand and silt loam.

The results of the hydraulic failure gradient tests (see Figures 4 and 5) do not show a very good relation to the chemical concentrations. If the treated soil is left to dry after applying the chemical, to allow uniform and stable aggregation to occur, the effect of the treatments versus the hydraulic failure gradient becomes a function of soil type.

Head Losses in the Soil

During the tests, the head (hydraulic potential) was measured at three levels within the non-treated soil and at three levels within the treated soil, and at the top and bottom of the permeameter in free water.

The highest flow discharge rate (104.4 cc/min.) that did not cause hydraulic failure in the tests was used to evaluate how the treatment concentrations influenced the head loss in the soil. It can be seen from Figure 6 that in the Layton soil there was little effect of using different concentrations of polyacrylamide even including drying the soil after chemical application.

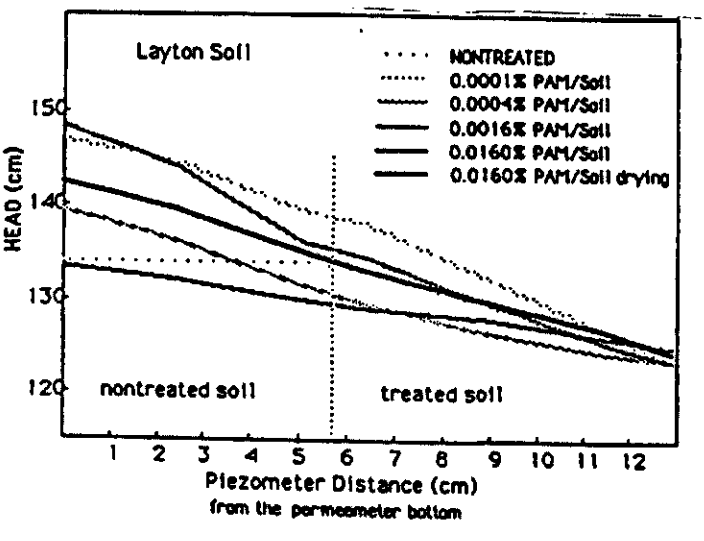

FIG. 6--The Effect of Different Concentrations of Polyacrylamide on the Head of the Layton Soil with a Flow Rate of 104.4 cc/min.

In Figure 7, there is a tendency to increase the head loss in the collet soil (the same as the effect of the asphalt in the Layton soil) as the concentration of PAM is increased. Drying the soil after chemical application was much more effective. PAM works better with drying the soil after application.

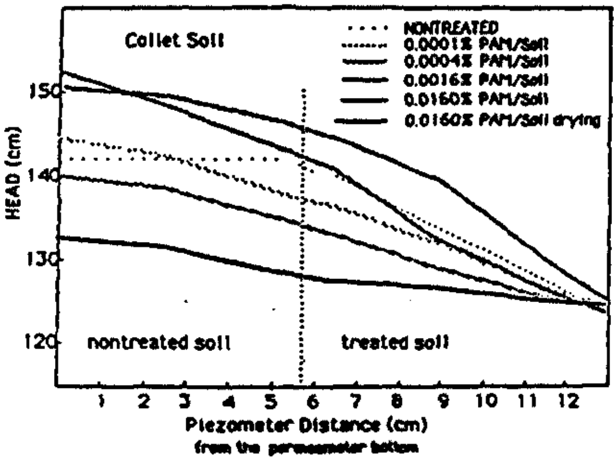

FIG. 7--The Effect of Different Concentrations of Polyacrylamide on the Head of the Collet Soil with a Flow Rate of 104.4 cc/min.

There is a tendency (Figure 8) for increased head loss in the soil with the increase of asphalt emulsion concentration in the Layton soil. The test for drying after application of asphalt decreases considerably the head loss and can be explained by the aggregation effect of the asphalt in the soil. This material also works better if there is drying of the soil after application.

For the asphalt emulsion on the Collet soil, the tendency was to decrease the head loss in the treated soil. Drying the soil after application of the asphalt improves the soil.

Cost of Chemicals

The costs of a cubic yard of treated soil material for different concentrations of the chemicals (the costs do not include cost of application, which can be done with a common garden sprayer) are shown in the following table:

Treatment	$/Yd^3
Gravel	7.0
0.625% Asphalt	3.1
1.25% Asphalt	6.1
2.50% Asphalt	12.3
0.001% PAM	0.07
0.004% PAM	0.029
0.0016% PAM	1.18
0.016% PAM	11.79

It can be seen that the highest concentration of asphalt emulsion that can be applied to the soil with a cost less than gravel is 1.25%. In the case of polyacrylamide the highest concentration that can be applied with a cost less than gravel is between 0.0016% and 0.016% PAM (about 0.008% PAM). The data in the table also indicate that the polyacrylamide (PAM) is a potentially economic means of stabilizing soil for use as drain envelope materials.

RECOMMENDATIONS

The results of this research have shown that the two types of soil conditioners work better when the soil is dried at least one time after chemical application and before packing in the permeameter. To more fully evaluate these soil conditioners (asphalt emulsion and polyacrylamide) using hydraulic failure gradient criteria, the following procedure is recommended for use in sample preparation to pack in the permeameter:

1. Wet the soil sample close to the field capacity and equilibrate at least 12 hours.

2. Spray the chemical conditioners on the wet soil.

3. Leave the soil sample to air dry.

4. Sieve the dry sample in a 4-4.75 mm sieve to make the size of the aggregates more uniform.

5. Wet soil again close to field capacity before packing in the permeameter.

More tests should be done, especially with the loamy sand, because this was the soil which did not respond satisfactorily to these chemicals.

In the clay soil that was used in this study (Cardon clay), the effect of the soil treatment, without drying, was negligible. In future studies it would be better to evaluate soils with less clay. High clay soils generally do not have problems of sedimentation in drains. It should be possible to increase hydraulic conductivity as well as the soil structural stability in all soils by use of these chemicals.

Comparing observed results for the highest flow discharge (approximately 104.4 cc/min.) that did not cause hydraulic failure gradient, the following observations can be made:

1. The clay soil did not show any improvement in soil physical characteristics due to application of the chemicals.

2. In the loamy sand soil, the polyacrylamide treatment had little effect even after drying the soil.

3. For loamy sand soil, the asphalt emulsion showed a slight tendency to decrease head loss in the treated soil.

4. For silt loam soil, the polyacrylamide and the asphalt emulsion both showed a strong tendency to decrease head loss and increase hydraulic conductivity of the treated soil especially in the samples subjected to drying after application of the chemical. The asphalt emulsion showed a better effect than the polyacrylamide.

The cost of soil treated with different concentrations of asphalt emulsion and polyacrylamide, was lower than for gravel for concentrations lower than 1.25 percent of asphalt emulsion by weight in dry soil, and concentrations lower than 0.008 percent of polyacrylamide by weight of dry soil. This application concentration is satisfactory only in the silt loam soil.

SUMMARY AND CONCLUSIONS

Summary

The main objective of the study was to determine the effect of different concentrations of two soil conditioners (asphalt emulsion and polyacrylamide) on hydraulic failure gradients of three different soils (loamy sand, silt loam, and clay).

Most of the samples were kept continuously moist, and a limited number of samples were tested after drying following application of the chemical treatment.

A permeameter, 10 cm in diameter and 15 cm long, with piezometers at 7 levels was used to determine the values of the hydraulic failure gradient in treated and untreated soils.

The hydraulic failure gradient did not show a very close correlation to chemical concentration. Better results can be expected if all the treated soil samples are allowed to dry after chemical application to allow the stabilization of soil aggregates and to prevent the aggregation of the mass of soil in the permeameter caused by movement of the water soluble chemicals that makes the hydraulic failure gradient procedure difficult to evaluate.

The cost of gravel compared to the cost of soil treated with different concentrations of asphalt emulsion and polyacrylamide, indicates that use of these chemicals is economic for concentrations lower than 1.25% of asphalt emulsion by weight of dry soil, and concentrations lower than 0.008% of polyacrylamide by weight of dry soil. The economic level of application is satisfactory only in the silt loam soil.

Conclusions

Hydraulic failure gradient of treated soil can be used as a design criterion only if the soil is dried after chemical application.

In soil with a medium clay content (silt loam), the effect of the chemicals.

The chemicals stabilize the soil particles by formation of adhesive bonds through adsorption or chemical reactions with clay particles. In the case of loamy sand, it was difficult to obtain strong aggregates that guarantee the stability of the soil around the drain pipe.

In soil with a high clay content that tends to form massive structural units rather than crumbs, the effect of soil conditioners does not improve the soil physical characteristics sufficiently for use as envelope material.

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RIDGE PLANTING ON POORLY DRAINED SOILS

Donald J. Eckert*

Many soils of northwest Ohio are characterized by silt loam to clay surface horizons overlaying clay subsoils. Prevailing slopes are often less than one percent and most soils are very poorly drained. The major constraints to profitable crop production are moisture related and include delayed planting due to soil wetness, denitrification, seedling rot, root diseases and often severe moisture stress later in the season. Degradation of soil structure due to tillage of and trafficking on too wet soils is an emerging problem. Tile drainage is effective in attenuating many of these problems on some fields but others have hydraulic conductivities so low that subsurface drainage improvements are not physically or economically effective.

Northwest Ohio is a major contributor of non-point source phosphorus to Lake Erie. A major portion of this phosphorus is delivered to the lake in association with sediments derived from erosion of soil from farm fields. Because of its potential to reduce erosion, conservation tillage has been recommended as an important phosphorus control strategy in the region (U.S. Army Corps of Engineers, 1982). However, the surface residue usually associated with conservation tillage, particularly no-till, reduces evaporative soil moisture loss in the spring and often aggravates the problems mentioned earlier. On fields without tile drainage no-till is usually not competitive with moldboard plow-based production systems. A conservation tillage system which maintains sufficient residue for erosion control but which does not aggravate problems associated with excessive soil moisture is needed in this region.

Current interest is focusing on the use of ridge planting systems to accomplish this objective. In such systems individual ridges are formed for each crop row by cultivation after crop emergence. After crop harvest no tillage is performed and the succeeding year's crop is planted on the undisturbed ridge the next spring. The cycle is then repeated. Generally, row widths of 76 cm or greater are required to provide enough soil to permit building ridges 15-20 cm high from peak to furrow. Thus, the system is well-adapted to corn (Zea mays L.) and soybean (Glycine max L., Merr.) production but is not as appropriate for production of small grains and forages.

The ridge planting system outlined above seems to possess several advantages over the more common tillage and planting practices in the region. Residue cover is preserved on the soil surface during the peak erosion period, allowing better erosion control than achieved with the moldboard plow. The residue tends to move to the ridge furrows over the winter, exposing the seedbed atop the ridge in the spring, allowing for early season warming and evaporative drying. Due to its elevation the ridge dries and remains relatively dry in the spring, which should permit earlier planting

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than on a flatter seedbed. The ridges also encourage controlled traffic patterns, which should attenuate the development of compaction across the root zone, though rather significant compaction should be anticipated in wheel tracks.

Early studies in Ohio involving no-till corn on elevated seedbeds have been encouraging. Fausey (1984) found that no-till corn planted on wide beds produced better stands and higher yields than when planted in a flat seedbed on a poorly drained soil in southwestern Ohio. Our early work involving ridge planting in northwestern Ohio (Eckert, 1987) has shown that date of planting advantages are real in some years and that ridge planting may eliminate the yield penalty associated with continuous no-till corn grown on flat seedbeds on poorly drained soils (Dick and Van Doren, 1985). However, most Ohio farmers grow corn in rotation with soybeans and realize a yield advantage in corn from the rotation. Soybeans normally produce higher yields when grown in row widths narrower than the 76 cm used for ridges in Ohio. Our present research effort is directed at determining whether the extra yield obtained from earlier corn planting will offset the yield penalty associated with growing soybeans in wider than optimum row spacings, thus improving the productivity and profitability of the entire rotation.

STUDY OVERVIEW AND RESULTS

The present study is located on two adjacent blocks of Hoytville silty clay (fine, illitic, mesic Mollic Ochraqualfs) at the Northwest Branch of the Ohio Agricultural Research and Development Center, Custar, Ohio, approximately 50 km south of Toledo. One block is tiled (15 m spacing), while the other is not. Both were planted with a small grain cover crop in 1983. The small grain was harvested in July and both blocks were plowed and graded to channel surface water from the block centers into adjacent surface drains. Ridges were formed on 76 cm centers, parallel to surface water flow, in predetermined locations on each block to allow for a statistical comparison of yields from ridged and moldboard plowed treatments.

In 1984 the blocks were planted to corn and soybeans in such a way as to permit continuous corn, continuous soybean and corn-soybean rotational cropping in separate areas of each block in succeeding years. In each June since 1984 ridges were reformed by cultivation with no apparent damage to the crop except for transient wilting in 1985. Each fall, moldboard plow plots have been plowed to a depth of 20 cm. These plots have been leveled with a field cultivator each spring immediately prior to planting. Individual treatment plots have been planted when soil moisture conditions were judged suitable for successful planting, corn planting generally occuring before soybean planting as is normal practice in Ohio. All corn has been planted in 76 cm rows. Soybeans have been planted in 76 cm rows on ridges and in both 76 and 18 cm rows on plowed plots. All plots have recieved uniform applications of phosphorus and potassium when needed and have received uniform applications of herbicide appropriate to the crop in question. Corn has generally received 220 kg nitrogen per hectare as injected anhydrous ammonia or surface-banded urea-ammonium nitrate solution (on ridge). Soybeans have received manganese as a foliar spray each year. All plots have been machine harvested at maturity.

In Ohio corn planted after the first week in May usually produces less grain than that planted earlier (OCES, 1985). In 1984 and 1987 it was possible to plant on undrained plots with ridges earlier than undrained plots that had been fall plowed (see Table 1). A two day planting date advantage was also seen on tiled plots in 1987. Generally, however, unusually dry April weather allowed all corn planting to occur prior to May 5 except in

1984 when undrained, plowed plots could not be planted until May 17, well past the optimum planting period.

Table 1. Planting date advantage obtained by ridge planting, 1984-1987.

Year	Corn		Soybean	
	Tile	No tile	Tile	No tile
	days			
1984	0	15	0	0
1985	0	0	0/34[a]	0/34[a]
1986	0	0	0	0
1987	2	8	3	3

a 18 cm row plots replanted due to poor stands

Soybean planting is usually less sensitive to soil moisture related delays than corn planting because it normally occurs several weeks later in the spring. As might be expected, ridges allowed earlier soybean planting less frequently than corn planting (Table 1). In 1985 the 18 cm row width plots achieved very poor stands on the May 3 planting date (all soybeans planted that day) and were replanted on June 6, giving both ridges and 76 cm row width soybeans on plowed plots a 34 day planting date advantage. In 1984 soybeans were planted on tiled plots one week earlier than on the untiled plots. In all years initial soybean planting was completed by May 17.

Yield data from the first three years of the study show differing effects of ridge planting in different years (1987 yield data were not available at the time of printing). In 1984 when both corn and soybeans followed oats corn planted on ridges produced higher yields than corn planted on plowed plots under both drainage conditions ($P<.05$, see Table 2). The yield advantage was greater on the undrained plots, this difference most likely reflecting the planting date advantage due to ridge planting on these plots. Soybeans in 76 cm rows produced equal yields on ridged and plowed plots under both drainage conditions; however, the 18 cm row width treatment produced higher yields than either 76 cm row width treatment ($P<.05$). The presence of tile drainage seemed to improve yields for both crops in all tillage-planting systems, though the design of the study precludes statistical analyses of these differences.

Table 2. Corn and soybean yields as affected by tillage-planting system and tile drainage, 1984.

Crop & drainage	Ridge	Plow	
	76 cm rows	76 cm rows	18 cm rows
	Mg/ha		
Corn			
Tile	10.4	11.3	-
No tile	8.3	9.8	-
Soybeans			
Tile	4.7	4.7	5.1
No tile	3.6	3.6	4.3

The effects of tillage - planting system and tile drainage on corn yields in 1985 and 1986 are shown in Table 3. For corn following corn in 1985 yields were higher on ridged than plowed plots under both drainage conditions ($P<.05$). Yields were equivalent for corn following soybeans between ridged and plowed plots with tile drainage but lower for ridged than plowed plots without tile ($P<.10$). These reduced yields were due to lower plant stands on ridged plots.

Table 3. Corn yields as affected by previous crop, tillage-planting system and tile drainage, 1985 - 1986.

Year & drainage	Previous crop: Corn		Previous crop: Soybean	
	Plow	Ridge	Plow	Ridge
	Mg/ha			
1985				
Tile	7.1	8.0	8.8	8.8
No tile	5.8	6.6	8.6	7.6
1986				
Tile	11.5	12.1	11.9	12.9
No tile	9.8	10.0	10.7	11.1

There were no differences in corn yield which could be demonstrated statistically in 1986. However, in all comparisons there was an apparent yield advantage associated with ridge planting. Apparent benefits to growing corn after soybeans rather than corn and to growing corn with tile drainage were seen in both 1985 and 1986.

Soybean yields in 1985 and 1986 are shown in Table 4. In 1985 when the 18 cm row width plots were replanted due to very erratic stands the effect of row width was variable. Row width did not affect yields in either crop sequence when tile drainage was present. In the absence of tile ridges produced higher yields than either row width in plowed plots in continuous soybeans ($P<.05$); however, in the corn-soybean rotation 18 cm rows produced the highest yields ($P<.05$), despite later planting, and ridges produced yields equivalent to 76 cm rows on plowed plots.

The major effect noted in 1986 was that of row width, with 18 cm rows producing the highest yields in all comparisons ($P<.05$). Ridge planting produced yields equivalent to 76 cm rows on plowed plots except in continuous soybean culture without tile where ridges produced lower yields. Apparent benefits of tile drainage and crop rotation did not appear as evident in 1986 as previously.

Table 4. Soybean yields as affected by crop rotation, tillage-planting system and tile drainage, 1985 - 1986.

Year & drainage	Previous crop					
	Corn			Soybean		
	Plow		Ridge	Plow		Ridge
	18 cm	76 cm	76 cm	18 cm	76 cm	76 cm
	Mg/ha					
1985						
Tile	4.4	4.2	4.2	4.5	3.8	4.0
No tile	4.1	3.5	3.5	3.0	3.4	3.8
1986						
Tile	4.7	4.4	4.3	4.6	3.9	3.9
No tile	4.6	4.2	4.1	4.6	4.2	4.0

DISCUSSION

The data from the present study are not conclusive enough to make a judgement regarding any overall benefits of the ridge planting system over the 18 cm soybean row width system in a corn-soybean rotation. Ridge planting has allowed earlier corn planting in two of the last four years and has generally produced higher corn yields than moldboard plowing; however these yield advantages for corn have been offset somewhat by the lower soybean yields incurred in the 76 cm row width system. Ridge planting has not generally resulted in earlier soybean planting due to the fact that this crop is usually planted later in the spring when soils have had more chance to dry normally. The overall yield potential of the ridge planting system seems very close to that of the moldboard plow system. Any profit advantages of either system would likely be affected more by the prevailing corn-soybean price ratio and any differences in production costs associated with implementing the systems than overall yield advantage.

It is interesting that the ridge planting system has produced higher corn yields than the molboard plow system in the present study. These results are contradictory to our earlier findings at another location on the same farm which showed equal yields between ridge planting and plowing (Eckert, 1987). The discrepency may be due to the present study being conducted during several rather dry years. The residue left on the soil surface in the ridge planting system may have conserved significant soil moisture which promoted higher yields.

While ridge planting has provided some yield advantage on the undrained site, the advantages of tile drainage seem much more significant. Tile drainage has generally resulted in higher yields of both crops in most years, regardless of rotation or tillage - planting system. Ridge planting will probably never be recommended as a long term substitute for tile; however, for farmers renting undrained land on a short term lease basis, ridge planting may offer a competitive alternative, particularly in continuous corn production systems.

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DRAINABILITY AND DRAINAGE OF HEAVY CLAY SOILS: STUDIES OF MOLE DRAINAGE IN SWEDEN

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Most of the soils in Scandinavia, a large part of northwestern Russia, and the most northern part of Europe including Great Britain were formed during the last "glacial time" and the period thereafter the "postglacial time". The icecover was 2-4 km thick and the heavy iceload pressed down the land 200-300 m. When the ice melted between 14000-6000 B.C. the land was flooded by the melting water. Simultaneously the land was raised when it was released from the iceload. Below the "highest coastlevel" the finest material was sedimented in alternatively salt, brackish or fresh water resulting in vast plains of todays claysoils of varying drainability.

The soils consist partly of intermediate clays with 30-50 % clay, and partly heavy and very heavy clay soils with 50-80 % clay in the topsoil.

The main area of clay soils have a well developed structure that gives a hydraulic conductivity of 0.1 m/day or more and a good drainability when normal drainage systems perform well. The heavy and very heavy claysoils often have less well developed structure and a permeability of less than 0.1 m/day or even 0.01 m/day. On these areas surface drainage with bedding systems and shallow ditch systems have traditionally been used.

When subsurface drainage was introduced on soils with critically low permeability, the need for shallow subsurface drains was realized. Mole drainage has been looked upon as a cheap supplementary method. However, in Sweden the technique has not been widely accepted in practice, in spite of the effect that has been shown in field trials. There is therefore still a need of a better understanding of the conditions and techniques required as well as of the economics of combined drainage and moling on heavy claysoils in the northwestern part of Europe.

STUDIES OF MOLE DRAINAGE IN SWEDEN

In Sweden mole drainage was first tried on peat soils in the beginning of this century and only in a few areas on clay soils. After the rapid development of moling in Great Britain in the 1940's, a program was formed for study of the method on a larger scale in Sweden. During the period 1948-1956 subsurface drainage on 34 fields was performed in combination with moling and then subjected to extended studies. The applicability of mole drainage was thereby classified and it was suggested that moling was a useful supplementary method on heavy clay soils (Berglund 1956). Mole drainage was however not taken up by farmers in Sweden as a part of drainage practice. In the 1980's many farmers realized that the degeneration of soil structure through compaction had put an even higher demand on the function of the soils in farming. Mole drainage was therefore again taken up for study in 1982.

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This time, again inspired by English findings (Godwin et al. 1981, Spoor et al. 1982, 1987, Leeds-Harrison et al. 1982), it was limited to the heavy clay soils, to combined drainage-moling and to user-friendly techniques (Olovsson 1984). The aim with these field experiments was to show the possibility through moling to improve the drainage effect and reduce the cost of drainage on heavy clay soils.

THE FIELD EXPERIMENTS, PERFORMANCE

The field trials during 1948-1956 were laid out in middle and southern Sweden with a rainfall of 600-800 mm. The clay mineralogy is predominantly illitic. In southern Sweden a small content of montmorillonite and similar mineraltypes gives the clays comparably higher plastic properties at equal clay contents.

The layout of the combined drainage and mole system varied with the field topography. Some trials were also set up for yield estimation (Fig.1).

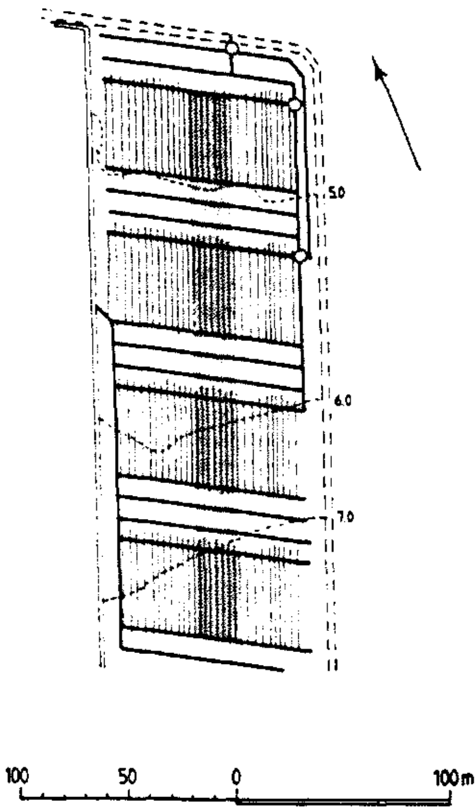

Fig. 1. Example of drainage-moling field experiment. The layout gives two treatments: 40 m drain spacing with moling and 10 m drain distance without moling. Through the field runs an area for yield estimates acc. to the strip method for harvesting.

Mole drains were installed using a standard mole plough of English beam type (foot diameter 75 mm and expander diameter of 90 or 110 mm). The moling was done in May in southern Sweden and in June in middle Sweden under clearly suitable soil conditions, a dry surface and field capacity at moling depth.

Various factors influence the life of mole drains. The experiences gained in the field experiments in 1948-56 underline certain significant factors viz. slope, frostaction, soiltype, the water content at moling, the season of the year when moling, channel diameter, depth, spacing and length.

The field experiments in mole drainage were followed over the crop season with accurate observations in the field of soil drying, trafficability, crop growth etc. The channels were also continuously monitored over a period of up to seven years. After 4 years the condition of the channels was especially checked. The moles were dug up in 3 to 5 places on each field, described and photographed. The state of the channel was also checked with plaster casts.

In Figure 2 the field experiments are grouped to show the connection between the channel durability and the field slope. Each field is marked with a circle with the figure for the clay content (particles < 2 μm).

slope	durability in years							
	1year	1 "	2 "	3 "	4 "	5 "	6 "	7year
< 5:1000	55, 72	55, 69	54, 54, 70, 60, 81, 72	65, 71, 55, 70				○ organic
5-10 : 1000	64 flooded			55	83	54, 55	40, 71, 69	62, 60, 55
> 10 : 1000			78			54, 61		64

Fig. 2. The connection between durability of the mole channels and slope in Swedish field experiments on moling during the period 1948-1956. Each field is marked with a circle with average % of clay particles (< 2 micron) in the soil. One test field had organic soil. One field was flooded soon after the moling.

Generally, where the slope was less than 5:1000 the channel lasted one to three years. Where the slope was larger than 5:1000 the life has been five years or longer. Exceptions to this rule appeared in a few cases. In two cases, the soil moisture was too low at the time of moling. Other reasons have been small slopes combined with surface depressions, and/or sandy pockets in the soil profile. Stagnant water in the channels invariably results in collapse. The reason for stagnant water can be those already mentioned and/or bad outfalls.

One of the field experiments was placed on an organic soil under grassland with root matted topsoil. The moling was still in a good state after 7 years.

SOIL TYPE AND SOIL CONDITION

The clay content on the experimental fields varied from 40 to 80 % (i.e. heavy to very heavy clay soils). The structure varied from well developed with cracks and biopores to weakly developed. The inspection of the channels showed that in both cases, the channel wall to a thickness of one centimeter was well remoulded by the foot and expander. The channel appeared like a "claypipe" clearly distinguished from the surrounding soil (Fig. 3).

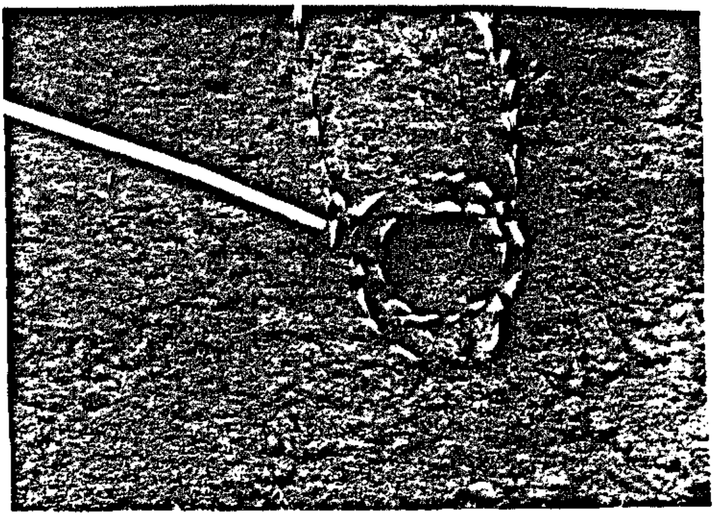

Fig. 3. A 'pipe' of plastic clay surrounding a mole channel. The uncovering of the clay pipe was done one year after moling.

The clay in the 'pipe' is plastic and dense, while the clay around it has not changed in structure. This change in structure is of utmost significance for the stability of the tubes. It was also seen in some inspections that the "claypipe" after some years had shrunk and became separated from the surrounding soil material (Fig. 4).

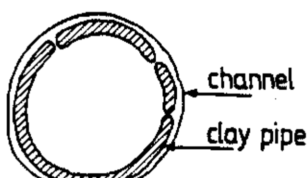

Fig. 4. A "clay pipe" around a mole channel can after some years shrink and separate from the surrounding soil material. Pieces of this "clay pipe" fall down esp. from the roof.

The "clay pipe" can also be seen cracked in oblong pieces of which some have fallen down to the bottom of the tube. This could be seen in the plaster casts (Fig. 5 and 6).

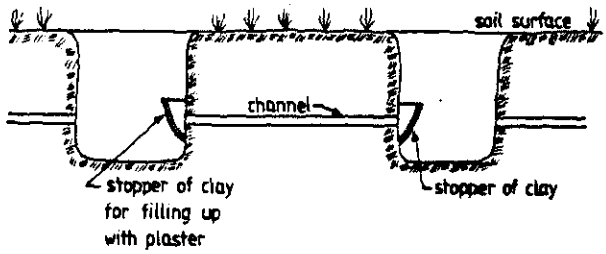

Fig. 5. A mole channel ready made for plaster casting.

Fig. 6. a) Plaster casts of 4-year old mole channels from a field experiment with 62 % clay. The plaster casts are shown from the side. The hollows which are seen in the plaster are soil-pieces from the channel roof.

b) Plaster casts from the same field after 7 years. The cast shows that the open area of the channel is still rather large.

FROST-ACTION AND FROST DEPTH

In cold climate with frost as in Scandinavia, the question arises as to how the mole channels can withstand frost action. In the years the field-experiments were run, it was only in a few winters that the frost reached down to or below the channels. In the cases it happened, there was however no obvious influence on the "clay pipe". The cracking and collapse of the plastified channel wall was more due to shrinking after drying as earlier described. A frost action would give a fine aggregated structure.

DISCUSSION AND CONCLUSIONS

The study of mole drainage in a series of field experiments in Sweden confirms that only the heavy and very heavy clay-soils and some organic (peaty) soils are suitable for mole drainage. Special studies show that the performance of a "clay pipe" at moling is of utmost importance for the durability of the mole channels especially on structurally well developed soils.

Further, the water content at moling is important, as is also the weather pattern during the first season. The frost action did not appear to affect channel stability in the period of the field trials in the 1950's. The best period for moling is May and June in Sweden. The depth most suitable is 50-60 cm. A channel diameter of about 90-100 mm seems to be adequate.

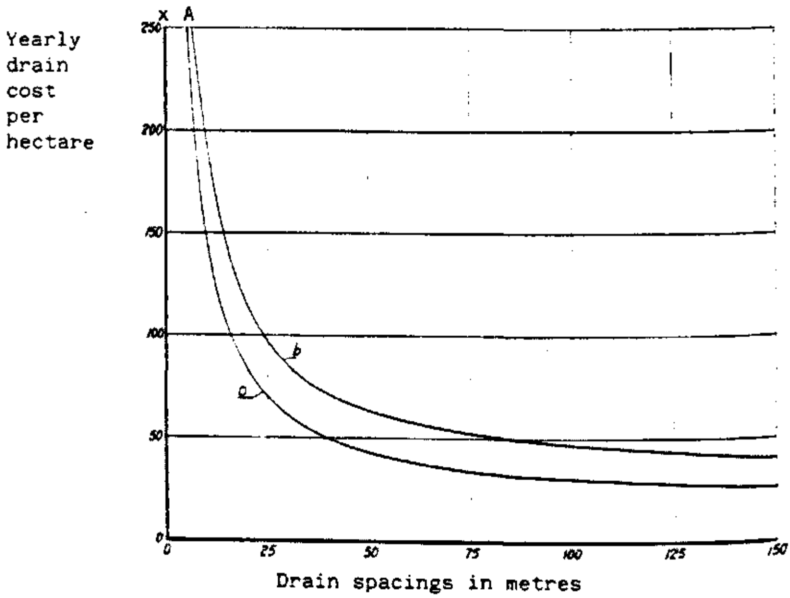

Fig. 7. The relationship between the drain distance and the yearly cost for drainage. The curve a gives merely the drain system cost (main and laterals), while the curve b also include 30 cm of gravel over the pipe and moling every 7 years. A = cost conversion factor (Berglund 1954).

The diagram in Fig. 7 is constructed assuming a pay-off period of 30 years. In the diagram one can directly read the cost for separate drainage alternatives with and without moling during the assumed pay-off period.

Thus the yearly cost for ordinary drainage with e.g. 25 metres lateral spacing is about the same as for drainage with lateralspacings of 50 m and moling. In combined systems the permeability of the gravel determines the channel length as does also the slope. It is obvious that stagnant water is a disaster for the channels. The channel length should therefore not exceed 100 m. A big cost in combined drainage-moling system is the gravel. At a drainspacing of 20 m the gravel cost is one third of the total cost.

The studies in the 1980.s stressed the need for a user friendly technique with a mole plough shape that forms channels of the highest quality. It also became clear that efficient drainage on very heavy clay soils depends on the durability of the mole channels and also on loosening by the leg of the soil profile above esp. the plow sole.

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COMPARING THE EFFECTIVENESS OF MOLES AND GRAVEL MOLES IN UNSTABLE SOILS

L. F. Galvin*

There are approximately 0.8 million hectares (2 million acres) of heavy impermeable soils in the Republic of Ireland; these constitute 14% of the total agricultural land area. Most of the impermeable soils have a deep tight subsoil and a varying depth of topsoil (in some cases as little as 100 mm). During wet periods, water saturates and weakens the topsoil which is then easily damaged by machinery and grazing animals.

Excess rainfall is a major factor in Irish agriculture and leads to many problems, especially in the wetter regions of the west. As outlined in Table 1, the annual rainfall in the west ranges from 1,000 to 1,600 mm. Potential evapotranspiration (PE) is 360-390 mm (annual) and 310-340 mm (April to Sept.). The normal April-Sept. rainfall is 400-650 mm but in a wet summer (1985) the April-Sept. rainfall ranged from 600 to 850 mm which is considerably in excess of the PE.

Table 1. Rainfall and P.E. Data for the Republic of Ireland (mm)

		East	West
Rainfall	Annual	700 - 1,200	1,000 - 1,600
	April - Sept.	350 - 500	400 - 650
	April - Sept. (1985)	450 - 550	600 - 850
P.E.	Annual	420 - 470	360 - 390
	April - Sept.	370 - 410	310 - 340

In these circumstances the heavy soils are invariably used for grass production; tillage is restricted to the free-draining soils. Even for grass production intensive drainage is needed and without it grassland farming can be a major problem in wet years. The realities of this situation were brought home very forcibly to farmers during the wet summers of 1985 and 1986. In many cases large areas of grassland became impassable to animals and machinery and where attempts at grazing continued, the pastures broke down completely. This resulted in severe hardship for many farmers and emphasised the necessity of installing effective drainage systems on these heavy soils.

DRAINAGE SYSTEMS FOR HEAVY SOILS

In draining heavy soils, there are two essential requirements:

(1) A system of closely-spaced drainage channels must be provided; and

(2) the soil in the vicinity of these drainage channels must be disrupted so as to establish a series of cracks and fissures extending from the surface to the drainage channels.

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These twin objectives are achieved by mole drains or gravel moles usually installed at a depth of 450-500 mm and at a spacing of 1.3 - 2 m. The installation work should be carried out under dry conditions to maximise crack generation between the ground surface and the moles or gravel moles. Either system provides excellent drainage if installed properly. However mole drains have been found to have a relatively short life in many Irish soils. In these unstable soils the moles clog up completely (mainly due to unconfined swelling) over a period of 1 to 3 years. In the early stages of channel deterioration, the effectiveness of the mole-drainage system is not noticeably reduced because the channel capacity at the usual 1.3 to 2 m spacing far exceeds the discharge requirements. However progressive channel and crack deterioration coupled with occasional channel blockages can result in reduced channel flow and raised water table levels. If the land is intensively used under these conditions, in wet weather, surface damage occurs and the cycle of deterioration escalates rapidly. In these situations, the gravel mole system (Mulqueen 1985) has proved very successful. The channel is not subject to deterioration and retains its flow capacity and an added bonus is that the wider leg of the gravel mole machine produces a crack system that is superior to that produced by the ordinary mole plough (Galvin 1983 and Youngs 1984/1985).

Even in situations where a mole or gravel mole system is operating successfully, the upper soil layers can be damaged by intensive grazing or by silage harvesting when the soil is wet. The crack structure in the topsoil breaks down causing a reduction in infiltration capacity. This, in turn, leads to surface saturation, ponding, reduced trafficability and an escalation of surface damage. The drainage of heavy soils therefore requires the installation of stable channels and contiguous fissure systems. Provision must also be made for the regeneration of the crack structure in the upper soil layers as required.

EXPERIMENTAL SITES

Since 1975, various types of disruption systems (moles, gravel moles, ripping and shallow moles) have been installed at a number of experimental sites. In the initial years 1975-'78, it was not possible to instrument the sites. In the circumstances, pilot schemes were installed on farms and consisted of 0.5 to 1 ha plots of mole drains, gravel moles, ripping and control (piped drains only). The sites were farmed commercially and the condition of the moles and the ripping channels was periodically examined over a 5-year period by excavation and by taking polyurethane casts. Over that period the moles and ripping deteriorated completely in all but one site on which the moles lasted for 8 years.

The educational value of the pilot schemes cannot be over-emphasised. The total breakdown in ground surface trafficability of the ripped and mole drained plots contrasted very sharply with the solid surface of the adjacent gravel moled plots during the wet summers of 1980 and 1981. These sites were then used by agricultural advisers to demonstrate the benefits of effective drainage to contractors and farmers.

Arising from the pilot schemes, instrumented drainage trials were installed at a number of sites throughout the country during the 1981-1984 period. All these trials included the following drainage treatments:

(a) Mole drains spaced at 1.3 m;

(b) Gravel moles spaced at 1.3 m;

(c) Control (piped drains only spaced 30-50 m).

On some sites one or more of the following treatments was also installed:

(d) Gravel moles + Ripping. The gravel moles are spaced at 2.6 m with intermediate ripping also at 2.6 m;

(e) Ripping (heavy-duty subsoiling) spaced at 1.3 m; and

(f) Shallow mole drains (300-330 mm deep) spaced at 1.3 m.

At each site, water table piezometric levels, ground scoring and continuous drain flow is recorded.

The results from three of these sites, Kanturk, Ballyroan and Kilmaley A are detailed and discussed. The Kanturk and Ballyroan sites represent the drier areas whilst Kilmaley is one of the wettest lowland areas in the country. An examination of Table 2 shows that there is no major difference in the physical properties of the soils although the silt content in Kilmaley is somewhat greater than in the other two sites.

Table 2. Particle Size Distribution, Atterberg Limits and Bulk Densities (Mg/m) of Subsoils

		Kanturk	Ballyroan	Kilmaley
Percentage passing	2mm	100	100	100
	0.6	97	96	99
	0.2	92	90	97
	0.06	77	77	91
	0.02	65	65	79
	0.006	50	45	56
	0.002	34	31	35
Percentage > 2 mm		9	5	4
Clay/silt ratio		0.52	0.48	0.44
Liquid limit		37	44	45
Plastic limit		21	25	27
Plasticity index		16	19	18
Bulk density		1.50-1.62	1.61-1.78	1.50-1.68

The disruption treatments were installed at Kanturk (1981), Ballyroan (1982) and Kilmaley A (1984). Monitoring continued at Kanturk from 1981 to 1984, at Ballyroan from 1982 to date and at Kilmaley A from 1984 to date. As well as monitoring the hydrological data on the sites, excavations are also carried out throughout the experimental period to check on the conditions of the channel and crack structure.

Site Observations

Observations undertaken at Kanturk and Ballyroan up to May 1985 are described in detail (Galvin 1986). These together with further observations at Ballyroan and at Kilmaley A are summarized as follows:

Kanturk: All the gravel moles are in good condition. The leg slot was invariably filled with topsoil which had migrated down to the top of the gravel and extended from there to the base of the topsoil horizon. This band of topsoil (up to 50 mm wide) was generally loose and permeable. The gravel in the mole had not been contaminated by the topsoil in the leg slot or by the surrounding subsoil.

The rip channels were generally filled with topsoil. The leg slots also contained topsoil which was up to 60 mm wide in some of the slots examined.

This topsoil was relatively uncompacted and capable of transporting some drainage water.

The moles were filled with loose slurry to such an extent that in 1982 (after 10 months) it was not possible to take polyurethane casts. However, at that stage the moles were still capable of transporting water to the collector drains. The slurry was more compact in 1983 and gaps between the mole infill and the original wall appeared to provide a passageway for water flow. However, by 1985 the moles were completely clogged with soil and small stones. Non-continuous gaps were found in one of three moles excavated whereas the other two were fully clogged. At that stage (1985) the dimensions of the plug of infill material ranged from 80 x 80 mm to 150 x 80 mm. This indicated that while the width of the original channel had not altered appreciably the vertical dimension had changed substantially in places. An examination indicated that the soft material extended below the base of the original channel, due to water softening, and upwards into the leg slot where roof collapse had occurred.

Ballyroan: The gravel moles are in good condition. There is no apparent contamination of the gravel in the mole by the surrounding soil. Topsoil has migrated into the wide leg crack to the top of the gravel mole and provides a direct connection from topsoil horizon to the gravel. The cracking and shattering of the subsoil in the vicinity of the gravel mole is also very good.

The rip channels which were almost completely blocked by a combination of topsoil ingress and subsoil swelling in 1985 were totally blocked in 1986. These bands of topsoil which are connected to the site topsoil are most probably still capable to transporting limited quantities of water to the collector drains, but the rate of discharge is likely to be very small.

The mole drains examined in 1985 were in good condition although two blockages were found. In 1986 the general impression created during excavations was that the moles had deteriorated substantially during the year. Many more blockages were found and the soil in the mole walls along unblocked sections appeared wetter and softer than in 1985. This was probably caused by downstream blockages which resulted in water ponding and consequent soil swelling.

At this site the moles have performed much better than on many other sites. The main reason for mole collapse appears to be the dislodgement of large stones which has resulted in random roof collapse and other forms of channel blockage. These blockages are leading to an escalation in channel deterioration which is likely to increase. However at this stage (after 5 years) the moles are still providing effective drainage.

Kilmaley A: The gravel moles are in good condition.

The mole drains (installed at the standard depth of 450-500 mm) had deteriorated substantially by 1986. All moles examined, contained considerable quantities of slurry and appeared to be failing due to unconfined swelling. The 1987 examination showed that the cycle of deterioration was continuing. In some cases the moles were almost completely blocked and the occurrence of randomly distributed wet patches on the surface of the moled plots indicated total mole collapse. These patches are particularly obvious near the lower ends of the mole drained plots.

In 1986 the shallow moles had also begun to fail but those examined contained less slurry and appeared to be in a better condition than the deep moles. There was evidence, in some of the trial holes excavated, that the complete roof had dropped down slightly without collapsing leaving an elliptically shaped channel (major axis horizontal). This is typical of the type of disturbance that occurs where moles are installed slightly above the critical depth. In 1987 it was impossible to find the shallow moles in some trial holes. However, shallow moles, found in other trial holes, were dry and solid but the diameter was reduced to approx. 30 mm. This random breakdown of the shallow moles, is borne out by the water level and flow hydrographs.

It should be pointed out that, despite the breakdowns that have occurred, the moled and shallow moled plots are still very much better than the control plots (piped drains only) in water level control and ground scoring.

The rationale governing the installation of shallow moles is that they can be repeated at low cost at regular (2 to 3 year) intervals by farmers using their own low-powered tractors. In that context the shallow moles at Kilmaley have fulfilled the requirements of providing effective drainage for 3 years and a new system was installed at the beginning of September 1987.

Water Table Measurements

Water table levels on all sites are measured in maximum reading piezometers (Davies 1969) installed in 20 mm diameter plastic tubes. The Kanturk and Ballyroan sites are read at weekly intervals and the Kilmaley site is measured weekly during the summer and at 2-3 day intervals (where possible) during the winter months. The results are illustrated in Figs. 1 to 6.

Kanturk: Figures 1 and 2 illustrate the failure of the mole drains and the partial failure of the gravel mole + rip system. As shown in Fig. 1 the gravel mole + rip plot is almost as effective as the gravel moles plot but the mole drained plot is less effective. One year later (Fig. 2) the deterioration in the mole drains is clearly illustrated by the increased water table levels. The reduced drainage effect resulting from the clogged rip channels accounts for the raised water table levels in the gravel mole + rip plot. The fall-off in the drainage effectiveness of the mole and gravel mole + rip treatments is borne out by an examination of Table 3 which shows the SEW (30) figures for all drainage treatments at Kanturk for 1982/83 and 1983/84. The reduced SEW (30) figure for the control plot is due to the drier year.

Table 3. SEW (30) Figures For Kanturk; 1982/83 and 1983/84

	1982/83	1983/84
Gravel moles	13	0
Gravel mole + rip	35	441
Moles	520	1,389
Control (piped drains only)	4,042	1,751

Ballyroan: The water table data for Ballyroan are illustrated in Figs. 3 and 4, which detail the water level fluctuations on the site in 1984/85 and 1986/87. There is a slight fall-off in the water level control on the mole drained plot and a rather significant but relatively small reduction in the effectiveness of the gravel mole + rip plot over the 3-year period. These variations are highlighted in Table 4 which shows the variation in SEW (30) figures between 1984/85 and 1986/87.

Table 4: SEW (30) Figures for Ballyroan; 1984/85 and 1986/87

	1984/85	1986/1987
Gravel moles	0	82
Gravel mole + rip	139	1,075
Moles	63	170
Control (pipe drains only)	1,492	3,464

Kilmaley A: There are a number of replicated plots at Kilmaley and to illustrate the variation in water table levels that has occurred over the last

3 years, four plots have been selected. These plots are a good reflection of the average conditions prevailing on the site.

The water table data for 1984/85 (Fig. 5) and 1986/87 (Fig. 6) show that the greatest increase in water table levels occurred in the mole drained plots and the smallest increase in the gravel-moled plot. As already discussed both the deep and shallow moles are nearing failure at this stage but are still providing reasonably good drainage. The variation in water table levels is illustrated in Table 5 which shows the SEW (30) figures for the three years the experiment is in progress.

Table 5. SEW (30) Figures for Representative Plots at Kilmaley A: 1984/85, 1985/86 and 1986/87

	1984/85	1985/86	1986/87
Gravel moles	394	459	763
Moles	716	998	1,783
Shallow moles	1,389	1,605	2,022
Control (pipe drains only)	3,216	4,685	3,911

SUMMARY

The results from Kanturk, Ballyroan and Kilmaley A are indicative of the general nature of drainage deterioration in impermeable soils under a grassland regime in the west of Ireland.

Mole drains have a variable life in unstable soils. At Kanturk the moles were almost completely ineffective, 3 years after installation. At Ballyroan the moles are performing quite well, despite random blockages, after 5 years while the Kilmaley moles are showing signs of serious deterioration after 3 years.

The basic difference between the sites is related to soil stability. The Kanturk and Kilmaley moles began to fail due to unconfined swelling during the first winter. This continued quite rapidly at Kanturk leading to almost total clogging within 2 years, while a similar pattern appears to be developing at Kilmaley. At Ballyroan the soil appears to be much more stable and while the walls of the moles are soft, the large-scale slurrying that occurred at the other two sites was largely absent in the early stages. At a later stage, however, roof collapse and stone dislodgement resulted in channel blockages. These in turn caused ponding in the moles and this is giving rise to increased wall wetness and slurrying.

The gravel moles are performing well on all sites but the attempts at doubling the spacing of, and ripping between, adjacent gravel moles was not successful. The cracks created during installation did not cover the full distance between adjacent gravel moles and when the rip channels silted up and filled with topsoil the rate of drainage water removal was reduced and the water table levels were raised accordingly.

All disruption systems are subject to deterioration arising from excess traffic by machinery and animals under wet conditions. This tends to seal off the upper crack structure within and just beneath the topsoil, and can result in poaching and ponding during a wet year. However, shallow moling or some similar form of shallow surface disruption should regenerate the cracks and rehabilitate the drainage system.

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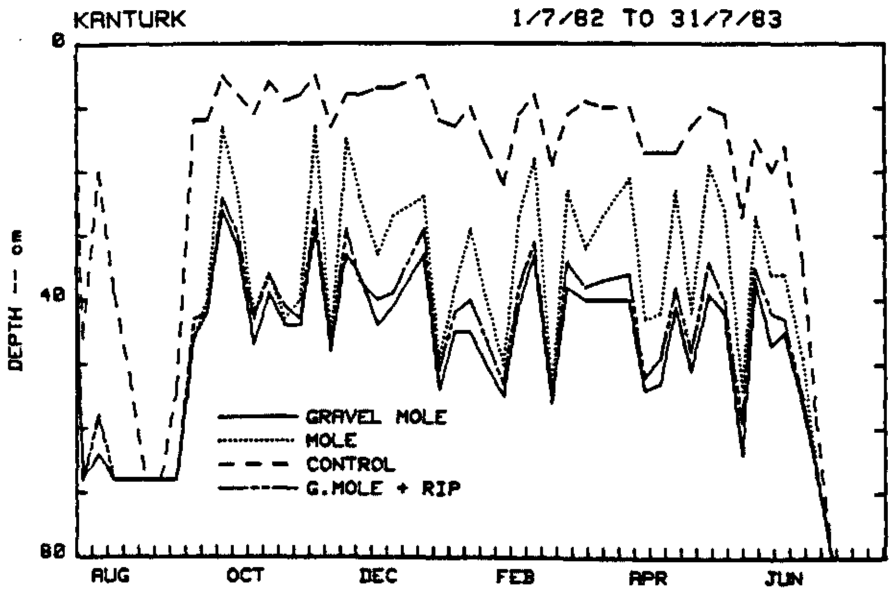

Fig. 1 Water Level Fluctuations at Kanturk, 1982/83

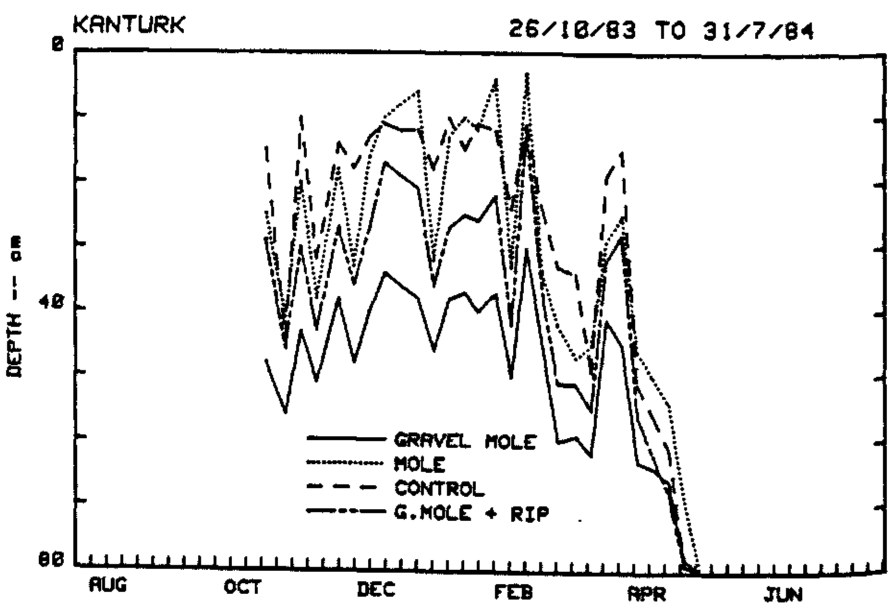

Fig. 2 Water Level Fluctuations at Kanturk, 1983/84

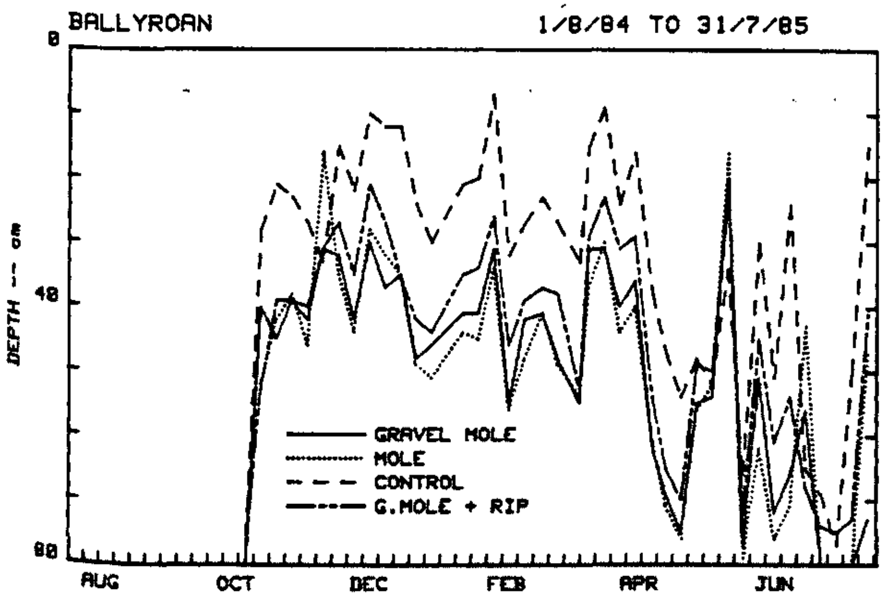

Fig. 3 Water Level Fluctuations at Ballyroan, 1984/85

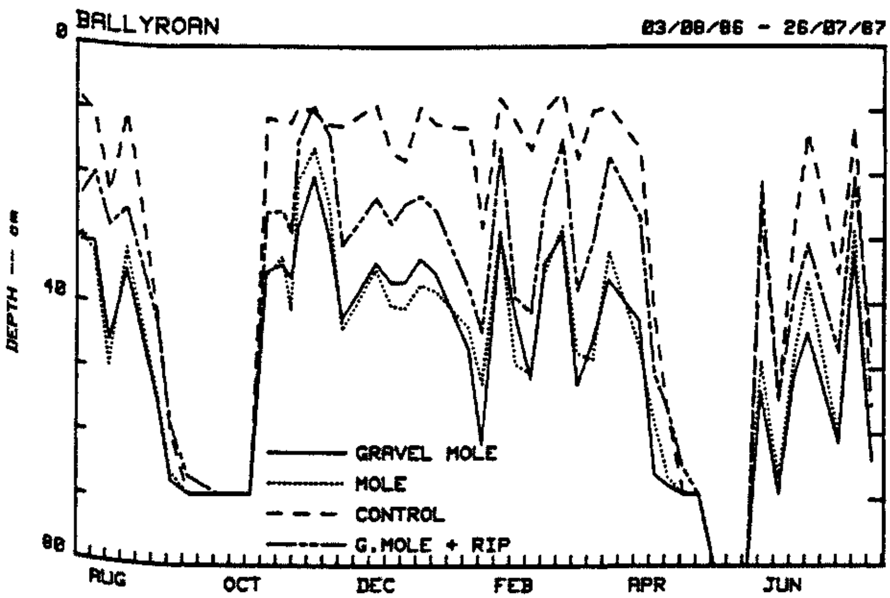

Fig. 4 Water Level Fluctuations at Ballyroan, 1986/87

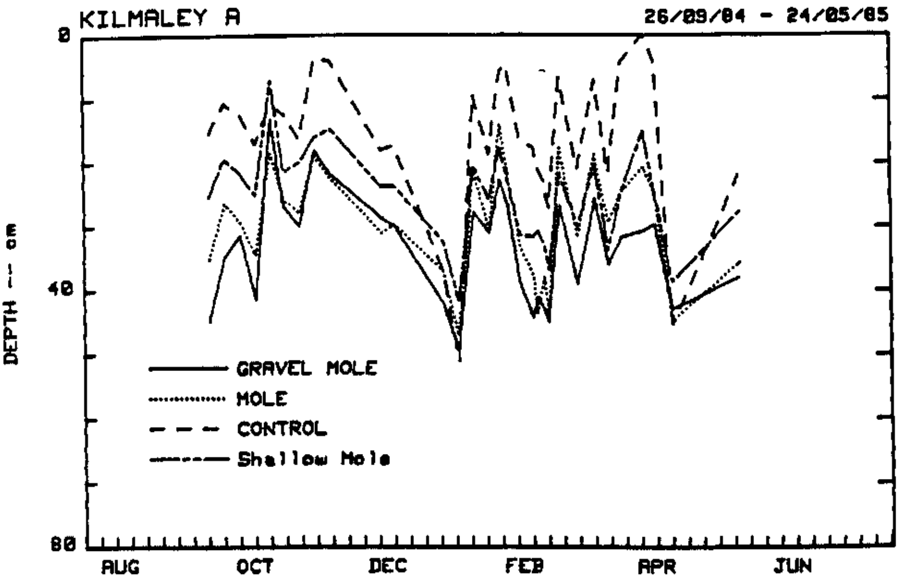

Fig. 5 Water Level Fluctuations at Kilmaley A, 1984/85

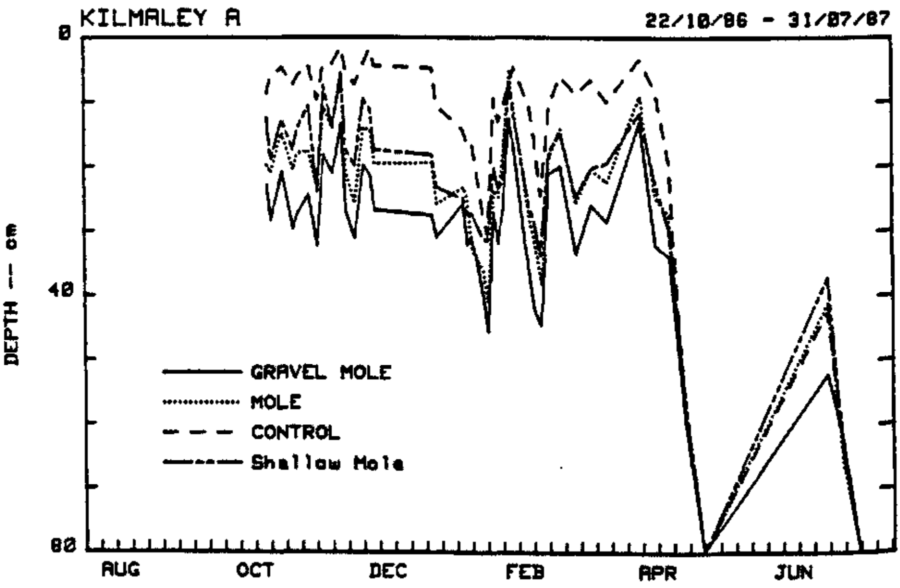

Fig. 6 Water Level Fluctuations at Kilmaley A, 1986/87

ASSESSING PATTERNS OF CRACKS IN HEAVY SOILS AS MEANS OF FORECASTING DRAINAGE RESULTS

K.H.Hartge*

Heavy soils are characterized by a grain size distribution where clay and silt prevail. The pore system in these soils necessarily consists of the voids between these small particles and therefore pore geometry is governed by small distances, i.e. small equivalent diameters.

Furthermore the particles of the clay fraction have no direct solid contacts to each other. They are separated by films of adsorbed water. Since the thickness of these films changes according to the hydrologic situation, the whole volume of a given soil body varies more or less regularly.

Since these changes again govern draining properties, they ought to be discussed first.

DEVELOPMENT OF CRACK SYSTEMS

Since soil mass cannot freely follow volume changes, the developing stress is relaxed by failure cracks. The principally isotropic process of shrinkage due to desiccation creates preliminarily vertical cracks (Fig.1). These are due to the relation between height (h in Fig.1) and lateral extension (l in Fig.1) of a clayey sediment and the friction that develops between shrinking upper and less shrinking lower part of the sediment.

The process of further development of the cracking system is shown in Figure 2 (for figures see following page).

The first generation of cracks starts in randomly distributed directions, usually forming a pentagonal or hexagonal pattern.

Since every consequent crack of higher generation originates from the same change of stress distribution, the angles between cracks of consequent generations are mostly equal, namely round about 90°.

There are cracks caused by swelling processes as well if water access is anisotropic (Wilding and Hallmark 1984). In this case the developing crack-system has prevalently angles between cracks that are influenced by soil consistency, i.e. by the angle of internal friction (Hartge and Rahte 1983).

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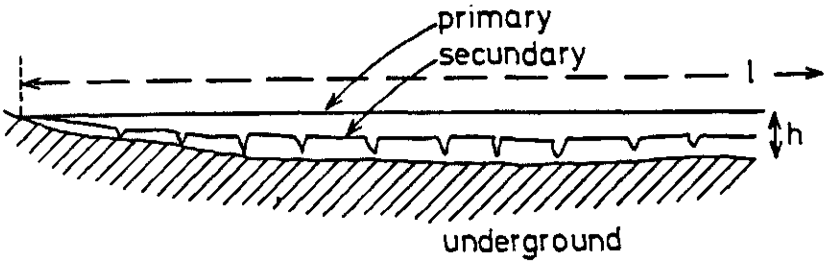

Fig.1 Fresh and Remolded Sediments Form Vertical Cracks First in Spite of Isotropic Shrinkage

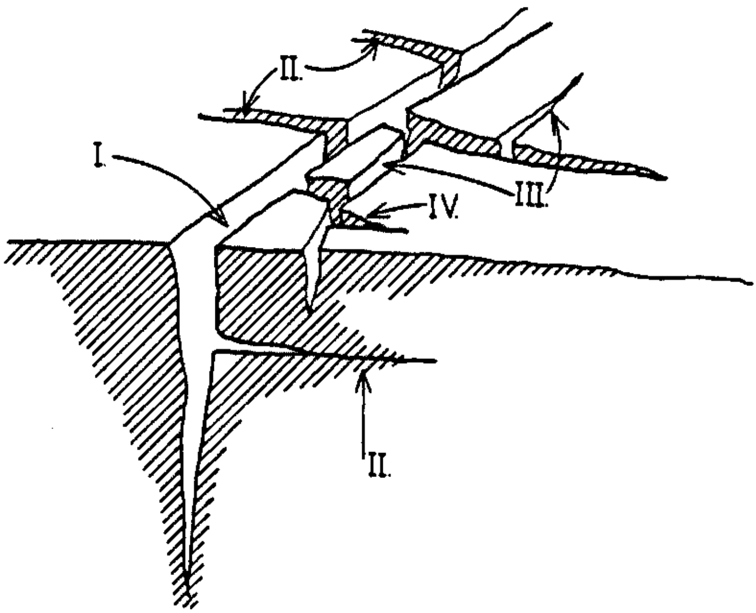

Fig.2 Higher Generation Cracks (II-IV) Develop ± Rectangularly, Originating from Randomly Orientated First Generation (I) Cracks

There are practically no heavy soils without a crack system down to a depth of ± 1m. The most common exception are very recent soils that have not yet had the time to develop cracks because they have not yet undergone an exceptional period of drought. These soils are generally soft and do not bear heavy equipment. Heavy soils found on material sedimented in earlier geologic periods may have very deep reaching crack systems due to deloading when they emerged to form soils again. In their crack systems non-rectangularity prevails. Under humid climatic and soil forming conditions these sediments however tend to swell. During this process the inherent crack system is often more or less destroyed and replaced by a new one which is similar to that of recent soils. This process is accelerated by all kinds of changes of the stress situation, like temporary loading by machinery, treading by cattle, wind impact on trees. It creates major difficulties to all kinds of foundation engineering.

ROLE OF CRACKS AS ONLY BIG DRAINABLE PORES

As a consequence of the cracks the pore system of shrinking soils is discontinuous in diameters.

There are relatively small voids between the primary particles and cracks that, compared to the former, are rather big. In hydraulically important parameters, the difference between them is generally more than one order of magnitude. The continuity of the primary void system is interrupted by the cracks. Water conductivity of the whole soil body therefore mainly depends on the development of the crack system rather than of the matrix that now forms the aggregates. These have gained density and therefore lost water conductivity under the procedure of shrinking.

These circumstances are important for the drainage behaviour of the whole soil body with the change of hydraulic head that is available. When lowering ground water surface by 2-7dm, only pores with equivalent radii of ≥ 0.03mm are drained. Consequently, the amount of air that can be brought into such a soil by draining is at its maximum equal to the volume of the cracks that exist or that will develop after draining.

From the development history of the crack-system that starts from the very surface of soil follows that the distance between draining pores increases with depth in profile. Thus aeration becomes less efficient the deeper the respective zone is situated in profile (Fig.3 on following page).

As soil is drying cracks not only increase in number per unit surface-area but as well in extension toward depth in profile.

This increase to depth however is frequently put to an end by the developing stress distribution. If the soil material is on its first desiccation the opening of cracks is counteracted by the horizontal component (σ_x) that is developed by the weight of the overlying soil. Shrinkage is thus strengthened in upper parts of the soil (Fig.4 on following page).

In young freshly sedimented material the progress of cracks into the soft underground is a slow one. Cracks that reach farther into the profile might be found rather in heavy soils, developed on precompacted re-exposed material of earlier geologic periods.

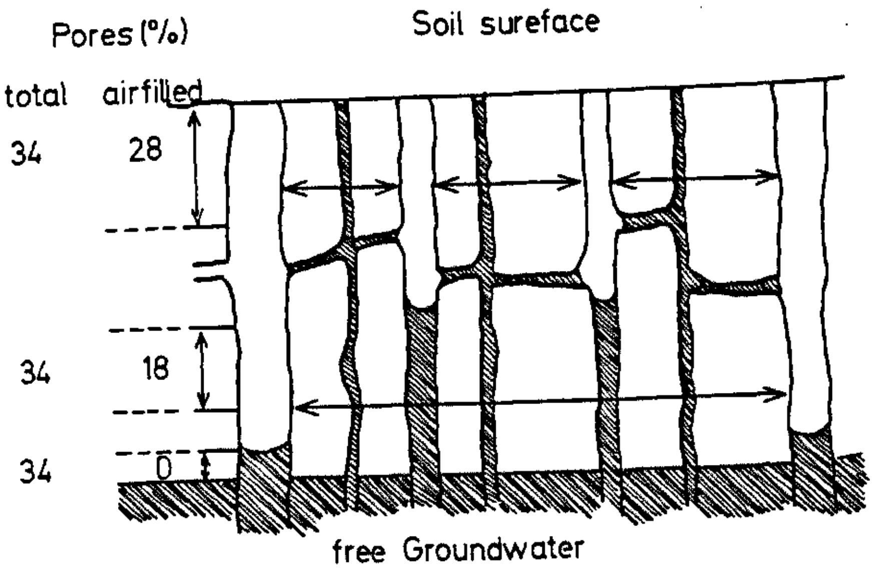

Fig.3 Distances of Draining Pores (Arrows) Increase and Air Percentage Decreases with Distance from Soil Surface

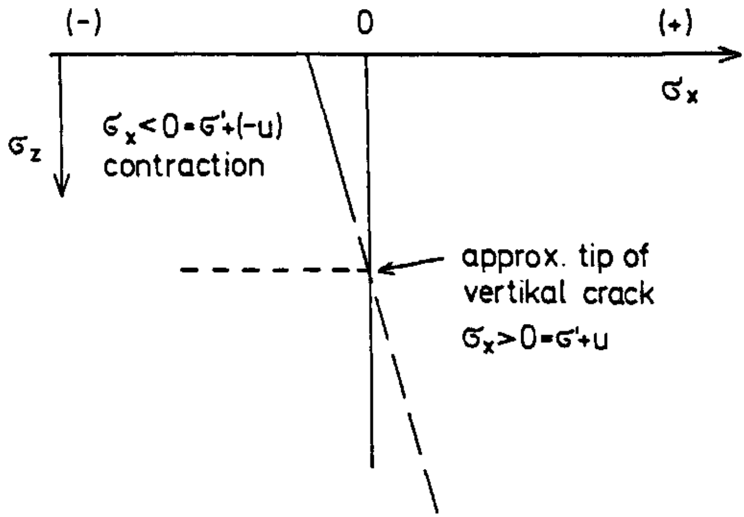

Fig.4 Stress Situation Necessary to Create Cracks in Saturated Soils. σ_x Depending on σ_z, It Takes Increasing Desiccation to Create a Crack with Growing Depth in the Profile.

Re-swelling of soil upon addition of water is mainly limited to volume extension of the aggregates or the walls of cracks in horizontal direction since this does not require any upheaving work. Upheaving can only start when horizontal swelling has closed the cracks so far, that further closing needs same or more force than upheaving of overlying soil.

Therefore cracks in subsoil are more frequently and more completely closed by re-swelling than those in the topsoil.

This is important because swelling pressures that are developed in stress situations that are common in humid climate are generally weak. This is partly also a consequence of the fact that re-swelling of aggregates is the slower they dryer they have become. Water intake is hampered then by low conductivity and thus higher swelling pressures do not develop. Any additional stress on the shrunken aggregates will act like remolding under these conditions, and thus increase swelling. This happens with all treading or traffic on soil surface.

EFFECT OF CRACKS ON WATER CONDUCTIVITY

As shown in Fig.1 and 2 the main direction of cracks in soils is vertical. Seen from above, the vertical crack-system has a polygonal pattern (Fig.5, below). These pores form a system of planes that is less tortuous for vertical water flow than for horizontal. This is a feature that has been well-known for quite a long time. Its existence is the basis for the functioning of the Dupuit-Forchheimer approach to drainage problems (Kirkham and Powers 1972).

Fig.5 Combination of View of Vertical (Above) and Horizontal Crack System (Below) Consisting of Cracks of Three Generations. Above Core Samplers Show Differences in Hitting the Crack System (4:7 in Upper, 2:9 in Lower Layers).

Due to the course of development of the crack-system water conductivity in heavy soils in saturation is complex. Conductivity of the relatively little desiccated lower parts of a profile is mainly governed by the matrix itself. The closer to soil surface, the more frequently cracks will occur and influence permeability. The fact that not so much width but rather the number of cracks increases, starting at a primarily relative large distance (Fig.5, on the previous page), is depicted by the frequency distribution of conductivity values measured on core samples. Measured values do not so much change individually but rather in frequency of occurrence of classes (Fig.6, following page).

Water movement in the upper parts of the profile is mainly vertically downwards after a precipitation. In lower parts of the profile however, horizontal flow must take over in frequency and amount (Fig.5 and 6).

Horizontal flow can be measured to some extent using auger hole methods. Use of core samples is complicated because of the fact that the profile pit grows in width with every core taken, thus changing the distance for the buttress.

Investigation of some cases have shown however that horizontal conductivity might be determined from frequency distribution of values obtained from vertically extracted samples. As shown, horizontal conductivity closely corresponds to the lowest measured value of a group of 15 parallel samples that are taken vertically (Hartge 1984).

CONCLUSIONS

Cracks and aggregates are aspects of the same process, both develop and both can be destroyed by the same mechanisms.

Pore systems of heavy soils change according to desiccation or remolding status.

The forming of cracks starts at the soil surface and proceeds down into the profile. It concentrates water flow to a few passes, whereas matrix of the aggregates contracts and its permeability decreases.

Mechanical load that compresses the matrix of the aggregates increases water pressure in them, because in unsaturated state water cannot escape easily, so that water films continuously start to bear the load. During this process shear resistance of the system is affected and sometimes completely lost. Thus deformation is promoted. Puddling or remolding are the most extreme aspects of this general process.

Aggregates or pore systems can be stabilized by all means that suppress the increase of water pressure on loading. Application of burnt lime on claysoils is an example for this (Bohne 1983).

The following generalisations can be formulated on properties and processes of or in heavy claysoils:

1) Vertical water conductivity is greater than horizontal as long as there is no human activity.
2) Horizontal water conductivity approximates minimal values of a set of parallels of vertical conductivity.
3) Changes of the water regime tend to change water conductivity.

4) Mechanical loading destroys cracks and reduces water conductivity until it reaches the value of the matrix.

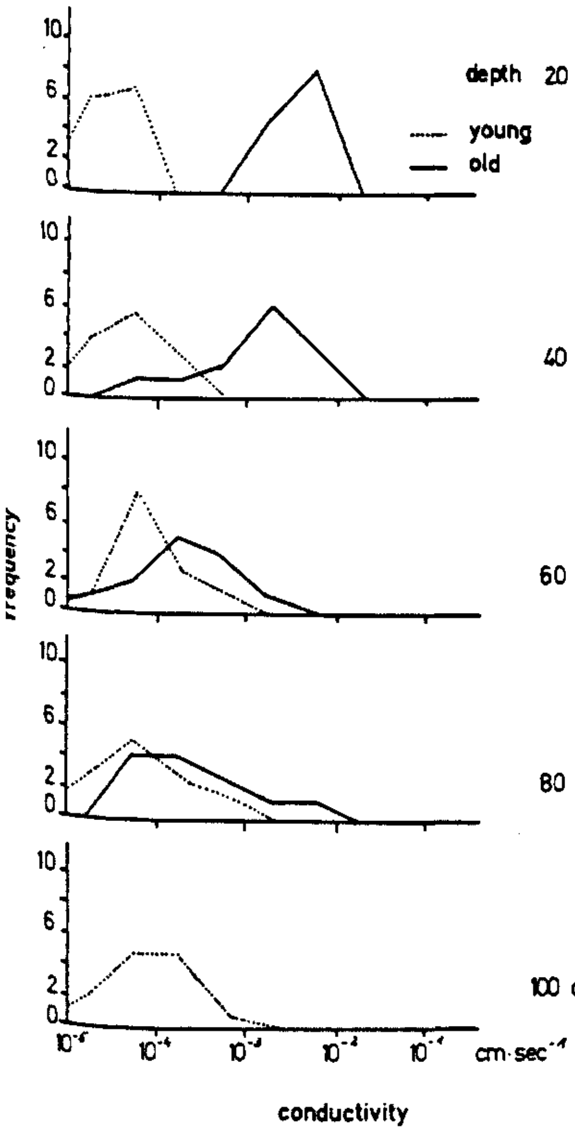

Fig.6 Frequency Distributions of Water Conductivity Obtained from Core Samples Showing a Profile with Poorly Developed Crack-System (Young = Diked A.D. 1960) and Profile with Well Developed Crack-System in the Top Soil (Old = Diked A.D. 1200).

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AN INVESTIGATION INTO MOLE DRAINAGE

D.J. Horne and K.W. McAuliffe*

For many years, in numerous countries, pipe drainage has been used as a cost-effective method for the rapid removal of excess water from the soil surface and root zone. However, pipe drain installation in fine-textured soils will not alter the structure of the impermeable subsoil, and as a consequence there will be little water movement through the subsoil to the collecting pipe. It is therefore common practice to mole plough fine-textured soils because when carried out under favourable conditions, moling initiates the development of improved soil structure and therefore increases the permeability of the soil (Trafford and Rycroft 1973; Leeds-Harrison et al. 1982). In a moling experiment on a clay soil, Rycroft (1972) showed that above the moles the effective conductivity was 4100 mm d^{-1} while in a plot without this secondary treatment the maximum effective conductivity was only 260 mm d^{-1}. Nicholson (1948) stated that mole channels work by opening up and fissuring the subsoil and thus providing pathways for water movement to the mole. Recent work by Goss et al. (1983) also showed that the principal route of water movement from the soil to the mole drain was not uniformly through the subsoil but was via large fissures induced by the mole plough blade.

It is unlikely that either the tension cracks induced by moling or the crack left by the blade will persist over many seasons. However, dye studies in the field (Scotter and Kanchanasut, 1981) have identified preferential pathways for water movement above the mole along channels left by roots and worms. It appears that the disturbance caused by the mole blade allows roots and earthworms to penetrate the less permeable horizons above the mole, and it is these factors, coupled with a tendency for the blade slit or tension cracks to re-open upon drying which permanently enhances the conductivity of the soil.

An appreciation for the effectiveness of mole drainage and an understanding of the processes by which moling drains wet land is needed so that improvements to the design of pipe-mole drainage systems may be made.As a first step to improving the efficiency of mole drainage, the major constraint in the system needs to be determined. Possible limiting steps are; water flow through the soil to the mole, water flow into the mole itself, water flow down the mole channel, water flow from the mole to the collecting pipe or water flow down the pipe to the outfall. In this paper the effect of mole drainage on soil water is described.

MATERIALS AND METHODS

The research site was situated on pasture land near Massey University, New Zealand (at an altitude of 56 metres). The soil type is Tokomaru silt loam, which is classified as an Typic Fragiaqualf (Soil Survey Staff, 1975) or as a gleyed yellow-grey earth (New Zealand Soil Bureau Staff, 1968). The soil has been described in detail by Pollok (1975) and Scotter et al. (1979). Pollok describes the profile as consisting of a silt loam A horizon of medium texture, underlain by a strongly developed, heavy textured clay loam B horizon. Another characteristic of this soil is the presence of a densely-packed fragipan located approximately 700 mm below the surface.

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The 4.6 ha experimental site was divided into 9 plots, each 80 by 50 m, with 10 m wide buffer strips separating the plots. In the spring of 1981, 3 treatments, pipe-mole, mole-mole drainage and undrained control, were imposed on the area. Each treatment was replicated 3 times in a Latin Square design. On the pipe-mole drained plots, 75 mm diameter mole drains were pulled to a depth of 450 mm at a 2 m spacing. Water collected by these mole drains was removed from the plots via slotted plastic pipe (110 mm in diameter), installed perpendicular to the mole drains at a depth of 700 mm, and 40 m spacing. On the mole-mole plots, mole drains were pulled as previously mentioned, but using major deeper moles instead of a pipe drain, as the collector. These major moles were pulled at a depth of 600 mm with a spacing of 20 m. The minor moles were junctioned to major moles by spearing.

Four perforated aluminium groundwater observation wells (50 mm in diameter) were installed in each plot to a depth of 450 mm. On the undrained plots the wells were installed equidistant from each other down the centre of the plot. On the drained plots, observation wells were placed both midway between adjacent mole channels and next to a mole channel (approximately 150 mm from the mole). Water table levels were measured using a dipstick.

Flow data were obtained from v-notch weirs with water level recorders installed at the outfall of each of the drained plots.

Water content was measured using a neutron moisture meter and by gravimetric sampling. Two neutron probe access tubes were installed to a depth of 1.3 m on each of the pipe-mole and undrained plots. The neutron moisture meter was calibrated by gravimetric sampling adjacent to the access tube. The water content of the top 30 mm of the soil profile was determined gravimetrically from 20 bulked cores removed from the plot with the use of a soil corer.

Rainfall was measured at the site by an automatic siphoning rain gauge.

In most instances the statistical significance of differences between treatments was determined using an analysis of variance based on a split-plot design, sometimes referred to as a split-plot in time analysis (Little and Hills, 1972). The statistical significance of differences in mean volumetric water content values , as determined using the neutron moisture meter, between undrained and pipe-mole plots was assessed using the t-test.

RESULTS AND DISCUSSION

Depth to the water table

In the unusually dry winter-spring period of 1982 mole drainage had only a small effect on the water table level. Daily water table levels and rainfall totals for July to September in 1982 are shown in Fig. 1. The winter (June to August) rainfall total was only 181 mm, which falls in the 10-20 percentile and the spring (September to November) total was 190 mm, which falls in the 20-30 percentile. Even in such a dry year mole drainage ensured that the water table declined more rapidly on the drained than the undrained plots following heavy rain. However, on only a very few days was the water table close to the surface on the undrained plots, indicating that the benefits of drainage in a dry year are likely to be minimal.

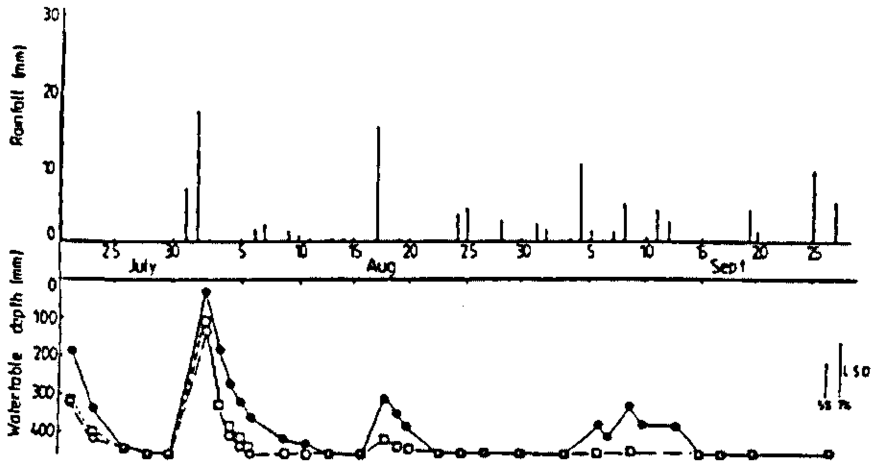

Fig. 1 Rainfall and watertable levels as measured for pipe-mole (o--o), mole-mole (□--□) and undrained (●—●) plots in the year 1982. If the watertable was deeper than 450 mm it was assigned a value of 450 mm. Least significant difference (LSD) at the 1% and 5% level.

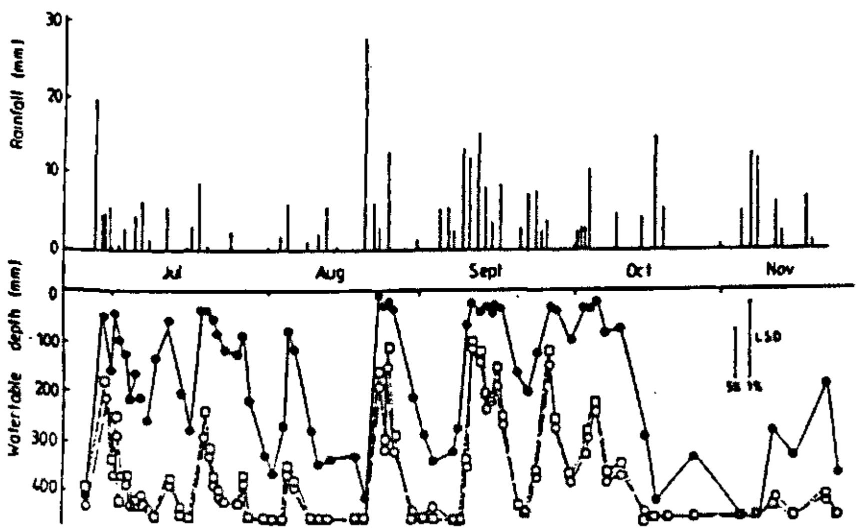

Fig. 2 Rainfall and watertable levels as measured for pipe-mole (o--o), mole-mole (□--□) and undrained (●—●) plots in the year 1983. If the watertable was deeper than 450 mm it was assigned a value of 450 mm. Least significant difference (LSD) at the 1% and 5% level.

In 1983, a year of average winter-spring rainfall, drainage had a marked effect on the water table level (Fig. 2). The water table on the undrained plots was significantly (often at $P \leq 0.01$) shallower than on the drained plots. Due to the presence of the fragipan very little deep drainage can occur, and so artificial drainage is necessary to remove excess water from the soil profile. Mole drainage is clearly seen to be an efficient way of lowering the water table in a fine-textured soil.

Groundwater observation well measurements (Fig. 1 and 2) showed that there was very little difference between the water table levels in the plots drained by moles in conjunction with collecting pipes and plots drained by a major-minor mole network. Because measurements were taken only for the first two years after installation no comparison between the long term efficiency of pipe-mole and mole-mole systems can be made. However, if soil conditions are ideal for moling and a farmer owns his own mole plough, major-minor mole drainage could offer a significant cost saving over conventional pipe-mole drainage.

<u>Flow in the pipe</u>

Further comparison between the initial performance of the two drainage treatments was made by measuring the flow data at the v-notch weirs. Typical examples of decay curves are presented in Fig. 3. Results show that there was little difference between the hydrographs for pipe-mole and mole-mole treatments.

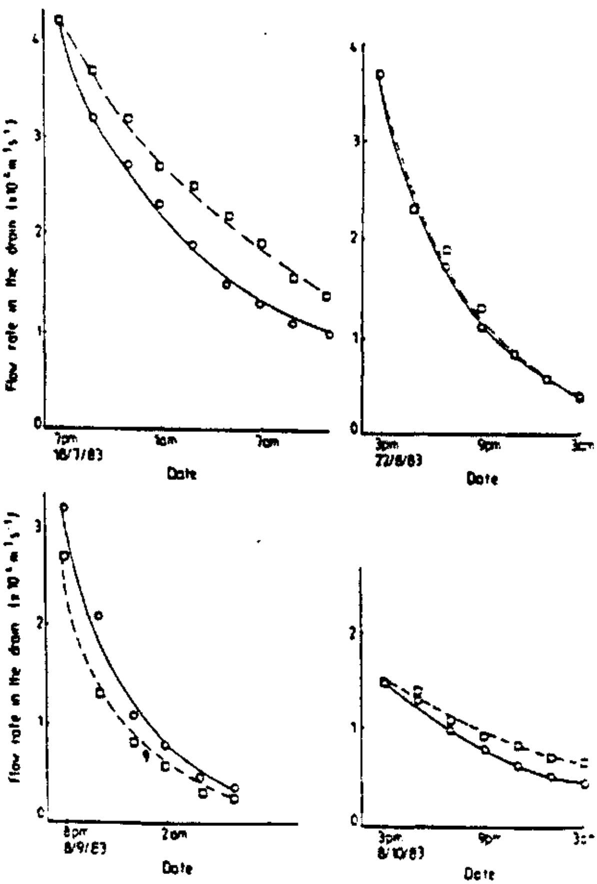

Fig 3. Decay curves following peak flow for pipe-mole (o—o) and mole-mole (□--□) plots.

During the course of measurement, the main line collecting water from the plots was observed to flow full for up to 12 hours after heavy rainfall. After that pipes did not flow full, suggesting that the capacity of the pipe causes a restriction for only a relatively short period and is unlikely to be a major limitation to water movement in a mole drainage system. Hydrographs showed that although drain flow peaked shortly after rainfall, the moles continued to flow for 4 to 5 days after rain had ceased, implying a protracted drainage process.

Despite the consistency of individual response times (i.e. time between the start of rainfall and the *commencement of drainage*) *for individual flow events* across all of the drained plots it is not practical to propose a mean response time. A wide range of values was observed for different events, depending primarily upon both antecedent moisture content and the intensity of rainfall, as was also found by Reid and Parkinson (1984). Early winter flow did not peak in the drain until some hours after rainfall because movement of water through the soil was retarded by absorptive losses to the dry soil matrix. In comparison, late winter flow peaked almost immediately after the rainfall event. Turner et al. (1976), reporting on the monitoring of flows from a 12 ha site on the same soil type found similar results and showed that the discharges increased from 40% of incident rainfall in June to a maximum of 82% for a mid-winter event. This increase in discharge of incident rainfall reflects changes in soil water storage as the wet season progresses.

Water table profile

In Fig. 4 water table levels measured in observation wells close to the mole channel are compared with levels measured in wells positioned midway between moles. After rain there is often a significant ($P \leqslant 0.05$) difference between the water table level close to the mole channel compared with the level midway between mole channels. The water table level next to the mole was approximately 200 mm deeper than the mid-mole level. This suggests that for most of the time the major limiting factor in the drainage process in the Tokomaru silt loam is the rate at which water moves through the soil towards the mole channel, rather than any restriction imposed by the carrying capacity of the moles or pipes.

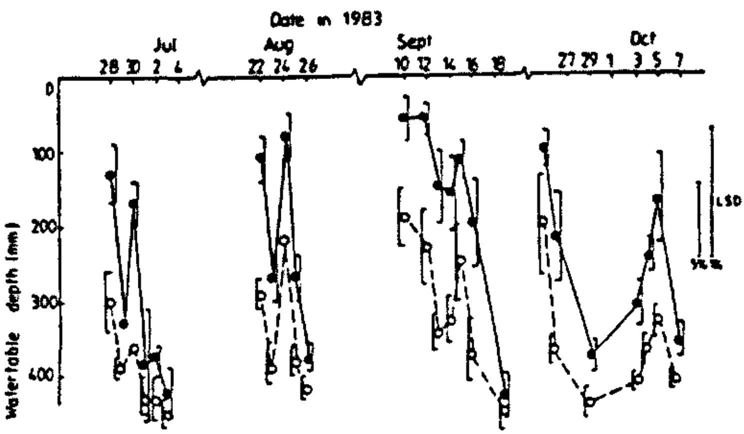

Fig. 4 Comparison of water table levels adjacent to the mole (O--O) with levels mid mole (●—●). Least significant difference (LSD) at the 1% and 5% level.

Soil water content

One of the most important functions of drainage under pasture is to lower the surface soil water content so that the bearing strength of the soil is greater than the load imposed by either the grazing animal or cultivating implements. Serious treading damage is observed when the resistance to penetration of Tokomaru silt loam is less than values 0.2 to 2 times the static load for sheep (200 kPa) which corresponds to a gravimetric water content in the top 30 mm of the soil profile of approximately 0.6 (Climo and Richardson, 1984).

Gravimetric water content data presented in Fig. 5, shows that from the end of June to early October 1983, the top 30 mm of soil was consistently and significantly ($P \leqslant 0.01$) wetter on the undrained than on the mole drained plots. As expected this difference in surface soil water content parallels the difference in water table levels seen in Fig. 2. The difference in surface soil water content between mole drained and undrained soil was greatest in the spring month of September, where the surface soil water content on the undrained plot was substantially greater than 0.6. As this is a time of high pasture growth rates and moderate stocking rates, the importance of lowering the surface soil water content by mole drainage takes on special significance.

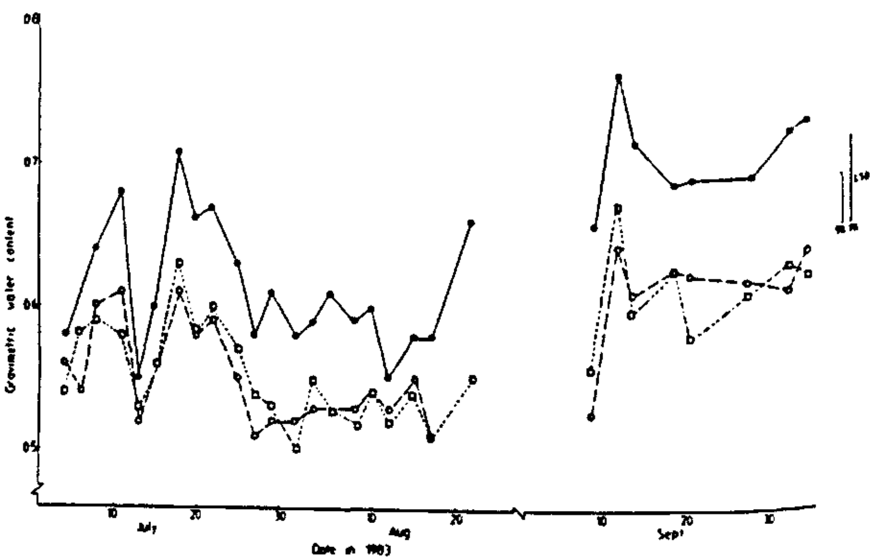

Fig. 5 Gravimetric water content of top 30 mm of pipe-mole (O--O), mole-mole (□---□) and undrained (●——●) profile in 1983. Least significant difference (LSD) at the 1% and 5% level.

Neutron moisture meter data measured in 1983 showed that mole drainage lowered the water content of the sub-soil as well as at the surface. Data recorded on two days in August are presented in Fig. 6. A feature of these data, which was typical of the graphs gathered over the winter-spring period, is the difference in the volumetric water content of the drained soil compared with the undrained soil to a depth of 400 mm. There was approximately 16 mm more water in the undrained than in the drained profile.

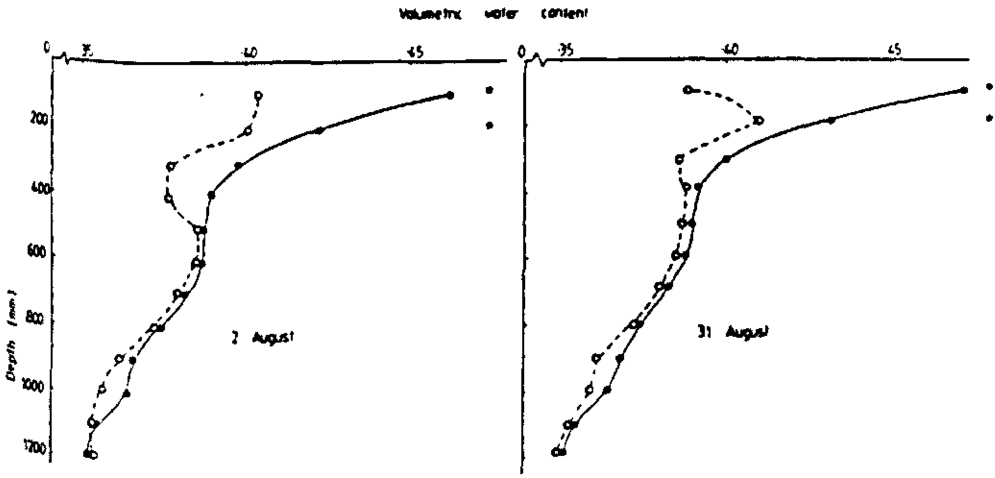

Fig. 6 Volumetric water content of pipe-mole (o--o) and undrained (●—●) profile on two occasions in 1983. For depths where a (*) appears the difference between mean values for the drained and undrained plots was significant at $P < 0.05$.

Other considerations

Consideration must also be given to the importance of other steps in the mole drainage process, namely; infiltration, movement of water into and along the mole and from the mole to the pipe.

Observations indicated that infiltration of water into the profile was not a problem, except if the soil surface had been severely pugged (poaching) or if the soil was completely saturated.

It is not unreasonable to expect that compressive forces associated with mole channel formation will restrict water movement into the channel. However, Kanchanasut (1980) has shown that any sealing around the mole channel is likely to be temporary, with earthworm activity and root penetration providing pathways for water entry into the channel.

As flow rates in excess of 500 l hr^{-1} have been measured for a single mole channel, it is unlikely that the capacity of the mole channel to conduct water will be a limiting factor. In fact, moles spaced at 2 m, flowing all day at a rate of 500 l hr^{-1} would be capable of clearing 150 mm of water.

If mole channels are capable of conducting 500 l hr^{-1} then an efficient connection is needed between the channel and the collecting pipe. This is one of the reasons why the use of highly permeable backfills such as gravel is advocated. Except where installation practices were poor and topsoil was returned in a powdered or slurried state, the passage of water from the channel to the pipe is unlikely to be rate determining.

CONCLUSIONS

During a winter-spring period of average or greater rainfall it is imperative that a soil with poor internal drainage is artificially drained, or else the soil will remain waterlogged for many days. Mole drainage is an efficient and cost effective way to lower the water table in a fine-textured soil.

As a consequence of lowering the water table, the water content of the surface soil is considerably lower in a mole drained soil than undrained soil for most of the winter-spring period. The lower surface soil water content induced by mole drainage gives rise to greater surface soil strength. This has major implications for stock and pasture management over the wet season and also the timing of cultivation for spring-sown crops.

For most of the time, the rate at which the water table declined was not determined by the carrying capacity of the moles or collecting pipes, but rather by the rate of water movement through the soil to the mole. That the greatest resistance to the movement of drainage water is the flow of water from the bulk of the soil to the mole, highlights the need for a cheap secondary drainage treatment such as moling to ensure that fine-textured soils are drained efficiently.

For twc years immediately after their installation, there was no difference in water table levels, discharge hydrographs or surface soil water contents between plots drained by pipe-mole or mole-mole drainage treatments. Further work is needed to assess the long term viability of mole-mole drainage systems.

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SOIL AND WATER MANAGEMENT IN DRAINED CLAY SOILS

P.B.Leeds-Harrison*　　　　　N.J.Jarvis**

The movement of water in clay soils is often dominated by flow in large pores. Work in many countries under differing climatic and soil management situations has shown that while flow in large pores (macropores) may contribute significantly to drainflow they may only contribute a small amount to the soils total porosity (Bouma et al. 1977, Germann and Bevan 1981, and Kneal and White, 1984). Leeds- Harrison et al.(1982) have shown that Drainage response is greatly influenced by the nature of the cracking and soil disturbance created by the drain plough at installation of the drain. In this work mole drains with well developed cracks adjacent to and above the drain had a much faster response to a given rainfall event than drains with no such cracking.

The ability of field tillage practices to change the packing density of soil structural units and in particular the proportion of large voids in the soil needs to be considered in both modelling and drainage design. Tillage usually increases cracking above working depth but causes very little disturbance below working depth. In these circumstances flow to drains may be restricted by the low macroporosity of the soil between the disturbed layer and the drain.

In heavy clay soils swelling and shrinking of the soil matrix under wetting and drying regimes, the action of frost and compaction under tractor wheels all contribute to changes in the extent, continuity and size of macropores. Thus an added complication to drainage design is that any naturally occurring or implement induced changes to soil physical properties will vary in time. This paper considers the effects of tillage and soil disturbance on the drainage response of heavy clay soils.

FLOW IN CRACKS AND FISSURES

The basic equation governing laminar flow in capillaries or in cracks is that of Hagan-Poiseuille. For crack flow Childs (1969) gives the equation as:

$$Q = g.\rho.(D^3/12\mu).\text{grad}\,\phi$$

where Q is the flow rate per unit depth in a planar crack of width D under an hydraulic gradient, grad ϕ , g is the acceleration due to gravity, μ is the viscosity term and ρ is the density of the flowing fluid. Inspection of this equation shows that larger pores will have a dominant role in water transmission in the soil.

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Measurements of soil water potential taken with fast response pressure transducer tensiometers in a well structured clay soil show that water moves very rapidly down the soil profile. Figure 1 shows tensiometer response at five depths in the soil following the onset of rainfall. Potentials at 100mm depth rise rapidly and there is little time lag between similar rises at depths to 700mm. This is consistent with water infiltrating in cracks. Near the surface the tensiometer detects water movement as soil water pressure rises to atmospheric pressure indicating that the surface of the crack is wetted but the crack has not filled. At 700mm depth water starts to accumulate in the cracks, saturating them and raising the soil water pressure to above atmospheric pressure. At 350mm depth this feature also occurs but the time to saturation in the cracks occurs 6 to 8 hours after saturation of the lower cracks. The decline in saturation at 350mm depth after rainfall has ceased indicates flow to drains at 550mm depth.

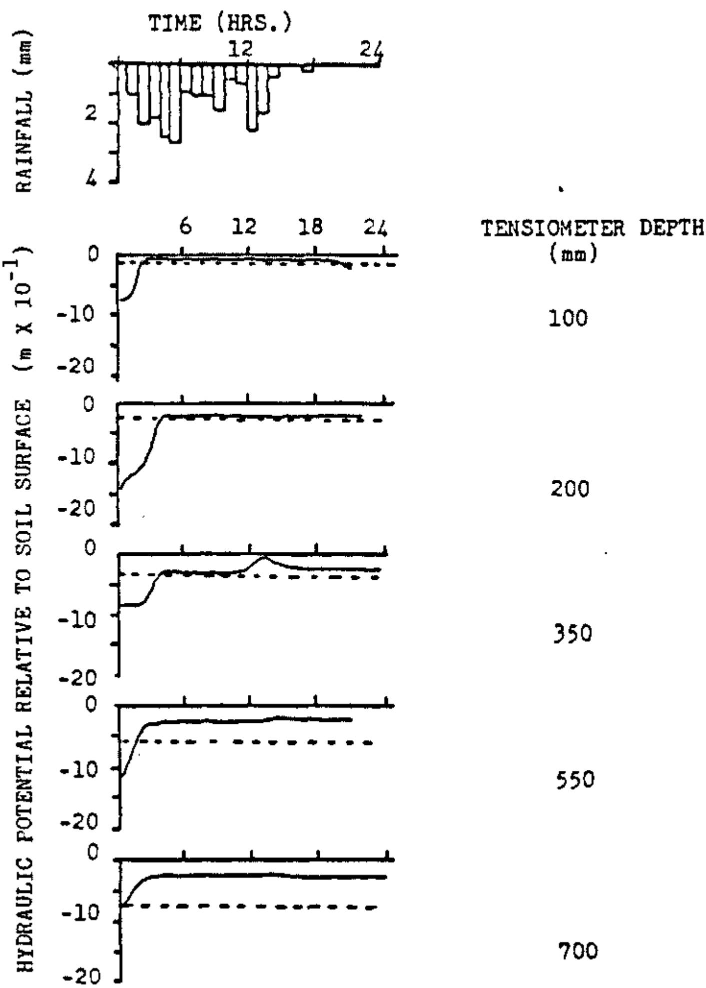


FIG 1 Variation in Hydraulic Potential at Five Depths in a Clay Soil Following Rainfall. (Dotted Line Indicates Zero Matric Potential)

Saturated flow in clay soils is dominated by flow in the cracks and estimates of the effect on flow of the extent and size of cracking can be made by assuming negligible flow in the fine pores of the clay matrix and considering crack flow only.

Simulating the cracking in a pedal soil by a simple mesh system shown in figure 2 and taking the case where water is ponded at the soil surface producing steady flow, then the above equation may be used to investigate the flow regime in the cracks. Continuity at each crack intersection must be satisfied and an iterative over-relaxation technique has been used to investigate the effect of crack width and soil disturbance in localised zones on the flow to mole drains spaced at 2m.

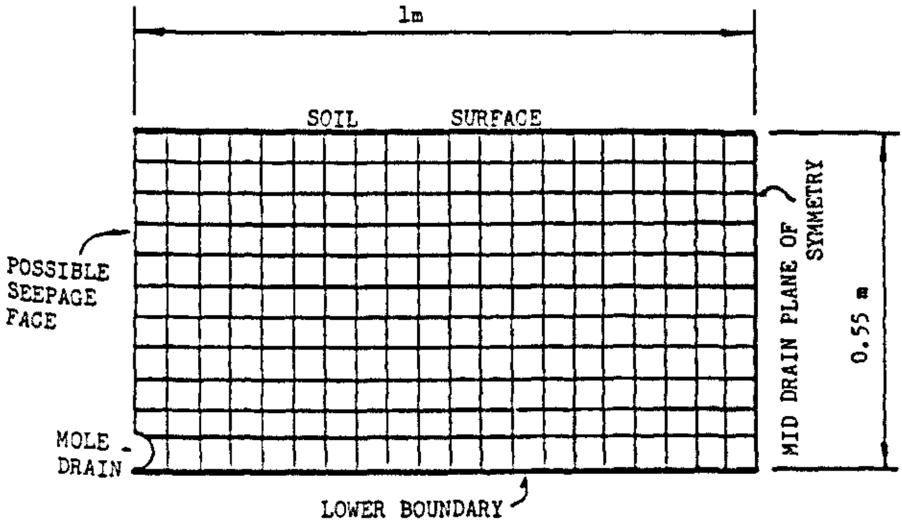


FIG 2 Simulated Network of Cracks in a Mole Drained Clay Soil

Figure 3 shows the model results for drainflow from eight different situations (T1 to T8) as a ratio of the drainflow from a uniformly cracked soil(T1) where the horizontal and vertical cracks throughout the soil have the same dimensions.

Comparing T1(control) with T2 it can be seen that the presence of a seepage surface above the drain significantly improves drain performance. Such a seepage surface becomes even more critical when comparing situations where the upper soil layer has larger cracks (hence higher permeability) than the subsoil (T3-T8). Such a situation often arises in the clay soils of the United Kingdom where structure development and cracking are much greater in the upper soil layers. T3 shows that the absence of a seepage surface greatly reduces drainflow in this two layered situation compared to the same situation with a seepage surface (T4).

Disturbing the soil above the drain increases the size of cracks. In this case (T5) flow is greatly increased and is similar to the seepage surface case (T4). Considering the difference between T4 and T5 it is seen that the difference between above drain disturbance and a seepage surface is small. In practice the mole plough leg produces a seepage surface at the leg slot and cracks the soil either side of this slot giving the situation shown in T6. In this case flowrate is further improved and is similar to that of T1.

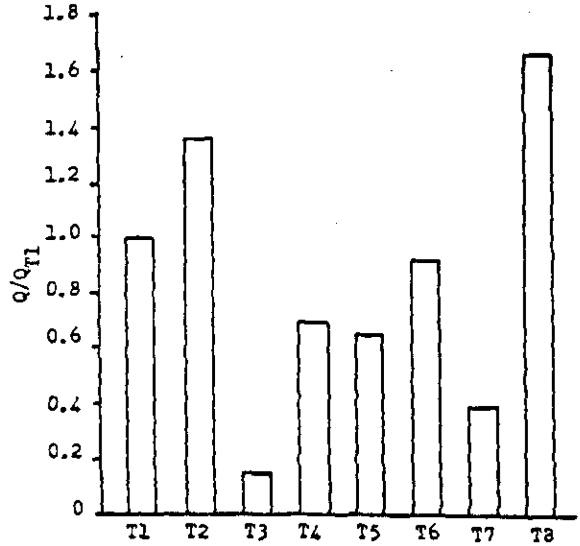
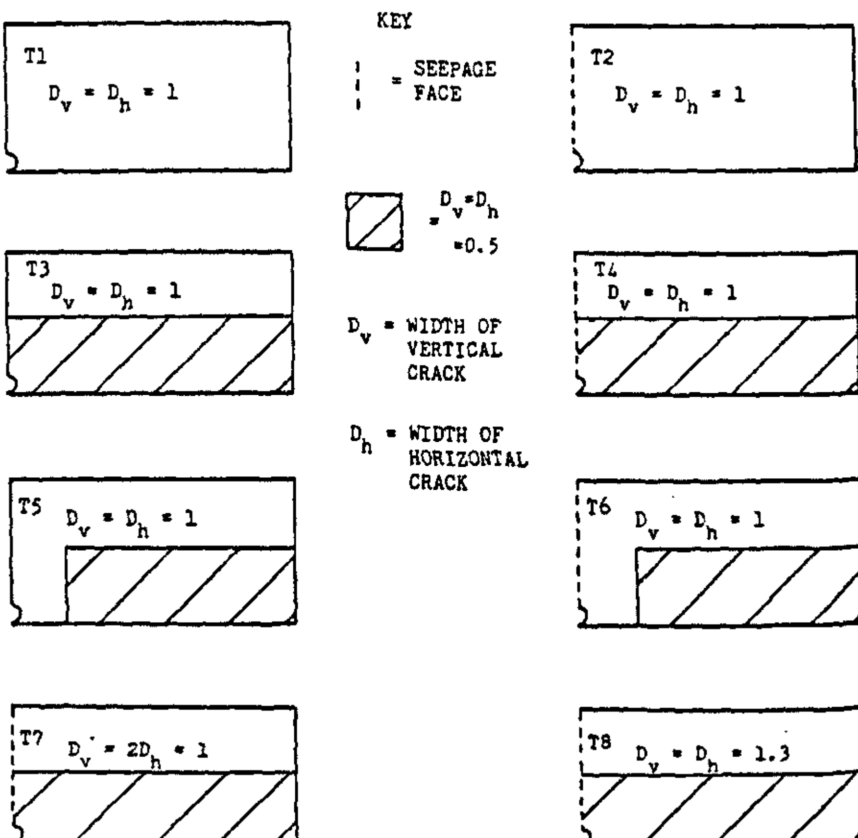


FIG 3 Drainflow Rate (Q) from Eight Cracking Systems in a Saturated Clay Soil as a Ratio of Drainflow from a Uniformly Cracked Soil (Q_{T1}) (Drain Spacing 2m, Drain Depth 0.5m)



In situations where compaction occurs horizontal cracks are more susceptible to closure than vertical cracks. In T7 cracks have been reduced to half the size of the vertical cracks in the upper soil layer. Flows are considerably reduced when compared to T4 indicating the importance of horizontal cracks to flow regime. In loosened soil crack sizes will be increased. T8 shows the case where the cracks have been increased to 1.3 times those in T4 in the upper soil layer. This increase in crack width doubles the apparent hydraulic conductivity of the upper soil layer. A very significant increase in flow is predicted. However soil loosening may often increase crack sizes by at least an order of magnitude. Where a seepage surface exists and the profile becomes saturated very high flow rates can be expected in loosened soil.

The condition where the whole profile becomes saturated may be considered the worst case situation in drained clay soils. The importance of creating a seepage surface above the drain is well demonstrated. In mole drainage the mole plough leg creates a large crack above the drain and this can be considered as a seepage surface. Modifications to the leg of the mole plough have been shown to enlarge the size of the leg slot and the fissures associated with drain installation (Webb 1981). Roughening the leg of the mole plough or increasing its width increases fissuring and can help produce a more stable leg slot shown in figure 4a which will act as seepage surface in wet soil conditions.

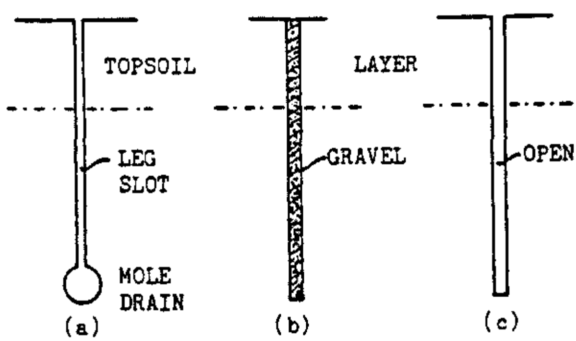


FIG. 4 (a) Mole Drain Showing Leg Slot Seepage Surface
(b) Gravel Filled Trench as a Seepage Surface
(c) Open Trench as a Seepage Surface

An alternative is to create a narrow vertical ditch into which gravel is placed, figure 4b. In stable soils a vertical trench may be cut without gravel fill, figure 4c. Equipment is available to install such trenches and they have had some success on grassland sites.

In soils where the topsoil is much more permeable than the subsoil layer a perched water table can often occur. In this case the permeable upper layer becomes saturated while the subsoil layer can remain unsaturated. Studies in sand tanks show that the sink for water in the topsoil can be considered to be the interface between the two soil layers at the top of the seepage surface.

In our field studies on heavy clay soils we have used fast response tensiometers to detect the presence of a perched water table. Perched water usually occurs in the top 250mm of soil which is often the depth of the topsoil or cultivated layer. Between 250mm and 350mm the soil may be unsaturated and between 350mm and drain depth at 550mm cracks may again become saturated. This situation often occurs in cultivated soils where cracking in the upper layers is much greater than the lower soil layers or where a destructured layer occurs at the bottom of the cultivated layer.

THE EFFECT OF SOIL DISTURBANCE ON INFILTRATION

While cracking can be shown to greatly influence saturated flow, the ability of a clay soil to transmit water rapidly down the profile to recharge the water table has been shown in modelling studies by Leeds-Harrison and Jarvis (1986) to depend on the rate at which water is supplied at the soil surface (i.e. rainfall or irrigation intensity) and by the density of cracking. Where the intensity of application is less than or equal to the infiltration rate of clay peds or aggregates then most of the water applied will infiltrate vertically from the soil surface. Increasing intensity of application causes water to flow off the peds into soil cracks from which it may infiltrate horizontally. This means that drainflow can be observed in a clay soil under intense rainfall conditions although the soil may be storing water in the peds.

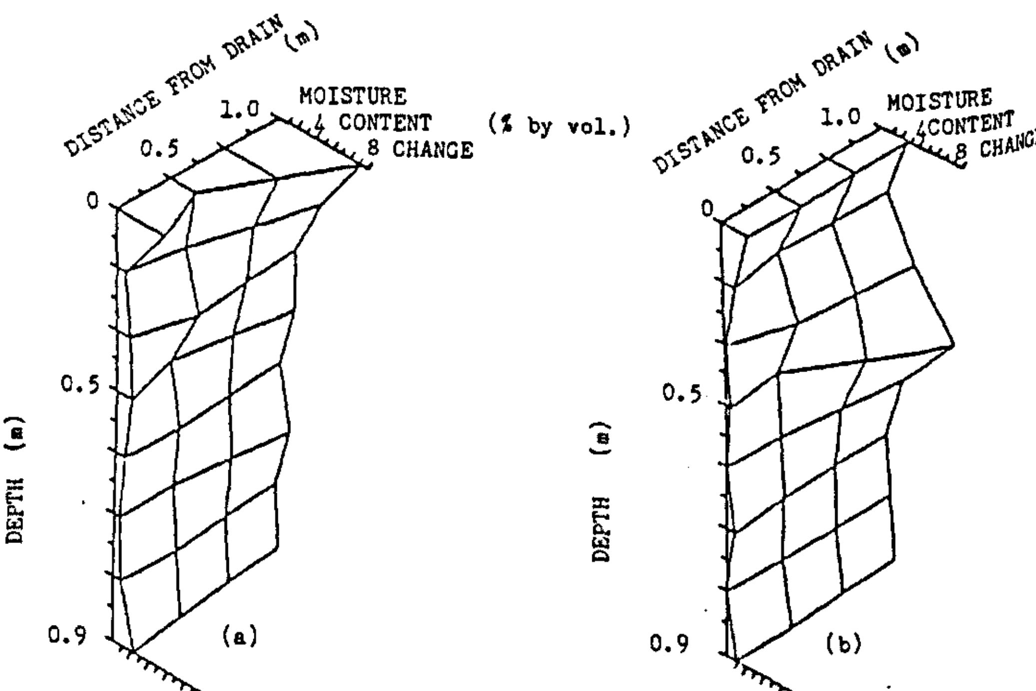


FIG 5 Changes in Moisture Content with Depth for (a) Loosened Soil and (b) Undisturbed Soil under Grass following a 24mm Rainfall Event (Shipway 1986)

In field studies water storage and drainflows have been compared for undisturbed and loosened clay soils (Shipway 1986). Figure 5 shows changes in stored water following a rainfall event for the two treatments. Less water is stored in the unloosened soil where a few large cracks exist than in the loosened soil with many cracks. Water is stored mainly at drain level (550mm) in the undisturbed soil but near the soil surface for the loosened soil. Figure 6 shows drainflow for the same treatments. As expected drainflow starts later and is less for the loosened treatment.

Increased cracking increases the number of internally wetted surfaces so that imbibition of water by the clay matrix is greater as the number of cracks increase. We therefore expect that soil loosening may allow increased storage of water in the soil matrix and consequently less drainflow in situations where rainfall is infiltrating into the soil. This situation is typical of the wetting situation in the soil in the period after harvest and seedbed preparation. In the spring the soil may be swollen leaving only stable cracks which conduct water to the drain. Although less water is stored in the already wet profile, flow rate can be low due to the low conductivity of the cracks. Such flow behaviour has been noted by in our field studies and is reported by other workers (Reid and Parkinson 1984, Robinson et al. 1987)

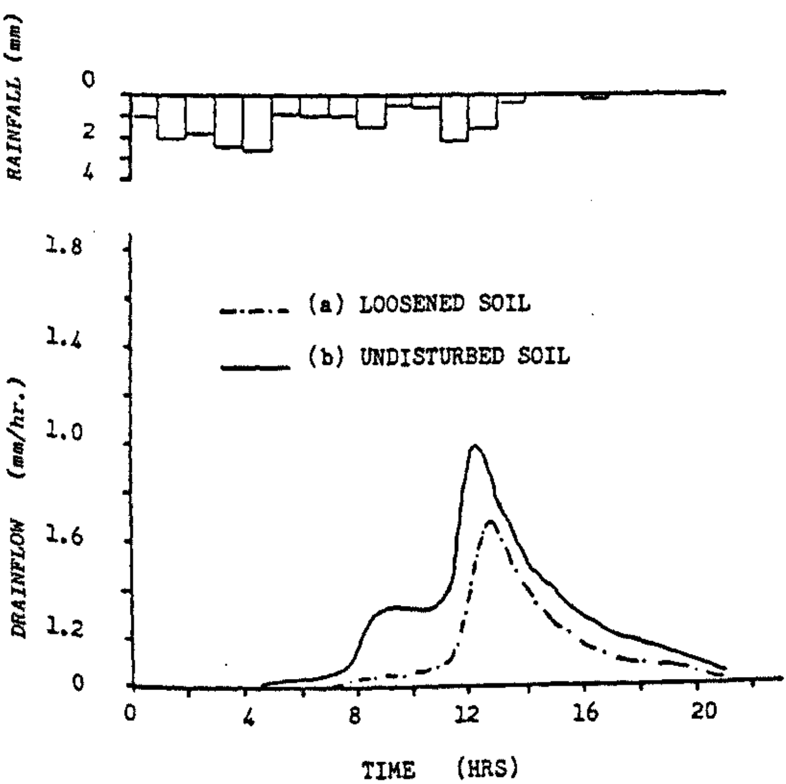


FIG 6 Drainflow Hydrographs for (a) Soil Loosened to 200mm and (b) Undisturbed Soil
(Drains Spaced at 2m, Drain Depth 0.55m)
(Shipway 1986)

DRAINFLOWS

Drainage theory shows that the flow rate,(q) from the drain depends on the mid drain water table height,(h) above the drain.

$$\text{i.e.} \qquad q = f(h)$$

In rainfall situations the rise in the water table is dependent on the drainable porosity of the soil and the quantity of water recharging the water table. Where the drainable porosity is small, small inputs of water will produce large rises in the water table.

In soils with a shallow depth of saturated soil below the drain or where the drain can be considered to sit on the impermeable layer we can state:

$$q \propto h^2$$

Thus where drainable porosities are small and exist in a few continuous large cracks drainflow will be rapid and have a short recession following a rainfall event (Leeds-Harrison et al 1986).

In loosened soil the movement of water to the drain may therefore be less rapid while in swelling clay soils where minimum tillage is practised and discrete cracking occurs high flow rates may be expected. However where plough pans or compaction in the soil can be identified then loosening has been shown to be very beneficial (Harris et al 1984).

DISCUSSIONS AND CONCLUSIONS

The effect of soil disturbance on the amount and rate of drainflow from closely spaced drains in clay soils depends on the nature and extent of the cracking system in the soil. The ability of soil management techniques to change the nature of this cracking needs to be considered in drainage design and in water balance models in these soils.

It is clearly demonstrated that in situations where soil structure is well developed in the upper soil layers but poorly developed below or where soil has been loosened, for instance by sub-soiling then the presence of a seepage surface and a direct connection from the loose soil area to the drain is essential for the rapid removal of excess rainfall. However when considering loosened soil it is observed that an increase in stored water in the soil profile when the soil is initially dry results in less drainflow. In addition it can be expected that the increase in drainable porosity as a result of soil loosening will also produce less rapid drainflows.

Drainage design must consider possible soil management scenarios and their effect on drainage response. In humid temperate areas where the removal of excess winter rain is of primary concern then drainage can be enhanced by the creation of a few large continuous cracks connecting the upper soil layers and the drain. Rapid removal of water in this case will mean less opportunity time for the soil to swell. Loosened soil however will allow greater uptake of water in the soil matrix resulting in more swelling. A result of this uptake of water is that the soil will become weaker and be more prone to damage under mechanised farming systems.

In dry climates soil shrinkage cracks may be extensive. In this case, under surface irrigation or intense rainfall, water which might otherwise be stored in the soil profile can be lost to drains. In this case soil management techniques to reduce shrinkage or to close shrinkage cracks once they have formed may be needed. Spoor and Leeds-Harrison (1986) report a drainage and reclamation study in Egypt on a highly swelling clay soil in which rapid movement of water through shrinkage cracks and implement induced fissures resulted in very inefficient leaching and a rapid dispersion of the clay which blocked the drains. Modifications to the drain installation technique were needed to prevent rapid movement of water to drains from ponded water. Localised surface compaction to close cracks at the surface resulted in satisfactory leaching.

Swelling that occurs as soil wets will reduce drainable porosity and hydraulic conductivity. This in turn will affect drainage response to rainfall events. Tillage and drainage operations should aim to create stable continuous cracks which will allow rapid movement of water to the drain even when the soil is wet. Rapid wetting of the soil following soil disturbance may cause rapid collapse of cracks and channels in the soil (Spoor and Ford 1987). While it is impossible to avoid rainfall, timing of drainage and soil loosening operations to drying periods will be beneficial.

It may be concluded that the drainage behaviour of clay soils is shown to be critically dependent on the cracks and fissures in the soil. The influence of soil disturbance by tillage has a significant effect on the storage of water in the soil and on the drainflow rate. Drainage design and installation in these soils requires an understanding of the water flow processes in soil cracks and the matrix.

Because of the phenomena of crack flow in clay soils drainage installation technique may have to be modified to take account of the drainage problem and subsequent soil management techniques. Modifications to drainage machines to ensure that seepage surfaces and stable cracks are formed are a possible means of improving drainage on clay soils.

The mechanisms of crack flow both in the saturated and unsaturated case differ from those in single grained rigid soils. Care must be taken in the use of soil and water management models for pedal clay soils which do not consider the flow of water through cracks and fissures. The modification of soil physical parameters from those measured to account for soil disturbance may only have limited success.

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TILE DRAINAGE WATER QUALITY: A LONG TERM STUDY IN NW OHIO

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Much of the northern Corn Belt of the United States, and in particular the lower Great Lakes states of Indiana, Illinois, Michigan, Ohio, and Wisconsin, is characterized by near level topography, small watershed gradients, and fine textured, poorly drained soils. This is most evident in the northwestern region of Ohio which is dominated by the late Wisconsin-age lake sediments of the lake plain and tills of the surrounding glacial till plain and moraines (Logan and Stiefel, 1979). This area is generally circumscribed by the present Maumee River Basin which drains northward from Indiana, Michigan, and Ohio into Lake Erie at Toledo, Ohio (Fig. 1).

The soils of NW Ohio are young (7000-13,000 years), fine textured and dominated by a mixture of illite, vermiculite and smectite clays. They are well to poorly structured in the surface because of relatively high organic matter levels, and poorly structured in the subsoil. The soil textures range from silt loams to clays. These soils occupy level to nearly level landscape positions and slopes are in the range of 0-6 percent. Hydraulic conductivities are low and seasonal high water tables within 20 cm of the surface are common. Because these soils are young, relatively unweathered, and formed from calcareous parent materials, they are inherently fertile and capable of producing high crop yields if drainage is improved. Drainage is the limiting factor to crop production on most of these soils, and all farmers use some form of surface or subsurface drainage. In the last three decades, there has been a tremendous increase in the installation of subsurface drainage systems, particularly precision installation of plastic corrugated tile, and a more recent interest in the use of ridge tillage systems for drainage. Northwestern Ohio represents one of the largest areas in the world with extensive use of subsurface drainage and, therefore, movement of chemicals via tile drainage from agricultural land to Lake Erie has been of concern for a number of years.

Lake Erie which, together with Lakes Superior, Michigan, Huron, and Ontario form the Great Lakes, has been the focus of considerable study during the 1970's and 1980's since that water body was found to be seriously polluted (PLUARG, 1978). The major pollution problems have been cultural eutrophication stimulated by excessive loadings of nutrients, and contamination of fish by heavy metals and organics. Of these issues, by far the most dominant has been cultural eutrophication from excessive loadings of phosphorus to the lake. It has been estimated that about 50 percent of the phosphorus entering Lake Erie is by runoff from agricultural land, the other major source being discharges from wastewater treatment plants (COE, 1982). The wastewater sources have been dramatically reduced over the last decade as a result of large public expenditures for advanced wastewater treatment by the U.S. and Canada, yet lake modelers estimate that significant reductions in river sources must be achieved in order to restore the lake to acceptable quality (COE, 1982). There is a strong consensus among the jurisdictions in the U.S. and Canada that the most effective means of significantly reducing agricultural sources of phosphorus is through erosion control, and that this control can best be achieved through wide-

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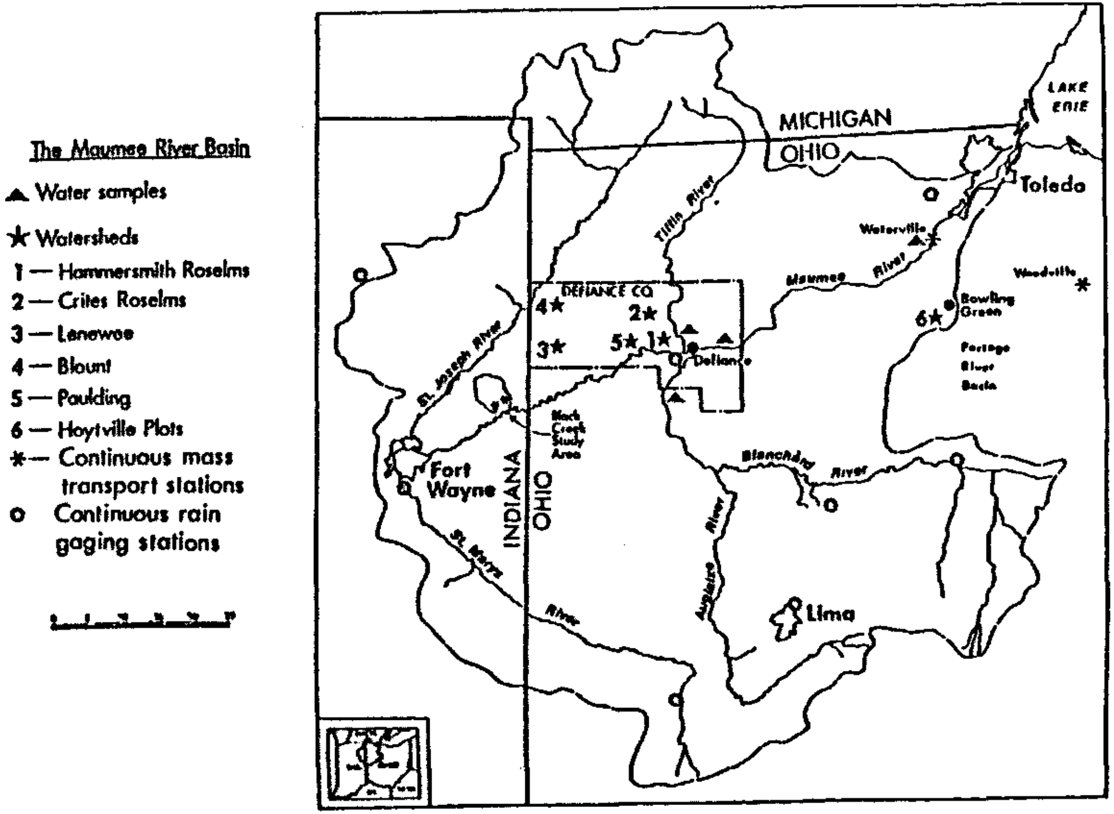

Figure 1. Sampling Sites in the Maumee River Basin

spread adoption of conservation tillage practices, including no-till, in place of the more widely practiced fall moldboard tillage (Forster et al., 1984). No-till can potentially reduce total phosphorus losses by as much as 90 percent and conservation tillage phosphorus reductions may be as high as 50 percent (Forster et al., 1984). Tile drainage can potentially affect the impact of conservation tillage and no-till on phosphorus losses in two ways: a) crop yields are often reduced with no-till on very poorly drained soils, and tile drainage may increase the potential for no-till adoption on these soils; and b) tile drainage may enhance the increased infiltration which is often observed with no-till compared to plowing. It is assumed here that any water that flows through tile will have lower concentrations of phosphorus than those in surface runoff because of the adsorption of phosphorus to soil particles.

Another agricultural water quality problem in the Maumee River Basin and other tributaries of northwestern Ohio has been high levels of nitrate (Baker, 1987). Peak concentrations often exceed the U.S. drinking water standard of 10 mg/l NO_3-N and the levels in these rivers are among the highest recorded anywhere. These levels can be attributed to the high percentage of agricultural land use in the watersheds, in particular the production of annual feed grains. In the case of nitrate, tile drainage is seen as accentuating the problem because of the high water solubility of nitrate and its minimal attenuation by soil. Baker (1987) has suggested that nitrate storm chemographs for northwest Ohio rivers are different than those for phosphate and sediment, and indicate that much of the nitrate in these watersheds is routed through tile drainage systems before returning to the surface drainage network.

In order to answer many of these questions, a long-term study was initiated in 1975 at the NW Branch of the Ohio Agricultural Research and Development Center (OARDC) at Hoytville (Fig. 1) and at several other sites in Defiance County in which losses of sediment and nutrients were measured in surface runoff and tile drainage as a function of soil type, crop, and tillage. A summary of the results from 1975-1982 are reported here.

STUDY LOCATIONS AND METHODS

A total of five sites were selected for study in the Maumee River Basin of northwestern Ohio, four in Defiance County on field-size plots, and a set of eight small plots in Wood County (Fig. 1 and Table 1). These were selected to represent the major soil types in the Basin (Table 1). Details of the instrumentation of these sites have been reported previously (Logan and Stiefel, 1979; Logan, 1981; Logan, 1987). The general approach on the field-size areas in Defiance was to use a Coshocton wheel for estimation and sampling of runoff and a sump and sump pump for estimation and sampling of tile drainage. At the Hoytville site, runoff and tile drainage from the eight plots is diverted to sumps and sump pumps are used to estimate and sample flow. This approach provides accurate estimates of total flow per event and an integrated sample from each event, but does not provide hydrologic data in the form of detailed hydrographs. Each site was equipped with manual or recording rain gauges. Samples were analyzed for sediment, total phosphorus, filtered reactive phosphorus, and nitrate-nitrogen using standard methods (Logan and Stiefel, 1979). Only data for the Blount, Paulding and Hoytville sites are presented here. The period of record is 1975-1983 for the Blount and Paulding sites and 1975-1980 for the Hoytville plots.

Tillage and crop management are given by year for each site in Table 2. On the Hoytville plots, half of the sites were fall moldboard plowed each year and the other half were no-tilled. Because of the wet and heavy nature of the soils of northwestern Ohio, almost all plowing is performed in the fall after crop harvest. Winter wheat is grown in Ohio, while oats are spring seeded. With the exception of the Hoytville plots, little or no fertilizer was used on these sites except for 100-150 kg N/ha for corn. On the Hoytville plots, approximately 100 and 200 kg/ha of P and K, respectively, were applied in the fall just prior to fall plowing, and approximately

Table 1. Characteristics of the Defiance County Watersheds (111, 401, 501) and Hoytville Plots

Site[a] code	Dominant soil series	Soil taxonomy	Physiographic region	Parent material	Slope (%)	Drainage area (ha)	Drainage systems monitored
401	Blount	Aeric Ochraqualf	till plain	clay loam till	3-4	0.9	surface runoff
402	Blount	Aeric Ochraqualf	till plain	clay loam till		0.9	subsurface tile
501	Paulding	Typic Haplaquept	lake plain	lacustrine clays	1	1.0	surface runoff
502	Paulding	Typic Haplaquept	lake plain	lacustrine clays		0.1	subsurface tile
611-681	Hoytville	Mollic Ochraqualf	lake plain	clay till	<1	0.04	surface runoff
612-682	Hoytville	Mollic Ochraqualf	lake plain	clay till		0.04	subsurface tile

[a] The first number indicates the site, the second number the plot (for Hoytville only), and the third number denotes runoff (1) or tile drainage (2).

Table 2. Summary of Tillage and Cropping Practices on the Monitored Areas

Year	Tillage	Crop
	Blount (401, 402)	
1975	fall moldboard plow	soybeans
1976	fall chisel plow	soybeans
1977	fall chisel plow	corn
1978	no-till	soybeans
1979	fall chisel plow	soybeans
1979/80	fall chisel plow	wheat
1981	fall chisel plow	corn
1982	no-till	soybeans
1983	no-till	soybeans
	Paulding (501, 502)	
1975	fall moldboard plow	soybeans
1976	fall chisel plow	soybeans
1977	fall moldboard plow	soybeans
1978	fall moldboard plow	oats
1978/79	fall moldboard plow	wheat
1979/80	fall moldboard plow	wheat
1981	fall moldboard plow	soybeans
1982	fall disk	wheat
1983	fall moldboard plow	idle
	Hoytville (611-681, 612-682)	
1975	fall moldboard plow and no-till	soybeans
1976	fall moldboard plow and no-till	soybeans
1977	fall moldboard plow and no-till	corn
1978	fall moldboard plow and no-till	corn
1979	fall moldboard plow and no-till	soybeans
1980	fall moldboard plow and no-till	corn

200 kg N/ha was applied to the corn crops. Available phosphorus levels in all soils were in the sufficiency range, and on the Hoytville plots reached very high levels until P fertilization was stopped in 1978.

RESULTS AND DISCUSSION

Annual precipitation, runoff, tile drainage, and sediment, phosphorus and nitrate losses are given in Tables 3-6 for the Blount, Paulding, and Hoytville sites. Seasonal trends in precipitation, runoff, tile drainage and soil loss are illustrated by data from the Blount site (Fig. 2, Logan, 1987).

The hydrologic response of the Blount soil (Table 3) was intermediate to that of the Paulding and Hoytville soils (Tables 4-6). About half of the total measured drainage from the Blount soil was surface runoff and half was tile flow. In general, however, the Paulding soil had higher runoff and less tile drainage, while tile flow was much higher on the Hoytville soil than surface runoff. These three sites are all nearly level, and the main differences in them affecting tile flow are soil texture and structure. The Blount soil is a silt loam and has good structure in the surface, the Paulding soil is clay-textured and formed from massive varved lacustrine clays, and the Hoytville soil is well structured in the surface and subsurface. The Hoytville site had been in continuous pasture for about 20 years prior to installation of the drainage experiment and this appears to have contributed to the excellent structure and internal drainage characteristics of this soil.

Sediment losses from the sites varied as a function of runoff, and was highest from the Paulding site and lowest from the Hoytville plots. Soil losses were low in terms of soil productivity losses, and it is, therefore, difficult to justify erosion control on these soils except as a means of reducing off site damages due to sediment and sediment-bound pollutants such as phosphorus and pesticides. Soil losses from the Hoytville plots were so low that there were no significant effects of no-till versus fall moldboard plowing. In contrast, no-till appeared to have reduced soil loss on the Blount soil in 1978, 1982, and 1983 (Table 3). Wheat also showed lower runoff erosion losses on Blount and Paulding soils than corn or soybeans (Tables 3 and 4). Sediment losses in tile were generally <500 kg/ha/yr and were not important in terms of overall soil losses. They can, however, account for a large part of the phosphorus discharged from tile lines and may also be important in the transport of some soil-bound pesticides.

Filtered reactive phosphorus losses were low in surface runoff except from the no-till plots on Hoytville soil (Table 6) where 100 kg P/ha was surface applied each fall from 1975-1978. By 1980, levels were beginning to fall to much lower levels. Tile drainage filtered reactive phosphorus losses were low on all sites and were not affected by P fertilization on the Hoytville plots.

Total phosphorus is comprised of filtered reactive phosphorus and sediment-bound phosphate. Total P losses from all sites were much higher than those of filtered reactive P, and total P losses were well correlated with sediment losses. At very low sediment concentrations in some of the tile drainage treatments (e.g., Hoytville, Tables 5 and 6), almost all of the total P was filtered reactive P. Soil loss reductions with no-till on the Blount soil (Table 3), and with wheat on the Blount and Paulding soils (Tables 3 and 4) also resulted in total P reductions. Total P losses in surface runoff from the Paulding soil were extraordinarily high (Table 4), among the highest ever reported from agricultural land. These levels can be attributed to the erosion rates from this soil and to the high clay content of this soil which results in an enrichment of phosphorus in the eroded sediment.

Total phosphorus concentrations in tile drainage were low compared to those in surface runoff, and most of the total P can be attributed to sediment in the tile discharge. In the case of the Hoytville soil, however, total P <u>loads</u> were higher than

Table 3. Annual Precipitation, Concentrations and Loads from Blount Soil in Surface Runoff (R) and Tile Drainage (T)

Year	Precipitation		Flow	Sediment FWM[a]	Sediment Load	Filtered reactive P FWM	Filtered reactive P Load	Total P FWM	Total P Load	Nitrate-N FWM	Nitrate-N Load
	(cm)		(cm)	(mg/l)	(kg/ha)	(mg/l)	(kg/ha)	(mg/l)	(kg/ha)	(mg/l)	(kg/ha)
1975	43.8	R	5.0	2014	891	0.09	0.04	2.57	1.14	4.4	1.8
		T	5.8	250	128	0.05	0.03	0.19	0.09	12.5	6.4
1976	66.1	R	15.6	2455	3421	0.07	0.08	1.68	2.33	3.1	4.3
		T	11.5	240	245	0.07	0.08	0.34	0.35	8.4	8.6
1977[b]	34.5	R	17.6	676	1055	0.02	0.02	1.13	1.76	11.6	18.1
		T	9.3	130	107	0.04	0.03	0.35	0.28	12.2	10.1
1978	67.5	R	13.8	53	66	0.07	0.08	0.30	0.37	2.2	2.7
		T	12.2	34	37	0.09	0.10	0.30	0.32	8.3	8.9
1979	83.1	R	17.0	390	515	0.03	0.04	0.31	0.47	5.0	7.5
		T	9.7	131	112	0.08	0.07	0.27	0.23	13.9	11.9
1980[b]	32.4	R	9.7	1265	1092	0.49	0.43	--	--[c]	0.0	0.0
		T	6.4	73	41	0.07	0.04	--	--	13.7	7.7
1981	83.1	R	17.3	4873	8411	0.12	0.21	4.14	7.15	11.8	20.4
		T	15.9	100	158	0.08	0.13	0.24	0.38	19.6	31.1
1982	78.8	R	24.1	443	1067	0.04	0.10	0.69	1.66	0.7	1.8
		T	29.5	132	390	0.10	0.29	0.38	1.12	2.3	6.9
1983	70.6	R	9.6	559	535	0.56	0.54	1.54	1.47	7.3	0.7
		T	14.7	323	473	0.10	0.15	0.68	1.65	1.7	2.5

[a] Flow-weighted mean concentration.
[b] Through May.
[c] Not measured.

Table 4. Annual Precipitation, Concentrations and Loads from Paulding Soil in Surface Runoff (R) and Tile Drainage (T)

Year	Precipitation		Flow	Sediment FWM[a]	Sediment Load	Filtered reactive P FWM	Filtered reactive P Load	Total P FWM	Total P Load	Nitrate-N FWM	Nitrate-N Load
Year	(cm)		(cm)	(mg/l)	(kg/ha)	(mg/l)	(kg/ha)	(mg/l)	(kg/ha)	(mg/l)	(kg/ha)
1975	52.1	R	19.9	2590	4576	0.07	0.13	1.14	1.97	3.6	6.3
		T	0.9	1192	100	0.08	0.01	1.54	0.11	5.3	0.4
1976	61.5	R	23.4	2131	4434	0.12	0.25	1.93	4.02	2.6	5.5
		T	2.8	353	89	0.03	0.01	0.31	0.08	32.5	8.2
1977[b]	35.8	R	39.4	1098	3849	0.29	1.02	1.97	6.89	4.1	14.3
		T	0.0	0	0	0.00	0.00	0.00	0.00	0.0	0.0
1978	61.6	R	52.1	946	4388	0.57	2.65	3.35	15.50	0.6	2.6
		T	3.7	289	94	0.18	0.06	0.47	0.15	5.6	1.8
1979	89.8	R	4.2	1204	453	0.03	0.01	1.49	0.56	0.0	0.0
		T	13.7	133	163	0.03	0.03	0.24	0.29	13.0	15.9
1980[b]	28.6	R	0.0	0	0	0.00	0.00	--	--[c]	0.0	0.0
		T	8.5	138	104	0.06	0.04	--	--	8.6	6.5
1981	59.7	R	16.3	1633	2661	0.13	0.21	1.64	2.67	5.1	8.3
		T	11.5	279	321	0.09	0.10	0.66	0.76	0.5	0.6
1982	83.0	R	56.6	495	2801	0.02	0.12	0.63	3.55	1.4	8.1
		T	12.7	313	397	0.05	0.06	0.61	0.78	4.1	5.2
1983	76.2	R	42.3	1142	4830	0.07	0.31	2.41	10.18	1.3	5.5
		T	13.2	361	477	0.11	0.15	1.50	1.98	2.8	3.7

[a] Flow-weighted mean concentration.
[b] Through May.
[c] Not measured.

Table 5. Annual Precipitation, Concentrations and Loads from Hoytville Soil in Surface Runoff (R) and Tile Drainage (T) with Fall Moldboard Plowing

Year	Precipitation		Flow	Sediment		Filtered reactive P		Total P		Nitrate-N	
				FWM[a]	Load	FWM	Load	FWM	Load	FWM	Load
	(cm)		(cm)	(mg/l)	(kg/ha)	(mg/l)	(kg/ha)	(mg/l)	(kg/ha)	(mg/l)	(kg/ha)
1975	79.4	R	5.2	2010	1455	0.07	0.05	0.18	0.13	4.3	3.12
		T	34.0		56	0.03	0.16	0.04	0.18	1.4	6.77
1976	67.9	R	6.7	96	90	0.18	0.17	0.38	0.35	0.8	0.79
		T	26.5	6	24	0.03	0.11	0.10	0.39	3.9	14.37
1977	94.4	R	10.4	241	351	0.25	0.36	0.67	0.97	2.8	4.07
		T	35.6	7	34	0.09	0.44	0.21	1.06	6.5	32.36
1978	65.8	R	25.1	78	135	0.25	0.44	0.62	1.11	3.2	5.8
		T	22.5	4	16	0.16	0.57	0.28	1.39	8.2	27.1
1979	98.7	R	30.2	54	111	0.28	0.59	0.67	1.39	3.4	7.2
		T	32.4	15	72	0.12	0.49	0.15	0.62	3.9	17.1
1980	28.6	R	3.5	78	135	0.25	0.44	0.62	1.11	5.8	13.6
		T	16.5	4	16	0.16	0.57	0.28	1.39	8.2	27.1

[a] Flow-weighted mean concentration.

Table 6. Annual Precipitation, Concentrations and Loads from Hoytville Soil in Surface Runoff (R) and Tile Drainage (T) with No-till

Year	Precipitation		Flow	Sediment		Filtered reactive P		Total P		Nitrate-N	
				FWM[a]	Load	FWM	Load	FWM	Load	FWM	Load
	(cm)		(cm)	(mg/l)	(kg/ha)	(mg/l)	(kg/ha)	(mg/l)	(kg/ha)	(mg/l)	(kg/ha)
1975	79.4	R	3.6	1084	541	0.28	0.14	0.28	0.14	1.5	0.73
		T	22.1	175	541	0.07	0.22	0.04	0.13	4.8	14.76
1976	67.9	R	5.1	83	59	0.25	0.18	0.49	0.35	0.6	0.44
		T	24.7	12	41	0.02	0.06	0.12	0.40	3.5	12.17
1977	94.4	R	9.7	86	117	0.68	0.92	0.77	1.05	2.5	3.35
		T	31.4	12	55	0.07	0.30	0.19	0.82	5.3	23.16
1978	65.8	R	19.9	57	94	0.48	1.37	0.78	1.87	2.9	8.1
		T	38.9	9	18	0.10	0.21	0.22	0.47	10.5	21.9
1979	98.7	R	23.5	45	101	1.79	4.76	2.28	5.92	1.9	4.6
		T	51.9	12	35	0.19	0.52	0.25	0.72	4.7	13.4
1980	28.6	R	6.3	48	15	1.00	0.30	--	--[b]	1.8	0.5
		T	16.8	5	7	0.05	0.07	--	--	2.5	3.7

a Flow-weighted mean concentration.
b Not measured.

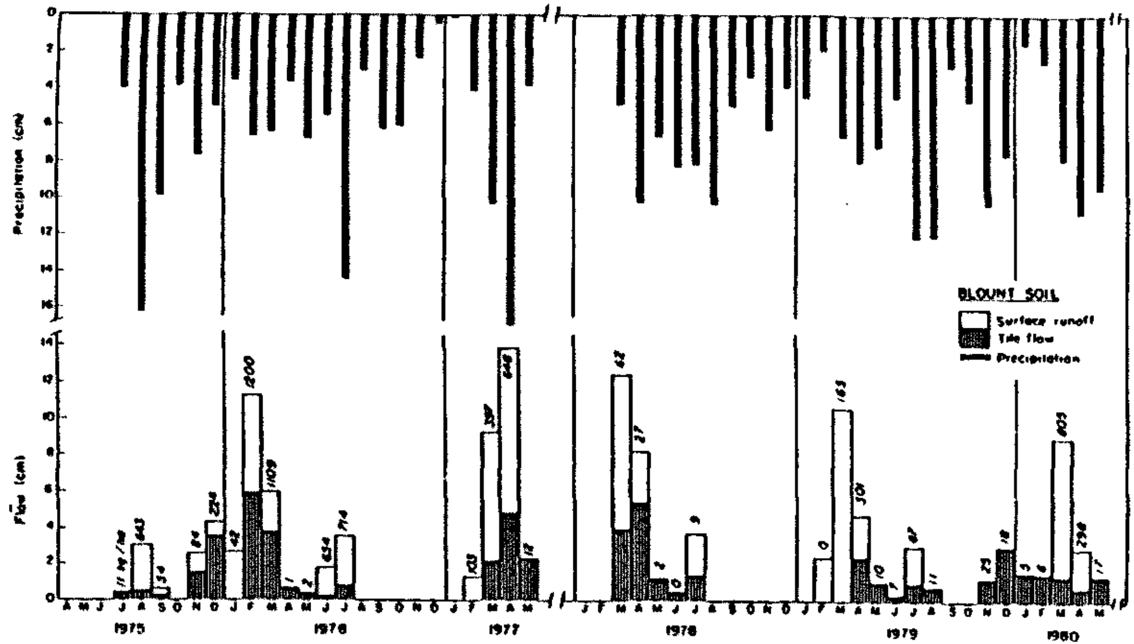

Figure 2. Precipitation, Runoff, Tile Flow and Sediment Loads by Month From Blount (401/402) in 1975-1980 (Logan, 1981)

those in surface runoff because of the much higher tile flows compared to runoff volumes.

Nitrate losses were generally much greater in tile drainage than in surface runoff except on the Paulding soil (Table 4) where tile flows were very low. Nitrate losses were somewhat higher with corn than with soybeans (Tables 3, 5 and 6) although the effect was not great. These data show that some nitrate losses from agricultural land can be expected with annual crop production even when chemical fertilizer is not used, as is the case with soybeans. Total losses of 10-20 kg N/ha in runoff and tile drainage are probably typical for corn/soybean production systems and levels less than this may not be easily achieved since there is nothing that can be done to reduce nitrate losses from soybeans.

Figure 2 illustrates the seasonal distribution of precipitation, runoff, and tile drainage for the Blount site. Similar results were found for the other sites. Precipitation tended to be greatest in late spring and early summer, but runoff and tile flow were always highest in the early spring after ground thaw. Soils are water-saturated in the early spring compared to the summer months. Also, the crop canopy is fully developed by late July, thereby protecting the soil surface and the soil has dried sufficiently to provide some moisture storage capacity.

CONCLUSIONS

A long term study of tile drainage quality in NW Ohio has indicated that concentrations and, in most cases, loads of sediment and phosphorus were lower in tile drainage than in surface runoff. Nitrate concentrations and loads were generally higher in tile drainage. Because of the extensive use of tile drainage systems in the Lake Erie Basin, pollutant losses from agricultural land to the Lake via this pathway should be considered in any analysis of land use impacts on Lake Erie water quality.

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THE MOVEMENT OF SALT IN CLAY SOILS

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The insatiable demand for irrigated land in the tropics has resulted in an increasing area of heavy clay land being developed for irrigation without there being an effective methodology for draining them. As a result increasing areas of these soils are being abandoned due to waterlogging and salinization. Many field trials have been conducted to try and find a practical method of reclaiming salt affected clay soils but to-date, effective methods applicable to a wide range of situations have not been developed. This study describes part of a larger investigation devised to shed light upon the principles controlling the movement of salt and water in heavy soils.

Clays are generally difficult to drain because of their low overall hydraulic conductivity (Mc Intyre et al 1982, Bouma and Wosten 1979). Most drainage flow and indeed hydraulic conductivity can be attributed to the continuous structure formed from biopores and the swell-shrink fissures developed on wetting and drying (Bouma et al 1977). Occasionally, the hydraulic conductivity may be sufficient to allow excess rainfall or irrigation to be removed (Bouma 1980, Farbrother 1972) but the flow, confined to the macropore structure, bypasses the main body of the soil which, under irrigation, contains the salt that drainage is intended to remove.

It is widely recognised that diffusion plays an important role in the movement of salts within the soil but most studies have concentrated either upon the diffusion of nutrients or of specific ions in artificially prepared clays (Nye and Tinker 1977). The studies described were aimed at providing basic information on the diffusion of salts commonly encountered in irrigated areas in natural clay soils and at assessing the importance of the diffusion process in the leaching of heavy clay soils.

THE DIFFUSION PROCESS

Ions diffuse as a direct consequence of random thermal motion resulting in a net movement of ions from areas of high to area of low concentration until equality of concentration is established.

In clays, ions may diffuse either in the free soil solution or in the adsorbed phase of ions clustering around the particles. The rate of diffusion in the adsorbed phase is many orders of magnitude lower than the rate in free solution and so for practical purposes may be ignored (Nye 1966). Ions diffusing in free solution may exchange places with other ions of the same species (Nye 1979, Self diffusion) or with other species (Olsen and Kemper 1968, Counter diffusion) or move as electrically neutral pairs (Barraclough and Tinker 1982, Mass diffusion). However, for practical salinity control mass diffusion only needs to be considered.

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The diffusion coefficient is affected by ion species (Robinson and Stokes 1959) by soil properties, especially moisture content (Vaidyanathan and Nye 1966) by concentration of salts in the free solution (Graham-Bryce 1965) by electrostatic effects (Tinker 1970) by anion exclusion and temperature (Lai and Mortland 1962) and by soil structure (Currie 1965). As this paper will show despite these influencing factors it is possible to obtain a representative value of the coefficient that might apply to a saturated clay in a field situation.

The mathematics of diffusion has been studied extensively and forms the basis for the analysis of the experimental work described herein.

Theoretical Analysis

Leaching into Infinite Volumes of Water from a Cylinder of Clay:
The rate of change of soluble salt concentration with time and position in a soil cylinder immersed in pure water and subject only to radial diffusion is described by the following equation (Crank 1965):

$$\frac{C_1 - C}{C_1} = 1 - \frac{2}{a} \sum_{n=1}^{\infty} \exp \frac{(-D\alpha_n^2 t) J_0 (r\alpha_n)}{\alpha_n J_1 (a\alpha_n)} \qquad (1)$$

where:

- C_1 = initial soluble salt/ion concentration in the soil solution (assumed to be uniform at 8.4 dSm^{-1})
- C = soluble salt concentration at time t and radius r within the soil solution
- a = outer radius of the soil cylinder
- α_n = positive roots of the Bessel function of the first kind of order zero
- $J_0 (r\alpha_n)$ = Bessel function of the first kind of order zero
- $J_1 (a\alpha_n)$ = Bessel function of the first order

Leaching into Limited Volumes of Water from a Cylinder of Clay:
The rate of leaching of salts from an initially uniformally saline soil cylinder into a limited volume of water also of uniform initial lower concentration is described by (Crank 1965):

$$\frac{m_t}{m_\infty} = 1 - \sum_{n=1}^{\alpha} \frac{4\alpha(1+\alpha)}{4+4\alpha+\alpha^2 q_n^2} e^{(-Dq_n^2 t/2)} \qquad (2)$$

where:

- q_ns = are the positive, non-zero roots of:-

$$\alpha q_n J_0(q_n) + 2J_1(q_n) = 0$$

α = the ratio of volumes of leaching solution/volume of solu ion in soil

m_t = the amount of solute leaving the soil cylinder in time t

m_∞ = the amount of solute leaving the soil cylinder in time $t=\alpha$

EXPERIMENTAL METHOD

Small cylinders of clay sub-soil were collected with the minimum of disturbance from a field at Selbourne in Hampshire, UK. The cylinders of clay soil (70% montmorillonite) were placed in a salt solution for six weeks containing respectively 45.7, 24.9 and 22.8 meq. l^{-1} of $Ca\ Cl_2.6H_2O$, $MgCl_2.6H_2O$ and NaCl. After salinization the cylinders of clay had a diameter of 55 mm and a height of 30 mm. The soil solution had an electrical conductivity (EC) of 8.4 dSm^{-1} and a sodium absorption ratio (SAR) of 3.58. The upper and lower faces of the cylinder were then coated with wax to constrain all salt movement to a radial direction.

In the first experiment radial diffusion was studied by immersing the cores in a bath of distilled water in which the purity was maintained by constant replenishment. Seven replicate samples were then taken at fixed intervals of time, upto 72 hours, and the cores sectioned into regular anulii, a procedure that effectively terminated further redstribution of salt. The samples were then oven dried and the soluble salt present in the samples measured in 5:1 soil/water extracts.

In the second experiment the clay cylinders were prepared as described above, but to minimize any complications due to ion exchange, they were made saline in a single salt solution of calcium chloride (EC 11.9 dSm^{-1}). After salinization the cylinders were immersed in limited volumes of leaching water. The limited leaching volumes either of 26.3 or 54.3 or 70 cm^3 enveloped each saline clay cylinder within a thin annulus of leaching water. The rise of salt concentration in the constantly stirred annulus of leaching water was then recorded as it rose to equilibrium.

RESULTS

Diffusion into an infinite volume of leaching water.

Figure 1 illustrates the decline in the overall salt concentration at various positions within the soil cylinder during the 72 hours of these tests.

Figure 2, based upon a similar set of experiments, but extended in time, shows the total fractional rate of removal of salt with minimally 50% soluble salt being leached by diffusion over the first 48 hours of leaching.

The apparent diffusion coefficients shown on Figures 3 and 4 were estimated by fitting the mean salt or ion concentrations of the seven replicates at each sampling position into equation 1.

The diffusion coefficients declined generally with time (or concentration) and with distance from the centre of the core. However, these variations were to be expected due to the complex interactions of salt concentration,

ion species and the physical properties of the clay/water/ion systems and the effect these have on changing the mathematical boundary conditions. Despite the variations it has proved possible, as Figure 5 indicates, to identify values of the apparent diffusion coefficent which yield sound correlations between measured and predicted leaching rates for whole cylinders. These values are:-

Table 1.Measured Diffusion

	D_a (cm^2s^{-1})	Correlation Coefficients r^2
Total Salts	3.5×10^{-6}	0.97
Sodium	3.5×10^{-6}	0.96
Calcium	5.5×10^{-6}	0.94
Magnesium	4.7×10^{-6}	0.89

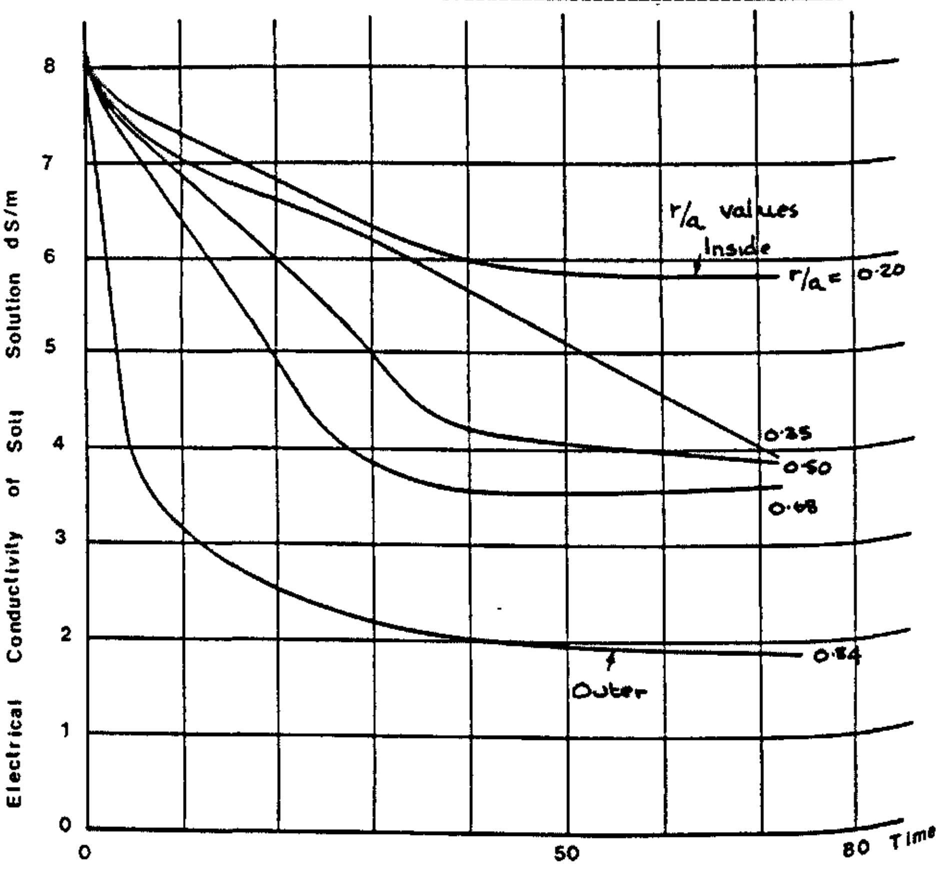


Figure 1 . Leaching of Salt from Soil Cores

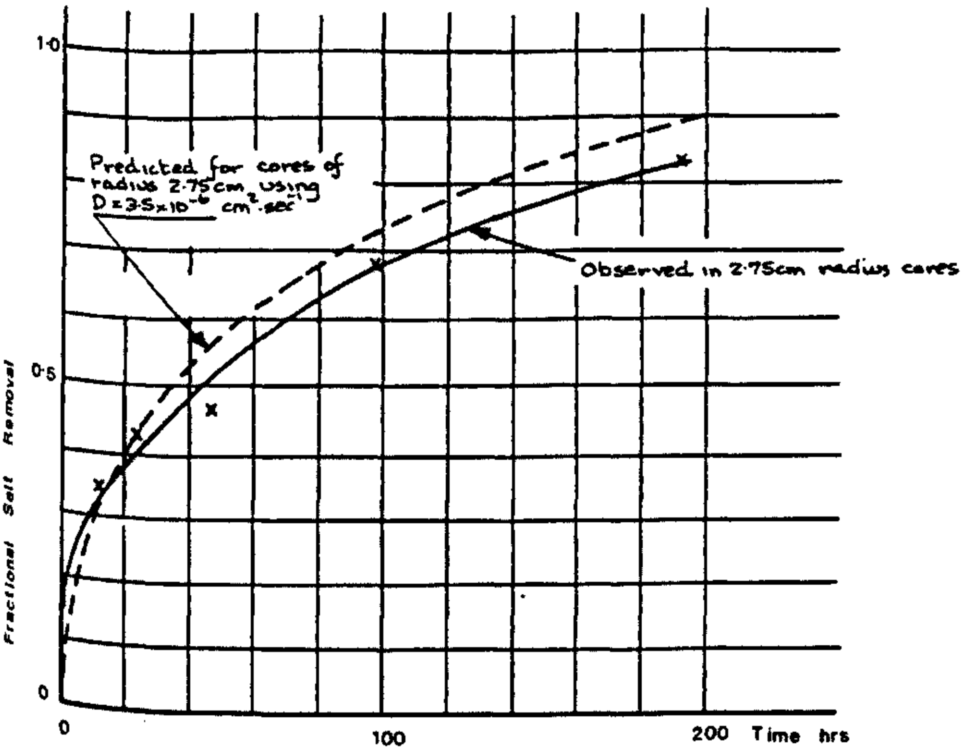


Figure 2 Leaching Rates in Small Soil Cores

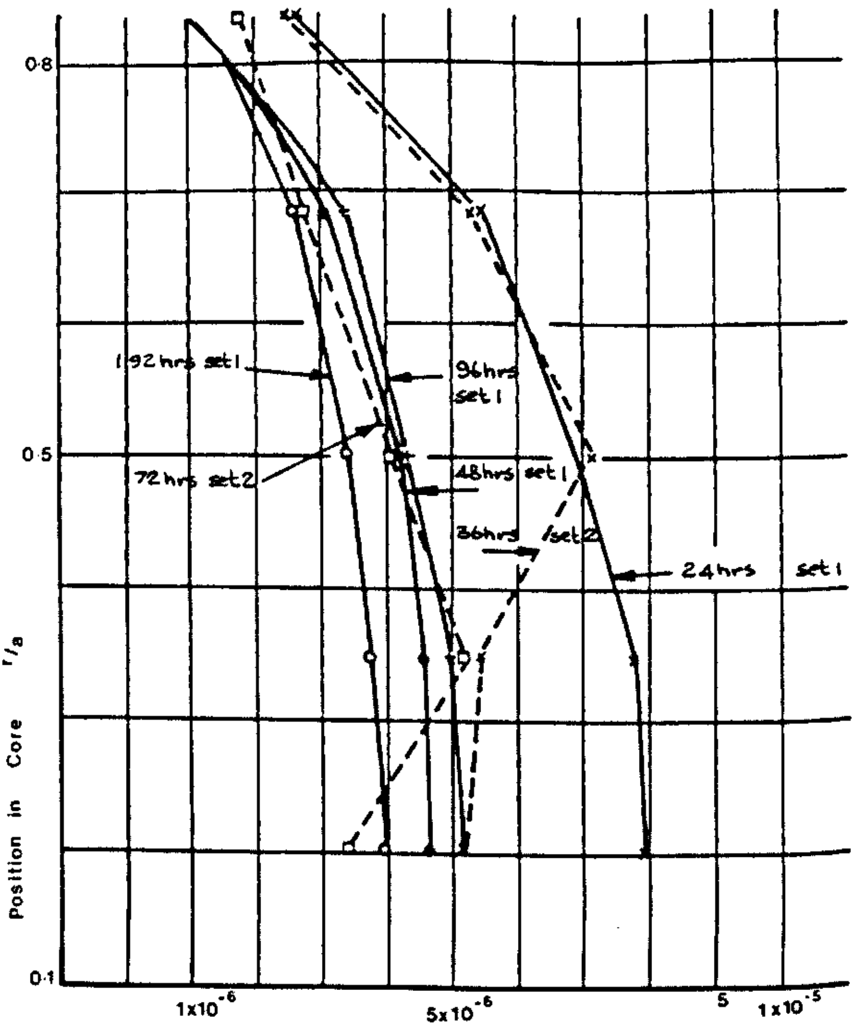


Figure 3 Apparent Mass Diffusion Coefficients

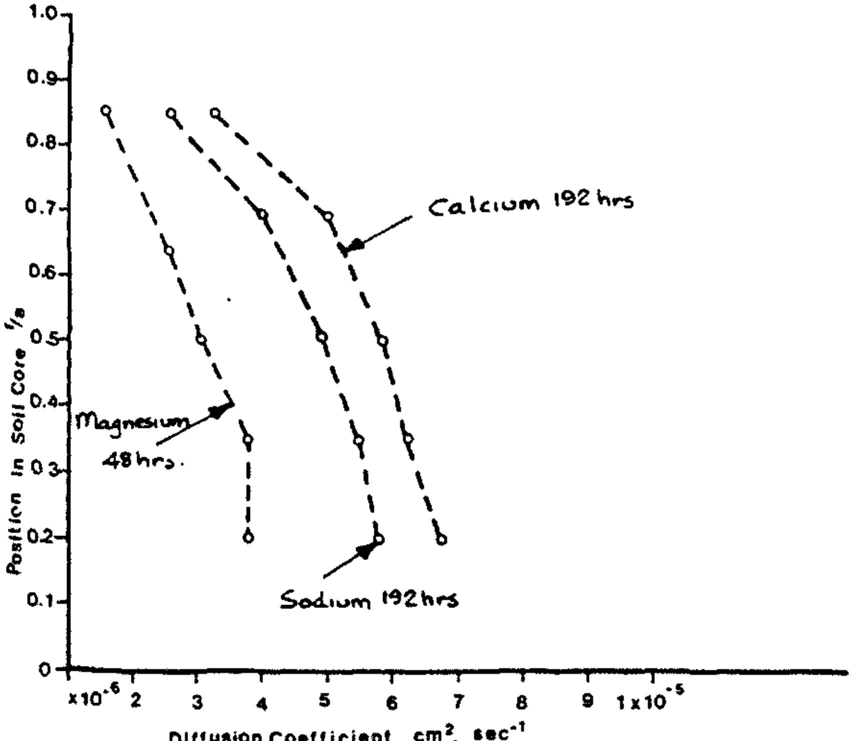


Figure 4 Diffusion Coefficients for Sodium . Calcium . Magnesium

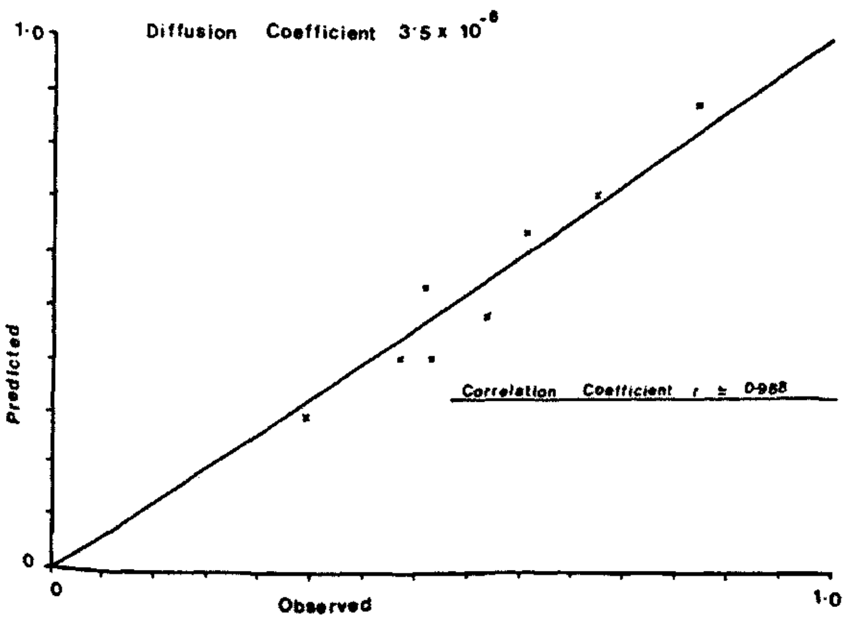
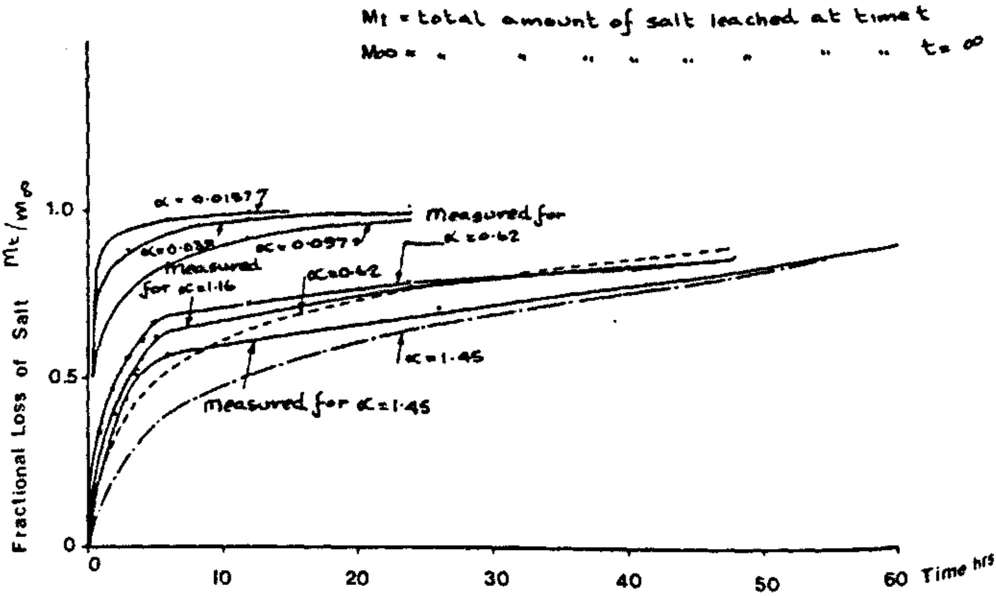


Figure 5 Correlation between Predicted and Observed Leaching Fractions



Measured and Predicted Leaching Rates

Figure 6

Diffusion into a Limited Volume of leaching water

In this set of experiments leaching by diffusion occurred into a limited finite volume of water and corresponded much more closely to the situation prevailing in a naturally structured clay soil.

The important physical parameters of the experimental system are described below.

Table 2. General Information on Limited Volume Leaching Tests.

Vol. of soil cylinders cm^3	Wt of soil cylinders gm	Moisture content W/W%	Vol. Soil Sol'n cm^3	Vol. Leaching Sol'n cm^3	1. Ratio μ	2. Ratio α
1) 71.3	142.3	42.6	42.5	26.3	0.27	0.62
2) 71.3	151.5	44.5	46.6	54.3	0.43	1.16
3) 71.3	146.9	48.8	48.2	70.0	0.50	1.45

Figure 6 shows the measured rates of leaching. As would be expected equilibrium was reached quickest in the case of the smallest external volume; 50% of equilibrium being attained in just over two hours in samples with an alpha value of 0.62 and four hours in experiments with an alpha value of 1.45. Simulated leaching curves based on equation 2 for the same values of alpha as were used in the experiments are also shown in Figure 6. The theoretical response is similar albeit slower than that observed, the difference being most pronounced at short time periods. This is thought to be due to the fact that the diffusion coefficient of $5.5 \times 10^{-6} cm^2 s^{-1}$ for calcium chloride does not take into account the passive movement of salts from within the core as a result of osmosis.

Footnote 1. μ = Volume leaching water/Volume of cylinder + leaching water
Footnote 2. α = Volume leaching water/Volume soil solution within cylinder

DISCUSSION

The results show that for practical purposes, over time periods greater than one day, standard equations for diffusion of salts can be used to model the movement of salt from within clay cylinders, although for shorter periods of time more complex models are required which take account of osmotic effects.

In heavy clay soils the crumbs and clods within an unconsolidated ploughlayer can be visualised as being spheres of varying sizes in which salt is stored in the entrapped water. The spheres are surrounded by voids through which bathing solutions of leaching water flows and, if the soil were perfectly drained, the salt concentration within the leaching solution would be very low. A similar conceptual model can be used to consider a deeply restuctured soil. If standardly available solutions are then used to model salt flow from such spheres, bathed by an infinite volume of pure water, the influence of clod size can be demonstrated (Figure 7).

It can be seen from Figure 7 that at the rate of diffusion determined in these experiments, loss of salt from small spheres occurs remarkably rapidly for small crumbs and even in larger spheres of 15 cm radius, which might correspond to the dimensions encountered in a strongly structured Vertisol, some 50% of soluble salts could be leached out in 20 days <u>if</u> the leaching solution could be replaced sufficiently rapidly to maintain a low concentration in the leachate.

The experiment involving diffusion of salts into a limited volume also confirms the rapidity by which salts are able to move out of clay cylinders into a bathing solution of leaching water.

In the field situation the boundary conditions of the leachate are rather different from those used in these experiments. Firstly, the volume of the leaching solution in the experiments was much greater than would be encountered in an undisturbed soil and so corresponds much more to a ploughed or otherwise restructured situation. Undisturbed clay soils have drainable porosities (μ) of between 1% and 5% corresponding to alpha values of about 0.0187 and 0.097. The predicted rates for attaining equilibrium for these much more realistic alpha values are also shown in Figure 7, with the salt concentration attaining 80% of its equilibrium level in time periods ranging from 1.25 hours (α = 0.0187) to 12 hours (α = 0.087). These findings simply reflect the fact that there is very little water available for leaching in the natural clay soil and emphasises the necessity for a continual rapid replacement of the leaching solution within the macropores of the soil if leaching is to be effective.

At the outset of the investigation it was supposed that flood irrigation would uniformly bathe the clay peds with leaching water which might then percolate slowly downwards or move laterally to a drainage system. However, studies of water movement carried out on the above soils and also under irrigation of vertisols in Turkey have revealed that flow is confined to a few limited pathways, eg old root channels corresponding rather more closely to flow down discrete channels. The effect of the density of these drainage channels on the rate of removal of salts from the soil was analysed by treating the soil as a matrix perforated by perfectly drained narrow channels, (Figure 8). This idealised situation is useful in identifying the possibilities for leaching when perfect drainage exists, the results indicating that with perfect drainage it should be possible to leach clays over a matter of some months. However, in practice the rate of flow is controlled by the continuity, or lack of it, of the flow channels to a drainage system. The field studies in Turkey have shown that discontinuity is the norm restricting the rate of flow and therefore the rate of salt removal (Rycroft el at 1986). It can be concluded from these results that although diffusion is a key process for the removal of salts from clay soils, *in practice it is not a limiting factor and that the problem* of leaching salts from clay stems from inadequate movement of water through the macropore structure of the soil. This lack of water movement does not stem from an inadequate macropore structure but is a result of discontinuites between water conducting passages of the soil and the main drainage system.

Thus there is clearly a need to improve soil structure if a way is ever to be found to successfully manage the salinity in these soils.

Finally it can be concluded that since the amount of water passing through the soil structure is most likely to be the main limiting factor on the rate of salt removal the diffusion process can largely be ignored in field models.

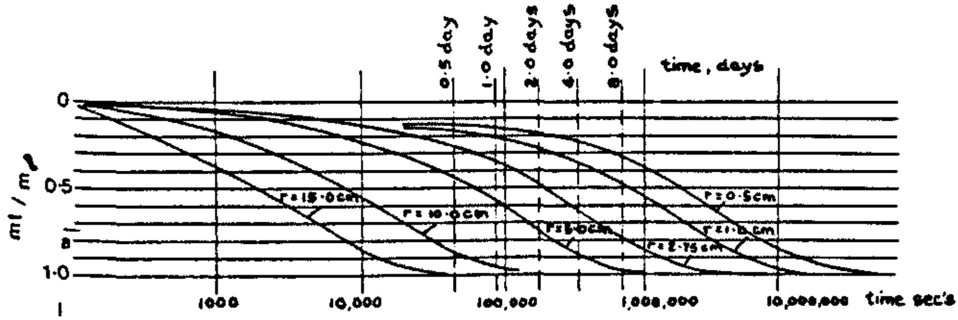


Figure 7 Leaching from Spheres of Various Radii

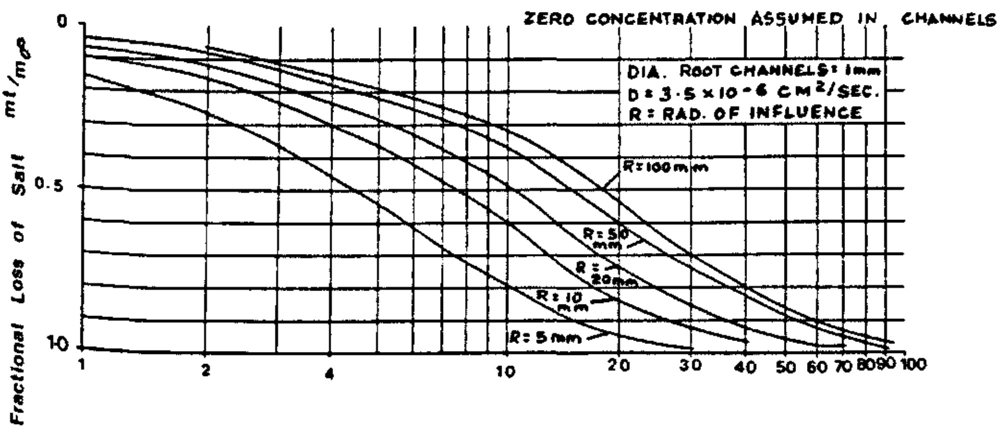


Figure 8 Time to Leach Soil Drained by Channels at Varying Radii

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POTENTIAL WAYS OF INCREASING MOLE CHANNEL STABILITY

GORDON SPOOR*

The life and nature of collapse of mole channels installed with the same standard type of mole plough vary, not only between soils and location, but also between different installations at the same location. Recent work at Silsoe College (Spoor and Ford 1987), has enabled the major types of failure mechanism responsible for channel deterioration to be identified. In addition it has been possible to establish links between the types of failure and the soil, implement and climatic conditions prevailing at and following channel formation. Knowledge of these links opens up the possibility of making suitable modifications to the standard implement or installation technique, to form a mole channel best able to withstand the failure mechanisms likely to be active in that particular situation.

The aims of this paper are:

1. to identify important precautions necessary at installation to maximise the chances of stable mole channel formation.

2. to suggest possible changes to the implement or moling technique, to improve channel stability in situations where the standard mole plough is currently not particularly satisfactory.

It must be emphasised some of these suggestions have not been fully proven in the field. They are presented as an aid to future mole drainage investigations and will require further field validation. The standard mole plough refered to has the following dimensions:-

leg width 25 mm, foot diameter 75 mm, expander diameter 90-100 mm

PRECAUTIONS TO BE TAKEN AT INSTALLATION

Channel collapse in any field situation is likely to be speeded up in the following circumstances:-

a. where significant drain flow occurs very soon after installation.

b. where water is ponded in the channel very soon after installation to a depth exceeding the half full condition.

c. where sudden changes in channel gradient occur.

d. where drain flow continues for long periods of time.

Soil disturbance at the time of installation significantly weakens or breaks many of the soil structural bonds which limit the swelling potential of a soil (Spoor et al., 1982). Wetting soon after installation before

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these bonds have had time to reform, causes increased soil swelling. This weakens all sections of the channel speeding up the rate of collapse. This risk can be reduced by:-

a. moling at the beginning of a dry period.

b. avoiding moling in the presence of free water in the profile. Where free water is present, a sacrificial moling system to dewater before the final moling should be considered.

c. cultivating the top soil particularly under drier conditions, to retain a greater proportion of incoming rainfall and slow down water flow to the channel.

Reverse grades in the channel, which could cause water ponding and sudden grade changes are very dependent upon the installation equipment, the magnitude of soil surface irregularities and the average grade of the field surface. Grade variations on irregular surfaces tend to be least and less sudden with floating long beam ploughs (Spoor et al., 1987a, 1987b), mounted ploughs tend to give the greatest variations, and variations with scrubbing long beam ploughs lie in between.

Good soil fissure development above the mole channel will ensure the most rapid discharge of drainage water, thus shortening the drain flow period and increasing the chance of a dry period in the channel between rainfall events.

IMPLEMENT AND INSTALLATION TECHNIQUE MODIFICATIONS TO COUNTERACT SPECIFIC TYPES OF CHANNEL FAILURE

Six major types of channel failure have been identified to date, namely, cyclical swell/shrink, expander, subsoiler, unconfined swelling, slurry and topsoil failures. Each type of failure is described briefly below (fuller details are given in Spoor and Ford (1987)), the circumstances under which each is likely to occur are identified and possible implement or technique modifications to counteract each particular failure mechanism are discussed.

Cyclical swell/shrink failure

Repeated changes in moisture content in the soil surrounding a mole channel causes swelling and shrinkage, which eventually weakens an initially stable channel roof area inducing roof collapse. This type of failure is most likely to occur in situations experiencing significant volume change cycles due to swelling and shrinkage at mole channel depth. The risk of failure through this mechanism will increase with increases in soil clay content, % smectitic clay, moisture deficit and the frequency of significant wetting and drying cycles.

Increasing mole channel depth to a zone where moisture changes are less will increase channel life. In the United Kingdom, moling depth in the lower rainfall, higher moisture deficit, smectitic clays of the east is commonly between 0.55-0.65 m. In the wetter, lower deficit west, with predominantly micaceous clays, moling depths range between 0.35-0.45 m.

Expander failure

In this type of failure, the soil in the channel roof area, disturbed by the expander at installation, collapses into the channel leaving an arch shaped roof section. Subsequent falls of soil may then occur, particularly in fine structured soils. A major reason for this failure is a weak bond between the expander disturbed soil and the surrounding "undisturbed" soil. Circumstances which increase the risk of this type of failure include channel formation at relatively low moisture contents (below the plastic limit) and significant swelling and shrinkage at moling depth. As the moisture content at channel formation increases into the plastic range, the bond strength will tend to increase, increasing stability. Moisture content at moling depth is dependent on the dry bulk density in saturated soils and upon the moisture deficit in the unsaturated condition. The extent of swelling or shrinkage at moling depth is dependent upon the factors identified in the cyclical swell/shrink failure section.

Possible ways of reducing the risk of expander failure include the following:

a. avoid the use of an expander.

b. ensure the mole foot is running parallel to the desired channel grade, thus forming a circular rather than oval channel.

c. increase the expander diameter relative to the mole foot diameter to achieve greater soil packing in the channel roof area. This will only be successful providing the larger expander does not produce a subsoiler failure (described later).

d. increase moling depth to reduce the extent of swelling and shrinkage. This would also allow the use of a larger diameter expander.

e. use a conical rather than a barrel shaped expander. This gives much more satisfactory soil packing in the roof area.

f. delay moling until the moisture content at moling depth reaches the plastic range.

Subsoiler failure

When the mole plough is working close to or above its critical depth, a complete wedge of soil is broken out to the surface from half way up the channel wall. With time this wedge settles, leaving the channel with either a flattened roof or with the upper channel section moving into the lower section. The cause of the problem is too shallow a moling depth for the prevailing conditions.

The potential problem can be avoided by increasing working depth, or by either reducing the diameters of the mole foot and expander or removing the expander.

Unconfined swelling failure

With this type of failure, the channel diameter decreases progressively without any significant change in shape, until it effectively disappears completely. The decrease in channel diameter occurs due to a steady swelling of the soil surrounding the channel into the channel area itself, a process termed unconfined swelling. This type of failure tends to occur in situations where there is rarely a moisture deficit at mole channel depth. Weak structured soils are more susceptible than strongly structured soils.

Although this type of failure is not directly affected by implement action, mole channel life in these situations can be extended by forming a larger diameter mole channel in the first instance. Care must be taken when attempting this with a larger foot or expander, not to cause a subsoiler failure.

Slurry failure

Slurry failure occurs mainly as a result of unstable structured soil moving into the channel and swelling excessively to form a slurry, which can block the channel completely. This situation is most likely to arise in the less stable structured soils when significant channel wetting and water flow occurs soon after channel formation.

The problem can be reduced by moling at the beginning of a dry period, so that time is available for the soil to age and restabilise after disturbance, before it is wetted. Alternatively, closure of the leg slot and leg fissures at the channel will help reduce the ingress of soil. This can be achieved by using a larger diameter expander to close the cracks, or through fitting a smooth narrower leg to the plough, to reduce the size of the cracks initially formed. Where the problem arises through the presence of free water in the profile at the time of moling, a sacrificial moling to dewater before the final moling will help minimise the problem.

Topsoil failure

Failure occurs in this situation as a direct result of topsoil falling into the channel through the leg slot and associated leg fissures formed by the mole plough. The rate of infill is frequently increased by surface cultivations when the cracks are wide. This situation can arise following installations under dry soil conditions when large leg fissures are formed, or as a result of extensive soil drying and shrinkage to mole channel depth later. It is most likely to occur on smectitic clay soils in the higher moisture deficit areas.

Moling at higher moisture contents will reduce the problem at installation and deeper moling to reduce leg crack shrinkage at moling depth, will inhibit infill during dry periods. The use of a larger expander would also assist in reducing crack width at the mole channel itself.

CONCLUSIONS

It has not been possible to date to fully quantify the benefits likely to accrue from the suggested modifications to the standard mole plough and moling technique in specific field situations. Nevertheless, results from the limited field trials which have been possible, are sufficiently encouraging to justify the presentation of these suggestions. The suggestions are made to aid future mole drainage investigations in areas where problems are being experienced with the technique at present.

ACKNOWLEDGEMENTS

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SOIL TYPES AND CHARACTERISTICS AT TWO DRAINAGE TEST PLOTS IN THE NILE DELTA

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ABSTRACT

Soil characteristics and their variability were studied at two drainage test plot areas, El Genina and El Sirw, to provide information for design and installation of subsurface drainage in the area. The land at El Genina is considered developed and matured, while that at El Sirw is newly reclaimed and has not matured.

The land at El Genina is more productive than that at El Sirw. Considerable spacial variability in soil salinity, soil texture and saturated hydraulic conductivity was found at both test plot areas. The soil conditions at El Genina indicate more potential difficulty in establishing effective subsurface drainage there than at El Sirw. Though it had a lower EC than that at El Sirw, its exchangeable sodium percentage and soil bulk density were greater and its saturated hydraulic conductivity was less than that at El Sirw. The better crop performance at El Genina than at El Sirw is attributed to maturity of the land.

The cultivated land in the Delta area of Egypt has been under perennial irrigation and multiple cropping since the early part of of the century. This has caused a rise in the water table in the water table and an aggravation of soil salinization in the area. About one third of the whole Delta area is salinized (Arar and Bishay 1973, El Gabaly 1979). The problem is worse in the northern part of the Delta area, where more than two thirds of the land is salt affected. Adequate drainage is required to lower the water table, remove the salts and improve the productivity of the land.

In 1984 Egypt and the Canadian International Development Agency (CIDA) entered into a program to increase the productivity of some 30 000 ha of land in the Governorate of Daqahlia. Part of the program included installation of two drainage test plots of about 80 ha each, to provide information necessary in designing subsurface drainage for the total area. One of the test plots in the southern end of the block of land to be improved (El Genina) located near Dikirnis, is in land that has been cropped for decades, referred to as mature developed land (Fig. 1). The other site (ElSirw) on the northern edge of the block of land to be improved is located near the salt lake Manzala, which opens into the Mediterranean Sea. The land has not been cropped as long as that at El Genina, and is referred to as newly developed and not matured.

At both sites the topography is flat, The soil is generally fine textured, though it is finer textured at El Genina than at El Sirw. At El Genina the land is well developed and productive. Its surface elevation is about three meters above sea level. At El Sirw the land, considered newly developed, is not as productive and has not been developed and matured as at El Genina. Its surface elevation is less than one meter above sea level.

Variability of the soils in this area is not known. A knowledge of the soil characteristics is necessary to properly design a subsurface drainage system for the area. One of the objectives for the drainage test plots was to study various soil characteristics and their variability throughout the test plot areas, and to relate these characteristics and their distribution to drain performance and land improvement. This information will be used in designing and providing subsurface drainage throughout the 30 000 ha project area.

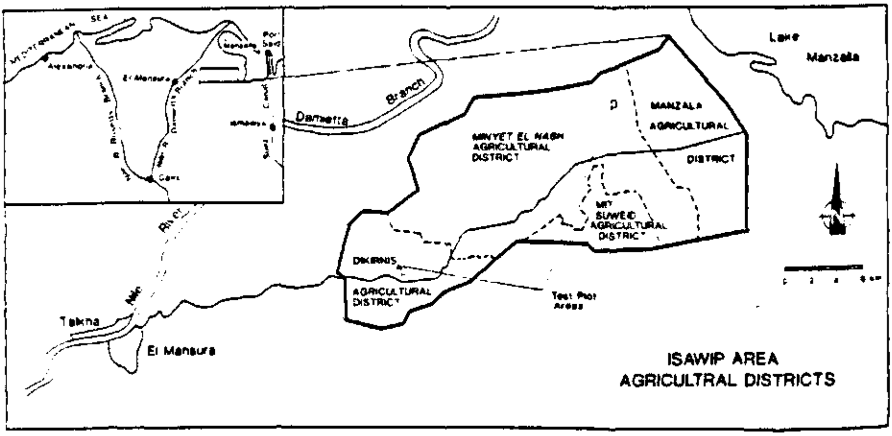

Fig. 1 Map indicating the block of land to be improved in the ISAWIP project and the locations of the test plot area within the block.

MATERIALS AND METHODS

Disturbed and undisturbed soil samples were collected from successive layers on a 200-m grid at each test plot for measuring chemical and physical properties. The pH of the soil paste, soluble cations and anions of the saturation extract and exchangeable cations were determined according to methods described by Page (1982). Particle size distribution was determined by the standard pipette method (Black 1965). Soil moisture retention characteristics and bulk density were determined on the undisturbed soil samples (Black 1965). In situsaturated hydraulic conductivity was determined by the auger hole method (van Beers 1979), using holes two meters deep.

The data for each soil property studied from each grid point were grouped into three depth intervals: 0 to 30, 30 to 90 and 90 to 150 cm from which the weighted average for that depth interval was derived. The 0 to 30 cm depth represents that depth most affected by management and evaporation. The 0 to 90 cm depth is the root zone, affected mostly by management and cropping practices. The 90 to 150 cm depth is that zone in which the subsurface drains are normally installed, and is that zone where groundwater movement can be limiting.

The data were summarized and analyzed, using means, standard deviations and coefficients of variability.

RESULTS

Chemical Properties - The soil at both El Genina and at El Sirw would be classified as non saline alkali, according to USDA Salinity Laboratory Staff (1954). Though the mean of the pH for the soil paste from the 0 to 30 cm depth, over all grid points, was 7.50 (sd = 0.27, range - 7.14 to 7.95) at El Genina, and 7.54 (sd = 0.27, range - 7.23 to 8.14) at El Sirw. Below this depth the pH at both test plot areas ranged from 7.08 to 8.31, except at the 90 to 120 cm depth at one location in El Sirw where it was 8.99. This was a local condition, as the pH immediately above and below was 7.50 and 7.52, respectively. There was calcium carbonate in the soil at all depths throughout both test plot areas, ranging from 0.2 to 4.7%. Generally, within each profile there was a zone where the $CaCO_3$ accumulation was greater than that in the rest of the profile.

The saturation extract from most of the area at El Genina, 0 to 30 cm depth, had an EC of less than 8 dS m-1 (Fig. 2). The mean was 4.1 dS m-1 (Table 1). The EC values for the 30 to 90 and 90 to 150 cm depths were 4.3 and 4.8 dS m-1, respectively (Table 1), indicating only a small net downward salinity gradient. The standard deviations at the 30 to 90 and 90 to

150 cm depths are smaller than that at the 0 to 30 cm depth. Except for about 10% of the area, on the side toward the north end, the data indicate salinity was not a serious problem at El Genina. Crop vigor support this statement.

Table 1. - Means, Standard Deviations and Range of Variability For Soil Chemical Properties at El Genina and at El Sirw.

Property	Depth cm	El Genina Mean	El Genina sd	El Genina Range	El Sirw Mean	El Sirw sd	El Sirw Range
EC (dS m^{-1})	0-30	4.1	3.4	0.9-13.5	4.9	3.2	1.2-11.3
	30-90	4.3	2.8	1.3-10.7	5.1	2.9	1.1-11.5
	90-150	4.8	2.7	1.3- 9.4	8.6	6.3	1.1-22.0
SAR	0-30	8.4	6.5	1.0-21.2	9.1	6.2	2.8-24.1
	30-90	15.3	18.3	5.7-77.7	13.3	7.5	2.6-23.3
	90-150	13.6	4.9	6.4-23.2	22.0	11.7	2.7-43.5
ESP	0-30	38.3	7.2	28.7-47.3	14.2	8.3	6.1-35.7
	30-90	41.5	4.0	27.9-49.4	22.8	7.5	9.8-36.5
	90-150	45.6	6.6	30.0-52.8	30.9	8.3	13.7-42.6

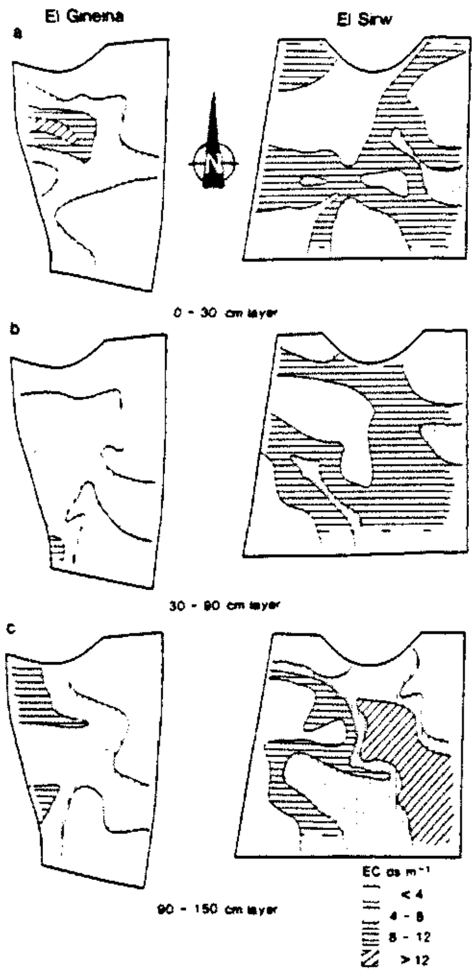

Fig. 2 Salinity distribution across the test plot areas, as indicated by EC, at 0 to 30, 30 to 90 and 90 to 150 cm depths.

At El Sirw the EC of the saturation extract from the 0 to 30 cm depth was mostly below 8 dS m-1 throughout most of the area (Fig. 2). Only small areas on the south and east sides had EC values greater than 8 dS m-1. The mean EC at this depth 4.93 (Table 1) was greater than that at El Genina. At the 30 to 90 cm depth about 50% of the area had an EC greater than 8 dS m-1 and more than 20% had an EC greater than 12 dS m-1. The mean EC for the the 90 to 150 cm depth was 8.65 dS m-1. A net downward salinity gradient is evident. The data and crop vigor both indicate that salinity is a greater problem at El Sirw than at El Genina.

Spacial variability of EC in the surface 0 to 30 cm and 30 to 90 cm depths was similar at both test plot areas (Table 1). But at the 90 to 150 cm depth there was more spacial variability at El Sirw than at El Genina.

The soluble cations in the saturation extract were dominantly sodium, and the dominant anions were chloride and sulfate. The ratio of sodium to calcium plus magnesium, as indicated by the sodium adsorption ratio (SAR) increased with depth at both test plot areas. However, that at El Genina at the 90 to 150 cm depth, 13.6 (Table 1), was considerably less than that at El Sirw, 22.0. The variability was also less at El Genina than that at El Sirw.

The exchangeable sodium percentage (ESP) of the soil was high at all depths at both El Genina and at El Sirw (Table 1). But, at El Genina, where the EC was lower than that at El Sirw, the ESP for all depths was higher than that at El Sirw. There was no correlation between ESP and SAR. The low ESP in the 0 to 30 cm depth at El Sirw is attributed to gypsum being applied to the land.

Fig. 3 Characteristic cracks, columns and structure of the soils at El Genina and El Sirw.

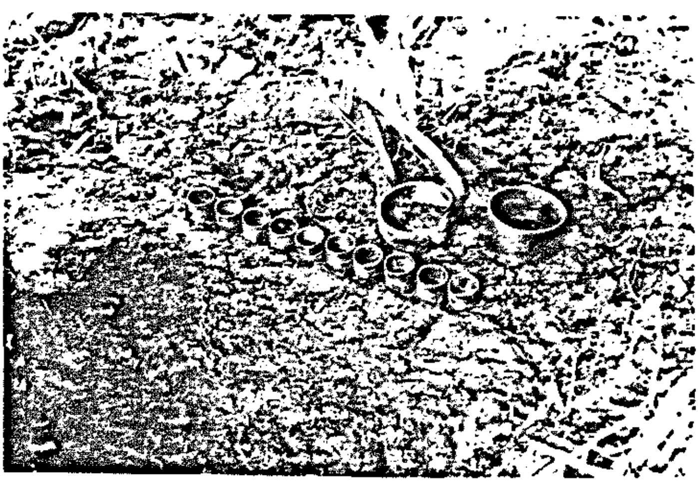

Fig. 4 Structured soil of wet soil, lower right, after months of flooding for rice.

Physical Properties - The soil at both El Genina and El Sirw was fine textured at all depths (CL, SiCL, SiC,and C), and the surface soil was well structured. When dry, wide deep cracks developed, forming soil columns (Fig. 3) as much as 30 cm across. The columns comprise blocky subangular aggregates. These blocky subangular aggregates (Fig. 4) retained their identity when wet, and the planer surfaces of the cracks, even after prolonged flooding for rice. Bouma (1986) reported that cracks in Dutch clays did not close completely upon swelling, also. When dry the aggregates became very hard and difficult to crush.

The clay content of the soil at El Genina exceeded 40% for most of the area and at all depths (Fig. 5). The averages were 44.3, 43.4 and 45.2% clay for the 0 to 30, 30 to 90 and 90 to 150 cm depths, respectively (Table 2). While at El Sirw the average clay contents were 39.4, 40.2 and 43.9% at 0 to 30, 30 to 90 and 90 to 150 cm depth. At El Genina the variability in clay content was less than that at El Sirw. Also, at El Genina the silt content was the most variable soil separate while at El Sirw the variability was similar for all separates (Table 2).

Table 2. - Means, Standard Deviations and Range of Variability For Soil Physical Properties at El Genina and at El Sirw.

Property	Depth cm	El Genina Mean	El Genina sd	El Genina Range	El Sirw Mean	El Sirw sd	El Sirw Range
Cse sand %	0-30	1.6	0.3	0.3- 1.4	0.9	0.6	0.1-2.6
	30-90	0.8	0.6	0.1- 1.9	0.4	0.4	0.1-1.6
	90-150	0.7	0.9	0.2- 2.9	0.6	0.4	0.1-1.3
Fine sand %	0-30	24.1	4.9	13.1-32.1	26.7	7.1	10.6-40.6
	30-90	22.3	8.0	11.8-39.3	23.4	6.3	9.2-35.0
	90-150	19.0	6.8	7.2-28.5	23.4	5.5	12.3-34.2
Silt %	0-30	30.0	7.2	16.8-45.8	33.0	6.2	17.2-50.5
	30-90	34.5	10.5	13.7-47.6	35.8	7.6	22.7-49.6
	90-150	32.6	8.1	19.0-47.9	32.4	7.5	19.1-45.3
Clay %	0-30	44.3	4.6	38.0-52.8	39.4	6.1	26.2-51.0
	30-90	43.4	2.1	39.8-45.5	40.2	6.2	30.8-56.4
	90-150	45.2	6.1	38.3-52.3	43.9	7.3	30.9-61.5
PAW[a] Vol%	0-30	24.7	3.1	20.0-31.0	21.2	2.1	17.0-23.0
	30-90	25.1	3.2	19.5-31.5	22.0	2.4	20.0-26.5
	90-150	25.6	4.0	18.0-29.0	21.9	2.6	19.0-26.5
db[b] Mg m^{-1}	0-30	1.20	0.07	1.12-1.40	1.05	0.02	1.02-1.18
	30-90	1.26	0.07	1.12-1.34	1.15	0.04	1.12-1.22
	90-150	1.32	0.07	1.21-1.44	1.23	0.03	1.18-1.26
DPV[c]%	0-30	16.6	2.5	11-21	16.5	3.3	12-21
	30-90	15.1	2.2	13-20	14.3	4.2	9-20
	90-150	15.1	3.4	11-22	14.7	3.9	11-18
Ks[d] m d^{-1}	0-30	0.12	0.08	0.02-0.26	0.46	0.32	0.02-0.94

a - Plant available water (30 - 1500 kPa suction)
b - Soil bulk density
c - Drainable pore volume
d - Saturated hydraulic conductivity

There was no statistical correlation between clay content and plant available water (PAW), ie, 30 to 1500 kPa suction, in the soils at both test plot areas. But the PAW at El Genina, where the soil was finer textured and more dense, was more than three percentage points greater than that at El Sirw, for all depths (Table 2).

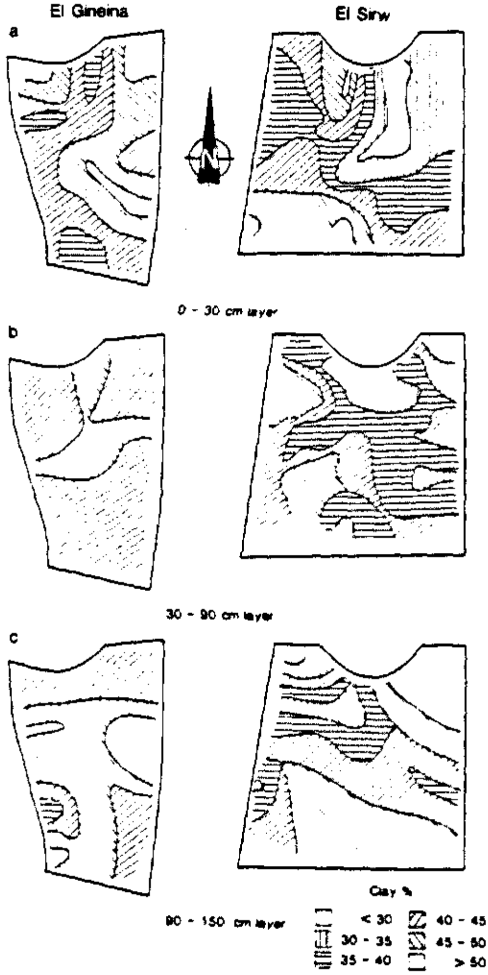

Fig. 5 Clay distribution across the test plot areas at 0 to 30, 30 to 90 and 90 to 150 cm depths.

Soil bulk density (db) at both El Genina and El Sirw increased with depth (Table 2). But at El Genina the db was from 0.09 to 0.15 Mg m-3 greater than that at El Sirw. This increased db resulted in 3 to 5% less porosity in the El Genina soil than that at El Sirw. Porosity at both test plot areas, at all depths, exceeded 50%. Classically, normal mineral soils have about 50% porosity (Baver et al 1972).

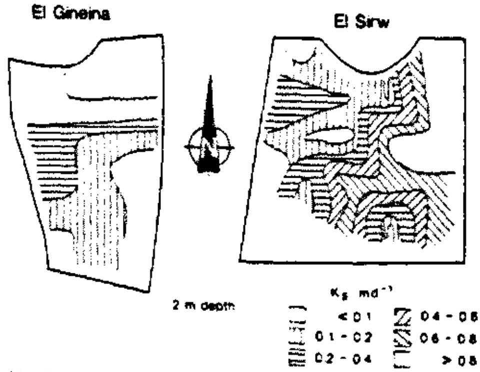

Fig. 6 Variability in saturated hydraulic conductivity of the soil across the plot areas, determined by 2-m depth auger hole method.

The saturated hydraulic conductivity (Ks), which indicates the rate of water movement in the soil, was smaller and more variable at El Genina than at El Sirw (Table 2). At El Genina there were areas along the east side and in the southwest corner where the Ks was less than 0.1 m d-1 and most of the area had Ks values of less than 0.2 m d-1 (Fig. 6). At El Sirw there were small areas where the Ks was less than 0.1 m d-1, otherwise, most of the area had Ks values exceeding 0.2 m d-1

DISCUSSION

Spacial variability of the soil properties studied was general at both test plot areas. Effective subsurface drainage is dependent on the ability of the soil to transmit free water, which is dependent on pore size distribution, saturated hydraulic conductivity and soil aggregate stability. These properties are dependent on soil texture and structure, and the salts in the soil. Usually, sodic soils become dispersed during reclamation, if amendments are not applied to prevent it.

Based on crop appearance, there was less limitation to crop production at El Genina than at El Sirw. Yet the data indicate there could be more soil problems in establishing effective subsurface drainage and reclamation there than at El Sirw. The soil at El Genina is more sodic and finer textured, has a greater bulk density and smaller saturated hydraulic conductivity than that at El Sirw. There is not really an indication of a net downward salt gradient at El Genina, while at El Sirw there is good indication of a net downward salt gradient.

Application of gypsum is recommended at both sites to displace the sodium on the clay complex, to prevent dispersion during reclamation. Currently gypsum is being applied to the land at El Sirw, where displacement of sodium to lower depths is apparent. Similar displacement in Israeli soils is reported by Nadler and Margaritz (1986). Subsurface drainage is necessary to prevent a salt and sodium buildup, to further limit soil productivity of this land.

The level of exchangeable sodium at both sites is sufficient to cause soil physical problems during reclamation, according to USDA Salinity Laboratory Staff standards (USDA 1954). Yet the soil remains well aggregated when wet. According to Wahdan et al (1985) the swelling and shrinking process during the wetting and drying cycles causes aggregation for good soil structure, pore size distribution, and air and water permeability. Care should be taken to maintain the good stable soil aggregation of these soils during reclamation. One of the reasons for nondispersion of these soils could be because of the low level of alkalinity, to give a lower surface potential of these soils than one could expect at higher pH values and thus reduce their dispersion tendency. Sommerfeldt (1984) has reported the dependence of surface potential of clays on pH. Another reason could be associated with the stability of the aggregates formed, to increase the amount of macro pores in the system. In irrigation, preferential flow of water would be through the macropores as explained by (Bouma 1981). The evidently has become stabilized along these preferential flow courses, through chemical and/or physical processes, so that dispersion does not happen during irrigation.

In conclusion, based on soil conditions, effective subsurface drainage would be easier to achieve at El Sirw than at El Genina. Yet, according to crop performance, location and setting El Sirw would benefit most from drainage. The soil at El Genina has more clay, has greater bulk density and lower saturated hydraulic conductivity than that at El Sirw. Yet El Sirw is at sea level and is located near a saline body of water, to prevent natural drainage. However in draining the area caution should be taken to prevent marine water intrusion under the area, at shallow depth, and further salinize the area.

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DETERMINING THE POTENTIAL FOR OCHRE FORMATION IN ALLUVIAL SOILS*

Cade E. Carter, J. S. Rogers, and J. L. Fouss**

The design of subsurface drainage systems is concerned primarily with depth and spacing of drain lines and whether or not envelope material is needed. Another very important consideration is whether iron ochre may form and clog the drain lines. If there is a potential problem with ochre, a solution should be included in the design. Thus, when collecting data for the design of subsurface drainage and irrigation systems, engineers should determine the potential for ochre formation and recommend suitable control measures.

Ochre was described by Ford (1982) as a red to tan gelatinous deposit containing iron in association with bacterial slimes. Iron ochre formation is a complex process whose detailed description is beyond the scope of this paper. In simple terms, iron ochre formation requires aerobic conditions and three ingredients: 1) ferrous iron (Fe^{++}), 2) a bacteria such as Leptothrix, Toxothrix, Gallionella, or Sphaerotilus, and 3) a carbon or energy source. In many soils, bacteria, carbon, and aerobic conditions readily exists; thus, all that is needed for ochre formation is sufficient quantities of Fe^{++}. Since Fe^{++} is the primary variable, it is often considered the controlling raw material for ochre formation.

Iron is found in most soils but not always in the ferrous form. In surveying soil for its potential for ochre formation, tests for both total and ferrous iron are desirable. A soil that tests positive for total iron but negative for ferrous iron may still be a candidate for ochre formation since flooding the soil can cause the iron to change its form. Reduction of iron from ferric (Fe^{+++}) to ferrous (Fe^{++}) forms is considered to be a result of respiratory metabolism of the microorganism (Takai and Kamura, 1966). In anaerobic conditions that occur in poorly drained soil, the form change is described by the following equation.

$$CH_3COOH + Fe^{+++} \longrightarrow Fe^{++} + 2\ CO_2 + CH_4$$

In several experimental subsurface drainage systems that were installed in Louisiana during the 1970s, ochre formed readily in the drain outlets of some systems but not in others. Interest in possible reasons why some drainage systems had ochre while others did not, prompted a Fe survey of these drainage sites. We were particularly interested in establishing criteria to determine which soil types were likely for ochre formation. In the future, particular attention could be given to those soil types when designing subsurface drainage systems. Thus, the purposes of this survey were: 1) to determine the presence of total Fe and Fe^{++} at nine subsurface drained sites in Louisiana to determine if the potential for ochre could

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have been predicted prior to the drain installation and 2) to relate the presence of iron in the soil and/or the presence of ochre in the drain outlets to various soil types to determine which soils were more likely to have an ochre problem.

PROCEDURE

Seven Parishes in South Louisiana were selected for this survey. These were selected specifically because of the availability of a subsurface drainage system in each where ochre, if present, could be observed in the drain outlets. The approximate locations are shown in Figure 1 and are labeled with the Parish name, numbered 1 through 7. In two Parishes, Iberville and Terrebonne, two systems were installed on different soil types. Some of the major soil types found in the lower Mississippi Valley such as Commerce, Sharkey, Mhoon, Baldwin, and Jeanerette, are represented in these Parishes.

A test kit developed by Ford (1982) which included a Hach*** total Fe test kit was used to estimate Fe concentrations in water samples taken in this survey. The kit included a small plastic container for collecting water samples, a Swinnex 47 mm diameter filter holder, filters (0.45 µm), syringes for handling the water sample, sulfamic acid-phenanthrolene reagent for treating the filter, an iron reagent for total iron determinations, and a cube color scale and reservoir for matching the color of the sample to obtain an estimate of the Fe and total Fe concentrations.

The ability to detect iron concentrations with the kit was determined in the laboratory by mixing a 5 g/ml solution of Fe^{++} and processing the sample as if it were a water sample from the field. The sample matched the 5 g/ml concentration color on the scale perfectly. A sample of distilled water was also processed as if it were a water sample from the field and it showed no Fe in the water. Since the kit indicated the correct iron content of these two extreme values, it was assumed that it would also indicate intermediate iron concentrations correctly.

At each test site: 1) a 70-mm diameter hole was augered into the soil to a depth just below the water table, 2) a water sample was collected from each hole by suspending a small plastic sample collector on a line and lowering it into the water, 3) the water sample was removed from the container with a syringe and forced through the sulfamic acid-phenanthroline reagent treated micropore filter into another syringe for the Fe^{++} test, 4) after allowing time for the color of the sample to stabilize, the sample was then placed in the color cube where its color was matched with one of the five shades on the color chart, each of which represented an iron concentration ranging from 1 to 5 g/ml, and 6) the concentration of iron, as indicated by the color chart, was recorded in g/ml.

Another sample of water was taken from the same hole, filtered through a nontreated 0.45 µm millipore filter, then placed in a color cube reservoir with a FerroVer iron reagent provided in the Hach test kit. After mixing the sample with the reagent and allowing time for the color of the sample to fully develop, the Fe total concentration was determined by matching the color of the sample with one of those on the color cube. The results were recorded as total iron in g/ml.

*** Trade and company names are listed for the benefit of the reader and does not imply endorsement or preferential treatment by the U. S. Department of Agriculture.

In this survey, a positive test for total iron was considered as an indication that ochre formation was possible, whereas the presence of ferrous iron indicated that ochre formation was likely. The standards provided by Ford in the test kit were used to indicate the severity of the ochre problem as follows: the potential for ochre was considered slight when tests for Fe^{++} showed some pink color, but were less than one g/ml on the color cube. The potential for ochre was considered severe if color cube readings were 3 g/ml or more .

Three or more holes were augered (six water samples collected) from the soil types on which the subsurface drainage systems were installed at each location. Additional holes were augered and the water was sampled and tested from other soil types at each location to determine if the presence of iron and the potential for ochre could be correlated with soil type.

Soil physical data for each site were assembled from USDA-SCS Soil Survey publications or from SCS personnel to determine if trends could be established to show areas where ochre may be a problem.

RESULTS AND DISCUSSION

The Fe^{++} test kit, developed by Ford (1982), and the total Fe test kit by Hach seemed to work satisfactorily. There were several cases, however, where the results were somewhat confusing. In each of these cases, the filter did not remove all the sediment from the water samples and these tests indicated relatively high Fe concentrations. If, however, sampling was delayed to allow some of the sediment to settle before the test was made, Fe concentration was considerably less. Thus, it was not known if the lower value of iron was correct or if the sample had become oxidized during the delay in taking a sample from the augered hole.

Fe^{++} was measured in water samples at five of nine subsurface drainage sites (Table 1). Ochre was observed in the drain outlets at five of nine sites. With two exceptions, the same sites at which Fe^{++} was measured also had ochre. The two exceptions were the Commerce site in St. James Parish where no Fe^{++} was measured but considerable amounts of ochre have been observed and the Baldwin soil in St. Mary Parish where iron was indicated by the tests but no ochre was observed in the drain lines.

The site with the highest Fe concentration and the most ochre accumulation in the drain outlet pipe was Commerce silt loam soil in Terrebonne Parish. Although ochre accumulated, the drains never clogged. During periods of little or no rainfall, the amount of water flowing from the drains declined and ochre accumulated in the drain outlet. Sometimes, ochre would fill over half of the 200-mm diameter drain outlet pipe. Before it completely filled the pipe, however, rainfall occurred which increased drain outflow and most of the ochre was flushed out of the drain outlets. The drains at this site, which were wrapped with Typar filter fabric, have been functioning satisfactorily since they were installed in 1977. There has been a problem, however, with the plumbing and valves associated with the pumping systems used in removing the drain outflow from the sump. A reddish-tan colored material similar to ochre but with no slime, accumulated in the plastic pipes. After seven years, this accumulation was so severe that the plumbing system had to be replaced. The material in the plastic pipes, could be removed mechanically but the accumulation in the ells and other bends was particularly difficult to remove.

High Fe concentrations were found in a Mhoon silty clay loam soil also in Terrebonne Parish about 8 km south of the Commerce site (Table 1). Some of the subsurface drains at this site were wrapped with nylon filter material while others had no filters. In both cases ochre formed readily in the drain outlet pipes and coated the sump, pump, and plumbing. This drainage system was installed in 1972 but abandoned in 1976 when land ownership changed. In 1976, several drains were excavated and examined for ochre. Some accumulation of both reddish and black slimy substances was found, but accumulation was restricted mainly to the grooves of the corrugated plastic drain tubes. This system, like the one on Commerce soil in Terrebonne Parish, was flushed by increased drain flows during large rainstorms. Clogging problems with plumbing associated with pumping systems in the sumps were not observed at this Mhoon site. Problems with clogging may have developed if the system had remained active.

A site where measurements indicated no Fe^{++} on one occasion and high values on another was Baldwin silty clay in St. Mary Parish. Measurements were made about a month apart and at different depths. Water samples for the first test, when no Fe^{++} was indicated, were from 1.22 to 1.65 m below the soil surface. The second measurements were made when the water table was over 2.0 m below the soil surface (Table 1). At these deeper depths, Fe^{++} was 3 g/ml and Fe total was over 5 g/ml. In spite of the high Fe measurements, ochre has not been observed in the drain outlets. Apparently, iron is in the soil but at a depth far enough below the drains that it does not affect them.

The Commerce silt loam site in Assumption Parish has high potential for ochre formation. Total Fe in the water samples was up to 3 g/ml. Ochre has been observed in the drain outlets at this site, but very little has accumulated since its installation in 1983 because this system has been used for water table management and the drains are submerged much of the time.

The East Baton Rouge (EBR) Parish site indicated higher Fe concentrations than the St. James site but ochre accumulation was observed only at St. James. Ochre accumulated readily at St. James but only a trace of ochre was observed at EBR. The drainage systems were installed in East Baton Rouge in 1975 and in St. James in 1976. Neither drainage system had filter materials on the drains. The subsurface drains at both sites were still working satisfactorily in 1987.

Water samples from Sharkey clay, Convent loam, and Jeanerette silty clay loam in Iberville, Iberville, and Iberia Parishes, respectively, did not show high potentials for ochre formation in the water samples and there was no ochre observed in the drain outlets of the subsurface drainage systems. The drainage systems were installed on the Sharkey soil in 1977 and on the Convent, and Jeanerette soils in 1978.

Soil Texture

One of the objectives of this survey was to determine if certain soil types were more likely than others to have an ochre problem. The soil type and texture at each subsurface drainage site were identified at the time of drain installation. Whether ochre was present in the subsurface drain outlets was determined by observing the drain outlets in the sumps. The soil types and textures were associated with the observations of the presence or absence of ochre in the subsurface drains (Table 1).

Sharkey clay: Sharkey clay soil was tested and no iron found. Since no iron was indicated by testing and since the subsurface drainage system that had been in operation for eight years had no signs of ochre in the drain outlet at the sump, this soil has a low potential for ochre formation.

Jeanerette silty clay loam: No iron was indicated by the Fe tests and the drain outlets in the sumps gave no indication of ochre. This soil has calcium carbonate concretions in much of the profile in which the hole for

Fe testing was augered. Liming to raise the soil pH to a very high level is a concept that has been proposed for controlling ochre. Since this soil is well limed naturally, it has a low potential for ochre formation.

Commerce silty clay loam: This soil has high potential for ochre formation. The Fe tests indicated high potential and ochre was observed in the drain outlets.

Mhoon silty clay loam: This soil has high potential for ochre formation. The Fe tests indicated high potential and ochre was observed in the drain outlets.

Baldwin silty clay: This soil is considered as having low potential for ochre formation although Fe tests from far below drain depth indicated otherwise. Fe tests at relatively shallow water tables (less than 1.65 m) where drains are likely to be installed indicated low ochre potential and no ochre has been observed in the drain outlet.

Tunica and Tunica-Sharkey clay: Water samples from these soils indicated that they have high potential for ochre formation. Since no subsurface drainage systems have been installed on these soil types, there were no ochre observations available. The water sample from the soil identified as Tunica clay, actually came from silty clay loam which was underlying the clay.

Methods for Ochre Control

Although the authors did not test ochre control methods, several means of control are listed here because of the apparent need for them in Louisiana. Several of these control methods were discussed in more detail by Ford (1982).

Submerging drains lines to provide anaerobic conditions is a popular way of attempting to control ochre. It has been effective in Finland (Maenpaa, 1974, 1977) but not in Germany (Kuntze, 1968). In Denmark, submerging the drains slowed the formation of ochre (Grant, 1986). In many cases, this technique is used after ochre is discovered. If this is the selected method of control, it should be considered when designing the system so drain depth can be adjusted accordingly.

Organic filter materials have been somewhat successful in reducing or slowing the ochre problem. Materials such as sawdust, straw, and coconut fiber aids in reducing ochre because of their gradual deterioration which prevents the ochre from becoming permanently attached to the filter material. Filters with bark chips from mimosa and oak trees were somewhat successful in Germany (Kuntze, 1972). The bark releases acid which keeps the iron in solution and thus prevents the formation of ochre.

Copper in the drain lines or filter, liming the drain trench, and increasing the size of water entry openings in the draintubes have all been used to reduce the ochre problem. A new effort to control ochre was announced recently by Hancor that involves marketing drain tubes that are impregnated with a chemical that controls ochre. This concept is excellent if the chemical does not pollute the ground water.

The need for ochre control measures should be determined in the planning stages for subsurface drainage or water management systems. If control measures are needed, they should be included in the system design.

SUMMARY

The test kit by Ford and Hach worked satisfactorily in evaluating iron content of water samples. Fe concentrations, as indicated by the test kits correlated reasonably well with observations of the presence or absence of ochre in the drain outlets.

The Fe tests and observations in Louisiana show that Commerce and Mhoon soils have a higher potential for ochre formation than does Sharkey clay, Convent loam, or Jeanerette silty clay loam. Thus, when subsurface drainage and water management systems are planned for Commerce and Mhoon soils, measures to control ochre should be included in the design of the system.

Baldwin soil showed high potential at deep but not at shallow depths. Since no ochre was observed in the drain outlet, it is considered as having low ochre potential.

Relatively high Fe concentrations did not always correspond with observations of ochre accumulations in the drain outlets. Depth of sampling may be an important consideration when evaluating ochre potential.

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Table 1. Iron Sampling Sites, Soil Types, Sampling Depth, Fe Concentrations, and Ochre Observations.

Site (No.)	Location (Parish)	Soil Texture	Soil Name	Hole Depth (cm)	--Fe Content-- Fe^{++} (g/ml)	Total (g/ml)	Ochre Observed
1A	E. Baton Rouge	loam	Commerce	91	<1	1	yes
1B	E. Baton Rouge	loam	Commerce	140	<1	1	yes
1C	E. Baton Rouge	loam	Commerce	107	<1	1	yes
1D	E. Baton Rouge	sicl	Mhoon	160	1	2	a
1E	E. Baton Rouge	sicl	Mhoon	160	0	1	a
1F	E. Baton Rouge	sicl	Mhoon	183	0	<1	a
1G	E. Baton Rouge	clay	Tunica-Sharkey	162	0	0	a
1H	E. Baton Rouge	clay	Tunica-Sharkey	91	1	2	a
1I	E. Baton Rouge	clay	Tunica-Sharkey	173	<1	1	a
2A	Iberville	clay	Sharkey	165	0	0	no
2B	Iberville	clay	Sharkey	173	0	1	no
2C	Iberville	clay	Sharkey	183	0	0	no
2D	Iberville	sicl	Mhoon	163	0	0	a
2E	Iberville	sicl	Mhoon	168	0	0	a
2F	Iberville	sicl	Mhoon	173	0	0	a
2G	Iberville	sicl	Commerce	91	0	0	a
2H	Iberville	sicl	Commerce	140	0	<1	a
2I	Iberville	sicl	Commerce	107	<1	1	a
2J	Iberville	loam	Convent	151	0	0	no
2K	Iberville	loam	Convent	160	0	0	no
2L	Iberville	loam	Convent	155	0	0	no
3A	Assumption	sil	Commerce	184	0	1	yes
3B	Assumption	sil	Commerce	166	0	3	yes
3C	Assumption	sil	Commerce	213	<1	3	yes
4A	St. James	sil	Commerce	173	0	1	yes
4B	St. James	sil	Commerce	165	0	0	yes
4C	St. James	sil	Commerce	165	0	0	yes
4D	St. James	clay	Tunica	145	<1	1	a
4E	St. James	clay	Tunica	144	<1	1	a
4F	St. James	clay	Tunica	142	1	2	a
5A	Terrebonne	sil	Commerce	173	3	3	yes
5B	Terrebonne	sil	Commerce	122	1	2	yes
5C	Terrebonne	sil	Commerce	127	0	1	yes
5D	Terrebonne	sicl	Commerce	120	5	>5	yes
5E	Terrebonne	sicl	Commerce	125	2	4	yes
5F	Terrebonne	sicl	Commerce	130	3	4	yes
5G	Terrebonne	sicl	Mhoon	120	2	3	yes
5H	Terrebonne	sicl	Mhoon	125	2	3	yes
5I	Terrebonne	sicl	Mhoon	130	<1	1	yes
6A	St. Mary	sic	Baldwin	131	0	<1	no
6B	St. Mary	sic	Baldwin	122	0	<1	no
6C	St. Mary	sic	Baldwin	165	0	0	no
6D	St. Mary	sic	Baldwin	213	3	>5	no
6E	St. Mary	sic	Baldwin	218	3	>5	no
6F	St. Mary	sic	Baldwin	202	0	1	no
7A	Iberia	sicl	Jeanerette	142	0	0	no
7B	Iberia	sicl	Jeanerette	130	0	0	no
7C	Iberia	sicl	Jeanerette	142	0	0	no

[a] No subsurface drainage system at this site.

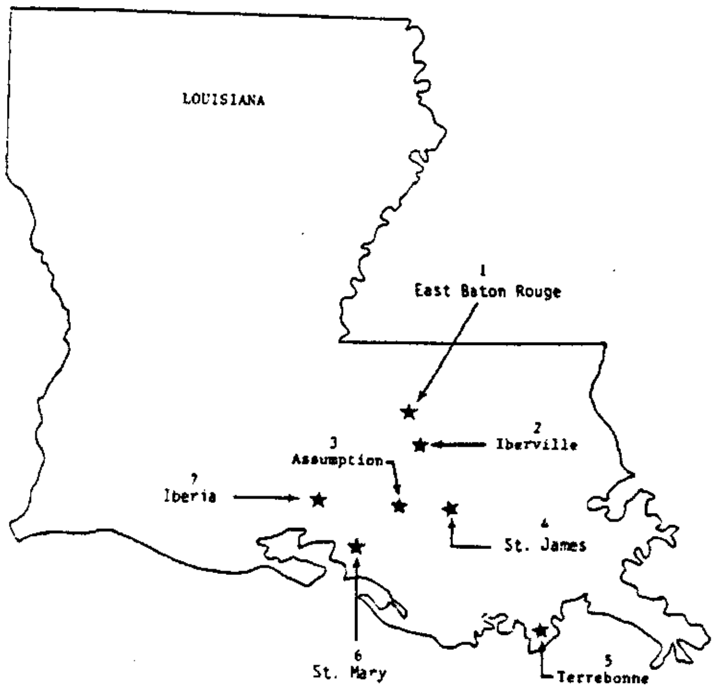

FIGURE 1. Location of iron sampling and subsurface drainage system sites in Louisiana, USA.

DESIGN PROCEDURES FOR WATER TABLE MANAGEMENT SYSTEMS IN NORTH CAROLINA

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Approximately 40 percent of the crops in North Carolina are grown on poorly drained soils. The drainage of cropland has been one of the most important components of land management in eastern North Carolina with drainage projects initiated as early as the late 1600's. Traditionally, drainage systems consisted of open ditches spaced approximately 100 m apart and provided predominately surface drainage. Surface drainage systems have made crop production possible on many soils that otherwise would not have been profitable. However, on many of these soils, this traditional drainage system does not remove excess water rapidly enough to provide an optimum soil water environment for crop production.

Subsurface drainage systems gained favor in North Carolina during the three decades prior to 1980. During this time, federal cost share programs assisted farmers in installing drainage tile or tubing on nearly 500,000 hectares. While production efficiency has been improved on many sites by subsurface drainage, over 50 percent of the poorly drained soils in North Carolina could benefit from more intensive subsurface drainage resulting in increased production efficiency and reliability.

As a result of the emphasis placed on drainage, agricultural runoff has been implicated for the degradation of water quality and the destruction of many saline primary nursery areas due to fresh water runoff (Gilliam and Skaggs, 1985; Jones and Sholar, 1981; and Magette and Weismiller, 1984). The restrictions on land development and drainage imposed by the 1985 Food Security Act in conjunction with the depressed agricultural economy have significantly reduced the expansion of many farming operations through land clearing and drainage. Instead, farmers are looking to more intensive management practices to increase yields and improve production efficiency on land already in cultivation.

In recent years, unusually dry growing seasons have resulted in reduced yields due to dry stress on many traditionally 'wet' soils. Drainage practices of the past did not encourage water conservation. As a result, intensive drainage systems that were necessary to protect cropland during wet periods have tended to overdrain many areas and increase drought damage during unusually dry periods (Doty et al., 1982).

The above problems and concerns have resulted in a rapid shift in North

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Carolina from conventional drainage systems to water table management systems. These systems provide drainage during wet periods, but also eliminate overdrainage by using control-structures to manage the water level in the drainage outlet, and provide subirrigation during dry periods. When properly designed and intensively managed, these systems have shown tremendous potential to improve drainage water quality (Deal et al., 1986; Evans et al., 1987a; Gilliam et al., 1978, 1979; and Skaggs et al., 1982).

It has long been recognized (van Schilfgaarde, 1965, 1970) that artificial drainage systems should be tailored to the soils, crops and climatological conditions in the area. However, most drainage systems, whether surface or subsurface, have been installed based localized rules-of-thumb. The 100 m ditch spacing used for most surface drainage systems in North Carolina was chosen for convenience of operating field equipment and simplifying system layout rather than on the drainage characteristics of the site. Subsurface drain spacings were recommended based on average soil properties for a given soil series. In many cases, these practices resulted in systems that were less than optimum because soil properties for a specific site are rarely average and thus many systems were either over or under-designed (Skaggs and Tabrizi, 1984).

Over the past 15 years, researchers have developed improved methods for designing and operating water management systems for poorly drained soils. The computer simulation model, DRAINMOD, (Skaggs, 1978) provides an objective method of relating water management system design to soil properties and climatological conditions. Simplified methods for estimating drain spacings for drainage or subirrigation have been derived (Skaggs and Tabrizi, 1986 and Skaggs et al., 1987); and management strategies to provide water conservation (Doty et al., 1982) and improve drainage water quality (Gilliam and Skaggs, 1985) have been developed.

Development of better design methods is indeed a major milestone towards the goal of more efficient operation of water table management systems. However, this alone does not guarantee the acceptance or implementation of these methods in actual practice. Training and guidance must also be provided to potential users. The purpose of this paper is to summarize the procedures and guidelines that are recommended to those individuals involved in the evaluation, design, installation and management of water table management systems in North Carolina. "Agricultural Water Table Management: A Guide for Eastern North Carolina" (Doty et al., 1986) should be consulted for more detailed information.

The design and operation of a functional and efficient water table management system involves five main task:

1. Preliminary evaluation and feasibility
2. Detailed field investigation
3. Design computations
4. System layout
5. Operation and management

The first four task are performed by the engineer or agency responsible for the design of the system and are discussed in this paper. Operational guidelines are considered by the engineer in the overall design process but are ultimately accomplished by the farm manager and are discussed under "Operational guidelines for water table management systems" (this issue).

PRELIMINARY EVALUATION AND FEASIBILITY

Often, an experienced engineer can determine the feasibility of a potential site for water table management by a qualitative site investigation. The presence of six general site conditions will usually indicate whether or not water table management is practical.

Improved Drainage

For most conditions in North Carolina, water table management is practical only on those sites that could benefit from improved drainage. Where drainage is not needed under natural conditions and the only benefit of the water table management system would be subirrigation, conventional irrigation systems will usually be more economical. A soil survey report will indicate the natural drainage conditions for a given soil series. Soils that are classified as either 'somewhat poorly drained', 'poorly drained' or 'very poorly drained' will usually benefit from artificial drainage and are candidates for water table management.

Slope

In eastern North Carolina, soils which can support water table management systems are usually relatively flat. Poorly drained soils rarely occupy landscape positions greater than 2 percent. In fact, very few systems have been installed on slopes greater than 0.5 percent. As the slope approaches 1 percent, the number and cost of control structures necessary to maintain a uniform water table depth usually becomes economically prohibitive. From a physical standpoint, the maximum slope which can be tolerated tends to be site specific and related to hydraulic conductivity. At slopes above 2 percent, a uniform water table depth is difficult to maintain due to lateral seepage when the conductivity exceeds 0.5 m/day. By contrast, when the conductivity is less than 0.5 m/day the cost for the closer drain spacing usually becomes prohibitive. In general, the limiting factor with respect to slope will be economics rather than physical slope conditions.

Hydraulic Conductivity

Hydraulic conductivity is the single most important factor affecting the feasibility of a water table management system. For preliminary planning purposes, hydraulic conductivity can be estimated from values reported in soil survey reports. As with slope, prohibitive hydraulic conductivity values are a function of economics rather than presenting a physical limitation to the design and operation of the system. Potential yield as well as the cash value of the crop will dictate the limiting conductivity for a specific site. At the present price for corn and a potential yield of 10,000 kg/ha, water table management will not likely be economically feasible when the hydraulic conductivity is less than 0.5 m/day.

Impermeable Layer or Seasonal High Water Table

The soils on a potential site must have a barrier at a reasonable depth to prevent excessive vertical seepage losses. A restrictive layer is usually encountered between 2 and 10 m. The existence of the barrier becomes increasing difficult to locate with a hand auger when its depth exceeds 3 m. The presence of a seasonal high water table close to the soil surface is usually sufficient evidence to indicate that the site can maintain a water table at an elevation suitable for subirrigation when the restrictive barrier cannot be located. In addition, the position of the seasonal high water table is a good indicator of the natural drainage of the site.

The location of the seasonal high water table can be determined from a soil survey or by inspection in the field. Gray mottles in the soil profile indicate the position of the seasonal high water table under natural drainage conditions. As shown in Fig. 1, when the gray mottles occur within 0.45 m of the soil surface, the site is a candidate for water table management. As the depth to the gray mottles increases to 1.0 m, the site is marginally suited and excessive seepage may be a problem. In this case, the actual depth to the restrictive barrier should be determined. Soils with gray mottles more than

1.0 m from the surface are naturally well drained. Unless the natural drainage condition can be managed, excessive seepage will occur and the site is not very well suited for water table management.

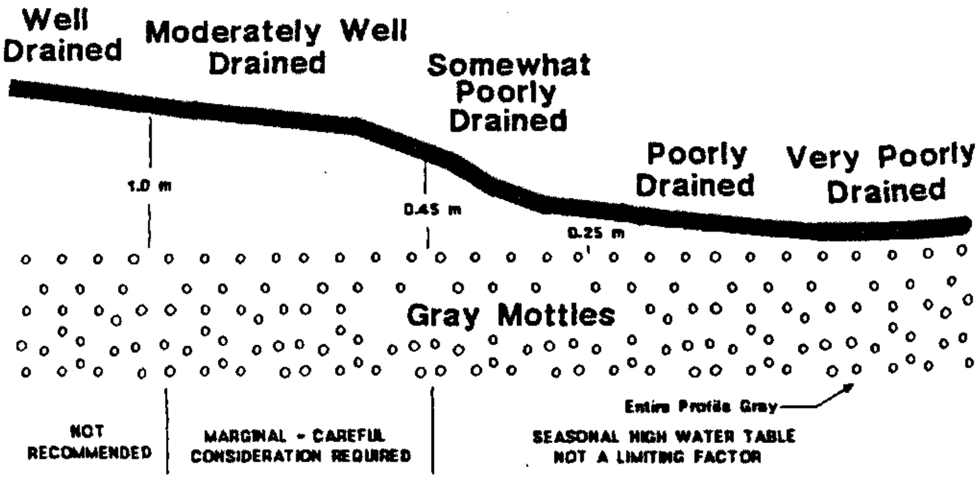

Fig. 1. Location of gray mottles as an indication of site suitability for water table management.

Drainage Outlet

When evaluating the potential of any site for a water table management system, drainage is a primary consideration. A drainage outlet must be available which will remove excessive surface and subsurface water within a 24 hour period. A gravity outlet to an existing stream or canal may be available, or an outlet can be constructed by diking the drained area and pumping the excess water. For a gravity flow system, the drainage outlet should be at least 1.2 m lower than the average land surface for the system.

Water Supply

An adequate source of water must be available if a subirrigation system will be installed. When planning, the location, quantity, and quality of the water source are the key factors which should be considered.

The water source should be located as close as possible to the water table management system to minimize conveyance losses and cost. The quantity of water needed for subirrigation will vary depending upon the weather, crop being irrigated and the rate water is being lost from the field by deep and lateral seepage. As a general rule, a water source must be capable of producing 70 L/min per hectare irrigated. In cases where losses from deep and lateral seepage will be nominal, 50 L/min per hectare irrigated will be adequate. Irrigation water quality in North Carolina seldom presents a problem for subirrigation.

Once the physical suitability of a site for water table management has been determined, the cost of the system should be estimated and discussed with the land owner before any additional time is spent on design. Average cost for many of the components of the system are available in the local Soil Conservation Service or Agricultural Extension Service offices. The dominant costs of the system will be tubing cost and the cost of the water supply. The drain spacing must be estimated before the tubing cost can be determined. At this stage of the design process, it is adequate to estimate the drain spacing from local rules of thumb for either subsurface drainage or subirrigation depending on which alternative is desired.

DETAILED FIELD INVESTIGATION

The field investigation may require several man days for relatively large systems of 100 hectares or more. Water table management systems in North Carolina are typically designed by county Soil Conservation Service staff with assistance from area SCS engineers. As the design of these systems is only one of many services provided by these individuals, they are encouraged to obtain a firm commitment from the land owner to implement the system based on the findings of the feasibility evaluation before proceeding with the detailed field investigation.

Soil Data

Several soil and site properties influence the design of a water table management system. Important properties include: lateral hydraulic conductivity, depth to the impermeable layer, soil-water characteristics, upward flux and drainable porosity as a function of water table depth, arrangement of soil horizons, infiltration, topography and potential rooting depth. The design of the system is more sensitive to some properties than others; some properties are more difficult to measure in the field than others; and some properties are more spatially varied than others. When all of these factors are taken into account, it is not practical to physically measure all of the important properties in the field for every potential site. As mentioned earlier, lateral hydraulic conductivity is one of the most important factors influencing the design of the system and is also one of the most spatially varied properties in the field. Therefore, every effort should be made to determine representative hydraulic conductivity values for each site. System design is also sensitive to upward flux as a function of water table depth, however this property is extremely difficult to determine in the field and is usually estimated from empirical relationships between soil-water characteristic and hydraulic conductivity data. This is also true of drainable porosity and infiltration parameters. The properties that are most practical to measure for a specific site are then: hydraulic conductivity, soil-water characteristic, arrangement of soil horizons, depth to impermeable layer and potential rooting depth.

Hydraulic Conductivity: One of the most important decisions of the field investigation is the determination of the hydraulic conductivity (K). Hydraulic conductivity tends to be spatially varied in most fields (Tabrizi and Skaggs, 1983). As a result, both the location and intensity of hydraulic conductivity measurements are important considerations.

Many methods have been developed for determining in situ hydraulic conductivity. The most commonly used methods are: auger-hole method, tube method, piezometer method, and multiple well methods. Methods for determining K from measured drawdown between drains and/or measured drain outflow have also been used (Dieleman and Trafford, 1976; Skaggs, 1976, 1979). The advantage of the drawdown methods is that they sample a large area and thus lump profile heterogeneities and anisotropys in such a way that a more reliable "field effective" K value is obtained. The disadvantage is that they require considerably more time and equipment than the other methods listed above. The auger-hole method (van Beers, 1970) is generally considered to be the simplest and easiest to use of the methods used in North Carolina.

As a general rule, at least one auger-hole test per 4 hectares is recommended in North Carolina, but as the complexity of the soil increases, more test may be needed to assure that a representative value is obtained. When the average K value measured is less than 0.5 m/day, one test per 2 hectares is recommended.

One conductivity value must be chosen to represent each area of the field to be designed as a single unit. Since K values are usually quite variable, simply computing the arithmetic average of all values measured is not adequate for most design purposes because the resulting design spacing would be too close where the localized K is greater than the average and too wide where the localized K is less than the average. Practice has shown that one of the four possible situations as represented in Fig. 2 are likely encountered under

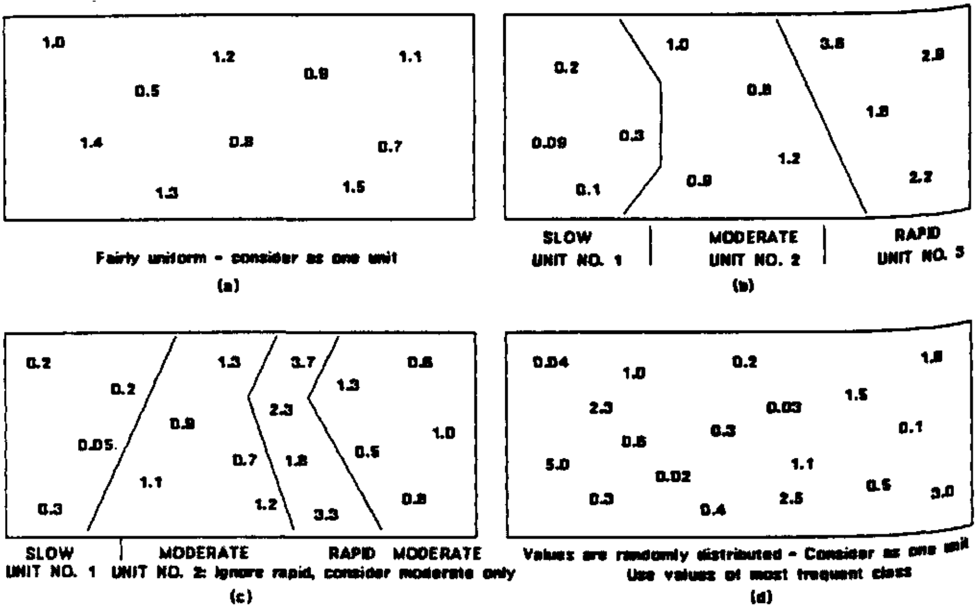

Fig. 2. Spatial variation of conductivity values typically encountered in the field.

field conditions. Practice has also shown that a more cost effect system will result when the field can be subdivided into design units or areas with relatively consistent K values. The range of K values frequently used parallels relative permeability classes found in soil survey reports, Table 1. A design unit is then the section of the field that can be represented by a given permeability class and the design conductivity value for each design area is determined by computing the geometric mean of all K values measured within that permeability class. The geometric mean has been recommended because it results in a slightly more conservative design than the arithmetic average. Preliminary results of an ongoing study (Bentley et al., unpublished data) indicates that the arithmetic mean may be a better estimate of the field effective K.

Table 1. Range of conductivity values used to define relative conductivity classes.

Class	Range of Conductivity Values[a]	
	m/day	in/hr
Very slow	< .03	<.05
Slow	0.03 - 0.31	0.05 - 0.5
Moderate	0.31 - 1.25	0.5 - 2.0
Rapid	> 1.25	>2.0

[a]Values shown are values typically found in soil survey reports. The designer may vary the range of these groupings based on the variability, magnitude, and arrangement of conductivity values found in the field.

Soil-Water Characteristic: Representative soil-water characteristic curves are most important to the system design when this information is used to compute upward flux and drainable porosity versus water table depth relationships. The system design is not as sensitive to spatial fluctuations of the soil-water characteristic relationship as compared to conductivity and thus the measurement frequency need not be as intense. One measurement per 10 hectares at each distinct profile horizon above the design drain depth is usually adequate.

Undisturbed soil cores taken from each layer can be used to estimate the soil water characteristic curve by the pressure plate apparatus (Hillel, 1980). Several weeks are normally required to complete this procedure. When time is limited, the soil-water characteristic curves can be estimated using known relationships for similar soils. Representative curves for fifteen benchmark soils that are frequently responsive to water table management in North Carolina have been developed.

Arrangement of Horizons: The arrangement of horizons within the soil profile affects placement of the drainage tubing and influences the interpretation of hydraulic conductivity data. For the situation shown in Fig. 3a, the drain tubing should be placed at least as deep as the base of the clay loam horizon to reduce the head loss of water entering or exiting the tubing. In addition, it would also be necessary to determine the conductivity of each individual layer. Soil profiles should be described for at least 10 percent of the auger-holes. Soil samples for textural analysis should also be taken at the probable drain depth if there is any question about the need for a drainage envelope. Six typical soil profiles frequently considered for water table management in eastern North Carolina are shown in Fig. 3 along with a brief interpretation of the influence of the horizon arrangement on water table management.

Impermeable Layer: The depth to the impermeable layer (restrictive horizon) is usually determined by boring holes and observing the textural changes which occur between horizons. The changes in texture are determined by feeling the soil. The horizon which is considered to be the most impermeable is determined by estimating the permeability based on texture.

The textural change is very abrupt in some soils, thus determining the depth to the impermeable layer is simple. A restrictive layer can be considered impermeable for design purposes if the conductivity of the layer is one-tenth (0.1) that of the overlying layer. In other soils where the textural change occurs very gradually, a true impermeable layer is very difficult to identify. In these soils, the depth to the most dense material should be considered the impermeable depth.

In many cases in eastern North Carolina, the depth to the impermeable layer cannot be found without a drill rig. Unfortunately, the use of a drill rig on many sites is impractical. As a result, holes are bored to 3-4 m with hand augers. If a restrictive layer is not found, it is considered to be the deepest point of penetration with the hand auger. This will result in a conservative design.

Rooting Depth: Potential crop rooting depths in North Carolina are frequently limited by either acidic subsoils or tillage pans. Thus, pits should be dug when crops are near maturity or at a critical stage of growth to determine actual rooting depth for a site. Most of the water used by a growing crop is extracted from the upper half of the root zone. Therefore, the effective root depth for most crops should be estimated as one-half the actual root depth for a given site.

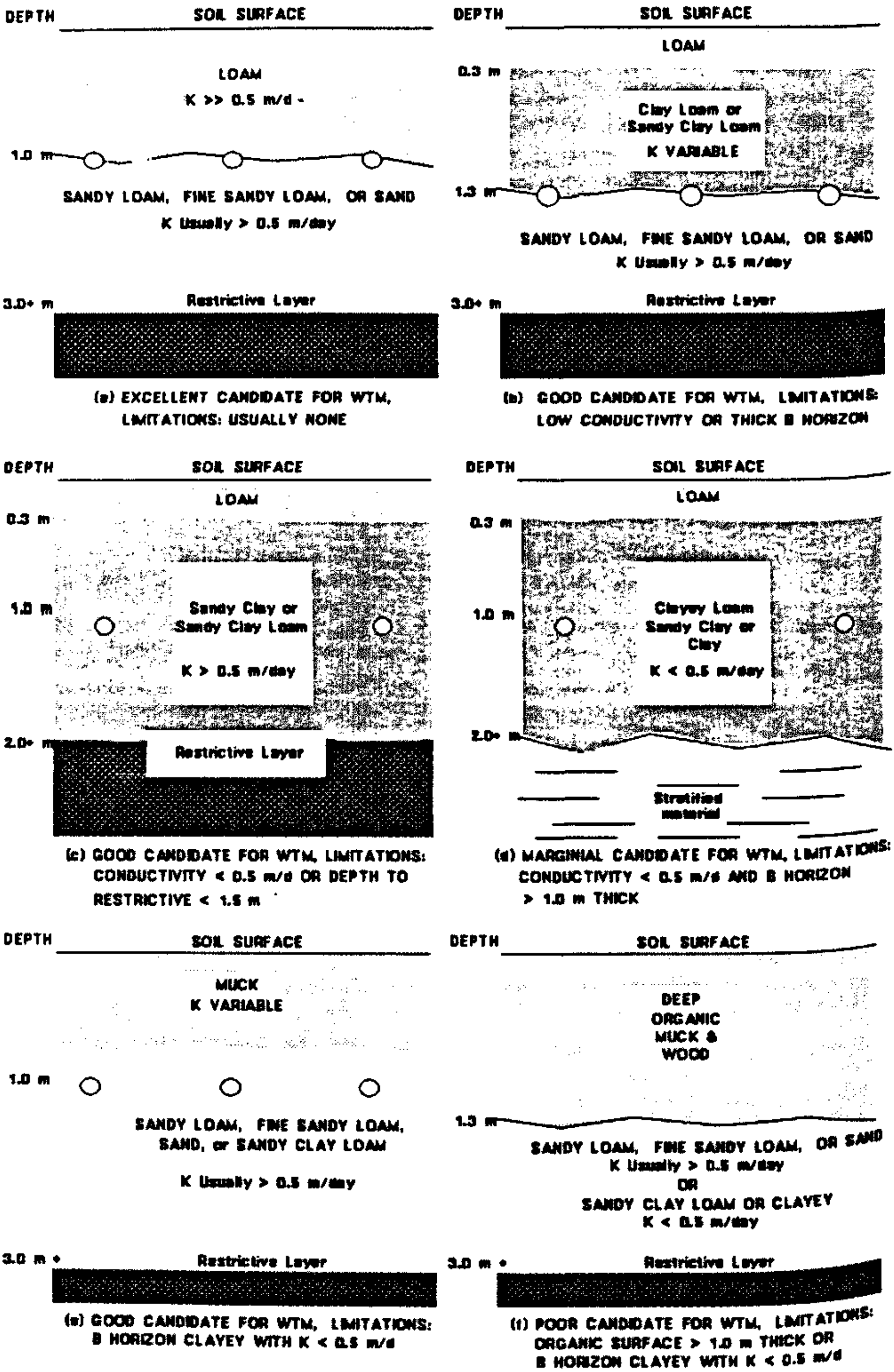

Fig. 3. Influence of soil horizon arrangement on site feasibility ofr water table management, drain tubing placement, and design limitations.

Site Investigation

As discussed earlier, the major thrust of water table management in North Carolina has been through modification of existing drainage systems rather development of new land. Thus, it is important to evaluate the status of the existing system and to fully utilize existing components when possible. Additionally, the topography of the site needs to be determined as this will influence the type of system used, the location and number of control structures and the location of the drainage outlet. The capacity and reliability of a water source should also be evaluated.

Evaluation of Existing System: Many poorly drained sites in North Carolina already have artificial drainage in place. In some cases, the existing ditches or tubing may be adequate for water table management. More frequently, the existing ditch or tubing spacing is too great for an optimum water table management system, but the cost of modifying the system may not be justified by the increased performance. For example, an existing system might have parallel drain tubing installed at 30 m. The economic optimum spacing for this site for subirrigation might be 20 m, but this spacing would not allow total utilization of the existing tubing. One alternative would be to design the system for a 20 m spacing, utilizing alternate lines of the existing tubing and installing two additional lines at 20 m for each 60 m of field width. Based on current prices of $ 2.00 per m for drain tubing, 10 percent interest, and $ 0.07 per kg for corn, the amortized cost of the additional tubing would be $70.24 per ha with a gross return of $ 53.86 per ha. Another alternative would be to install additional tubing between existing lines resulting in a drain spacing of 15 m. The amortized cost of this alternative is $ 68.48 per ha with a gross return of $ 60.16 per ha. The gross return for neither alternative will cover the cost of the additional tubing as compared to the original 30 m spacing; thus, it would be more economical to simply add subirrigation to the existing drainage system without adding additional tubing. In many cases, design of water table management systems involve a retrofit of alternative water management strategies such as controlled drainage or subirrigation to an existing drainage system.

Topography: In some cases, several thousand hectares are affected by the installation of one water control structure. Intensive surveys, such as the 30 m grid traditionally used for drainage designs, are not practical. The goal of the survey is to identify and locate contour intervals of 150 or 300 mm (depending on the water table control interval required) to locate control structures, and to orient tubing and/or ditches with respect to the slope. This goal can usually be accomplished by determining the elevation of obvious depressions and ridges in the field.

Water Supply: The source and reliability of the water supply should be determined before subirrigation is finally selected. The water supply should be located as near as possible to the point of discharge into the subirrigation system to minimize conveyance system costs and conveyance water losses. Potential seepage losses should also be identified. In poorly drained soils, vertical losses are normally small. Lateral seepage losses, on the other hand, may consume more than 25 percent of the pumping capacity. Lateral seepage losses can be minimized with good planning, system layout, and management. Whenever possible, supply canals should be located near the center of subirrigated fields rather than along field boundaries. Perimeter ditches and outlet canals should also be equipped with control structures. When seepage losses cannot be controlled, it is necessary to determine the length of the seepage boundary, the hydraulic gradient and hydraulic conductivity along the boundary. Skaggs (1980) has described methods for estimating seepage losses under steady state conditions.

DESIGN COMPUTATIONS

Once the necessary field, crop and site parameters have been determined, the final design drain spacing, drain depth, water table control level, and management strategy can be determined. The drain depth will often be dictated by the arrangement of profile horizons or local standards for drain grade and cover in conjunction with the topography of the field. Should site and soil characteristic allow drain depth flexibility, a depth of 1 to 1.5 m will usually be optimum.

Determination of Drain Spacing

Several methods are now available for selecting design spacings. On a field to field basis, all of the methods will provide a better estimate of the required drain spacing if the saturated hydraulic conductivity and depth to the impermeable layer have been determined as discussed earlier rather than using average values from the soil survey or local drainage guide.

The operation of the system, i.e., whether it is in the drainage or subirrigation mode, varies from day-to-day and from year-to-year. It is not clear for most locations whether the most demands on the system design are to provide good drainage under a high water table condition or to provide sufficient subirrigation during the driest periods. For these reasons, DRAINMOD is the most objective method presently available for the complete analysis and design of the system. The final design should be based on several simulations using DRAINMOD; however, a good estimate of the drain spacing can be obtained from some short-cut methods that have recently been developed. Occasionally, it may not be practical to run DRAINMOD simulations, either because the necessary inputs are not available, or because time is too short. In this situation, the design spacing can be estimated by one of the short-cut methods.

Short Cut Methods: Three short-cut methods that can be used to estimate drain spacing for subirrigation are:

1. Fixed percentage of the spacing shown in the drainage guide. Typically, 65 percent is used in North Carolina.
2. Fixed percentage of the spacing required for drainage alone using the Hooghoudt steady state drainage equation (Design Drainage Rate Method, DDR).
3. Drain spacing based on steady state evapotranspiration (ET) for subirrigation only.

The Design Drainage Rate Method (DDR) suggested by Skaggs et al. (1986, 1987) has been shown to provide a design spacing which most closely approximates the spacing that would be predicted by DRAINMOD. Skaggs suggests using the Hooghoudt steady state drainage equation with a predetermined design drainage rate. The drain spacing for drainage would be determined as:

$$S_d = \left(\frac{4K_e m(2d_e + m)}{DDR} \right)^{0.5}$$

Skaggs and Tabrizi (1986) using 12 benchmark soils for North Carolina, showed that the best estimate for the DDR for corn was 11.2 mm/day with good surface drainage and 13.0 mm/day with poor surface drainage. This method predicted design spacings that would result in average profits that were at least 90 percent of the optimum profit (as compared to DRAINMOD) about 90 percent of the time when "m" was assumed equal to the drain depth (i.e., the steady state water table position was at the soil surface rather than 0.3 m which is the value usually recommended in the SCS National Engineers Handbook).

When using the DDR method, the subirrigation drain spacing is determined by multiplying the design drainage spacing by 0.63 if good surface drainage is available, or 0.61 if poor surface drainage is provided. Both the design drainage rate and the fixed percentages discussed are specific to North Carolina. At this time, these values have not been determined for other locations or other crops.

Final Design using DRAINMOD: DRAINMOD can now be run on an IBM compatible micro-computer which has 256K of RAM internal memory and a math co-processor. Documentation for using DRAINMOD is readily available (SCS, NCCI) and should be consulted if any problems arise. The following procedure will provide guidance for first time users.

1. Using one of the short cut methods, calculate a first estimate of the drain spacing.

2. Soil inputs
   a. If soil-water characteristic data was measured, compute upflux vs WTD and drainage volume vs WTD using the 'Soil Preparation Programs' included in the DRAINMOD package.
   b. Otherwise, select the soil properties from the appropriate benchmark soil.

3. Select crop information (corn and soybean crop input data presently available.

4. Select weather data for site location

5. Run DRAINMOD
   a. Start with estimated spacing from 1 above.
   b. Select 2 simulation spacings both above and below the first estimate (5a). Thus 5 spacings will be simulated.
   c. Plot yield vs spacing and determine the spacing with the highest yield, then select a second spacing approximately 3 to 5 meters wider than the spacing with the highest yield.
   d. For the 2 spacings selected in 5c, run additional simulations, this time vary the weir setting. Normally weir settings of 0.45, 0.52, and 0.60 meters will be best.

6. Perform an economic evaluation for all simulations.

7. Select the spacing and weir setting with the highest projected net profit. This will be the design spacing and weir setting.

8. Finally, using the spacing and weir setting selected in 7, run 3 or 4 additional simulations, this time varying the start-up time for subirrigation. Start pumping about May 1 for corn and vary this start time from 7 to 10 days until mid-June. Evaluate water usage and pumping cost for the different start-up times.

Economic Evaluation

The combination of system components that results in the maximum net profit should be the best design and management strategy to be recommended to the farmer. The system may be technically feasible, but the the final decision should be based on the feasibility of the system not only to pay for itself but to return a profit to the farmer for his investment. For typical conditions in North Carolina, systems being designed from scratch will be very close to the economic optimum when the projected yield is between 93 and 95 percent. Since most systems involve a retrofit to existing drainage systems, target yields in the range of 93 to 95 percent often will not be the most economic alternative. Therefore, it is very important that the final decisions for these situations be based on a through economic evaluation of the system.

The three major expenses of installing and operating a water table management system are the costs of the water supply, the underground tubing, and the necessary land grading. Also to be considered are the costs of control structures, culverts, drop inlet pipes, field borders, and annual operating and maintenance expenses. These cost are often site specific, so in preparing an economic analysis, the actual cost of each these components should be obtained from manufacturers and contractors. Evans et al. (1987b) have prepared some cost estimates for many of the system components. They have also developed guidelines for performing an economic evaluation of water table management systems.

SYSTEM LAYOUT

Now that the system components have been selected, the final step in the design process is to lay out the system for installation. The first step is to the utilize the topographic survey to determine the number and location of control structures to stage the water across the field due to differences in surface elevation. Grain crops can usually tolerate a range in the water table level of 0.3 to 0.45 m. Shallow rooted vegetable crops, on the other hand, can only tolerate a water table fluctuation of 0.15 to 0.2 m without showing signs of water stress during dry periods. A control structure is then needed for each change in surface elevation corresponding to the tolerable water table fluctuation. The area controlled by one structure represents a management zone. Each zone can be managed independently provided the subirrigation water is added to the system at the highest elevation of the system.

Most water table management systems in North Carolina utilize an open ditch as the main drainage outlet and main water conveyance mechanism. Drain tubing outlets directly into the open ditch and thus the system is referred to as an open system. The main advantages of an open system are that the ditches eliminate added cost of installing large main outlets and failure of one drain line does not result in failure of the entire system. The disadvantage is that there are many more tubing outlets to maintain and tubing outlets are susceptible to damage when the ditch is cleaned-out or mowed. When several drain lines empty into a larger drain (submain or main), the system is referred to as a closed system. Closed systems are not used frequently in North Carolina because outlet ditches are already in place; however, they are used occasionally on steeper slopes.

Once the farm has been divided into management zones, the final system layout involves orienting drain tubing or ditches to take advantage of natural topography, locating and sizing main lines or outlet ditches, sizing control structures, and sizing the water conveyance system. Standard guidelines to accomplish these task are well documented in the SCS Engineers Handbook (SCS-NEH) and are not discussed here.

SUMMARY

Low prices for agricultural commodities and perceived detrimental environmental effects of agricultural drainage has tremendously reduced drainage activities in North Carolina. Instead, farmers are looking to more intensive management practices such as water table management to increase yields and improve productions efficiency on existing agricultural lands. Water table management systems are often expensive and thus careful planning and design of these systems is crucial.

In response to these changes in production practices, practical, objective strategies have been developed to design water table management systems. These methods incorporate soil and site properties, crop requirements and weather conditions into the design of the system. Guidelines were presented to assist the user in evaluating soil and site properties necessary to utilize the new design methods. The importance of an economic evaluation of all water management alternatives as a part of the planning and design process was also emphasized.

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CURRENT DRAINAGE DESIGN PRACTICES IN FRANCE

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In France 1.8 million hectares of humid areas benefited by subsurface drainage. About 5 millions hectares (i.e. 15 % of the agricultural land) have still to be drained in the future. Half a million hectares is permanently waterlogged due to a high ground water-table. The rest is seasonally waterlogged because of either outside flow (run off, springs...) or winter storage of rainfall in the permeable and often shallow soil lying above an impervious barrier (temporarily perched water tables). The main effect of excess water is to delay farm operations in winter and spring.

Subsurface drainage systems are always composed of corrugated PVC pipes ; they sometimes include mole channels. Relief drainage systems are mostly random *interception drains are often needed. Arterial drainage systems (disposal systems)* are composed of ditches. In the early 70s, only 20 000 hectares per year were drained ; drainage works were achieved in the cereal areas of Northern France and Paris Region. From 1982 on the annual subsurface drainage acreage has risen to 130 000 hectares and is now mainly located in dairy and mixed farms of Western France.

As a result of this drainage boom and of its development in new areas, works are more and more often done in difficult soils (heavy clay soils, clogging soils...) with ever stronger economic constraints. Increased knowledge of drainage requirements, suitable drainage techniques and drainage effects on farm management is therefore requested by farmers. Emphasis has been placed on the scheduling of preliminary surveys, which is herein presented in the next section. Current design methods are discussed, in the light of recent experimental results.

PRELIMINARY SURVEY SCHEDULE

Many French farms are divided in several distinct small plots for two reasons : (a) the average area used for agriculture (AUA) is 25 hectares per farm ; and (b) land regrouping (land re-allocation) is not yet completed everywhere. As a result, the average size of drainage work sites is about 7 ha, and it usually take years to have a watershed fully drained.

Due to this social background, drainage planning includes the following points : (a) farmers' drainage associations are encouraged so that they presently deal with more than half of the drained lands ; in addition local communities are most often in charge of arterial drainage ; (b) the extension and localization of the areas to be drained and the drainage recommendations are determined by a semi-empiric approach.

This approach, which has been used since the late 70s, relates a zoning of the waterlogged lands to the **survey of soil reference areas.**

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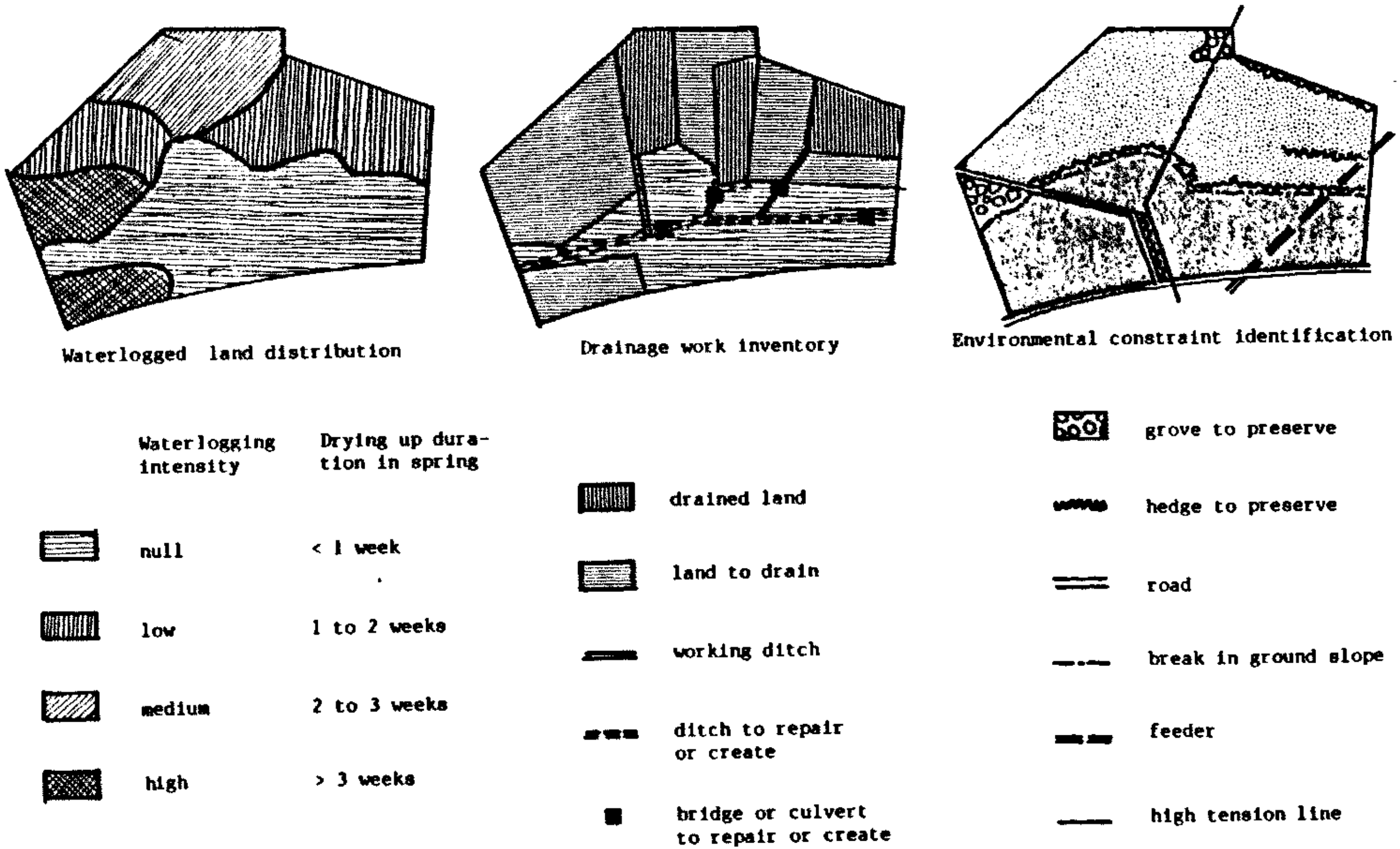


Fig. 1 Waterlogged land zoning

Waterlogged land zoning

Zoning of waterlogged lands is not meant to record on a national scale humid zones of high environmental interest but to assess on the drainage project scale the agricultural cost for excess water. So far, this type of zoning has been chiefly implemented within continental watersheds the size of which ranges from 100 to 1000 km². The purpose is to determine : (a) the surface of the lands to be drained ; (b) their space-distribution and the size of possible grouping ; (c) the drawbacks resulting from excess water, and the drainage profitability ; (d) the length of the arterial ditches to be created or improved ; (e) the obstacles due to the plot pattern ; and (f) the type of drainage ownership required (Fig. 1).

A "local jury" is formed, comprising farmers and local representatives well informed of agricultural water management problems, an agricultural adviser and a drainage officer. Lands are classified according to their spring drying up duration, which is related to a drop in the agricultural income. The limits of the lands thus indexed and the existing or required drainage facilities are reported on a 1 : 10,000 map. Concurrently, an economic survey under the form of a questionnaire assesses the cost for excess water. The final document, submitted to farmers and local representatives for approval, presents additional advantages : (a) the arterial drainage design rate can be modified according to the waterlogged land surface - watershed surface ratio ; (b) the soil surveyor refines his further diagnostic on soil hydromorphy while avoiding over- or under-estimation ; (c) the reference areas are selected according to the distribution of waterlogged land categories ; (d) work planning is made easier, all the more so since the various funding institutions can be possibly informed on the basis of an objective and priced report.

This approach has a double interest : (a) the farmers' "know-how" is disclosed then transcribed into a form which can be understood by both funding and technical parties ; and (b) long before the works are performed, all the partners involved in the drainage process are associated. A mutual relationship of confidence is created and makes it easier to take into account various human and environmental constraints.

Soil reference areas

As the drainage operation depends on soil properties, a soil survey is required prior to the drainage works in order to map the soils together with a thematic representation applied to drainage. Due to the low watershed drainage rate, it is not reasonable to map a large area systematically and from the start. The "Pays d'Ouche" example (Devillers et al 1978), where 40 000 hectares were surveyed from 1975 to 1977, demonstrated that the same information could have been obtained on a smaller and properly selected area. Indeed each "agricultural region" seems to be homogeneous as for the following features : (a) pedoclimatic conditions (identical rainfall pattern, recurrent soil types) ; and (b) farming systems (crops produced, tillage constraints, land system). Besides, the 1 : 10 000 scale seems sufficient to define soil series according to their hydraulic operation.

Moreover, due to the small size of the working sites, it is very costly, or even impossible, to immediately undertake the 1 : 5 000 plot survey. It is likely that the analyses and measurements required for designing the project would not be performed in time or would be multiplied for each plot surveyed. Previous results could be used without their reliability to be ascertained.

Consequently, the "reference area" approach (Favrot 1984) consists in combining, on a small area (500 to 1 500 ha) representative of the agricultural region, the following points (Fig. 2) : (a) a 1 : 10 000 scale soil map ; (b) field measurements of the soil hydraulic properties and physico-chemical analyses ; (c) consistent use of the acquired knowledge via a survey of existing networks operation ; (d) field experiments on soil types which are difficult to characterize and/or which require secondary drainage treatments (moling, subsoiling) ;

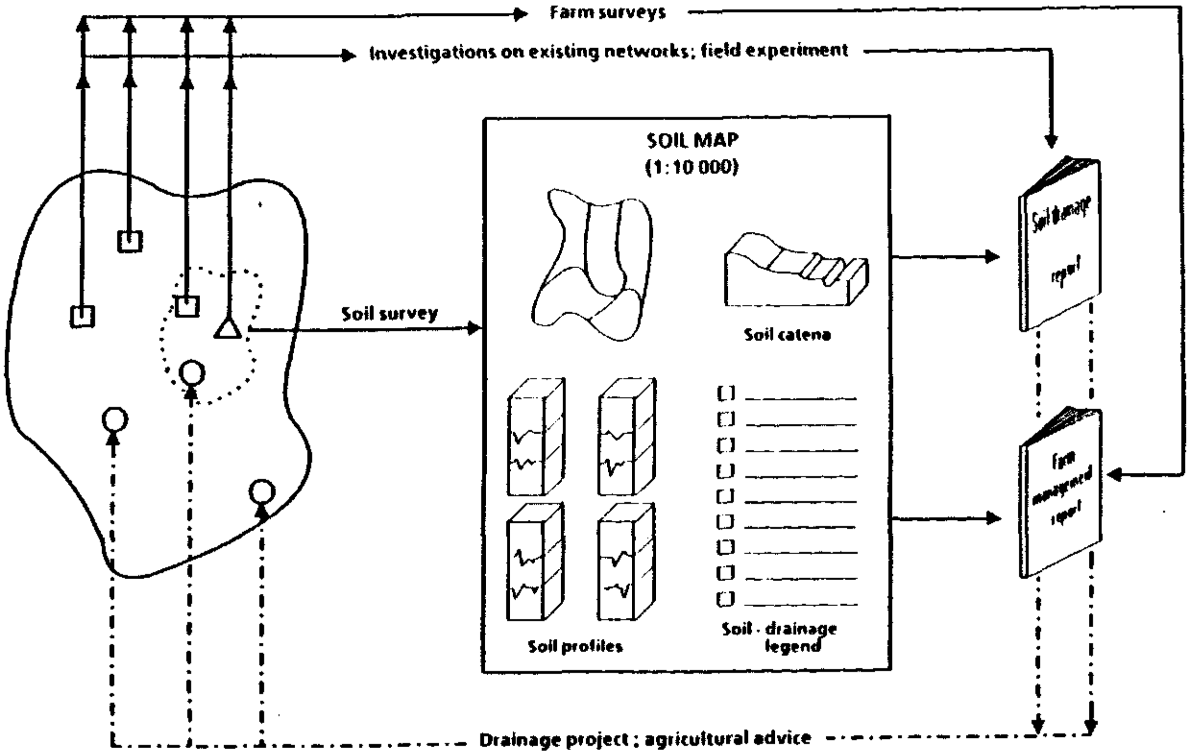


Fig. 2 Principles and main steps of the reference area method (adapted from Favrot 1984)

→ Reference acquisition ← · – Reference utilization △ Field experiment

○ Plot to drain Agricultural region □ existing network reference area and (e) an agronomic and economic follow up, in order to determine the ways of getting the best from drainage.

The soil file established from these works is used by the soil surveyor in charge of the 1 : 5 000 preliminary plot survey to determine, without any additional analysis, the relevant drainage methods. Seventy reference areas have been created so far.

DRAINAGE CRITERIA AND DESIGN METHODS

In seasonally waterlogged soils, typical winter subsurface drainage hydrographs comprises two stages : (a) the **peak-flow stage**, during which discharges increase and decrease very quickly with respect to rainfall ; discharges are high and their durations are short ; and (b) the **tail recession stage**, which corresponds to the water table drawdown without rainfall recharge ; discharges are low and their durations are long. Determination of drainage spacing and of drainage design rate is related to either of both operation stages.

Drain spacing computation

Theory and field experiment results : During the tail recession stage, water-table level and drainflow rate constantly decrease, according to well-known unsteady state formules which have been confirmed through field experiments. Drain spacing is usually computed by using the assessment of time required for a convenient trafficability. The basic formula used in France is Guyon- Van Schilfgaarde's, established for homogeneous and isotropic soils. The authors (Guyon 1964, Van Schilfgaarde 1965) assumed that the shape of falling water table remains constant. When the drains reach the barrier (which is the common situation in France) and are not surcharged, the equation is :

$$t = \frac{C}{4}\frac{f}{K} S^2 \left(\frac{1}{h} - \frac{1}{h_o}\right) \quad (1)$$

where t is the time, S the drain spacing, K and f are the soil hydraulic properties (respectively the hydraulic conductivity and the drainable porosity), h_o and h are the initial and final midpoint water-table heights above the barrier (usually taken as the plough layer basis and 45 cm depth respectively), C is the first water-table shape coefficient (equal to 8/9 when the water-table is elliptical). A similar formula is used when drains do not lie on the barrier : flow convergence near the drain is taken into account using Hooghoudt's equivalent depth.

Guyon (1980) extended Eq. (1) to anisotropic and vertically heterogeneous soils, using the concept of equivalent horizontal hydraulic conductivity $\tilde{K}(h)$:

$$\tilde{K}(h) = \frac{2}{h^2} \int_o^h K(z)(h - z)dz \quad (2)$$

where z is the elevation above the barrier and K(z) is the horizontal component of the local hydraulic conductivity.

The relationship between drainflow rate and water-table height is, when drains reach the barrier and are not surcharged :

$$q(t) = \frac{4B}{C} \tilde{K}(h) \frac{h^2}{S^2} \quad (3)$$

where q(t) is the drainflow rate per unit surface and B is the second shape coefficient (equal to $\pi/4$ when the water table is elliptical). In low permeable soils, **the drainflow rate during the tail recession stage may be much lower than the design drainage rate.**

Application : For design purposes, soil hydraulic properties are usually measured in situ using the pumping test method. A well (20 cm in diameter) is installed in the saturated permeable layers down to a depth of one meter or more : under

French conditions, it commonly reaches the barrier. Two piezometers are located on either side of the well, at a distance of 0.5 and 2 m from the well axis. Using a pumping device specifically designed the water table is first depressed during about 2 hours, so that the drainable porosity can be calculated from the ratio between the pumped water quantity and the cone depression volume. Once the steady state is reached, the equivalent hydraulic conductivity is computed using the following formula when the hydraulic head is negligible in the well (Guyon and Wolsack 1978) :

$$\tilde{K}(h) = \frac{Q}{\pi h^2} \operatorname{Ln} \frac{r}{r_o} \tag{4}$$

where Q is the constant well discharge, h is here the water-table height above the barrier in the furthest piezometers, r is the furthest piezometer - well axis distance, r_o is the well radius. A chart is used when the well does not reach the barrier.

Although more difficult to use than the well-known auger hole method, the pumping test is widely used in France, since it is more accurate and it provides "field effective" values of both hydraulic properties of heterogeneous soils. The method is currently used within the reference areas, so as to characterize the soil series defined by the soil surveyor.

Drainage criteria are often more difficult to assess than soil hydraulic properties. The soil bearing strength is considered to allow workability when the water table level is less than 0.45 - 0.5 m : investigations are presently performed in order to improve this criteria. The time required by the farmer to enter his field is usually derived from farm surveys carried out within reference areas.

The method described herein is not suited for heavy clay soils, which account for about 20 % of the waterlogged land surface (Bouzigues et al 1982). From field experiments installed within reference areas, there is evidence that secondary drainage treatments are often the most adequate drainage techniques. But local experience shows that, in some cases, moling or subsoiling are not necessary. Further research is needed in this field.

Subsurface drainage design rate

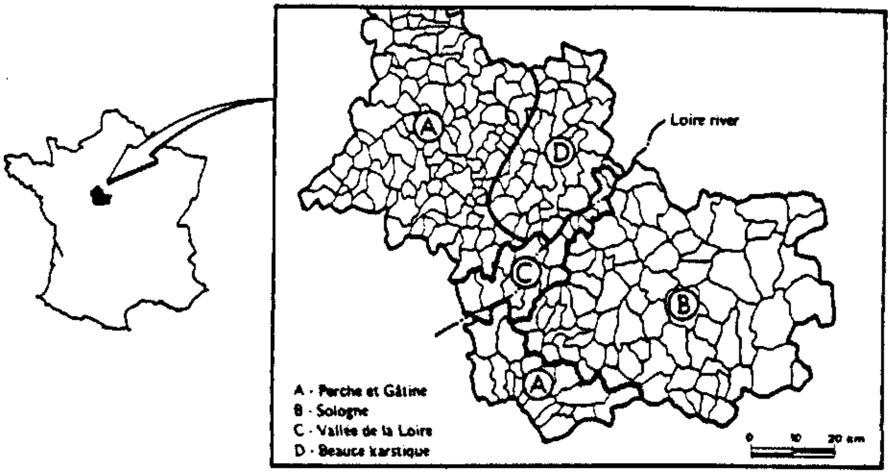
Historical background : In French drainage practice, main pipe diameter and lateral maximal allowable length are computed using a drainage design rate, under which networks are not surcharged. This rate was previously related to the crop value in terms of risk of exceedance. The design rainfall was usually the 1 year in 1 n-day rainfall occuring from October to May, n ranging from 1 for very high crop value (specialist and horticultural crops), to 3 for medium crop values (cereals and intensive grass) and to 6 - 7 for low crop values (grassland). Most drainage projects were designed using the three day rainfall.

Recent developments : During the peak-flow stage drainflow rate varies very much, whereas water-table level fluctuates more slowly. Most authors (see the review of Lesaffre and Morel 1986) consider that peak flows in low permeable soils are caused by water flowing along the surface and within the plough layer, reaching the drainage trench and percolating towards the pipe. But, when infiltration is not restricted by a plough pan, peak flows can be related to the water table shape (Lesaffre and Zimmer 1987). Equation 3 then becomes :

$$q(t) = \frac{4B}{C} \; K(h) \frac{h^2}{S^2} + \left(1 - \frac{B}{C}\right) R(t) \tag{5}$$

where R(t) is the recharge rate. The term (1 - B/C) R(t) represents the major part of the flowrate during rainfalls.

During high rainstorms, drains can be surcharged. The drain surcharge duration



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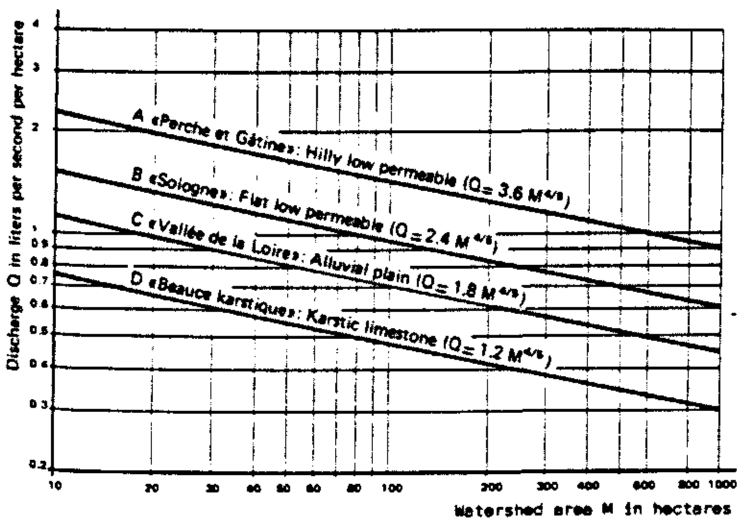

Fig.3 : Drainage runoff curves

must not exceed a few days per year : (a) a too long duration would maintain a too high water-table level resulting in a lengthened drawdown ; (b) from experience and field observations (see the review of Fausey and Hundal 1980), there is evidence that trench efficiency is related to its surcharge duration, even if the relation is not yet known. The previous design practice happens to meet these requirements (Lesaffre and Morel 1986) and is consequently used. The 1 year in 1 three day rainfall is presently available in 300 weather stations. Its rate usually ranges from 10 mm/day to 20 mm/day. It can reach 50 mm/day in mountainous areas.

Arterial drainage design rate

Criteria for the arterial drainage design rate are the following : (a) hydraulic operation of subsurface drainage systems must be satisfactory ; (b) flooding risks must be related to a certain degree of crop and environment protection ; and (c) the river flow must not be increased.

In agricultural lands, the usual design rate (called Q_a) is the 1 year in 1 one day discharge. The level of protection of structures such as bridges is higher : the design rate is not less than the 1 year in 10 instantaneous discharge (Q_d). Q_d (in m^3/s) is often determined by the general formula :

$$Q_d = R \left(\frac{P}{80}\right)^2 M^{4/5} \qquad (6)$$

where P is the 1 year in 10 one day rainfall (in mm), M is the watershed area (in km^2), R is a regional coefficient. This formula has been statistically derived from the analysis of 630 watersheds, the size of which ranges from 2 to 2000 km^2. R is usually equal to 1 ; it may be lower for very permeable watersheds and it is scarcely higher.

Statistical analysis shows that the ratio Q_d/Q_a is about 3-4. As P is available in most weather stations, Q_d and Q_a are consequently readily computed by local engineers : regional charts providing "drainage runoff curves" (i.e. the relationship Q_a/M versus M) have sometimes been drawn (Fig. 3).

SUMMARY AND CONCLUSIONS

5 millions hectares of humid areas are still to be drained in France. Most soils are seasonally waterlogged. Due to the recent drainage boom and to the type of land use, emphasis has been put on preliminary survey schedule. Two methods are widely used : (a) the **waterlogged land zoning**, as a result of farmers' experience : and (b) the **soil reference areas**, defining soil type distribution, drainage requirements and suitable drainage techniques on an area representative of a whole agricultural region. French design practices in the field of subsurface drainage and arterial drainage are then discussed, taking into account recent field experimental results.

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THE CHANGING DRAINAGE SCENE IN NEW ZEALAND

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Pastoral farming has been the basis of New Zealand's economy since our trading first began. With some 70-80 million sheep, compared to a human population of around 3 million, the importance of pastoral farming is still highly evident. However the last 5 years years has seen a significant decline in the profitability of conventional sheep and dairy farming, which in turn has prompted the development of alternative land uses. Of particular significance has been the expansion of orcharding, with the development of numerous pip fruit, stone fruit and berry fruit plantings.

The current recession in agriculture and changing land use has brought new challenges to our land drainage industry. Current techniques will need upgrading and new techniques will need to be developed. Of particular relevance are:

- Improving design and installation practices.
- Coordination of the New Zealand land drainage industry.
- Determining the drainage and aeration requirements of new horticultural crops.
- Coping with canopy support and other structures when draining established orchards.
- Minimising pipe blockage from shelter tree root systems.

Massey University is regarded as the centre of drainage research and extension in New Zealand. This paper summarises the programmes currently underway within the University to investigate the above issues.

Improving design and installation practices

The success of low cost, yet effective drainage for pastoral or cropping systems in New Zealand is largely attributable to the use of mole drainage. A combination of suitable topography, soil type and climate allows stable mole channel formation.

With the current downturn in farming, it is imperative that expenditure on land developments such as drainage be kept to a minimum. Moling is therefore likely to remain an important technique. Work is currently underway at Massey University to examine ways of further improving the effectiveness of mole drainage. Of particular note are projects investigating:

- high speed moling
- development of a mole plough with a grading facility
- ways of improving the smoothing index of mole channel grading
- reducing the volume (hence cost) of backfill materials by using narrow trench widths.

The above projects have been described in somewhat more detail by Baker et al. 1986.

A further development likely to bring about more effective drainage design has been the introduction of the 'SWIG' (soil water investigations group) programme by the NZ Soil Bureau (Cook, 1986). This programme aims to provide a data base of soil hydraulic properties throughout New Zealand. The information provided by SWIG, particularly the relative hydraulic conductivities throughout the soil profile, will be of great assistance to the drainage designer.

Coordination of the N.Z. Drainage Industry

The last 6 years has seen significant development in the administration of land drainage activities in New Zealand.

The 1st National Land Drainage Seminar in 1982 brought together for the first time all parties interested in land drainage. This Seminar not only outlined the 'state-of-art' of drainage in New Zealand but also provided guidelines for future direction.

Two additional National Drainage Seminars have since been held (1984 and 1986) and a detailed Proceedings compiled from each. Arising out of the third Seminar came the official formation of the N.Z. Land Drainage Association. This Association has responsibility for: coordinating the industry's activities, organising events such as conferences, and disseminating information. An occasional newsletter, published on behalf of the Association, 'The Drain Age', keeps members informed about new developments within the industry.

Developing new, innovative drainage techniques

It is an unfortunate fact that an ever-increasing proportion of new horticultural plantings are sited on less than ideal soil types. This has largely arisen out of the ever-widening disparity in the value of prime and second grade land. So that now there is not only a need for more drainage in our established horticulture regions, but there is also a demand for creative and innovative ideas to help drain impermeable soils where conventional drainage techniques have proven unsuccessful. One approach gaining popularity is a technique in which the soil profile is reconstructed (Wilson 1986). It has application with row crops, such as orcharding. Although the design specifications will be site specific, the general principle in all cases is to re-construct the root zone using a soil horizon with suitable drainage characteristics.

Growers are also beginning to appreciate the benefit of biologically-induced macropores for soil aeration. The promotion of soil biological activity, particularly earthworm activity, is therefore an important objective in marginal soils. Management techniques such as mulching and minimising pesticide spraying will help encourage soil biological activity.

The sportsturf area is another where innovative drainage developments have taken place. The introduction of narrow trenching equipment and small diameter pipe has meant that sportsfields, golf greens etc can now be drained with less surface disruption. A new pipe material 'stripdrain' appears particularly suited for sportsturf use.

Researching the drainage needs of new horticultural crops

Despite the extensive development of orcharding in New Zealand little is known about the drainage and aeration needs of many of these crops. For example, it is was first thought that kiwifruit vines required at least 1 metre of friable, free draining soil. However, successful crops in soils where this criteria was not met indicate that this crop is more tolerant that first thought.

One kiwifruit orchard with drainage problems is currently being monitored by the Department of Soil Science at Massey University. Investigations to date indicate that the sensitivity of this crop to excess soil water is seasonally dependent. Disease or 'wet wilt' problems were more apparent when the vines were subjected to high soil moisture levels during periods of active growth (and soil microbial respiration), undoubtedly reflecting the more rapid consumption of soil oxygen over this period (Table 1).

Table 1. Observed vine die-back in a 3 year old kiwifruit orchard block over a wet spring - early summer period (October 1986 to January 1987).

Date	No. of vines died
Up to Oct 7	26
Oct 7 - Oct 29	4
Oct 29 - Nov 7	11
Nov 7 - Nov 14	22
Nov 14 - Jan 5	35
Total vines dead =	98 out of 306 vines monitored

Efforts to identify the drainage requirements of kiwifruit have also been reported by several drainage designers (Eden, 1986; Kyle, 1986; Tilsley, 1986,).

Observations from around the country indicate that poor irrigation management can compound any inherent wetness problem. With water supplies being virtually a free resource in New Zealand, many farmers or growers with irrigation apply far in excess of the plant water requirement. Part of the drainage remedy in these cases should be to educate the irrigator on the basics of irrigation scheduling.

Coping with structures

Unfortunately not all growers appreciate the need to identify the soil drainage status prior to development of the orchard. There are too many cases where growers become aware of the need for artificial drainage only after a wet year subsequent to development.

Subsurface drainage installation in a developed orchard is no easy matter. Most fruit crops are supported by trellis structures, with support wires and irrigation lines running parallel down the rows. These areas will be inaccessible to large trenching machines and therefore low slung, narrow trenching equipment will be needed.

Massey University is currently developing a winch-along mole plough and subsoiler. This device will have the capability of travelling below support structures and wires, thus allowing a secondary treatment operation to be carried out perpendicular to the tree rows.

Since prevention is better than cure, future development of our horticultural drainage industry should encompass grower education, so that they become aware of the need for accurate soil survey information prior to orchard development.

Preventing pipe drain blockage by shelter tree root systems

A further hurdle the designer must overcome when faced with orchard drainage stems from the widespread use of natural shelter for wind protection. Tree species, such as willows, poplars, and eucalypts, make fast growing and effective shelter belts, but at the same time have vigorous root systems, capable of moving into and blocking pipe drains.

Again there is little current research information to help guide the designer on procedures and "safe" distances for pipe installation near shelter. A rule-of-thumb often cited is to use solid, unperforated pipe when a pipe approaches within 5 mm of a shelter line, and to annually root prune to about 50 cm depth between any pipe drain and shelter line. Yet a recent study at Massey University showed that roots from 4 year old willows and poplars migrate beyond a 5 m distance and well below a 50 cm depth.

In order to help provide more accurate guidelines for pipe design in relation to shelter trees a trial has been set up at Massey University. This trial incorporates several different trench backfills and pipe materials, and a root periscope will be used to study tree root system development in and around the backfill and pipe. It is also hoped that an inter-regional survey can be carried out to evaluate the full extent of this shelter tree root system blockage problem.

Summary

Over the last 5-10 years a significant number of new challenges to New Zealand's drainage industry have arisen. Possibly the expansion of orcharding has provided the greatest challenge. Research will be needed to accurately determine the soil drainage and aeration requirements of our fruit crops. New machinery and innovative techniques will be required to effectively improve marginal horticultural soils. Specific problems, such as root blockage of pipes by shelter trees, will need to be investigated.

Other land users are also starting to place greater emphasis on land drainage. Of particular note here is the sportsturf arena, where players now demand higher standards of playing surface, and the land disposal industry, with spray disposal of liquid effluents on to land becoming increasingly widespread. How well our drainage industry copes with these changes remains to be seen.

The recent formation of the New Zealand Land Drainage Association is undoubtedly a step in the right direction to assist in the development of our drainage industry.

Perhaps we would also be well-advised to refer to the experiences of other drainage industries throughout the world.

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PRACTICAL EXPERIENCES OF PEAT LAND DRAINAGE IN NORTH-CALOTTE

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The northern areas of Scandinavia present, because of the difficult natural circumstances, many special barriers to the earning a living. To overcome these difficulties the governments of Norway, Sweden and Finland cooperated in the setting up of an ad hoc committee on North-Calotte in 1971. The area of North-Calotte is situated at the top-most part of Europe in the region of the Arctic Circle (Fig. 1).

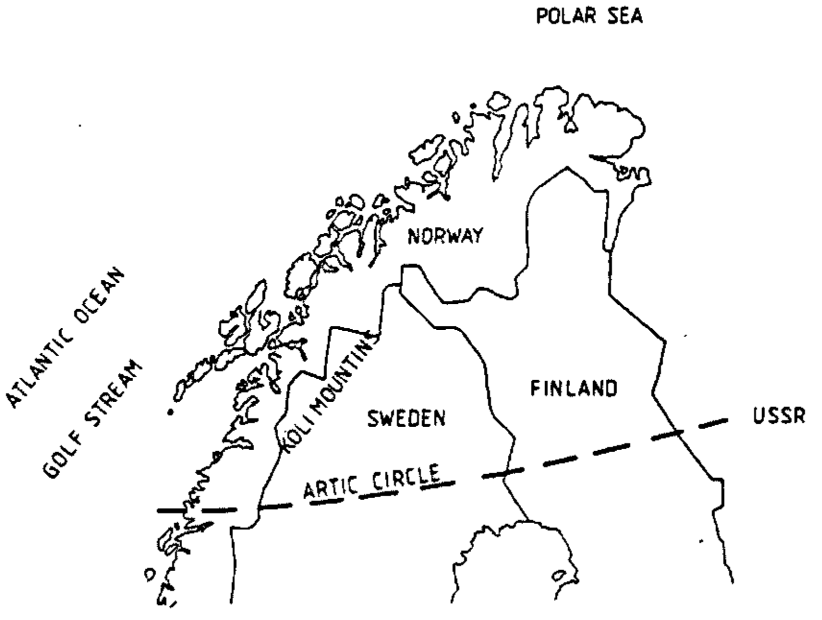

Fig. 1. The area of North-Calotte includes the most northern districts of Norway, Sweden and Finland

The significance of agriculture to the area of North-Calotte has been seen as important for many reasons, of which one of the most important is the preservation of the population in the area. The significance of drainage in plant production under these circumstances is very central. The North-Calotte committee granted an appropriation in 1987 by which the clarification of the ability to function and the mapping out of research needs of drainage measures, farm by far, was speeded up.

Climate

The length of the growing season in the North-Calotte area is 100-140 days and the sum of the effective temperature sum 700-1000 degrees Celsius (based +5 degrees Celsius). The length of the day in summer as is known is long and the development of plants is fast.

Annual rainfall on the coast of Norway is 350-1280 mm and in Sweden and Finland 500-700 mm. The precipitation of rain as snow is 40-50 %. The May-September precipitation, evaporation and precipitation deficiency in the Research station in Finnish Lapland can be seen in the chart below.

	Precipitation	Evaporation	Precipitation deficiency
May	33		
June	56	120	64
July	69	110	41
August	66	67	1
September	63	26	
total	287	323	36

The water equivalent of snow at the end of April is on average 160 mm. The soil of the fields freezes in very different ways in different years. In peat areas the depth of freezing fluctuates 0.4-0.8 m and it melts on average at the beginning of June. In an exceptional year such as 1987 freezing can reach a depth in peat soil of almost a metre and its melting is delayed even to August.

Soil types

Of arable land the share of peat soil in the North-Calotte area is about 10 % in Norway, 15 % in Sweden and 45 % in Finland. Mineral soils are for the most part sand or moraine.

Drainage

Traditionally the fields have been drained by shallow 0.5-1.0 m deep open ditches whose spacing distance has been 10-25 m. Subsurface drainage has been used to a significant extent over the last twenty years. At the moment arable land in the North-Calotte area is drained by subsurface drainage in Norway 50 %, in Sweden 10 % and in Finland 8 %. According to feedback received from subsurface drains in use most of mal-functioning of pipe drains has appeared in peat soil, estimates vary 3-6 % of subsurface drainage surface area. Insufficient drainage has been observed particularly as trafficability difficulty in farms that produce intensively grass silage.

The installation depth of subsurface drains in the area has been 1.0-1.5 m and in Sweden and Finland subsurface drain spacing 16-20 m. In Norway's area of heavy rainfall a 5-10 m drain spacing has been used.

Farm by farm survey

During the summer of 1987 the situation of 17 farms were looked into concerning the state of repair of subsurface drainage. Six of the farms were in Norway, five in Sweden and six in Finland. It was known beforehand that these farms had difficulties with their subsurface drainage. Along with this clarification factors concerning the quality of peat among other things was determined - type of peat, degree of decomposition according to von Post, bulk density and quality of hydraulic conductivity. K-value was determined according to the field measurement system on the spot (Merva, 1979, Saavalainen & Rintanen, 1986).

Results

Table 1 shows the soil properties of the research targets country by country. As fas as the type of peat is concerned it can be said that the same types of peat appeared in each country but the emphasis was such that sphagnum peat was more in Norway while in Sweden and Finland types of peat were carex centred. Degree of decomposition on the von Post scale H2-H7 and the most decomposed peat was found in Norway at a depth of 0.5-0.7 metres of the samples taken. Bulk densities varied in the surface layer 136-406 g/dm3 and in subsoil 106-216 g/dm3. No difference worth noting appeared in different countries. Permeability coefficients defined by MSU falling head permeameter varied 0.6 metres in the defined layer where the figures were 1/4 - 1/6 of Sweden's and Finland's corresponding average values.

TABLE 1 INFORMATION CONCERNING SOIL ON THE FARMS SURVEYD: DEPTH OF PEAT LAYER, TYPE OF PEAT, DEGREE OF DECOMPOSITION, VOLUME WEIGHT AND HYDRAULIC CONDUCTIVITY.

	NORWAY (6 FARMS)	SWEDEN (5 FARMS)	FINLAND (6 FARMS)
PEAT DEPHT	1,0 - >1,5	0,4-0,9	0,4 - >1,5
TYPE OF PEAT			
DEPTH 0-0,3 M	St,Sct,Lct	Ct,Lct	Ct,Bct
DEPTH 0,5-0,7 M	St,Sct	Ct,LSCt	Ct,LCt
DEGREE OF COMPOSITION/ VON POST			
DEPTH 0-0,3 M	2 - 5	3 - 5	2 - 5
DEPTH 0,5-0,7 M	3 - 7	3 - 4	3 - 4
VOLUME WEIGHT G/DM^3		RANGE/MEAN	
DEPTH 0-0,3 M	170.258/200	247-343/295	136-406/267
DEPTH 0,5-0,7 M	106-154/142	158/158	116-216/165
HYDRAULIG CONDUCTIVITY K VALUE CM/H		RANGE/MEAN	
DEPTH 0,1 M	0,13-2,82/0,81	0,12-5,26/0,96	0,12-1,53/0,58
DEPTH 0,3 M	0,03-0,17/0,25	0,07-2,04/1,55	0,12-8,16/2,61
DEPTH 0,6 M	0,03-0,15/0,10	0,18-3,75/1,42	0,04-1,36/0,44

Discussions

Farming practiced in Scandinavia near the Arctic circle places great demands on the drainage of fields. In these circumstances of abundant melting snow in spring, freezing of soil and short summers, the confirming of the functioning of subsurface drainage is particularly stressed in peat soils which play an important role in the Calotte area. Modern intensive grass silage production technique means considerably larger demands for trafficability at the same time as the abundant use of suspended solids manure and nitrotgenous fertilizer is suspected of weakening peat structure (Sveistrupt 1986) thus affecting its drainage more than ever. Thus it is to be expected that the

16-20 metre drain spacing in use in Sweden and Finland will more often than previously prove insufficient. Because of the greater amount of rainfall in Norway even 5-10 metre drain spacing has been used. In connection with this survey the hydraulic conductivity values measured in peat is in theory adequate for the functioning of subsurface drainage. Any exact measurement was not made, but in practice the situation, however, was often such that the surface layer of peat had so fine texture and compact structure and thus it almost totally lacked hydraulic conductivity, and the water had remained on the surface and this caused difficulties in trafficability. Deeper down the peat was adequately dry and the network of subsurface drains functioned.

In Norway a study has been conducted on surface drainage and the improvement of physical properties of peat by adding additional mineral soil so as to secure the functioning of subsurface drainage of replacing them entirely (Linberg K. 1987). The aim has been to reach 40-50 metre spacing between open drains by structuring the surface and adding mineral soil. A 3-5 % convexity between open drains has given promising results. In practice carrying out such structuring demands great transferences of masses and for that reason causes high expenditures. In theory under Swedish and Finnish circumstances there is no need for such thorough surface structuring to supplement subsurface drainage. On the basis of the survey one can forcast, however, that alongside subsurface drainage there will be an ever greater need to use surface drainage both in peat and mineral soil in the North Calotte area. More experiment and research work is needed to develop methods of carrying out surface and shallow drainage combined with subsurface drainage.

Summary

A survey into the subsurface drainage in the North Calotte area in northern Scandinavia was carried out in the summer of 1987. The project was financed by joint Nordic funds. The aim of the survey was to map out the use of drainage in different countries and how it functions with regard to modern cultivation techniques. At the same time information concerning ongoing research and development work was compiled. On the basis of the survey it can be said that under present cultivation techniques the weakening of the hydraulic conductivity of peat soils' surface layers causes the greatest risk for the functioning of traditional subsurface drainage. Surface or shallow drainage as a supplementing system for subsurface drainage is becoming ever more important. On the basis of research being carried out in northern Norway, with adequate cambered bedding system one can reach as a 50-metre-wide beds without subsurface drainage.

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DROUGHTINESS IN SANDY SOILS AFFECTED BY DEPTH OF SUBSURFACE DRAINS

by

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Subsurface drains are needed on at least 1,500,000 hectares of the Québec portion of the St. Lawrence lowlands if the food production capabilities of these lands are to be achieved (Jutras 1967). Almost an equal area of farmland of the Ottawa and Saint Lawrence lowlands in eastern Ontario needs subsurface drainage improvement.

Subsurface drains are being installed to improve the drainage of about 80,000 hectares of land in this region each year; this rate of installation represents an increase from about 8,000 hectares per year 16 years ago.

Until recently, the majority of subsurface drain installations have been in clay, clay loam and silty loam soils. Only a small portion of installations have been in soils with a high percentage of sand size material. Recently, there have been indications that some sandy soil fields have suffered from droughtiness because of excessive loss of moisture owing partly to the placement of drains at depths greater than about 0.60 metres.

It is unlikely that more than about 12 percent of the volume of clay and silt loam soils will be drained regardless of the depth of subsurface drains. However, the moisture release characteristics of some sandy soils are such that 30 percent or more of the soil volume might be drained by subsurface drains, if those drains were placed 1.2 metres deep or deeper. This would exceed the needs for air space, for which 5 to 15 percent of the soil volume has been deemed to be adequate for most economic crops (Grable and Siemer 1968, Wesseling 1974). The drainage of more than 15 percent of the soil volume can reduce seriously the quantity of water available for evapotranspiration. Also, if drains are placed at depths much greater than about 0.6 metres and the water table is drawn down to these depths, the suction exerted by the pore water on the soil in the top 200 to 300 mm would cause a drastic reduction in the unsaturated hydraulic conductivity. This in turn will lead to a reduction in the upward flux of water to plant roots (Gardner 1958, Skaggs 1978).

Apart from the low quantity of available water in sandy soils with deep drains or deep water tables, fertilizer with a high mobility such as NO_3-N (nitrate-nitrogen) leaches rapidly with the water flux through the soil profile (Lembke et al. 1980).

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OBJECTIVES

The objectives of this research were:

1. to conduct laboratory measurements on undisturbed core samples to determine the moisture release characteristics of some sandy soils of the croplands of the St. Lawrence lowlands,

2. to use the moisture release characteristics to determine the quantities of available water for cases with subsurface drain depths of 0.60 and 1.20 metres, and

3. to use data on weather and corn crops to determine the extent of droughtiness that can result for soil cases with different amounts of available soil moisture.

METHODS

Four field sites, three in Québec and one in Ontario, Canada, within a 120 km radius of Montréal, were selected for this research. The soils in these fields had textures ranging from very fine sand or silt through medium sand. The natural drainage ranges from poor for the soil at the McRae farm in Bainsville, Ontario through good for the Saint Benoit soil at the Macdonald Farm in Sainte Anne de Bellevue, Québec. The particle size distributions of soil samples obtained from the top 0.34 to 0.45 m of the soils in these fields are presented in Fig. 1.

In each field, core samples were obtained in 74 mm inside diameter by 40 mm long aluminum rings, using a specially designed sampling device. Samples were obtained from six 1-metre diameter pits dug down to a depth of at least 1.2 metres.

Two soil depths were sampled: 0.40 to 0.65 m and 0.75 to 1.10 m. At each depth, samples were obtained in duplicate or triplicate. Additional samples were also obtained in aluminum rings for determining the field value moisture content and the soil bulk density.

After obtaining each core, its ends were trimmed with a 0.5 mm thick coping saw. Each core was then placed in a polyethylene sock and sealed in a metal can. Cans were placed in internally padded metal carrying cases and transported to the laboratory.

Physical features such as soil layering, the depth of the water table and general soil appearance were noted at the time of sampling. Detailed descriptions of the soils in three experimental fields are given by Rashid-Noah (1981). One or two days after sampling, the additional core samples obtained from each hole were oven-dried at 105°C, cooled in a desiccator and weighed. From the initial and final masses and the volume of the core, the soil moisture content and bulk density were determined.

For the measurement of the soil moisture characteristics, one end of each of the remaining cores was covered with a cloth mesh held by a rubber band to retain the soil during saturation and measurements. Saturation was accomplished by using de-aerated water which had previously been boiled and cooled to room temperature. Samples were then mounted onto a sand suction table. The suction table was then covered with plexiglass to minimize evaporation from the samples. Suctions were applied in 0.20 m increments up to a maximum of 0.60 m. At the end of each equilibration period (generally 24 to 36 hours was found adequate for equilibration for these sandy soils) samples were weighed, re-mounted onto the suction table and allowed to re-saturate for approximately 6 - 8 hours. Since the air entry value of the porous medium was approximately 0.70 metres, samples were transferred to Haine's suction funnels after a total suction of 0.60 m had been attained on the sand suction table and the measurements were continued. A suction of at least 1.2 metre was attained with the Haines suction funnels. At the end of the measurements, the samples were oven-dried at 105oC, cooled in a desiccator and re-weighed.

For each suction level, the oven-dry mass of the core plus ring was subtracted from the mass of the ring plus moist soil to obtain the mass of water retained. Values of moisture content, percent by volume, at each suction were arranged for the two or three samples and these were plotted against suction.

RESULTS AND DISÇUSSION

Table 1 shows some values of field moisture content, together with other parameters determined for the soils investigated.

Figure 2 shows the soil moisture characteristics of a typical soil sample obtained from a depth of 0.65 m from the Charbonneau farm near St. Louis, Richelieu County, Québec, Canada.

If the water table is 0.60 m from the soil surface and the soil above the water table is drained to equilibrium, the volume of the soil drained would be the nearly triangular area labelled VD1. The soil at the surface with a suction of 0.60 m has a drained pore volume of 19 percent. The soil at zero suction representing a position at the water table 0.60 m below the surface has zero drained pore volume. The average volume of soil drained is 8.8 percent over the 0.60 m depth.

For the case of an effective rooting depth of 0.40 m, the available soil moisture (AW) is obtained by measuring the area bounded by the permanent wilting point line, (PWP), the soil moisture content axis, the 0.60 m moisture retention curve and the 0.40 m depth line. From this graph the AW is calculated to be 105.5 mm^3/mm^2 of soil surface, or a water depth of 105.5 mm.

If the effective rooting depth of the crop were 0.60 m, the available soil moisture would be 176 mm^3/mm^2.

Where the water table is at 1.20 m depth and the soil above it is drained to equilibrium, the volume of soil drained is represented by the area labelled VD2 in Fig. 2. The soil near the surface is excessively drained, as 29.7 percent of the volume is drained. The average volume of soil drained over the 1.20 m depth is 17.6 percent. The available soil moisture, for a crop rooting depth of 0.40 m, would be 44 mm.

From the results of these calculations, it can be seen that the depth of the water table has a profound effect both on the amount of soil volume drained and on the quantity of water available for plant use from soils with moisture release characteristics such as in Fig. 2. The percentage of pore volume which is drained for a water table depth of 1.20 m is double the drained pore volume for a water table at 0.60 m depth. Such drainage is considered excessive as it far exceeds the air space requirements for root respiration.

In terms of the available soil moisture at a crop rooting depth of 0.40 m, the 1.2 m water table caused a decrease in AW from 77.5 mm to 40.0 mm. The difference to the crop growth will be even greater, since much more water will be able to move up to the root zone by capillarity from the 0.60 m water table than from the 1.20 m water table. Table 2 shows the quantities of available soil moisture obtained by calculations done using Fig. 5 and Table 1. The permanent wilting point moisture contents shown in Table 1 were used in the calculation of AW.

Figure 3 shows composite graphs of drainable porosity (f) vs. suction for all core samples obtained from each of the fields used in this study. These graphs demonstrate the effect of soil texture on the drained pore volume for fields having subsurface drains. Referring to Fig. 1, for example, it can be seen that the soil at the McRae farm in Bainsville, Glengarry County, Ontario, Canada, is a very fine sand. Figure 3 shows that for a sample obtained from this soil, a suction of 1.20 m can be expected to cause as little as 9 percent of the volume of the soil to be drained if this sample were located at the soil surface. However, the same suction causes approximately 31 percent of the volume of the St. Benoit soil at the Macdonald farm to be drained. The St. Benoit soil is a fine to medium sand.

The values of AW obtained by calculations based on Fig. 4 have been used in water balance calculations to demonstrate the effect of AW on the extent of droughtiness of the soil on which Fig. 2 is based. The calculations were done using the water balance equation which has been used by Foroud and Broughton (1978).

$$SMC_t = SMC_t-1 + PRE_t - AE_t - EX_t$$

where

- SMC_t = soil moisture content at time t;
- SMC_{t-1} = soil moisture content at time t-1;
- PRE_t = precipitation or irrigation between time t-1 and time t;
- EX_t = excess water between time t-1 and time t.

The soil moisture content at the beginning of the calculations ($SMC_{t=0}$) is taken as the maximum available soil moisture and is obtained from Fig. 4. PRE is obtained from climatic data; data for Macdonald College have been used in the present calculations. Actual evapotranspiration (AE) has been calculated from graphs of actual evapotranspiration/potential evapotranspiration (AE/PE) ratios vs. available water used up from the soil profile. These graphs have been interpolated from those prepared by Chieng and Broughton (1979) and are shown in Fig. 4. Data on PE were obtained from tables that have been prepared by Russelo et al., (1974). The calculations of PE are based on the Baier-Robertson formula given by Baier et al.

The excess water (EX), after accounting for AE, appears either as sub-surface drainage or as surface runoff. Drainage takes place from the transient storage (TR) as long as this is not depleted. AE takes place from the PRE falling on any day at the PE rate for that day, otherwise AE takes place from the AW at a rate of AE/PE x PE. The water balance calculations have been done for the period from April to July for 1976, a wetter than normal year, and from April to October 1978, a drier than normal year. In other regions one could expect weather much drier than the 1978 weather at Macdonald College. For such regions the droughtiness associated with excessive drainage would be more severe.

Sample results of water balance calculations are shown in Tables 3 and 4. Computer programmes were developed to continuously evaluate the AE/PE ratios shown in Fig. 4 for values of AW on any particular day. These AE/PE values were then used in the water balance calculations to determine the quantity of soil moisture deficit for the various values of AW.

Table 5 shows the percent soil moisture deficits based on calculations shown in Tables 3 and 4. Clearly, the magnitude of the deficit is dependent on the quantity of AW, the depth of subsurface drains and hence the depth of the water table if this eventually recedes to or below the depth of the drains, and on the amount of PRE that has accumulated over a certain period of time.

For example, for the 0.60 m drain depth and a rooting depth of 0.40 m, the soil moisture deficit for the period from April to July is approximately 40 percent of the total water need in 1978; for the same conditions, the soil moisture deficit is approximately 16 percent for 1976. The corresponding values for the 1.20 m drain depth are approximately 57 percent and 33 percent, respectively.

Figure 5 shows graphs of cumulative soil moisture deficits vs. time for different values of AW for 1978 weather data for Macdonald Campus. The lowest AW of 27 mm gives consistently higher values of deficit than the other three AW values. Also, the deficit occurs much earlier for an AW of 27 mm than for soil-crop situations with greater AW. The severity of the effects of soil moisture deficits will also depend on the stage of growth of the crop. For example, Robins and Domingo (1953) observed a highly significant yield reduction for maize grown on fine sandy loam soil, when the available soil moisture was depleted about three weeks after tasseling. However, following maturity, the depletion of the available soil moisture had no effect on the yield.

Figure 5 shows that the soil moisture deficit is nearly linearly related to the quantity of AW for the weather conditions of 1978.

CONCLUSIONS

Based on the results of this study it can be concluded that:

1. the extent of droughtiness of a sandy soil is dependent on the amount of drained pore volume, the permanent wilting point of the soil, the depth of the crop roots as well as the rainfall;

2. the depth of subsurface drains has a profound effect on the amount of soil volume drained in sandy soils and hence on the quantity of available moisture in the crop root zone;

3. the moisture deficit in any year is nearly linearly related to the available water holding capacity of the soil;

4. a relatively small increase in the coarseness of a sandy soil can give rise to a very large increase in the drainable porosity. Thus it is much better to measure the drainable porosity than to merely measure the particle size distribution if one wishes to determine whether a sandy soil might have the potential to be excessively drained by subsurface drains placed deeper than 600 mm.

SUMMARY

Soil cores were obtained from four sandy soil fields in Ontario and Québec, Canada. The moisture retention and drainable porosity characteristics were determined by using a sand suction table. The drainable porosity curves were used, together with possible drain depths, to calculate quantities of available soil moisture (AW) for crop rooting depths of 0.40 and 0.60 m. A water balance model was used to determine the extent of droughtiness occurring for various amounts of available water and 1976 and 1978 weather conditions. The extent of droughtiness was found to be significantly affected by the quantity of available water in the crop root zone and by the depth to which the water table could be lowered by subsurface drains. The drainable porosity characteristic was found to be the most important factor in determining whether subsurface drains can cause a sandy soil to be excessively drained. The soil moisture deficit was nearly linearly related to the amount of available moisture the soil could hold.

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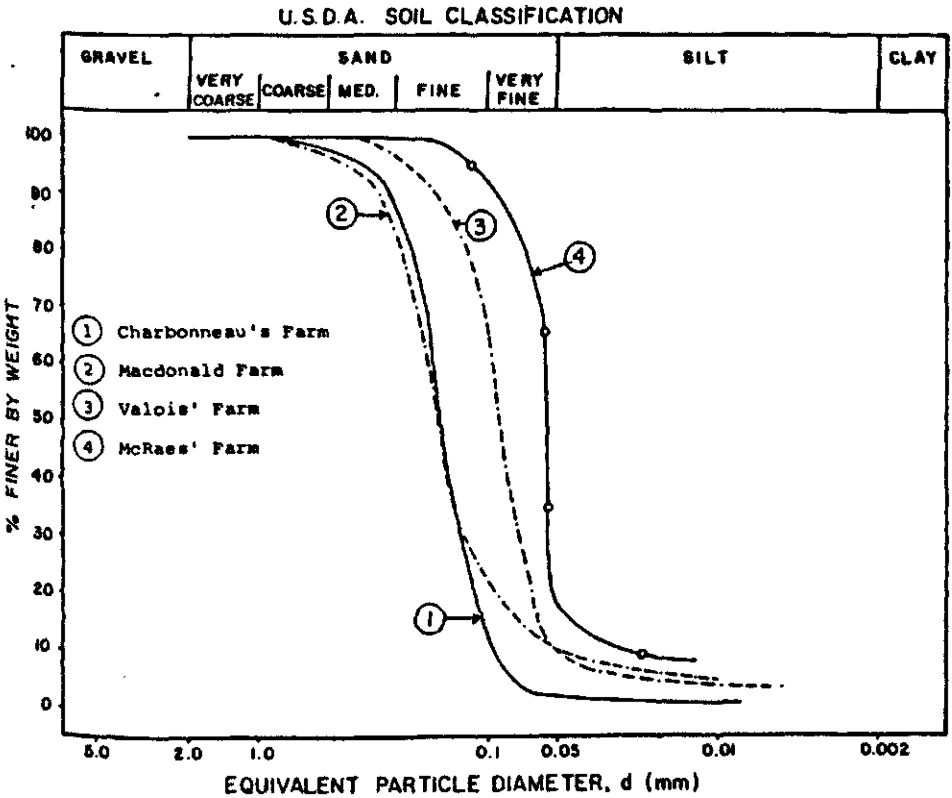

Figure 1: Particle size distributions of the soils from the four farms studied.

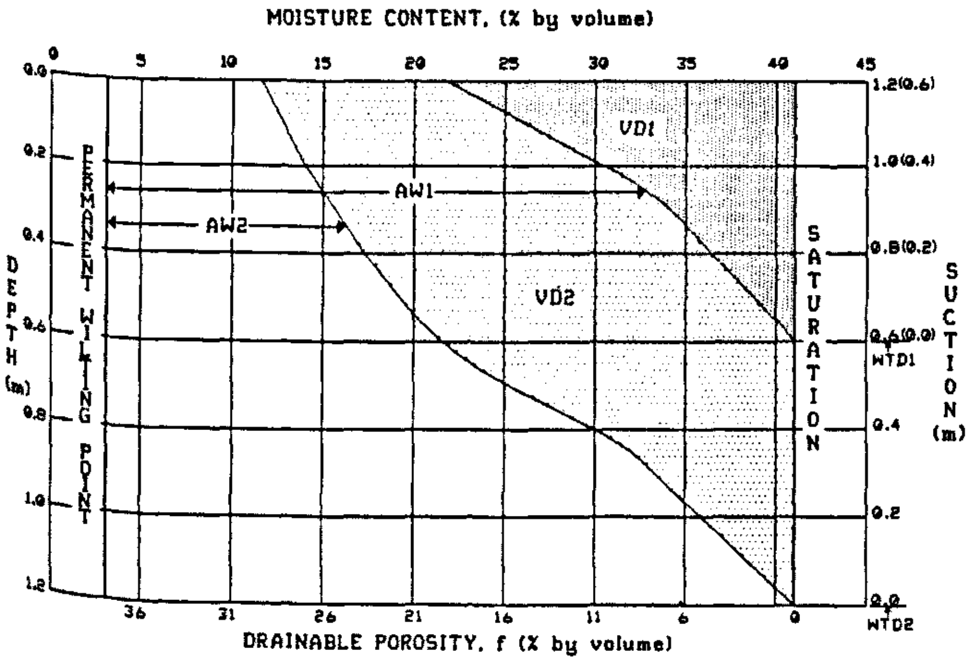

Figure 2: Soil moisture characteristics for a soil sample from Charbonneau's farm.

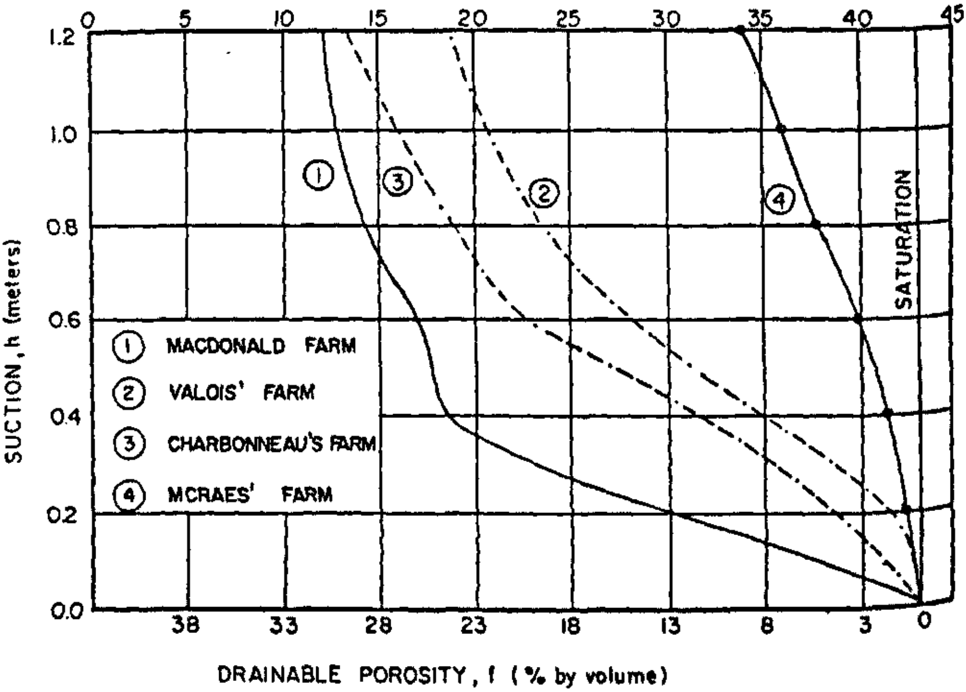

Figure 3: Mean values of drainable porosity vs. suction for all for all core samples obtained from each of the four farms.

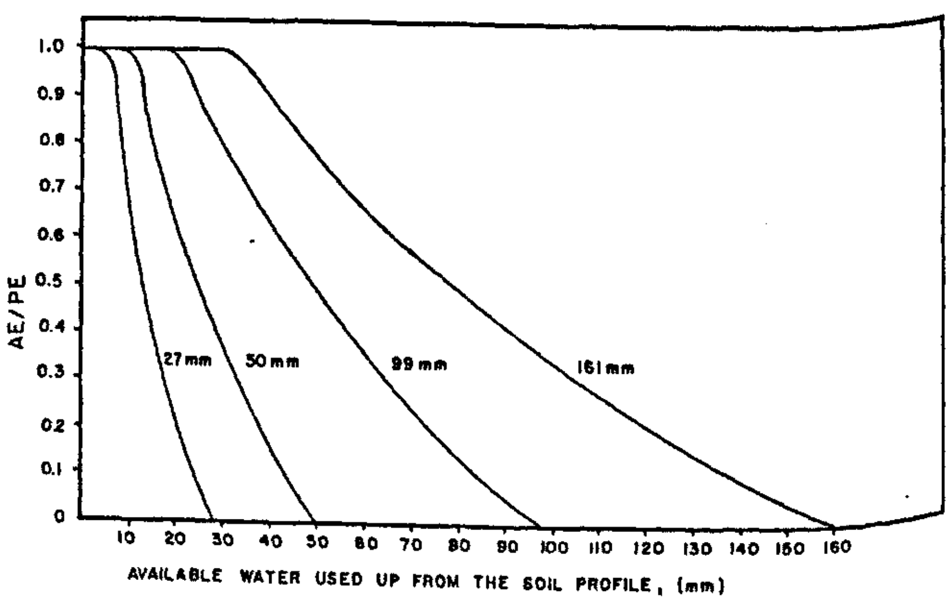

Figure 4: AE/PE ratio vs. available moisture used up for the root zone total available moisture capacities of 27, 50, 99 and 161 mm.

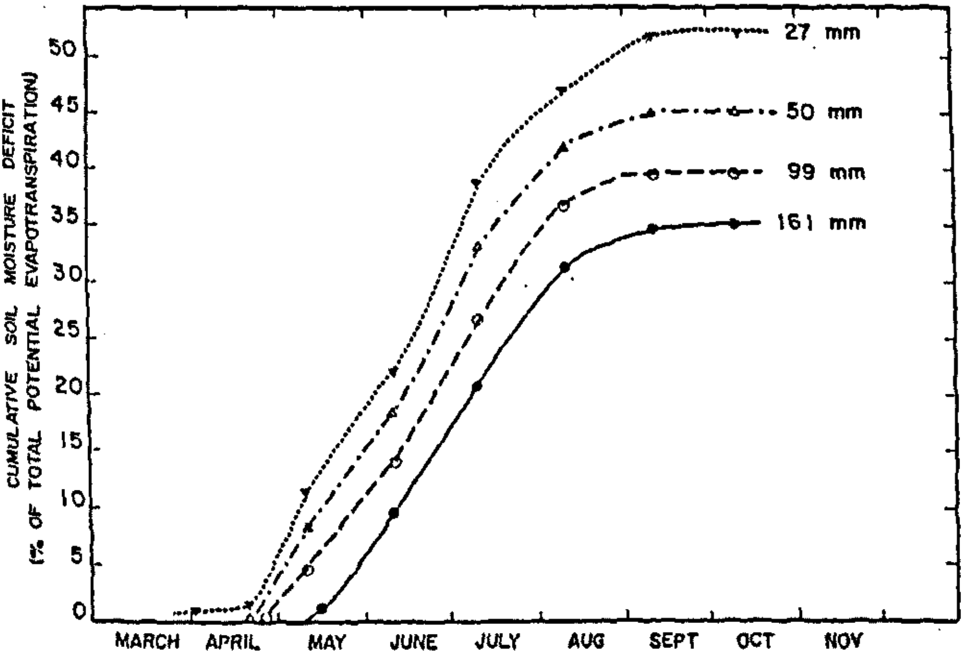

Figure 5: Cumulative soil moisture deficit.

Table 1. Mean values of pertinent soil-water parameters obtained in the present study.

Experimental Site	Depth of Soil Sample m	Field Value Moisture Content % by Volume	Moisture Content at 60 cm Suction % by Volume	Moisture Content at 15 Bar % by Volume	Water Table Depth at Time of Sampling m
Macdonald Farm	0.40	19.80	17.10	7.97	> 1.20
Valois' Farm	0.65	17.69	28.00	3.52	1.00
Charbonneau's Farm	0.45	25.72	22.50	3.12	> 1.20
McRae's Farm	0.34	38.46	39.50	14.94	1.20

Notes: 1. Field values of soil moisture indicate the moisture content at the time of sampling. These values should be approximately the "field capacity" values since sampling was done shortly after a period of rainfall.

2. The moisture content at 15 Bars is considered to be the permanent wilting point.

Table 2. Available soil moisture for a soil depth of 0.40 m for several water table depths for four farm sites.

Experimental Site	Available Soil Moisture (mm) for Water Table Depths 0.60 m	1.20 m
Macdonald Farm	36.52	17.72
Valois' Farm	97.90	58.00
Charbonneau's Farm	77.50	40.00
McRae's Farm	98.20	76.20

Notes: 1. Calculation of available soil moisture is based on soil moisture content data from Fig. 5 and permanent wilting point moisture contents (15 bar moisture contents) shown in Table 1.

Table 3. Sample water balance calculations for an available soil moisture of 27 mm, using climatic data for Macdonald Campus for April 1976.

Day	PE mm	AE/PE	AE mm	PRE mm	AW mm	SUP mm	DEF mm	ACDEF mm
					27.00	0.00	0.00	0.00
1	0.00	1.00	0.00	27.00	27.00	27.00	0.00	0.00
2	0.00	1.00	0.00	0.00	27.00	0.00	0.00	0.00
3	0.00	1.00	0.00	0.00	27.00	0.00	0.00	0.00
4	0.00	1.00	0.00	0.00	27.00	0.00	0.00	0.00
5	1.40	1.00	1.40	0.00	25.60	0.00	0.00	0.00
6	0.00	1.00	0.00	0.00	25.60	0.00	0.00	0.00
7	0.00	1.00	0.00	0.00	25.60	0.00	0.00	0.00
8	0.00	1.00	0.00	0.00	25.60	0.00	0.00	0.00
9	0.00	1.00	0.00	0.00	25.60	0.00	0.00	0.00
10	0.00	1.00	0.00	0.00	25.60	0.00	0.00	0.00
11	0.00	1.00	0.00	3.80	27.00	2.40	0.00	0.00
12	0.00	1.00	0.00	0.00	27.00	0.00	0.00	0.00
13	0.00	1.00	0.00	0.00	27.00	0.00	0.00	0.00
14	3.00	1.00	3.00	0.00	24.00	0.00	0.00	0.00
15	3.60	1.00	3.60	0.30	20.90	0.00	0.00	0.00
16	3.60	0.74	2.67	6.10	24.33	0.00	0.93	0.93
17	3.20	1.00	3.20	0.00	21.13	0.00	0.00	0.93
18	5.70	0.75	4.28	0.00	16.85	0.00	1.42	2.35
19	5.70	0.60	3.40	0.00	13.44	0.00	2.30	4.64
20	3.40	0.48	1.62	0.00	11.83	0.00	1.78	6.43
21	3.80	0.42	1.58	1.50	11.74	0.00	2.22	8.64
22	3.40	0.41	1.41	6.40	16.73	0.00	1.99	10.63
23	1.80	0.59	1.07	6.90	22.57	0.00	0.73	11.37
24	2.10	1.00	2.10	0.00	20.47	0.00	0.00	11.37
25	0.30	0.73	0.22	0.00	20.25	0.00	0.08	11.45
26	0.90	0.72	0.65	19.30	27.00	11.90	0.25	11.70
27	1.30	1.00	1.30	8.60	26.10	7.30	0.00	11.70
28	1.70	1.00	1.70	0.80	26.10	0.00	0.00	11.70
29	3.30	1.00	3.30	0.00	22.80	0.00	0.00	11.70
30	3.20	1.00	3.20	0.00	19.60	0.00	0.00	11.70

Table 4. Sample water balance calculations for an available soil moisture of 27 mm, using climatic data for Macdonald Campus for April 1978.

Day	PE mm	AE PE	AE mm	PRE mm	AW mm	SUP mm	DEF mm	ACDEF mm
					27.00	0.00	0.00	0.00
1	0.40	1.00	0.40	0.00	26.60	0.00	0.00	0.00
2	0.00	1.00	0.00	0.00	26.60	0.00	0.00	0.00
3	0.00	1.00	0.00	0.30	26.90	0.00	0.00	0.00
4	0.00	1.00	0.00	22.40	27.00	0.00	0.00	0.00
5	0.00	1.00	0.00	0.00	27.00	22.30	0.00	0.00
6	0.00	1.00	0.00	1.80	27.00	0.00	0.00	0.00
7	0.00	1.00	0.00	0.00	27.00	1.80	0.00	0.00
8	0.00	1.00	0.00	0.00	27.00	0.00	0.00	0.00
9	0.00	1.00	0.00	0.00	27.00	0.00	0.00	0.00
10	0.00	1.00	0.00	10.40	27.00	0.00	0.00	0.00
11	0.10	1.00	0.10	4.60	27.00	0.00	10.30	0.00
12	0.10	1.00	0.10	0.10	27.00	4.50	0.00	0.00
13	1.30	1.00	1.30	5.00	25.80	0.00	0.00	0.00
14	0.70	1.00	0.70	0.00	27.00	3.10	0.00	0.00
15	0.10	1.00	0.10	0.00	26.90	0.00	0.00	0.00
16	1.30	1.00	1.30	0.00	25.60	0.00	0.00	0.00
17	1.60	1.00	1.60	0.00	24.00	0.00	0.00	0.00
18	1.40	1.00	1.40	0.00	22.60	0.00	0.00	0.00
19	2.10	1.00	2.10	3.60	24.10	0.00	0.00	0.00
20	0.80	1.00	0.80	15.00	27.00	11.30	0.00	0.00
21	0.30	1.00	0.30	2.00	27.00	1.70	0.00	0.00
22	1.20	1.00	1.20	0.00	25.80	0.00	0.00	0.00
23	1.20	1.00	1.20	0.00	24.60	0.00	0.00	0.00
24	2.90	1.00	2.90	0.00	21.70	0.00	0.00	0.00
25	2.70	0.77	2.08	0.00	19.62	0.00	0.62	0.62
26	3.50	0.70	2.44	0.00	17.18	0.00	1.06	1.68
27	3.70	0.61	2.25	0.00	14.92	0.00	1.45	3.12
28	3.30	0.53	1.74	0.00	13.18	0.00	1.56	4.68
29	3.30	0.47	1.54	0.00	11.64	0.00	1.76	6.44
30	1.70	0.41	0.70	0.00	10.95	0.00	1.00	7.45

Table 5. Percent soil moisture deficits resulting from the placement of subsurface drains at different depths (2).

	Depth of Subsurface Drains (m)			
	0.60		1.20	
Root depth (m)	0.40	0.60	0.40	0.60
AW (mm)	99	161	27	50
1976				
April	0.01	0.00	1.67	0.50
May	7.32	3.96	17.23	12.12
June	20.50	16.25	32.99	26.70
July	39.94	34.98	57.43	49.34
1976				
April	0.09	0.00	2.88	1.13
May	0.58	0.00	8.70	3.18
June	9.70	4.83	20.95	14.49
July	15.75	10.39	32.88	22.60

Notes: 1. The soil moisture deficits given in the table are cumulative over the period of calculations.

2. Soil moisture deficits are expressed as percentages of total potential evapotranspiration for the period from April to July.

CURRENT DRAINAGE DESIGN PRACTICES IN FINLAND

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Finland is the world's most northern agricultural country. If one were to estimate the use of the earth's land area globally bearing in mind the whole world, one would hardly recommend the practice of agriculture to the north of the 60th degree of latitude. At a quick look there are no preconditions for the agriculture in such a northern area.

The climate of Scandinavia, however, is warmer than its latitude would suggest. This is due to the warm Gulf stream. And as the use of the earth is not planned globally, in order to manage the Finns have been forced to take advantage of all the available resources including agriculture.

Compared to her neighbours too, Finland is situated in the north. 90 % of Sweden's cultivated area lies to the south of the 60th latitude, Finland is entirely to the north of this latitude.

A short growing period, a cold winter, a thick snowcover and small farms have been the starting points for Finland's agriculture. At first leaning on experience gained from trial and error, later through research and experimentation, methods have been developed by which farming has been succesfully practiced. Since the beginning drainage has been one centrally basic improvement, at first drainage by open ditches and later subdrainage. The development of strains of plants suitable to the climate and the development of orher methods have led to the fact that Finland is not only self-sufficient in regard to agricultural products but that there is significant overproduction in some areas. The degrees of self-sufficiency are as follows:

Grain	87 %
Dairy products	124 %
Beef	122 %
Pork	110 %
Eggs	159 %
Sugar	54 %

As early as the 1920's experimental fields were set up by which it was aimed to ascertain which methods of subdrainage were most suitable to Finland's soil types and climatic conditions, primarily questions of drain spacing, drainage depth and dimensioning of the pipes. As the growing season is short, only 100 days in northern Finland and only 160 days in southern areas of the country, drainage must prepare the soil for cultivation as quickly as possible. The rule of thumb "a day in spring is a week in autumn" well describes this aim.

Yearly precipitation in Finland is 500-700 mm, less in the north and more in the south. Of the precipitation 200-500 mm comes as snow. Precipitation is at maximum in August and at minimum in March.

About half of the precipitation in southern Finland evaporates, in northern Finland one third. During the melting period spring runoff is 100-200 mm. Summer runoff is only 10-40 mm as most rain evaporates or soaks into the ground. As evaporation decreases in the fall runoff increases; it can be 50-100 mm.

The date of the settling of the seasonal snowcover is at the end of October in Lappland and snowcover disappears at the end of May. In southern Finland the snow comes in the middle of December and melts in April. The maximum water equivalent of snow varies according to area from 60 to 200 mm, which corresponds to 20-70 cm of snow coverage.

The best clay soils were formed below the sea level when the continental glacier melted in southern Finland. There are areas of peat all over the country, but in northern Finland peat areas are the primary areas of cultivation. There are also sand and morain areas under cultivation.

The hydraulic conductivity of the soil is strongly affected by soil frost. In winter the earth freezes to 20-100 cm depth depending on the thickness of the snowcover, the type of soil etc. Soil frost affects drainage in many ways. It is harmful in pring when the hydraulic conductivity of frozen soil is very low and the water from the melting snow flows over the surface of the ground. On the other hand, soil frost has a significant effect as an improver of the structure of the soil. Aggregate structure forms in soil subjected to frost which improves the soils hydraulic conductivity.

These preconditions have had a determining effect on the planning criterion of subdrainage. The melting of the snow in the spring over a short period of time causes flooding in both fields and waterways. The removal of excess water quickly is a precondition for the warming of the soil to a fertile condition. - One can mention that in northern Finland it is often necessary to sow when the topsoil is dry even though the subsoil is still frozen.

The systematic planning of subsuface drainage began in the 1920's when the Finnish Subsurface Drainate Association (precessor to the Finnish Field Drainage Centre) was founded. At the beginning planning principles and criteria were defined, where the reliability at all stages of work was stressed. With the aid of experimental fields the planning criteria were verified. The following principles were set:

1. <u>Map filing</u> Plans were always made on a map. The maps were filed at the central office. Plan changes made during work time were drawn on the maps. Thus it was always possible to find the individual subsurface drains if it was necessary to carry out repairs to the drains of if other measures such as the construction of roads, water pipes, cables etc came inte question.

2. <u>Slopes</u> The minimum slope of lateral drains was set at 0.3 %. A system's slopes were planned in such a way that the speed of the water grew as it went down the drainage pipes. The idea was that soil particles that had got into the pipes would not settle to the bottom of the pipe but would be carried along and out of the drainage system. If the speed of the water decreased because of slopes in the terrain a manhole was planned at such a place that earth particles would be able to settle.

3. <u>Pipe size</u> At the beginning the smallest inside diameter of a pipe was 30 mm, later 40 mm. Other pipes were dimensioned according to the amount of water using the design criteria (drainage

coefficient) of 1 liter per second per hectare (equal to 8.64 mm/day). The small pipes flow full of water almost every spring and the water there reaches its maximum velocity at which time the pipe is cleaned of sludge which has possibly been collected there.

4. Installation accuracy

The subsurface drains were installed very accurately at the planned depth. Permitted deviation in depth was less than 10 mm.

5. Work order — The subsurface drains were first dug open in their entirety and the clay tiles were installed from the top downwards so that the water flowing in the trench did not bring sludge into the completed pipe system.

6. Gravel cover — The pipes were always covered with a 5-10 cm thick gravel envelope. In unpermeable soil blind inlets were constructed regularly at 8-10 m distance.

7. Drain depth — The average depth of the drains was planned to be 120 cm, in northern Finland 140 cm. The absolute minimum depth was considered 90 cm.

8. Drain spacing — The average drain spacing of the subsurface drains was defined on the basis of the hydraulic conductivity of the soil. In poorly permeable soil the spacing was 16 m, in sandy soil 18-25 m, in peat soil 20-30 m.

The principles presented above were drawn up under circumstances when there was little experience and professional skill in the execution of subsurface drainage in the country. We can count to the benefit of the tight instructions that the subsurface drains have had a very long life. In Finland there are still plenty of fully operative drains from the 1920's dug with spades.

The modern planning of subsurface drainage is based to a large extent on the criteria presented above. Naturally some closer specifications have been made with the increase of knowledge and development of techniques.

- The map archives of the Finnish Field Drainage Centre still contain all the country's subsurface drains.
- A minimum slope of 0.3 % is still kept to, exceptions are under-water drains and large pipes.
- A minimum size of 40 mm is still in use. It is cheap and conveying capasity is sufficient. 32 mm pipes have been planned to be used in complementary drainage.
- Installation accuracy is kept within the 2 cm range.
- Pipes are laid straight from the digging machine.
- As well as gravel, sawdust and pre-wrapped envelopes are also used as envelope material.
- The share of plastic pipes is already 80 %.
- Normative drain depth is 100 cm, the minimum depth is 80 cm.

- The intensity of drainage has been increased as the demand of trafficability of cultivated land has grown. Drain spacing depends on the type of cultivation as well as the type of soil. Generally a spacing of 12-16 metres i used.

- The laterals are placed perpendicular to the field slope, perpendicular to surface drains and perpendicular to plow direction.

Subsurface drainage work in Finland is in the region of 2 million hectares of which half has been completed. The aim is to drain 700 000 hectares by the year 2000.

Planning is taken care of by the Finnish Field Drainage Centre, which has 100 technicians around the country. Each year 35 000 hectares are planned. In planning and field research work computer based technique is also used.

Research and testing is carried out in a number of organizations, research institutes and universities. During the last few years research activity has increased.

Subsurface drainage work is carried out by about 300 contractors. Their drainage machinery are mainly wheel-digging or chain-digging machines manufactured in Finland. These machines move on rubber-tyre wheels. Over recent years a few trenchless machines have been introduced into the country. Drainage work costs are on the average 9000 FIM (about US$ 1800)/hectare. The state supports subsurface drainage work with grants and loans.

The present problems of Finnish subsurface drainage are ochre glogging and compaction. Ochre blockage is being combated by designing under-water pipes and developing flushing systems. Additional drainage has been developed against the compaction problem of clay soil. The problems of peat soil are partly unresolved. Help seems to be coming by forming the land surface in such a way that surface water problems are eliminated. This is especially a problem of the north.

EVALUATION OF A SOIL MOISTURE MODEL

S. E. White* T. S. Colvin* J. Sacks*
Member ASAE

An evaluation was made of a simulation model designed to predict available field operation time. The simulation model was based on the premise that workable field days could be accurately predicted if a field's tractability condition was known. The model determined a field's tractability condition as "good" or "bad" using local soil characteristics and daily weather factors. A model such as this may be useful worldwide for operational planning of time and machinery systems. Based on an analysis of four environmentally different regions in the midwest, the model worked reasonably well. But further investigation is needed to determine the extent of the models applicability.

INTRODUCTION

In their agricultural operations, farmers' must be able to accurately forecast the number of days during a month that a field will be workable. Field operations performed at inappropriate times, such as when the soil is too wet, can be damaging to the soil tilth, overly time consuming, inefficient, and hence uneconomical (Hassan and Broughton, 1975). Therefore, a model that accurately predicts the number of workable field days could save farmers time and money, lead to better farm practices and better soil health. Such a model might also be extendable to uses such as evaluating the relationship between machine characteristics and soil moisture conditions in order to optimize machine use (Babeir et. al., 1986). A model that can be customized to a specific location by using local soil and climate factors, such as this one, could be useful to farmers over a large geographic area, perhaps even worldwide.

Babeir (1984) designed a simulation model based on the premise that workable field days could be accurately predicted if a field's tractability condition was known. Tractability here refers to a field's ability to sustain tractor operations without soil damage.

Tractability is a function of the soil's moisture content which Babeir's model estimated using four climatic factors: daily air temperature, precipitation, evaporation, and snow cover, as well as two soil factors: initial moisture content and moisture content at

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field capacity. His model was developed using the soil characteristics, and one year of climatic and observed number workable day's data specific to Central Iowa. A preliminary evaluation of the model was preformed by way of regression analysis using data from both Central and Northwest Iowa (Babeir it. al., 1986). Climatic data was taken from the Des Moines weather station for the Central Iowa region and from the Sioux Falls, South Dakota weather station for the Northwest Iowa region. However, the same soil characteristic inputs were used for both regions. In addition, these two regions are relatively close to one another geographically, and thus their climates may not differ significantly either. To satisfactorily evaluate the model, simulations needed to be made on more regions which differed from Iowa in soil composition and climate.

Our objective is to evaluate Babeir's model for a wider area of applicability by comparing the average difference between the number of observed and predicted workable field days for each month, for four different regions of the United States. Regional comparisons will be made in a pairwise fashion using analysis of variance contrasts.

METHODS

The Model

Babeir's (1986) soil moisture balance model established the daily tractability condition of a field. Tractability conditions were classified as "good" if the daily soil moisture content was below an established soil moisture criterion and "bad" if above the criterion. The soil moisture criterion was determined by trial and error (Babeir, 1984) and expressed as a percentage of the soil's field capacity. It was found that a soil moisture content less than or equal to 99% was necessary for tractability. Daily soil moisture content of a field was determined by the model using, as inputs, five daily weather characteristics: maximum air temperature, minimum air temperature, pan evaporation, snowfall, snow on the ground, and precipitation. Two soil characteristics --diffusion and drainage of water-- were then incorporated into the submodel and a tractability condition was estimated (Figure 1). The soil moisture criterion was determined by trial and error (Babeir, 1984) and expressed as a percentage of the soil's field capacity. It was found that a soil moisture content less than or equal to 99% was necessary for tractability.

Empirical Data on Workable Field Days

Test regions outside Iowa were selected based on availability of observed workable day data in regions suspected to have different soil composition and climate than Iowa. Indiana and Missouri were chosen as the additional regions. Long range averages of monthly rainfall indicated that these regions should be climatically different from each other and from Iowa (Shaw et. al., 1960).

Both Iowa and Indiana collect their observed workable field day data in the same manner. Each state is divided into nine reporting districts composed of 8-16 counties each. Volunteer reporters in each county keep a weekly record of workable days for field work of that season. Reporters give each day a value of one if it is workable and zero if it is not. Thus, a district's rating for its region's field workability is the average of values for all the counties in that district (Personal communication with the Iowa Crop and Livestock Reporting Service, 1987; Parsons and Doster, 1980). Data on workability has been collected in Indiana since 1951, but yearly termination of data collection has varied through the years, so that data may not reflect the days suitable for work in late November and early December. Missouri uses weekly instead of daily averages from reporters in each district to generate their data on the number of workable field days (Personal communication with the Missouri Crop and Livestock Reporting Service, 1987).

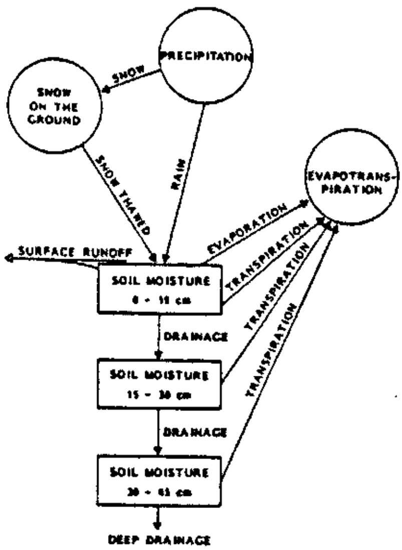

Figure 1. Components of soil moisture balance model.

The Analysis

The model was tested on four regions: Northwest Iowa (years 1965-80); Central Iowa (years 1965-80); West Central Indiana (years 1969-78); and Central Missouri (years 1975-86).

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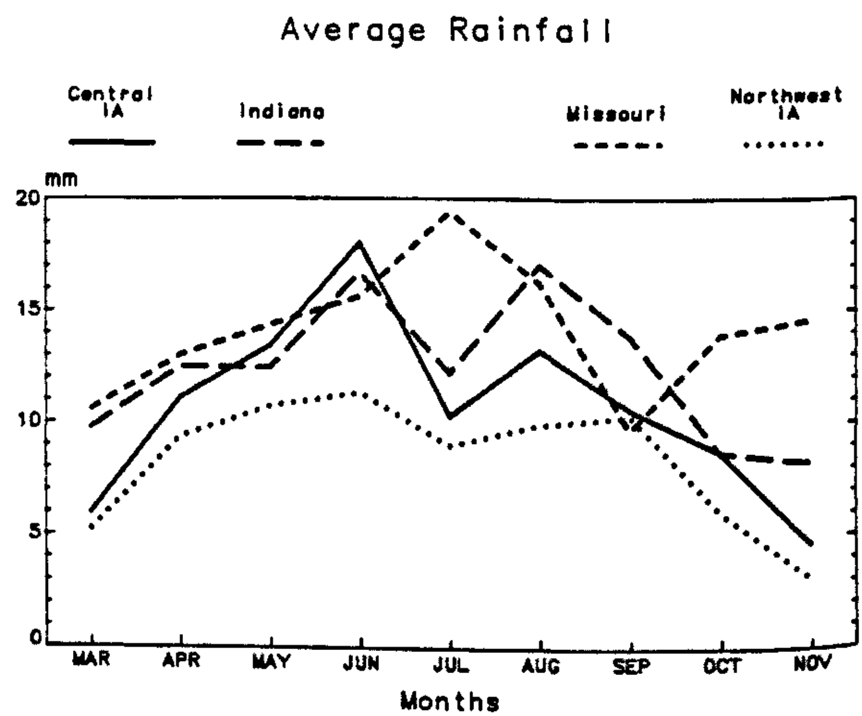

Figure 2. Average regional rainfall.

The Analysis

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The soil characteristics used by the model were abilities to drain

The soil characteristics used by the model were abilities to drain (measured in terms of a soil's permeability) and diffuse water. The model was more sensitive to a soil's representative drainage value than to its diffusion value (Babeir et. al., 1986). Therefore, permeability was the only soil characteristic examined. The permeability values used by the model were determined by the proportional weighting of average permeability values for the two most abundant soil types in a region. The range of permeability for the two most abundant soils in both Iowa regions tested was from 0.6 to 2.0 in/hr (Andrews and Dideriksen, 1981), that for Indiana was from 0.6 to 6.0 in/hr (Langlois, 1982), and that for Missouri was from 0.06 to 2.0 in/hr (Held, 1978). These values indicated to us that the regions were sufficiently different with respect to soil drainage.

Babeir et. al.'s (1986) sensitivity analysis indicated that rainfall substantially affected the determination of workablity or nonworkablity of a field (Fig. 2 -3). Therefore, regional distributions of rainfall were analyzed using analysis of variance contrasts to determine if regional climatic differences existed.

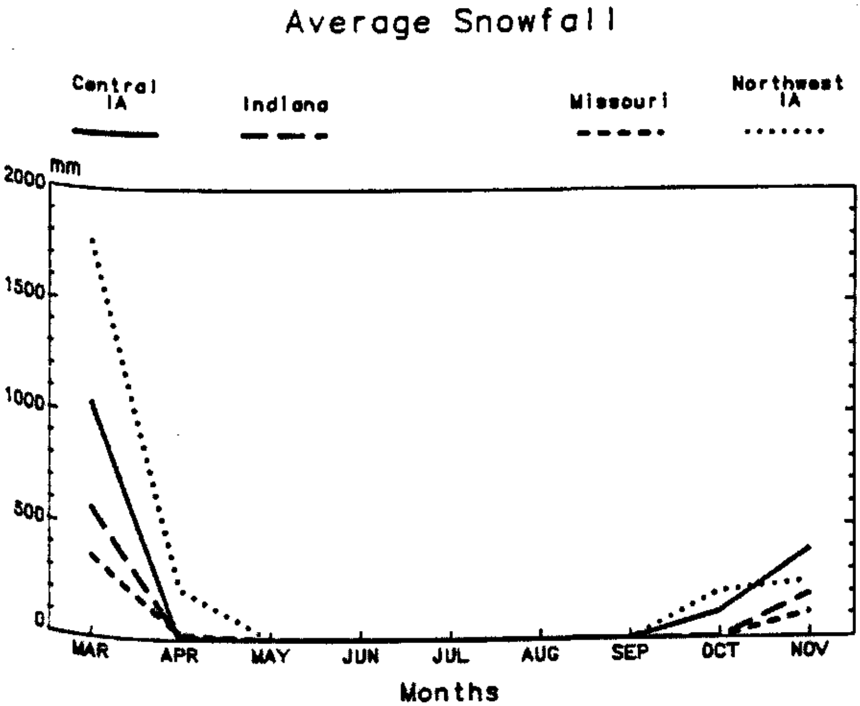

Figure 3. Average regional snowfall.

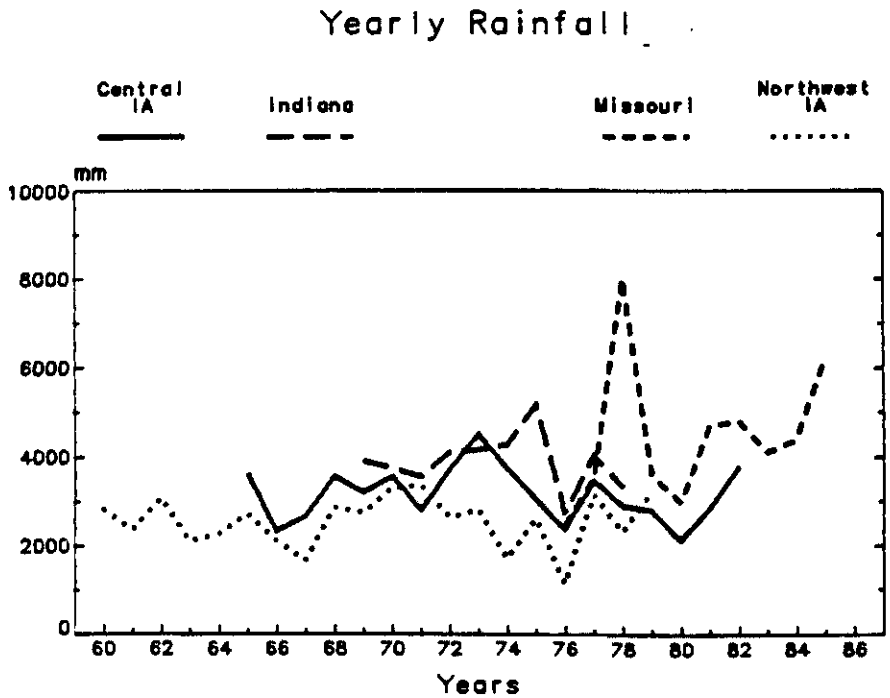

Figure 4. Yearly regional rainfall.

Three contrasts were made: Central Iowa versus Northwest Iowa, Missouri versus Indiana, and Central Iowa combined with Northwest Iowa versus Indiana combined with Missouri. Central Iowa and Northwest Iowa were contrasted to determine if they were significantly different climatically and thus contributed to the model's evaluation or whether they were too simalar. The constrast of Central and Northwest Iowa against Indiana and Missouri allowed for a third constrast that was orthogonal to the other two. The following model was used to determine if differences existed in rainfall among regions:

$$Y = U + r + y(r) + m + r*m + e$$

Where Y represents the response, rainfall;
U represents the overall mean;
r represents the regional effects;
y(r) represents the within region yearly variation;
m represents the monthly effects;
r*m represents the interaction of region and month;
and e represents the random error associated with each observation.

The discrepencies between observed and predicted number of workable field days were analyzed by the same model to see if Babeir's model fit some regions better than others. When this was done, the response Y, represented discrepency between observed and predicted number of workable field days.

RESULTS

There was no significant year to year variation in average rainfall within regions ($p > .10$). Overall average yearly rainfall did differ among regions ($p < .01$). Central and Northwest Iowa differed significantly ($p < .05$), as did Iowa vs "others" ($p < .01$). However, Missouri and Indiana did not differ significantly ($p > .10$). This lack of significance appeared to result from the large variation in yearly rainfall for Missouri. In particular, 1978 was an exceptionally heavy rainfall year for Missouri.

Monthly average rainfall also varied significantly ($p < .01$), but the monthly rainfall and region interaction was not significant ($p > .10$). Thus, as fig. 4 demonstrates, all four region's monthly rainfall distribution patterns were similar, though not identical, with the average rainfall amount varying from month to month.

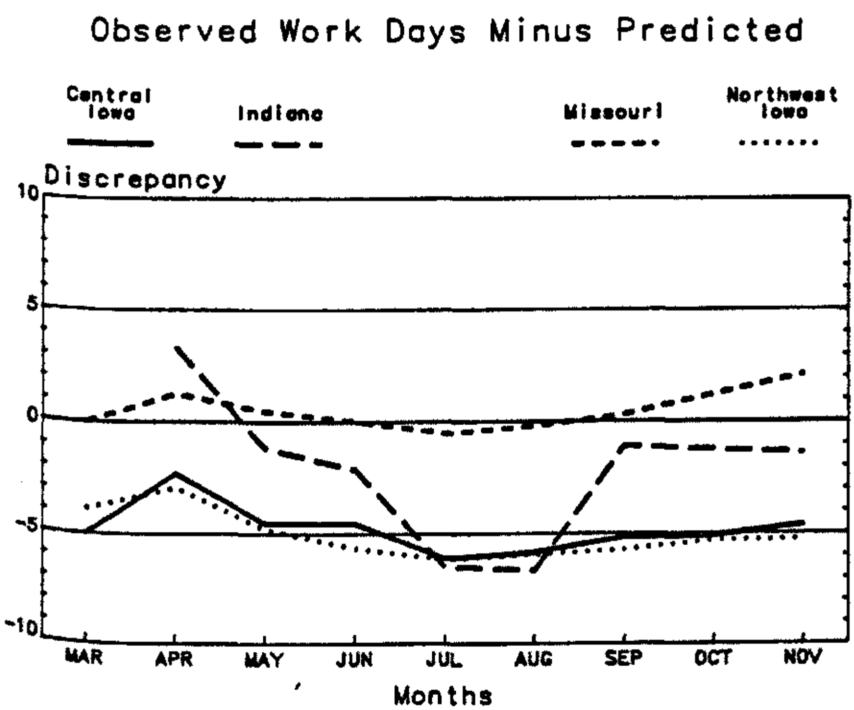

Figure 5. Observed minus predicted workable days.

The Iowa vs "others" contrast interaction with month was significant ($p < .01$), but due to the large differences between Indiana's and Missouri's distributions, the interaction effect of Iowa vs "others" with month was also not readily interpretable.

DISCUSSION

The model was tested on four regions which were distinct with respect to soil and climatic. The general reliability of the model was good as was demonstrated by no significant year-to-year variation of discrepencies within regions. The result of contrast and month interactions and an examination of fig. 5, indicate that the model performed consistently for both the Central and Northwest Iowa regions. Though the model overpredicted the number of workable field days in a month for both these regions, the overprediction did not vary through the year. The Missouri versus Indiana contrast with month interaction indicates that the model did not perform consistently over months for this pairing. Figure 5 shows that this significant interaction effect was probably due to the model's erratic performance for the Indiana region. The model appeared to work very well for the Missouri region.

Salmon and Wallis (1982) stated that a model analysis without an associated loss function could lead to evaluations using statistical criteria that seem resonable but were seldom rigorously justified. As an alternative to a loss function, the model could be evaluated using the following criteria: the discrepency between observed and predicted number of workable field days be no greater than five days (fig. 5). Since the model performed consistently for both the Iowa regions, a linear adjustment to the models predictions could be made to bring the average monthly discrepency close to zero for these regions.

Though, in general, our results indicate that Babeir's model may be useful for agricultural operation planning in the midwestern United States, further testing should be done. The model performed erratically for the Indiana region suggesting there may be some other environmental factor that should be incorporated into the model. Another possible factor that may account for the model's erratic behavior in the Indiana region is the range of field operations in different months represented in the observed data set. If these operations tended to be concentrated on different soils with different characteristics or required different tractability conditions on the same soils, then testing this model with a single set of parameters would not appropriate. For this to be a cause of the model's erratic behavior in the Indiana region, Indiana would have to have been different in this regard as compared to the other three locations. More testing of the model would need to be done before it could be recommended for wider use.

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CONTRACTORS' PRACTICE IN PLANNING AND MAPPING SUBSURFACE DRAINAGE SYSTEMS IN ILLINOIS

Scott F. Day
Day Drainage, Inc.

The installation of drainage tile is a necessity for farm land in the central region of Illinois, USA. However, equally important is the documentation of this drain tile installation. This documentation can be provided by a map, usually made or furnished by the drainage contractor.

HISTORY OF MAPPING

Mapping has a small history in central Illinois that dates back to the 1880s. Hiram Sibley's Burr Oaks Farms of Sibley, Illinois, were the pioneers in mapping from drainage in central Illinois. These farms, consisting of over 20,000 acres, became interested in drainage in the late 1800s due to some very wet problem areas. Since a portion of the land was swamp land, drainage ditches were excavated to drain the runoff so the land could be put to good use. Wet areas remained in low lying areas and side hill seepage areas. The only way to drain these areas was by some type of subsurface drainage. Clay tile was used as the conduit and is thought to be some of the first ever installed in central Illinois. Even though this tile was installed with spades and shovels and back-breaking manual labor, approximately 200 feet per acre, involving some type of grid pattern, was installed on these 32 sections of farm ground. The mapping was a process done without much detailed measurements, therefore, locating these drain tiles is somewhat difficult today. Although documentation was not very accurate, it is some of the first maps ever made of drain tile installation.

When the depression hit the United States in the early 1930s, tile drainage as a whole slowed to near extinction. This caused agricultural expenditures to be carefully monitored in which drainage became the last consideration.

"Ditch Diggers" began sprouting up in the small rural communities with nothing more than spades and shovels. Then, ditching machines began replacing manual labor, which lead one company — St. Anne Farm Drainage Company of St. Anne, Illinois — to travel around central Illinois installing subsurface drainage tile. There were several machines and operators with mapping personnel documenting the installation. These maps were a vast improvement over the Burr Oak Farms and were very well drawn and measured. Most of the tile was installed in a random fashion with some system work involved. The maps were drawn on mylar paper with copies given to the landowners.

With the St. Anne Company dissolving, more individuals became attracted to the tile installation business. However, with a great work load and limited time, mapping became one of the least thought of requirements of a "job well done." Maps were made on scratch paper, notebook pages, and even parts of cardboard boxes, whatever was convenient to the contractor at the time. Measurements were not accurate and legibility was certainly less than desirable. However, at least an attempt was made to document the installation location.

With the increased number of contractors in the 1970s, mapping became a selling tool for each company - a good map suddenly became very intriguing. Landowners were interested in accurate maps because they were having difficulties in locating the tile installed in the early 1900s. The prospect of having an accurately drawn map would be ideal for current and future references.

Our particular drainage company has a very rare policy — mapping is as important as the tile installation itself. Today our company has an almost unique mapping process that dates back to 1980. Since most contractors do not concentrate their abilities in the mapping field, this important task is sorely neglected. Unfortunately, a standardized mapping system for drainage contractors has not been established, or at least none commonly used by contractors in the Central Illinois area. This leads to a wide variety of mapping techniques being used. The easiest way to draw a map also seems to be the most popular -- a freehand drawing or sketch of the tile installation that is not to scale. Other contractors make use of the U.S. Government's aerial photos available to landowners. Contractors use these aerial photos to indicate the location of tile lines on them. A third method is to use the 8" X 11" scaled grid sheets which eases the mapping task. Some contractors do take advantage of this accessability and if drawn neatly and to scale, it is a vast improvement over the two previously described types.

Another way of mapping tile jobs, although expensive and somewhat inconvenient, is with the use of aerial photography that is done by the contractor. After completion of a subsurface drainage project, contractors can rent a small private aircraft with a pilot and, riding along with a basic 35mm camera, take photographs of the land. Although this is not a good way to determine an accurate location of the lines for future reference (because of no actual field measurements), the advantage is that several jobs can be photographed in just a matter of hours.

MAPPING DESIGN PROPOSAL

Mapping begins with the initial customer contact. When a customer has a wet area on his farm and is seeking subsurface drainage as a possible solution, the contractor should use mapping as a selling tool for systematic tile installation. In central Illinois, subsurface drainage is often thought of as installing tile in a "random type fashion." This results in inadequate drainage. Therefore, it is good policy to insist on surveying the entire field or, if the area is too large, at least the water shed area of the field which contains the wet problem.

There are a number of reasons for this particular procedure:

1. This can be used as a selling tool. Informing the landowner how system drainage works and how it can be practiced on their farm.

2. Sizing of main tile lines can be determined and proposed for future considerations using the Illinois Drainage Guide (1984).

3. An accurate cost estimate can be established through neat and precise mapping using correct design.

Upon completion of a topographical survey of the field, a rough elevation map of laterals and mains is drawn to scale using layout design guidelines as those listed in the Illinois Drainage Guide (1984). This map is for design purposes only. With a clearprint tracing paper layed directly on top of this drawing, the tile lines can be traced in the correct location. This clearprint copy becomes the final subsurface drainage design. It should contain tile line and reference point measurements and any other important distances. A reference measurement is the distance from a fixed point to a point of interest. For example, the distance between a tile line and the center line of a road (assuming these two are parallel) is a reference measurement. This measurement is used to locate that particular tile line and can be located at any given time. Measurements are drawn on a map only if they are important. These should be kept at a minimum; too many written measurements will clutter a map and make interpretation of the map very difficult. If there are many measurements of the same distance in a series, as in the spacings of laterals in a tile system, the measurement should be written once with the abbreviation for typical (TYP) written underneath. This indicates that all laterals have the same spacing. Another method is writing the words "these tile lines are equally spaced X number of feet apart unless otherwise shown," on a leader line to one of the spacings. Other critical information, such as tile sizes, existing tile lines, etc., should also be contained on this particular map. An example of a design proposal map is shown in Illustration 1.

Along with these measurements, a design proposal map should contain a statement to protect the author against any legalities stemming from an incorrect design. For example, the statement "not responsible for design" could be written.

TILE INSTALLATION COMPLETION PROCEDURES

Certainly, the most important part of a drainage system is the actual tile installation. However, once this has been completed, a detailed map accurately displaying location of the drainage tile becomes equally critical. Knowing the difference between a design proposal map and the final subsurface drainage map is important. The proposal map is a guideline for tile installation where changes can occur. The final map is the tile installation as it was actually installed. If the contractor retains the original map, future additions can be easily drawn on this map.

Measuring should be done immediately following completion of a job to ensure accuracy. Some contractors use measuring tapes or a measuring wheel to do this. Others may use distance measuring instruments (electronically controlled devices installed in a vehicle set up to measure footages).

SUBSURFACE DRAINAGE INSTALLATION MAPPING - STEP BY STEP

Mapping can become less burdensome by using the proper equipment. Various equipment items available to ease the complex task of graphic design include:

1. a drafting table or drawing board;
2. a drafting machine or sliding-T square;
3. an engineers' scale or rule;
4. 30 - 60 triangle;
5. 45 triangle;
6. geometric design template (for drawing circles, squares, triangles, arrowheads, etc.);
7. french curve (for drawing curved lines); and
8. drafting pencils;

The first step is to select the correct sized paper. Using a 1 inch equals 200 foot scale, the appropriate sizes of paper are as follows: size "B" for 80 acres, size "C" for 160 acres, and size "D" for 320 acres.

Next, using drafting tape, tape one of the upper corners of the paper to the drafting table or board. Then by lining the borderline with the straight edge, tape the opposite corner while easily stretching the paper to prevent wrinkling. Tape all four corners.

The use of two different pencil leads is sufficient (a soft and hard lead). Use a .05mm drafting pencil to ensure neatly drawn lines. As shown in Figure 2, the soft lead is used for dark and heavy lines such as:

1. object lines or tile lines
2. lettering and numbering
3. border lines

The hard lead, also shown in Figure 2, are used for lighter lines such as:

1. cross hatching lines
2. construction lines
3. dimension lines
4. leader lines
5. extension lines
6. lettering guidelines
7. existing tile lines
8. utility lines

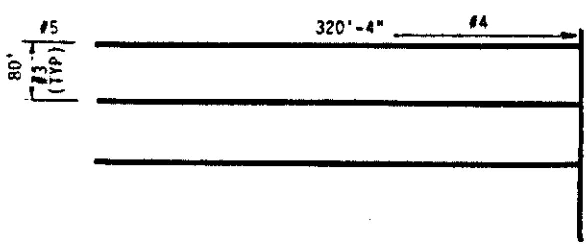

Fig. 1 Lines Example

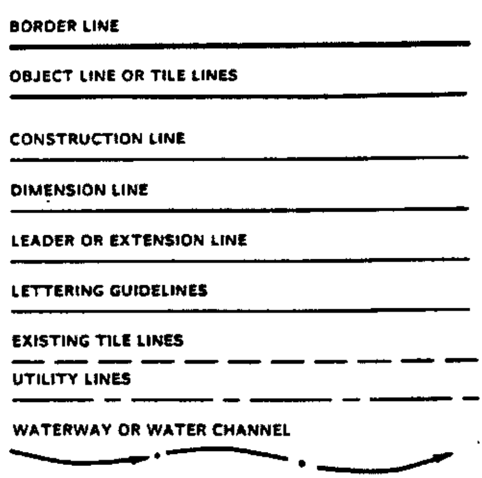

Fig. 2 Line Weights

Always draw with the soft lead as the last step. When drawing parallel lines, move away from each line drawn. This will prevent smearing the map. Drawing additional features, such as hedge trees, drainage ditches, farm buildings, underground utilities, roads, etc., help improve a drawing. Indicate which direction is north to prevent confusion. The following list is a set of recommended guidelines to follow:

1. Lettering

   a. should be at least 1/8" high but not more than 3/16"
   b. can be slanted or vertical
   c. should be neat and legible
   d. should be underlined with line 1/16" below lettering (underline should be nearly as heavy as object line)

2. Arrowheads

   a. should be 1/4" long and 1/16" wide
   b. should be dark and neat

3. Dimensioning

   a. should read from bottom of drawing or from right hand side
   b. should be located approximately at center on dimension line (unless interfering with other lines)
   c. should be no closer than 1/2"
   d. should have uniform spacing of dimension lines throughout the drawing.

Existing tile should be marked and displayed on the map. When a contractor cuts through an old field tile, the direction in which it was running should be determined and shown on the drawing. As noted previously, the hidden line is used for existing tile lines. With the approximate angle determined, a letter is placed by each existing tile line. Using a geometric design template, this letter should be circled with a 5/32" circle. In an isolated area on the map, a label describing the existing tile should appear as a heading to an organized list. By using the alphabetized order, each letter should be listed with the following information:

1. tile size;
2. type of tile conduit (clay, concrete, plastic, etc.)
3. the amount of sedimentation (50% or whatever); and
4. what was done to repair this particular tile line.

The most important part of a map is the title box. A title box should contain this information:

1. landowner's name
2. nearest town or village
3. scale
4. date
5. designed by:
6. drawn by:
7. description of location (township and section number)
8. county
9. type of map
10. drawing number

The drawing number is used for filing purposes. A filing system will work more effectively with the use of these identification numbers. My numbering system consists of a three digit chronological number with a two letter prefix. For example, if a tile installation job was done in Champaign County, the letters CC would serve as the prefix.

Upon completion of the clearprint copy of the map, select a blueprint store or other means of blueprinting your map. Two copies are recommended. One blueprint copy is given to the landowner/customer along with the invoice. The second copy belongs to the contractor and filed accordingly. The clearprint original should also be filed by the contractor for future use. An example of a subsurface drainage installation map is shown in Illustration 2.

CONCLUSION

Time seems to be the main ingredient for appropriate mapping. The correct form of mapping is detailed and scaled in a neat, organized fashion. This can only be accomplished by certain contractors — those determined to attain the knowledge of, and actually practice, good mapping techniques. This is very time consuming; thus, is difficult to fit in a contractor's busy schedule. Therefore, organization is the key to a good mapping program for the typical drainage contractor.

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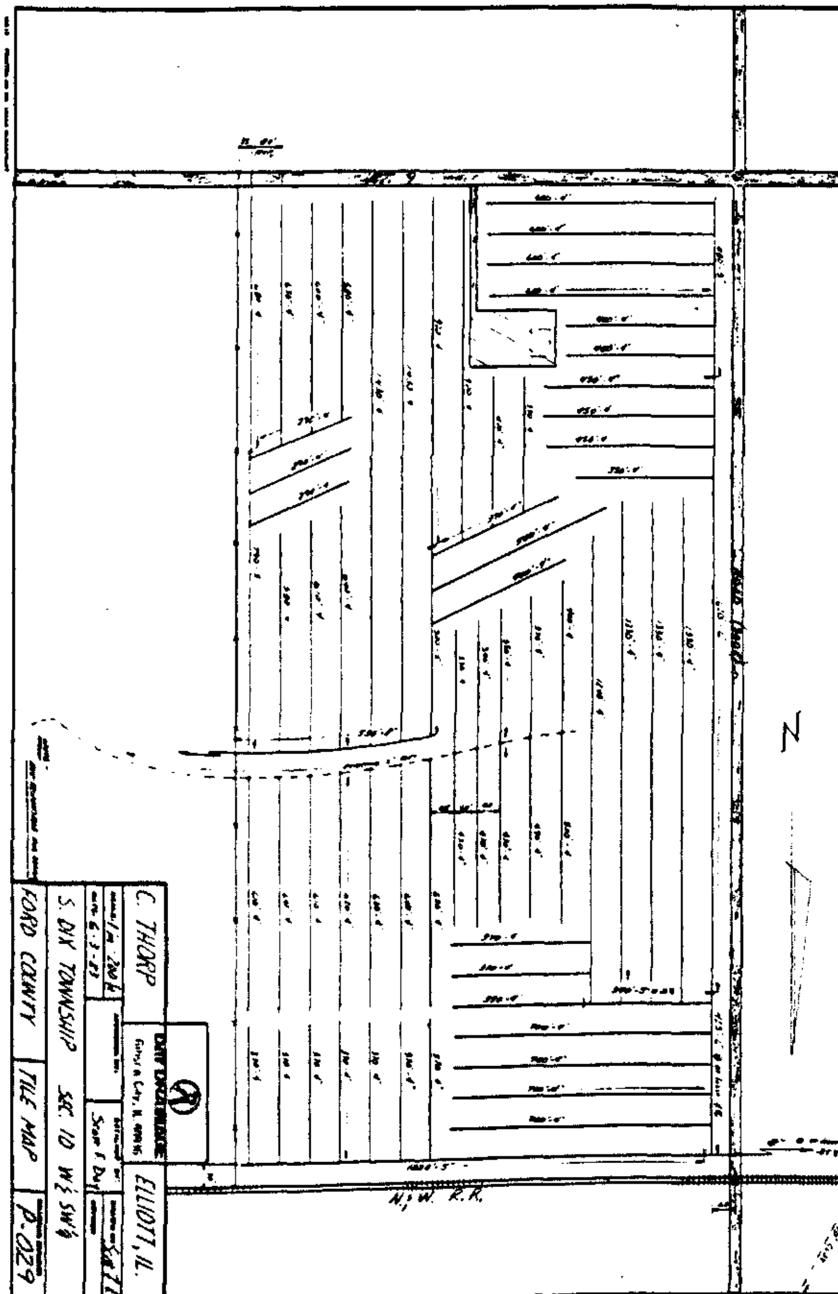

Illustration 1. Design Proposal Map

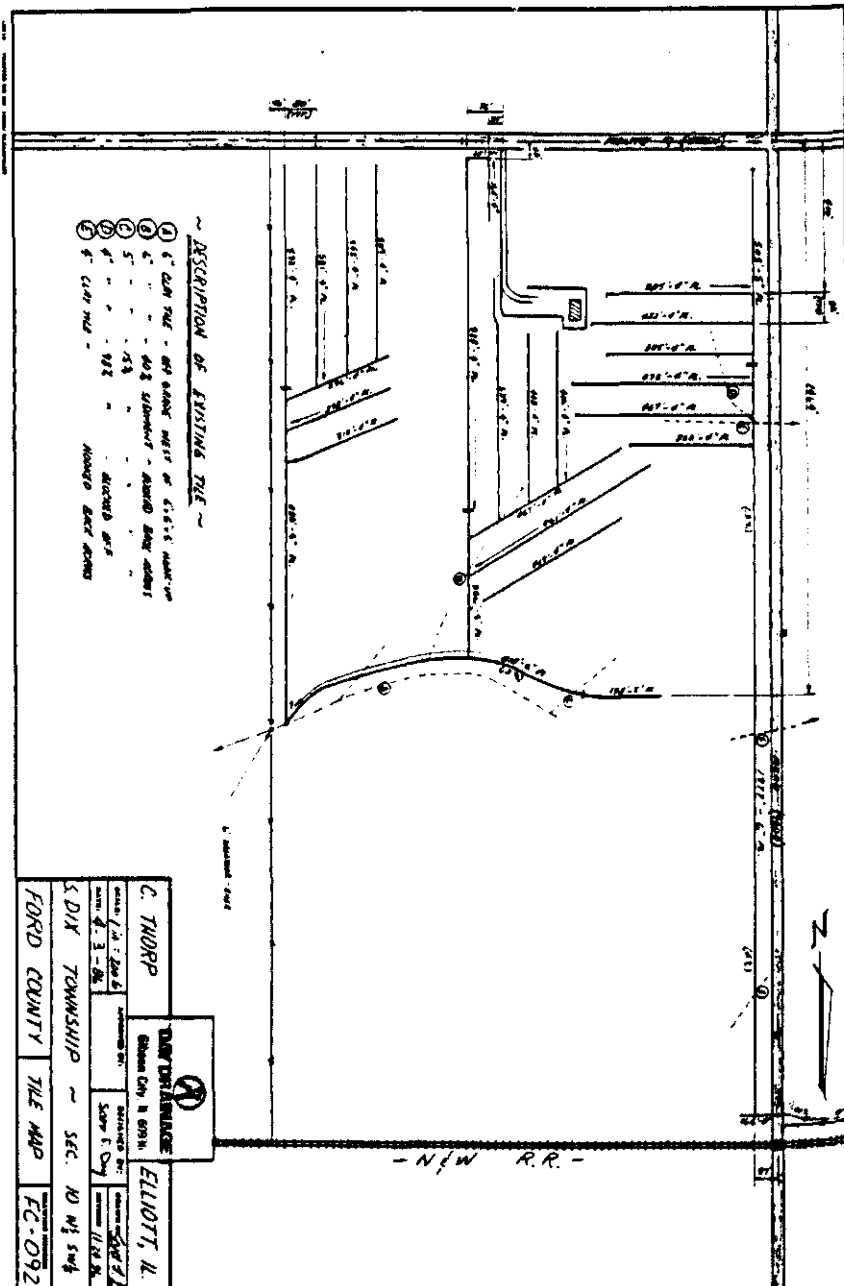

Illustration 2. Subsurface Drainage Installation Map

OPERATIONAL AND MANAGEMENT GUIDELINES FOR WATER TABLE MANAGEMENT SYSTEMS IN NORTH CAROLINA

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The successful performance of a water table management system is dependent on proper system design and management. Even well designed systems have occasionally not performed up to expectation due to improper operation and management. Many of the factors that influence the design of a water table management system are difficult to quantify and are often spatially varied in the field. As a result, it is reasonable to expect that many design limitations can be corrected with adjustments in management strategy during the initial years of system operation. In fact, the management strategy of many controlled drainage and subirrigation systems installed in North Carolina are still being fine-tuned, even after 4 years of operation in some cases, as the farm manager gains a better understanding of how the system should perform.

The purpose of this paper is to address some of questions frequently asked by farmers who are just beginning to practice water table management. In addition, a procedure is discussed that has been used successfully in North Carolina to provide management guidance to farmers and help them gain a better understanding of how to diagnose performance problems.

INITIAL MANAGEMENT GOALS

The primary objective of a water table management system is to provide the farmer the opportunity to maximize his per unit production efficiency. Often, the engineer must assume some relative management intensity in the design of the system. The challenge to the farmer is to learn to manage his system at least as intensively as was assumed in the design; and often, the farmer can improve his production efficiency by considering design limitations and physical limitations of the system in his management strategy. He must learn how to diagnose system inefficiencies and what kind of corrective measures will improve performance. Major management decisions include: determination of system limitations, selection of the optimum water table control elevation and adjustments to this level in response to seasonal variation in weather conditions, the influence of water table depth on trafficability, timely application of irrigation water and management decisions concerning drainage and irrigation water quality.

Consideration of System Physical Limitations:

System constraints often provide clues for management strategies. The constraints most frequently encountered are: 1- water table management is undertaken on a site that was originally designed for conventional drainage; thus, the system has limited capacity to supply water to the crop during

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prolonged dry periods and to remove excess water from the soil profile when the water table is elevated, 2- a sufficient water supply is not available, thus there is a tendency for the farm manager to try to conserve more of the natural rainfall by holding outlet controls higher than optimum, 3-the surface topography is uneven resulting in uneven moisture distribution, and 4-tillage operations were performed when the soil was too wet "to work" which have resulted in tillage pans that restrict potential root development. Each of these situations can compound problems associated with the other limitations.

Water table management on a system originally designed for drainage may result in poor system performance during both wet and dry periods. When it is dry, the drains may be too far apart to adequately supply subirrigation water to the entire field. To compensate, the operator may raise the water level in the outlet to near the surface. Elevating the outlet water level reduces the drainage gradient thereby reducing the drainage capacity of the system. Should the water table be elevated at the beginning of a large rainfall event, there is high probability that the crop will be damaged due to the inability of the drainage system to remove the excess rainfall in a timely manner. In some cases, this damage is obvious as the crop will "wilt" or "discolor" if the root zone remains saturated for a prolonged period of time. In other cases, the direct damage due to wet stress may not occur, or at least is not visible, but indirect damage may occur resulting in 'root pruning' an effect which could make the crop more susceptible to drought stress later in the growing season. As shown in Fig. 1, a water table depth not less than 0.6 m will usually encourage good root development. When the crop is in the vegetative stage of development, roots will penetrate no deeper than the water table, thus if the water table is maintained at 0.30 m, this will be the maximum root penetration at this stage of growth.

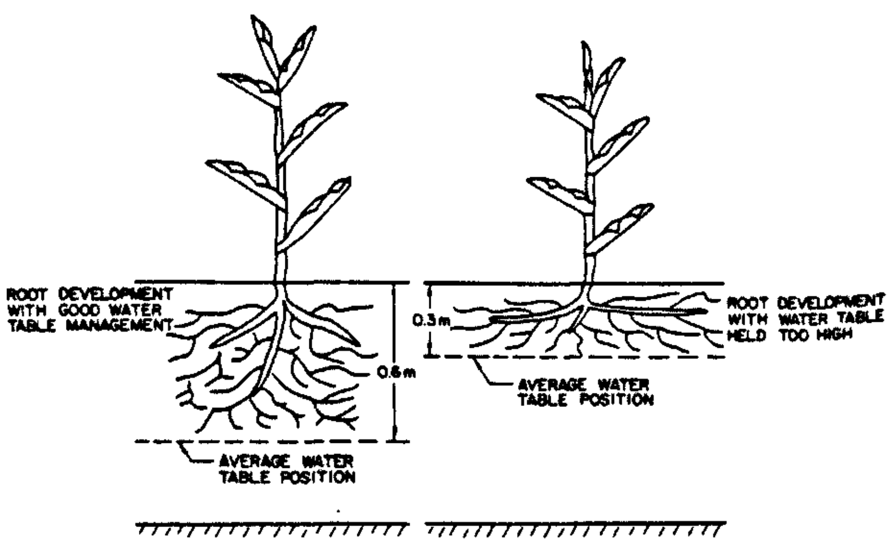

Fig. 1. Influence of control setting and water table depth on root development.

Historically, dry periods frequently develop when the crop is nearing the end of the vegetative growth stage and the water table recedes rapidly. The upper portion of the root zone dries out within a few days and crop wilting ultimately occurs because the developing root system cannot keep up with the receding water table. On several occasions, crop wilting has been observed in fields where the water table was elevated above 0.6 m early in the growing season while in adjourning fields with free drainage, wilting was not observed. Observations to date suggest that the water table should not be artifically elevated above the potential rooting depth of the crop until the end of the vegetative growth stage to encourage maximum root development during this stage crop of development.

The above considerations are further complicated by uneven topography. Quite often, fields have not been precision land graded, thus soil surface elevations frequently vary by as much as 0.30 m within a management zone. As a result, some compromise is necessary to select a water table depth that benefits the greatest portion of the field. As seen in Fig. 2, some areas of the field are likely to experience wet stress while others may experience dry stress. Elevating the water table higher than normal may eliminate the dry stress in the high areas of the field , but will likely increase the potential for wet stress in the low areas. The reverse is also true.

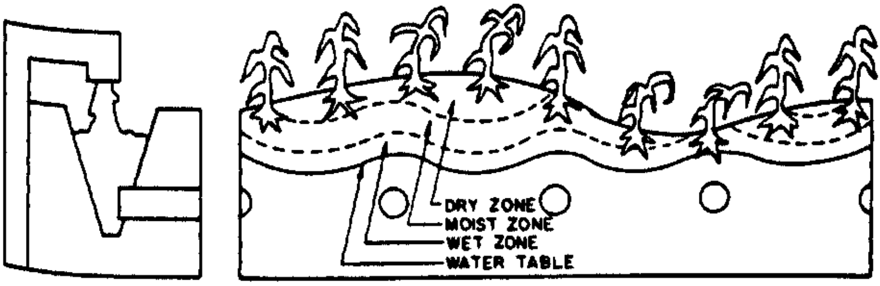

Fig. 2. Uneven moisture distribution that can occur with water table management when the field topography is uneven.

<u>Selecting the Optimum Water Table Control Level</u>:

The question most frequently asked by farmers, yet the one most difficult to answer, is "At what depth should I try to control the water table". In North Carolina, the optimum water table depth for most crops is approximately 0.6 m; however this varies with differences in soil texture, plant available water above the water table, weather conditions, the crop being grown, crop development and root depth. Most crops can also tolerate a fluctuation in the water table of ±0.15 m and still be within the optimum range. Although not very well documented, experience has shown that yield reductions will not occur on most soils from short term fluctuations in the water table provided the water table depth is not less than 0.30 m or greater than 1.0 m for a duration of 24 hours or more. In the absence of site and crop specific information, it is recommended that farmers who are using water table management for the first time begin with a target water table depth of 0.6 m and then follow the procedure discussed later to determine the optimum water table depth for their specific site and crop conditions.

<u>Water Table Management and Trafficability</u>:

Farmers may severely impair the production potential of their fields by trying to perform tillage operations when the soil is too wet resulting in tillage pans that significantly reduce potential root development. With artificial drainage, tillage operations can be begun sooner than in undrained fields; but often, these operations are begun too soon, particularly when an unusually wet season has delayed the farmer's schedule. On some occasions, farmers have attempted to resume tillage operations in their artifically drained field almost immediately after it stopped raining. Many times the problem is not apparent during the tillage operation because there is no apparent trafficability problems, particularly with the higher flotation tillage equipment being used today. Yet the resulting tillage pan is similar to the tillage pans that have been well documented on many of the well drained upper coastal plain soils of the Southeast. The problem occurs most frequently in soils with a shallow sandy loam or loamy sand surface horizon less than 0.5 m thick with a clayey subsoil. This problem may be compounded by water table management, particularly where the water supply is limited. Farmers with limited water supplies tend to start managing their drainage water earlier in the season (in some cases all winter where drainage water quality is a concern). The water table is lowered just enough to get on the field with their tillage equipment so that as much water can be conserved as possible. The result maybe a tillage pan that restricts root development and increases the potential for drought stress later in the growing season.

Problems resulting from the development of tillage pans have been observed on two well designed water table management systems in North Carolina. The soils at both sites are Rains fine sandy loam; Fine-loamy, siliceous, thermic Typic Paleaquults. The Rains series has been intensively studied in North Carolina and is very responsive to water table management. The Rains series is typically found in the same drainage catenna as the Norfolk series-a well drained coastal plain soil with frequent tillage pan problems. Historically, the Rains series has not experienced tillage pan problems. Conventionally managed Rains soils adjacent to the two problem sites do not have tillage pans. System a was installed in 1982 as a controlled drainage system, and system b was installed in 1983 as a subirrigation system. Tillage operations at both sites have been conducted when the water table was high at some time during the last three years, and both sites now have extensive tillage pans. The typical tillage practice at site a is disk-bed and at site b is disk-rip-bed.

The most obvious problem at site a, Fig. 3, has been failure of the drainage system. A perched water table was observed above the tillage pan in July, 1984 two days after heavy rainfall. The subsoil was dry and no water was exiting the tile lines yet water was standing in the field unable to infiltrate through the tillage pan. Subsoiling was recommended to the farmer as well as more timely scheduling of other tillage operations when the soil was dry which after two seasons has improved the performance of the system, yet the system is still not performing up to expectation.

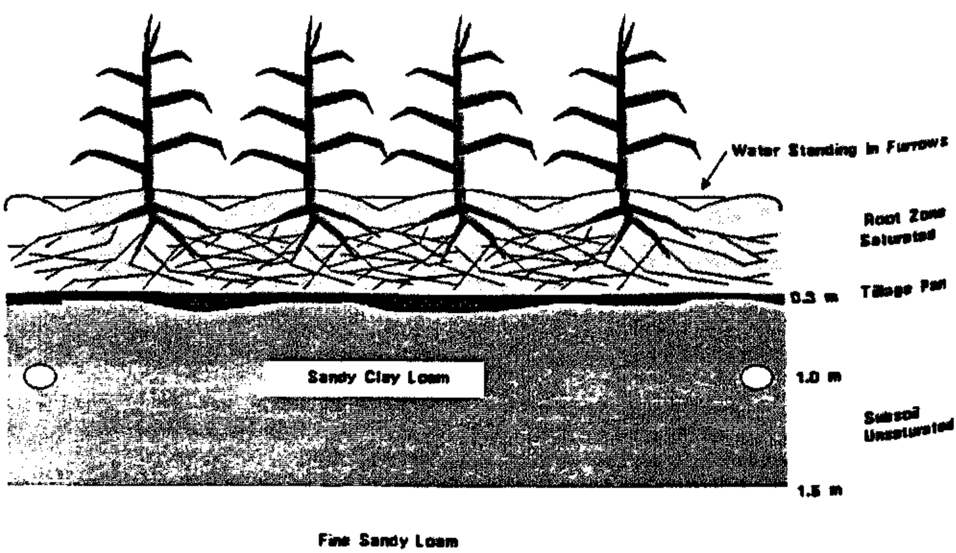

Fig. 3. Tillage pan development on a water table management site designed for controlled drainage. The soil is Rains sandy loam and the drain tubing is spaced 40 m apart. The tillage pan has impeded water movement from the root zone to the drain tubing.

The problem at site b, Fig. 4, thus far appears to be related to root restriction by the tillage pan. No drainage problems have been observed thus far at this site. A site evaluation in August, 1987 revealed that the water table ranged from 0.75 to 1.1 m at one location in the field. The subsoil above the water table was adequately moist for crop growth. A well developed traffic pan had formed in this soil at a depth of 0.15 to 0.2 m and ranged from 35 to 115 mm thick. The tap root of the crop had extended into the subsoil slit but most of the feeder roots were restricted to the topsoil zone above the traffic pan. The root zone was powdery dry and the crop was experiencing drought stress even through the system was operating in the subirrigation mode and the subsoil at a depth of 0.3 to 0.45 m was moist suggesting that the tillage pan was severely limiting upward water movement to the root zone as well as the depth of the root zone.

The interaction between water table management, trafficability and the potential development of tillage pans is not well understood. Farmers in North Carolina have not experienced any apparent trafficability problems when the water table was at least 1.0 m deep. In many cases, trafficability has been possible and in fact, often occurred when the water table was in the range of 0.6 m deep. The interaction between soil texture, soil moisture, water table depth and the potential development of a tillage pan on poorly drained soils has not been evaluated. Historically, the development of tillage pans on poorly drained soils with conventional drainage practices has not been considered a problem. Since the adoption of water table management on some of these soils, there have been occurrences of problems associated with tillage pans.

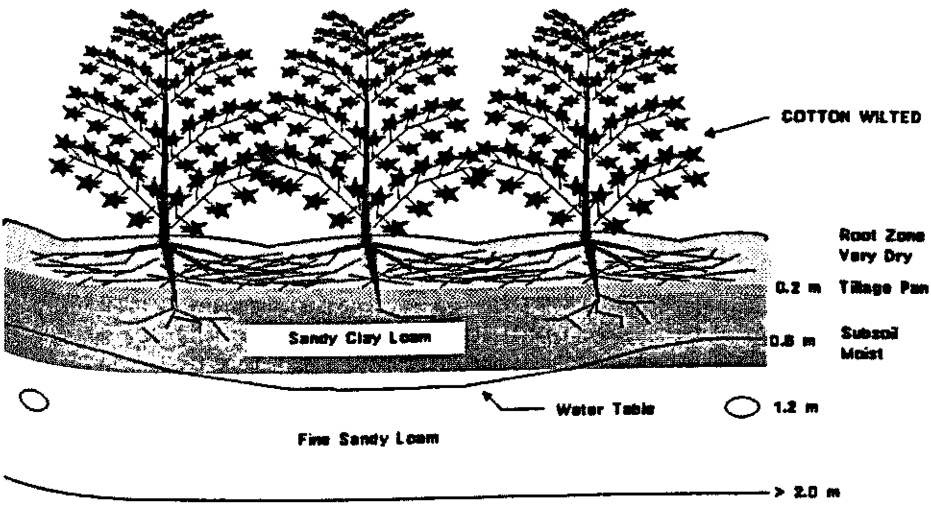

Fig. 4. Tillage pan development on a water table management site designed for subirrigation. The soil is Rains sandy loam and the drain tubing is spaced 20 m apart. The tillage pan has restricted root penetration and upward water movement from the water table.

Subirrigation-Adding Water to the System:

Farmers frequently ask when should they begin adding subirrigation water to their system. This decision is influenced by system constraints, the crop and prevailing weather conditions. Unlike sprinkler irrigation where crop response is almost immediate, the crop response to subirrigation may be slow. This is because as the soil dries out, the hydraulic conductivity of the soil decreases drastically and the volume of water needed per unit rise of the water table height increases. Therefore, the main concern is not to let the soil get "too dry" before starting to subirrigate. Most subirrigation water travels laterally in a zone 1 to 2 m below the soil surface. In general, the water table should not be allowed to drop below this zone during any part of the growing season. The water table should be maintained such that not more than 7 to 10 days are needed to raise the water table to the normal subirrigation level of 0.6 m. Experience indicates that this can be accomplished when the maximum water table depth does not exceed 1.25 m at the start of subirrigation. In some cases where the water table has been allowed to drop below this depth, more than 21 days have been required to raise the water table to the normal subirrigation level. In fact, in a few cases, the soil was allowed to get so dry that even with continuous pumping, the water table could not be raised to the desired level during the critical moisture use period of the crop and crop stress was observed.

Subirrigation decisions for farmers who have limited water supplies are even more critical. These farmers will typically need to start pumping 2 to 3 weeks sooner than farmers with adequate water supplies. Precise management of the drainage water is also required. As discussed earlier, these farmers must conserve as much drainage water as possible to supplement their irrigation capacity, but there is a risk of restricting root development if pumping begins too soon or if the water level is managed too high early in the season. Farmers with limited water supplies should not allow the water table to drop much below 1.0 m once the tillage operations have been completed. In some cases, this may require occasional pumping soon after planting.

Managing for Drainage Water Quality:

As discussed earlier (Evans et al., this issue), water table management has shown tremendous potential to improve the quality of agricultural drainage water. From a production standpoint, water table management is most important during the growing season. Studies have shown that the most critical period to manage these systems for water quality is during the winter and early spring months. Farmers in North Carolina are now encouraged to manage their systems year round. This further complicates the management decisions that must be made by the farmer. Table 1 summarizes a management strategy for a 2-year rotation of corn, soybeans and wheat that is recommended to North Carolina farmers to enhance their production benefits and to improve drainage water quality.

FINE TUNING THE SYSTEM PERFORMANCE: A MANAGEMENT STRATEGY

It should be apparent at this point that intensive management is required for water table management systems. This is often surprising and frustrating to farmers who have been accustomed to utilizing artificial drainage systems which by comparison required very few management decisions on the part of farmer. The frustration occurs because many of the management indicators are hidden from the farmers view and the response to changes in management strategy are usually not immediate. Experience has also shown that design limitations can be tempered with good management.

Water table management systems are very complex and most farmers have limited knowledge or experience with these types of systems. As a result, a strategy is needed to guide the farmer through the first year of operation of his system. The farmer must be taught the principles of operation of the system which will in turn assist him in evaluating his system performance.

Monitoring the System:

Locating observation wells: Initially, systems cannot be properly managed by merely observing the water level at the drainage outlet or control structure. The response time for water table fluctuations in the field is typically several days longer than similar water level fluctuations at the control structure. Until this response time has been determined, it is absolutely essential that observation wells be installed at several locations in the field.

Table 1. General water table management guidelines to promote water quality for a 2 year rotation of corn - wheat - soybeans.

PERIOD	PRODUCTION ACTIVITY	CONTROL SETTING[a]	COMMENTS[b]
		- meters -	
MAR 15 - APR 15	TILLAGE, SEEDBED PREPARATION, PLANTING	1.0	JUST DEEP ENOUGH TO PROVIDE TRAFFICABILITY AND GOOD CONDITIONS FOR SEEDBED PREPARATION
APR 15 - MAY 15	CROP ESTABLISHMENT EARLY GROWTH	0.6 - 0.75	DEEP ENOUGH TO PROMOTE GOOD ROOT DEVELOPMENT
	NITROGEN SIDEDRESS	0.5 - 1.0	JUST LOW ENOUGH TO ALLOW TRAFFICABILITY
MAY 15 - AUG 15	CROP DEVELOPMENT AND MATURITY	0.5 - 0.6	TEMPORARY ADJUSTMENT DURING WET PERIODS
AUG 15 - OCT 15	HARVESTING, TILLAGE, PLANT WHEAT	0.75 - 1.0	LOW ENOUGH TO PROVIDE TRAFFICABILITY
OCT 15 - MAR 1	WHEAT ESTABLISHMENT	0.6	LOWER DURING EXTREMELY WET PERIODS
MAR 1 - MAR 15	SIDEDRESS WHEAT	0.6 - 1.0	LOW ENOUGH TO PROVIDE TRAFFICABILITY
MAR 15 - JUN 15	WHEAT DEVELOPMENT AND MATURITY	0.5 - 0.6	TEMPORARY ADJUSTMENT DURING WET PERIODS
JUN 15 - JUL 15	HARVEST WHEAT TILLAGE, PLANT BEANS	0.75 - 1.0	DEPENDS ON SEASON
JUL 15 - NOV 1	SOYBEAN DEVELOPMENT AND MATURITY	0.5 - 0.6	TEMPORARY ADJUSTMENT TO ALLOW CULTIVATION
NOV 1 - DEC 15	SOYBEAN HARVEST	1.0 - 1.25	LOW ENOUGH TO PROVIDE TRAFFICABILITY
DEC 15 - MAR 15	FALLOW	0.3 - 0.45	

[a]Values shown are the control setting and should not be considered the actual water table depth in the field which will actually be lower except during drainage periods.

[b]Most adjustments are related to trafficability and must take into account weather conditions and soil-water status at the time

- in an unusually dry season: control can be 0.07-0.15 m higher
- in an unusually wet season: control should be 0.07-0.15 m lower
- in coarse textured soils: trafficability can be provided with the water table approximately 0.15 m higher

The location of the observations wells is an important management decision. In reality, management zones are usually not entirely uniform due to variation in soil properties and topography. Often, it is not practical to maintain the water table at the "optimum" level throughout the entire management zone. The relative proportion of low and/or high areas to the majority of the management zone must be considered. Low, or depressional areas, are usually most restrictive because field operations are interrupted when these areas become wet. In general, the water table in these areas must be maintained higher than optimum in order to adequately treat the majority of the field. Although, when these areas occupy a significant acreage of the management zone (greater than 10 percent) the overall yield in the field will be reduced when the water table is held too high in these low areas. Therefore, from a management standpoint, these areas are considered to be "strategic" areas. Strategic areas are readily identified because these areas have historically presented drainage problems for the farmer. These areas continue to pose a problem after the design and installation of the water table management system because it is often not economically feasible to eliminate the problem when the areas are relatively small.

Since strategic areas are the most limiting, it is desirable to locate observation wells in these areas. However, these areas are often located in very remote areas of the field. When this occurs, observation wells should be located in accessible areas as well as in the strategic areas, Fig. 5. During the first year of operation, the water table fluctuations in the strategic areas can be correlated to the water table fluctuations in the more accessible areas and at the control structure. In subsequent years, one or two observation wells in the more accessible areas will usually be adequate.

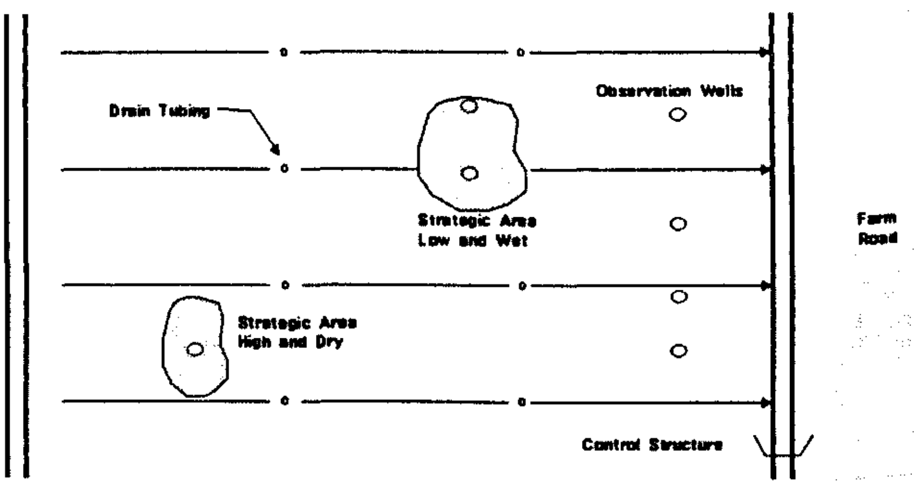

Fig. 5. Strategic location of observation wells for the first year a water table management system is in operation.

Installing observation wells: Observation wells can be made of any type of material. PVC pipe is the most commonly used material. The water level in the well should fluctuate simultaneously with the water table in the field. To assure that entry of water into the well is not limiting, approximately 20 small diameter holes should be bored in the sidewall of the well. The diameter of the hole will depend on the amount of fine sand and silt in the soil, but generally holes of 5 mm will be adequate. The most popular size observation well has been 100 mm in diameter and 1.5 to 2 m long. This size will accommodate a typical toilet bowl float with dowel rod or wire to easily measure the level of the water in the well. The pipe should extend above the ground surface and the soil should be crowned around the sides of the pipe to prevent surface water from running in along the sides of the pipe, Fig. 6. The elevation of the top of the observation well should be measured and correlated to the average ground elevation around the well and to the control structure for reference.

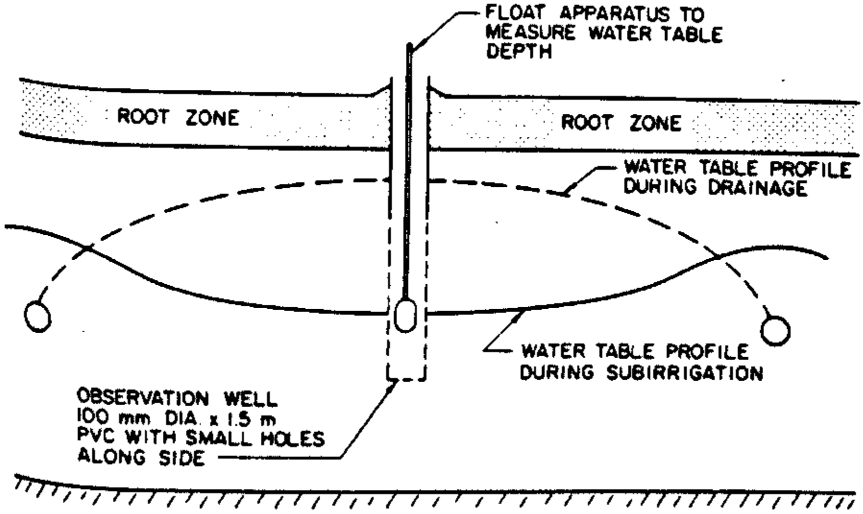

Fig. 6. Proper installation of observation well.

Fine-Tuning the System:

A water table management system should be calibrated or fine-tuned during the first year of operation. To calibrate a new system, the ground elevation of the zone requiring the highest degree of management (strategic area) as well as the average ground elevation of the entire field should be permanently marked on the water control structure. This will allow the farmer to observe and understand the relationship that exist between the water level in the outlet and the water level in the field.

The farmer should be encouraged to keep accurate records during at least the first year of operation of the system. These records should include as many of the following as possible.

1. daily water table levels at the control structure and all observation wells,
2. daily rainfall (daily maximum temperature could also be helpful),
3. adjustments in control level elevation,
4. dates of all field operations noting any trafficability problems,
5. subirrigation volumes (which can be determined by knowing the pump capacity and the daily pumping period),
6. any apparent crop stress and the root depth at all locations and times when stress was observed,
7. average yield, localized yields near each observation well and localized yields in areas where crop stress occurred.

The performance of the system cannot be accurately evaluated when any of the above information is incomplete. From this information, the farmer can establish criteria for managing the system in future years. He can identify situations requiring that the control structure be lowered to provide additional drainage capacity following large rainfall events to minimize potential wet stress or to provide trafficable field conditions. In addition, the start up time and pumping frequency for subirrigation can be determined. This information will provide clues for future adjustments in management strategy, and when used in conjunction with weather forecast, allow the farmer to prepare the system for approaching weather conditions.

SUMMARY

Water table management systems are very complex and the successful performance of these systems requires good management in addition to proper design. While guidelines can be recommended for new systems based on the performance of existing installations, a system will not perform at peak efficiency until a management strategy has been developed that is soil and site specific.

There are many factors which influence the overall performance and long-term effectiveness of water table management systems. While our understanding of the mechanisms that affect system performance is increasing, many of the guidelines being developed for the management of these systems continues to be more art than science. The interaction of many of the mechanisms on the long-term performance of the system is not well understood. In particular, considering the rapid rate that water table management is being adopted, especially in North Carolina, there is an urgency for better information on the interaction between water table management, trafficability and tillage pans. Better management guidelines are needed to minimize the potential impairment of the production potential on soils that have a tendency to develop tillage pans in the presence of water table management.

ACKNOWLEDGEMENT

R. D. Hinson, Soil Conservationist, H. J. Gibson, State Conservation Engineer, and W. B. Williams, Water Management Specialist, Soil Conservation Service and C. W. Doty, Agricultural Engineer, USDA-ARS related field experiences that contributed to this paper.

STRENGTH-TO-WEIGHT AND HYDRAULIC FLOW CHARACTERISTICS OF SMOOTH-CORE CORRUGATED PE PLASTIC PIPE

James L. Fouss * Eric G. Christiansen **

U.S. market demand continues upward for standard corrugated-wall polyethylene (PE) pipes of 305mm (12 in.) diameter and larger in land drainage applications. These corrugated plastic pipes are also extensively used in culvert applications previously dominated by concrete and corrugated steel pipe (Fouss and Reeve, 1987). All three types of pipe are comparably priced, but the light-weight corrugated plastic pipes are easier to handle and less costly to transport and install for many applications, and provide superior service life in corrosive environments. Despite these significant advantages, the limiting characteristics of reduced flow capacity and the less than optimum resistance to deflection under soil loading with the standard corrugated-wall PE, especially for the larger diameters, have kept the corrugated plasitic pipes from achieving the full engineering use potential often inherent to the corrugated type of structural design configuration.

Recent advances in manufacturing technology have made it possible to economically produce a smooth-core corrugated plastic pipe by thermally bonding a smooth interior core to an external corrugated shell (Fig. 1). This combination of the desirable hydraulic flow of smooth-walled pipe with the exceptional strength-to-weight ratio of corrugated pipe greatly improves performance in land drainage and culvert applications and opens up major new applications such as storm sewers. The smooth interior core also permits the use of deeper corrugations to significantly increase the structural strength of the pipe without diminishing its resistance to stretch under axial loading. Still other benefits accrue as a result of advances in structural performance of high density polyethylene resins in piping applications and improved corrugated pipe joining systems. Thus, the new smooth-core corrugated plastic pipe has the potential to become the "I-Beam" of the plastic piping industry as a high strength-to-weight ratio engineered pipe capable of efficiently and economically meeting stringent performance requirements of a wide variety of applications. New performance standards and specifications for the smooth-core corrugated product are now being developed by national authorities in the U.S. for land drainage, culverts, and for an increasing number of new applications including storm sewers, conduits, and others.

This paper presents analytical comparisons of strength-to-weight and hydraulic flow characteristics between smooth-core corrugated PE plastic pipe and other piping materials including, standard corrugated-wall PE,

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* Agricultural Engineer, P.E., USDA-ARS, Soil and Water Research Unit, Baton Rouge, LA, USA; work reported herein was conducted as a private consultant; appreciation is expressed to USDA-ARS for granting permission to participate in the consulting project on personal time.
** President, Plastic Tube Machinery Co., Toledo, OH, USA.
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smooth-wall plastic (e.g., PE or PVC), concrete, and galvanized corrugated steel. Analytical procedures employed are described.

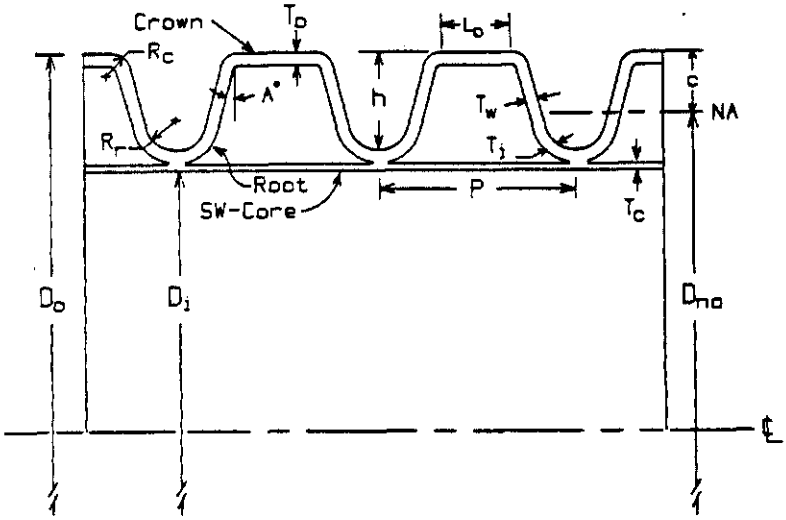

Fig. 1 Cross-Section of Smooth-Core Corrugated Pipe-Wall Profile with Definitions of Geometrical Terms and Dimensions.

The pipe-wall dimensional parameters shown in Fig. 1 are defined as follows:

- A = angle of corrugation 'web'
- Lo = length of 'crown' flat
- To = corrugation 'crown' thickness
- Tw = corrugation 'web' thickness
- Ti = corrugation 'root' thickness
- Tc = thickness of SW-'core'
- h = corrugation depth
- P = corrugation pitch
- Rc = radius of crown fillet
- Rr = radius of corrugation root
- NA = neutral-axis of pipe-wall
- c = distance NA from O.D. of pipe
- Dna = neutral-axis diameter of pipe
- Do = outside diameter of pipe
- Di = inside diameter of pipe
- ℄ = center-line of pipe diameter

ANALYSIS OF PLASTIC PIPE STRENGTH

The structural strength of a plastic pipe was expressed as a function of its deflection resistance when loaded between parallel-plates. This pipe test method is required in ASTM Standard Specification F-667 for Large-Diameter Corrugated Polyethylene Tubing. The strength-deflection characteristic determined for a conduit tested by this method and defined as the "Pipe Stiffness", was expressed in units of applied load per unit length of pipe sample per unit of vertical deflection (flattening) of the pipe sample; i.e., (kg/mm/mm or kg/mm^2). The parallel-plate pipe stiffness was expressed mathematically in terms of geometrical, physical, and pipe-wall material properties of the conduit structure, as shown below.

$$\text{Pipe Stiffness} = (W/\Delta Y) = 53.6 * E * I / (Dna)^3 ,$$

where,

- W = parallel-plaste load on pipe sample, kg/mm of pipe length
- ΔY = vertical pipe deflection under parallel-plate load, mm
- E = modulus-of-elasticity for pipe-wall material, kg/mm^2
- I = moment-of-inertia of pipe-wall cross-section, mm^4/mm pipe length
- Dna = diameter of pipe to the neutral-axis (NA) of pipe-wall, mm
- 53.6 = dimensionless constant related to angular position of parallel-plate loads on pipe circumference, and to convert from pipe radius to pipe diameter.

This formula applies for the linear range of deflection between parallel-plates for high-density PE plastic corrugated-wall pipe, which typically occurs from 0 to between 5 and 10% deflection of the inside pipe diameter (Fouss, 1973). At a specified pipe stiffness (W/ ΔY) for a regular corrugated-wall or smooth-core corrugated plastic pipe of given inside diameter (Di) and assumed neutral-axis diameter (Dna), and which is made of a given plastic resin material of known modulus-of-elasticity (E), the only term unknown in the above formula is (I), which represents the pipe-wall moment-of-inertia. Corrugation shape and smooth interior wall features govern the magnitude of (I), the major structural parameter of the plastic pipe determined or controlled through product design and fabrication.

Pipe-Wall I-Value

In a previously published corrugation design procedure (Fouss, 1973), specific geometrical features of the corrugated-wall cross-sectional profile were represented in simplified forms or standard geometrical shapes (e.g., rectangular sections) to simplify the development of analysis equations for the I-value of the pipe-wall. The smooth-core corrugated pipe-wall profile shown in Fig. 1 is represented in simplified form as shown in Fig. 2 for the analysis procedure presented here. This simplification is similar to that presented earlier by Fouss (1973), but the corrugation "root" is represented with a 'semi-circular' area, which is more typical of the pipe-wall profiles used for current pipe products. No attempt has been made for this paper to consider the more complex profile features, such as curved sections or fillets, the angle of the corrugation web, wall thickness variations within each corrugation section, etc. Analysis procedures for complex pipe-wall profiles have been developed and are in use by industry, but the development of such equations for the profile in Fig. 1 was beyond the scope of this paper.

A set of formulas was derived to compute the moment-of-inertia (I) of the simplified smooth-core corrugation profile below on a per corrugation pitch (P) basis, and per unit length (mm) of pipe. The classical principles of engineering mechanics were applied for these derivations. Published formulas for computing the (Ix-x) for standarized shapes or sections (such as rectangles or circular arcs) about their own neutral-axes (x-x) were

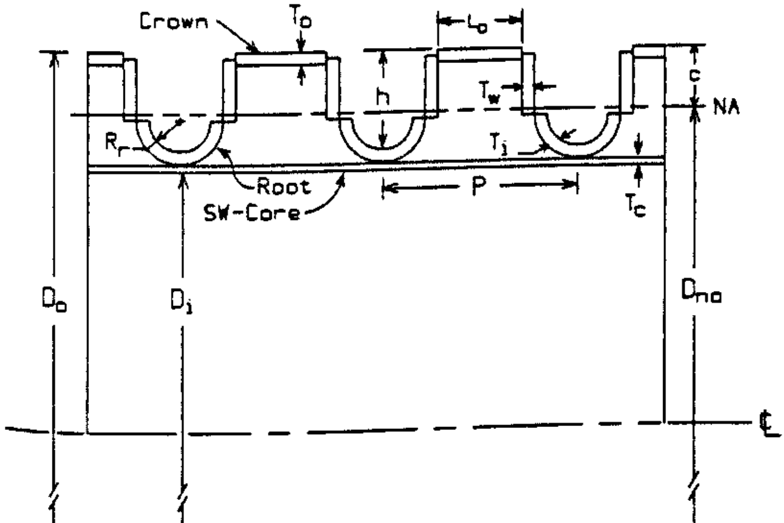

Fig. 2 Simplified Representation for Cross-Section of Smooth-Core Corrugated Profile for Analysis.

used, then the (Ix-x) values were "transferred" to the neutral-axis (NA) of the complete smooth-core corrugated pipe-wall profile (Fig. 2) by the "rule", [(section-area) x (square of the distance between x-x and NA)]. Thus, the I-value for the complete pipe-wall profile about the NA of the pipe-wall became the summation of a series of composite values for the various geometric shapes in the profile. The derived formulas to compute the I-value-component for the various area shapes to represent the total pipe-wall profile (Fig. 2) are given below. The formulas were not reduced to their simpliest form, but rather the first terms represent the (Ix-x) for the shape about its own neutral-axis, and the remaining terms are for the "transfer" of the Ix-x value to the pipe-wall NA. A formula to compute the distance "c" (for the position of the pipe-wall NA) is not shown; "c" can be determined by the summation of area-moments method (reference an engineering mechanics text).

The following formulas were derived to compute the I-values of the component areas of the simplified profile (Fig. 2), <u>per corrugation pitch</u> (P):

$$\text{I-crown} = \frac{Lo\,(To)^3}{12} + Lo\,To\,[c - (To/2)]^2$$

$$\text{I-web} = \frac{2\,Tw\,[h - (To/2) - Rr]^3}{12} + 2\,Tw\,[h - (To/2) - Rr] * \{c - To/2 - [h - (To/2) - Rr]/2\}^2$$

$$\text{I-root} = \frac{\pi}{8}\,[(Rr + Ti)^2 - (Rr)^2]^2 + \frac{\pi}{2}\,[(Rr + Ti)^2 - (Rr)^2] * (h - Rr - c)^2$$

$$\text{I-core} = \frac{P\,(Tc)^3}{12} + (P\,Tc) * [h + Ti + (Tc/2) - c]^2$$

The I-value <u>per unit length of pipe</u> was given by summation of the parts,

$$I = (\text{I-crown} + \text{I-web} + \text{I-root} + \text{I-core}) / P, \quad \text{in } (mm^4/mm).$$

For regular corrugated-wall pipe, the I-core term would not be used to compute the I-value for the pipe-wall profile. For regular smooth-wall pipe, $I = [(Tw)^3]/12$, where Tw = pipe-wall thickness.

HYDRAULIC EQUIVALENCE OF CIRCULAR PIPE

From fluid mechanics the basic equation for computing the hydraulic "full" flow capacity of circular cross-section pipes is:

$$Q = [\,1.49 * A * R^{(2/3)} / n\,] * s^{(1/2)},$$

where,

- Q = flow capacity or rate, m^3/sec
- A = cross-sectional area of pipe, m^2
- R = hydraulic radius of pipe, m
  - R = A/p, where p = wetted perimeter, m
  - or, $p = \pi * Di$ <$\pi = 3.1416$>
  - Di = pipe inside diameter, m
  - [for circular pipe R = Di/4]
- n = Manning's hydraulic roughness coefficient (dimensionless)
- s = hydraulic gradient of pipe, m/m
- 1.49 = proportionally constant, 1/sec

A coefficient 'F' was defined from the above equation that is proportional to the relative "full flow" capacity of pipes installed at the same grade. For conditions when the hydraulic gradeline (gradient, s) is parallel to the bottom grade of the pipe, and the pipe flows full without back pressure, the flow capacity (Q) will be EQUAL to that of other pipes with the same value of 'F', defined as:

'F' = [1.49 * A * R^(2/3) / n] , with units of (m^3/sec).

This 'F' value was used to compare relative full flow capacity of smooth-core corrugated PE, corrugated-wall PE, corrugated galvanized steel, and smooth-wall plastic and concrete pipes for various diameters, as presented herein.

STRENGTH-TO-WEIGHT RATIO

The strength-to-weight ratio was used as an indication of plastic-use-efficiency for smooth-core corrugated vs. corrugated-wall vs. regular smooth-wall PE pipes of "example" designs. The parallel-plate strength (load carrying capacity) at a pipe deflection of 5% of Di was used. That is, the parallel-plate load carrying capacity (@ 5% deflecton) per unit of plastic material weight in the pipe wall, as defined below:

$$\text{Strength/weight} = \frac{(W/\Delta Y)}{w} * 0.05 * Di \text{ , (kg-strength/kg-weight), or (kg/kg).}$$

where,

w = pipe weight, kg/mm length.

Analyses were conducted for example smooth-core corrugated and corrugated-wall PE pipes with "selected" physical and material characteristics which provided some hypothetical design consistency between pipes of the various diameters. For regular corrugated-wall pipes with diameters from 203 to 914 mm, principal corrugation profile dimensions were determined by the following equations for the example pipes:***

$h = 0.085 * Di$, $P = 0.153 * Di$, for 203 mm $\leq$ Di $\leq$ 457 mm;

and $P = 1.0 + 0.097 * Di$, for Di > 457 mm.

Analyses were conducted for smooth-core corrugated pipes with the h and P values also determined with these equations. An additional design option for the smooth-core corrugated pipe was analyzed, where the h-dimension was increased by 20%; i.e., h = 1.2 * 0.085 * Di.

The structural analyses were conducted for a required pipe stiffness value of (W/ ΔY) = 3.234 x 10^-2 kg/mm^2 (46 psi), which meets the strength requirements for corrugated plastic pipe as specified in ASTM D-3034 and AASHTO M252. A high-density polyethylene (HDPE) plastic resin was assumed to have a modulus of elasticity (E) of 63.3 kg/mm^2 (90,000 psi), and a specific gravity (p) of 0.954. For the smooth-core corrugated pipe analyses, a plastic material distribution ratio in the pipe-wall was assumed as, (%corrugated / %smooth) = (65%/35%).

*** NOTE: Numerical examples used in the paper to illustrate strength-to-weight relationships are hypothetical, for reader informational purposes only; plastic material strength characteristics were assumed and do not represent a commonly used HDPE resin. The examples DO NOT knowingly describe any pipe now on the market or planned for production by any particular manufacturer. The equations used to estimate h and P for the example pipes are not intended as design guidelines; pipe on the market would indicate that these relationships, if they exist, are non-linear with diameter.

A personal computer (PC) program was developed (not included here) to solve the above equations for (I) and ($W/\Delta Y$) in an iterative method to determine the minimum pipe-wall thickness to meet the pipe stiffness requirement. The PC program also estimated the pipe weight and computed the strength/weight ratio. The results of these structural analyses are summarized graphically in Fig. 3, where the strength/weight (str/wt) ratio is plotted as a function of pipe diameter for example smooth-core corrugated, corrugated-wall and smooth-wall PE pipes. The smooth-core corrugated profile with the same depth of corrugation (h) as that for the corrugated-wall pipe increased the strength/weight ratio by 23 to 34% over that for the corrugated-wall profile. For the smooth-core corrugated profile with corrugation depth (h+) increased by 20%, the strength/weight ratio was 21 to 29% higher than that for the smooth-core corrugated profile with the previous (smaller) h-value, and 58 to 68% higher than that for the regular corrugated-wall profile with the smaller h.

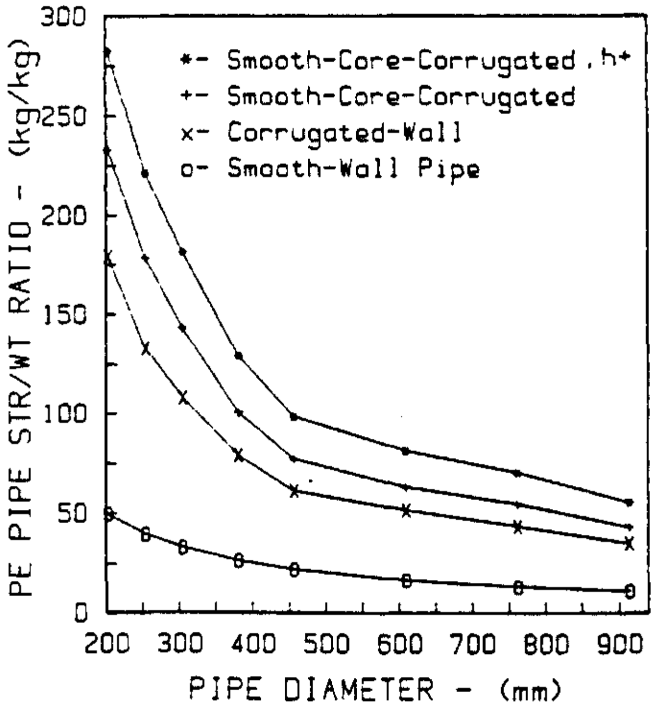

Fig. 3 Strength/Weight Ratio vs. Diameter for Smooth-Core Corrugated, Corrugated-Wall, and Smooth-Wall HDPE "Example" Pipes; Pipe Stiffness Constant at 3.234 x 10^-2 kg/mm^2 (46 psi).

RELATIVE PIPE WEIGHT

The weight of a pipe per unit length is an important parameter in evaluating its handling and transport characteristics. A "relative pipe weight" parameter was used so that various piping materials could be compared. The weight of the "example" 203-mm (8-in.) diameter smooth-core corrugated, with standard corrugation depth (h), was assumed equal to "1.0". The unit weights of all other example pipes used in the analyses were divided by the estimated weight of this pipe, thus computing a relative pipe weight for each. The results of this evaluation are presented graphically in Fig. 4; the reader should note that the ordinate for the concrete pipe is on the right-hand side of the graph. The lightest pipes were the smooth-core

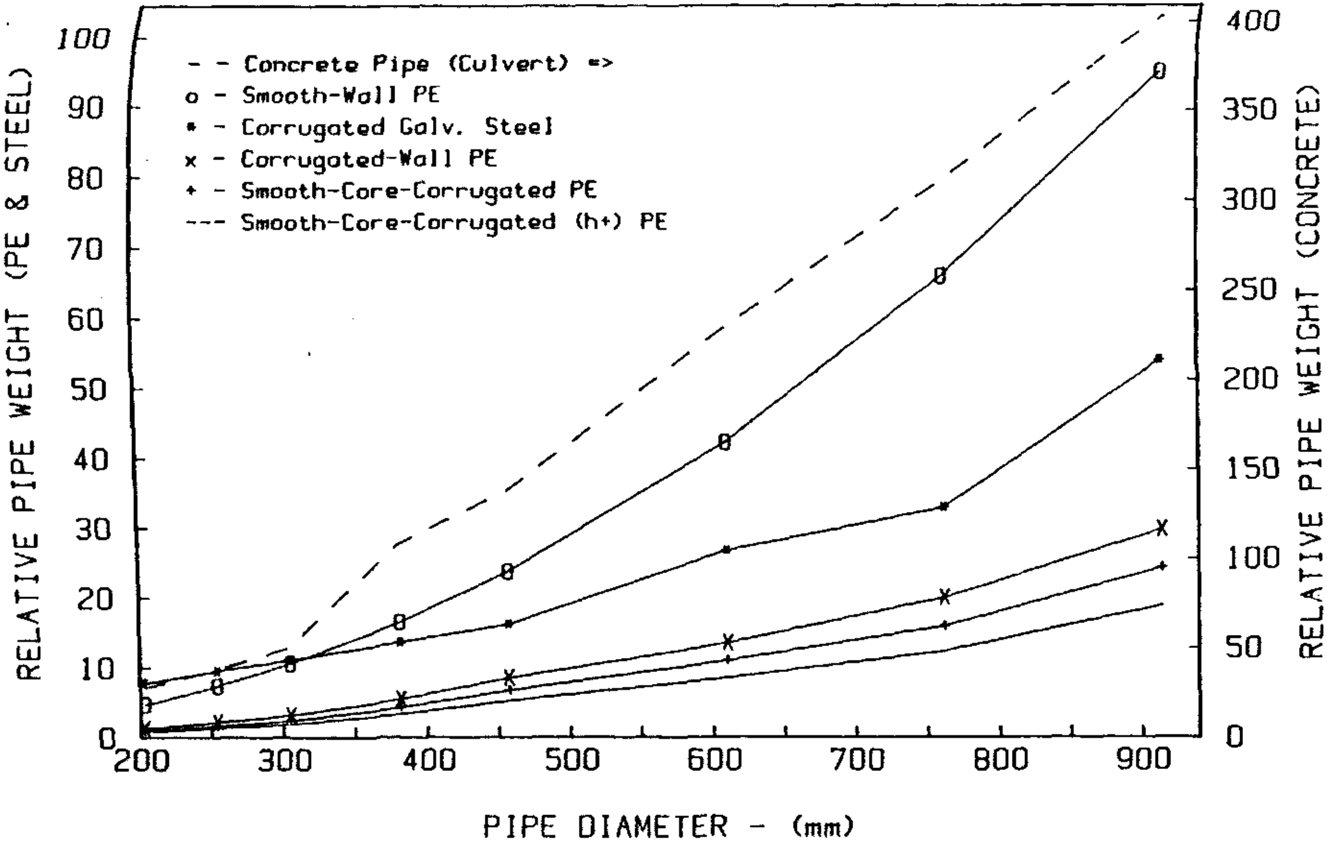

Fig. 4. Relative Pipe Weight vs. Diameter for Smooth-Core Corrugated PE, Corrugated-Wall PE, Smooth-Wall PE, Corrugated Galvanized Steel, and Concrete Pipe (Note: Ordinate for Concrete is on the right.) [Assumed: Weight of 203 mm Dia. Smooth-Core Corrugated = 1.0]

corrugated and corrugted-wall PE, which ranged from 13 to 45% less relative weight than the corrugated galvanized steel pipe; the greatest weight reductions were estimated for the larger diameters. The estimated relative weight for smooth-wall PE pipe was significantly greater than that for the example PE corrugated pipes, and was also much greater than that for corrugated steel at diameters larger than 457 mm (18 in.), see Fig. 4. The concrete culvert pipe (Class I), assumed reinforced with steel for diameters larger than 305 mm (12 in.), was approximately 4 times heavier than the smooth-wall PE pipe, and ranged between 16 and 27 times heavier than the corrugated PE pipes (largest difference at the smaller diameters).

RELATIVE HYDRAULIC CAPACITY

The various values of Manning's hydraulic roughness coefficient, n, used for the different pipe materials, diameters, and pipe-wall configurations are given in the Table 1. The value of "n" = 0.012 for the smooth-core corrugated pipe was within the range, 0.011 to 0.014, typically used for concrete pipe (CE Handbook, 1982; ASAE SW-232). The relative flow coefficient 'F' was computed for each of the pipe material, diameter, and n-value combinations (Table 1), and the results are summarized graphically in Fig. 5. The full flow capacity of the smooth-core corrugated pipe was nearly equal to that for smooth-wall PE or concrete pipe. The regular corrugated-wall PE pipe flow capacity was slightly greater than that for corrugated galvanized steel pipe for all diameters (203 to 914 mm). The increase of flow capacity for the smooth-core corrugated pipe over that for the corrugated-wall pipe varied from 24 to 83%; the flow capacity was proportionally greater for the larger diameter pipes because of the higher n-values. For the popular 457 and 610 mm (18 and 24 in.) diameter pipes, the flow capacity for the smooth-core corrugated pipe was estimated as 67% greater. For the "example" pipes shown in Fig. 5, a 381-mm (15-in.) diameter smooth-core corrugated pipe is equivalent in flow capacity to a corrugated-wall pipe of 457-mm (18-in.) diameter. Similarly, a 610-mm (24-in.) diameter smooth-core corrugated pipe is equivalent to a 762-mm (30-in.) diameter corrugated-wall pipe, and finally a 762-mm smooth-core corrugated pipe exceeds the capacity of a 914-mm (36-in.) corrugated-wall pipe.

Table 1. MANNNING'S ROUGHNESS COEFFICIENT, n, FOR CIRCULAR PIPES OF VARIOUS MATERIALS AND DESIGNS; DIAMETERS from 203 TO 914 mm.

Pipe-Wall Cross-Sect. Design	Pipe Diameter(s), Di (mm)	(in.)	Manning's Hydraulic Roughness Coefficient (n)	Source for "n" Value
Regular Smooth-Wall PE or Concrete *	203 to 914	(8) to (36)	0.011	CE Handbook
Smooth-Core Corrugated PE Pipe	203 to 914	(8) to (36)	0.012	Est. from: ASAE SW-232 & CE Handbook
Corrugated-Wall PE Pipe	203	(8)	0.015	ASAE SW-232
	254, 305	(10, 12)	0.017	ASAE SW-232
	381	(15)	0.018	<estimated>
	457, 610	(18, 24)	0.020	ASAE SW-232
	762, 914	(30, 36)	0.022	<estimated>
Corrugated Galvanized Steel Pipe	203 to 914	(8) to (36)	0.024	CE Handbook

* For concrete pipe with "well" aligned joints.

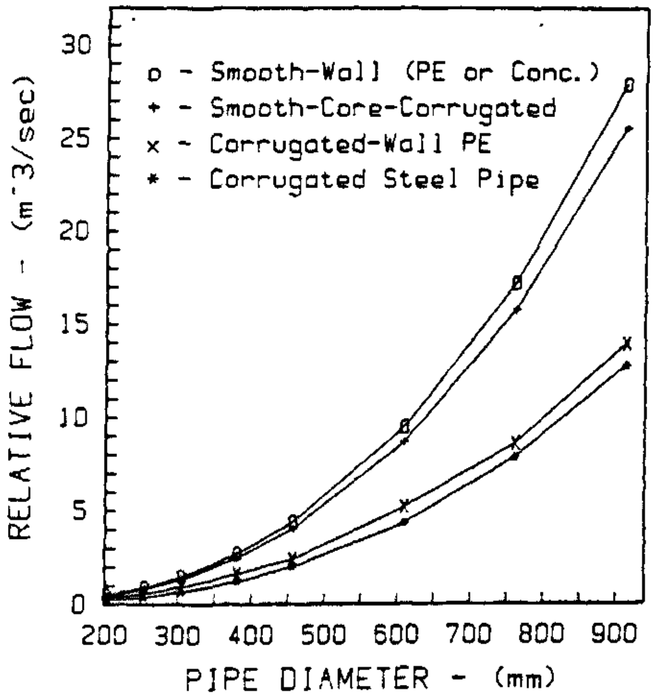

Fig. 5 Estimated Relative Flow Capacity of Various Circular Drainage and Culvert Pipes, 203 to 914 mm in Diameter.

SUMMARY COMMENTS

The structural and hydraulic characteristics of smooth-core corrugated and corrugated-wall PE pipes were analyzed and compared analytically. The smooth-core corrugated pipe-wall configuration significantly increased the efficiency-of-use of plastic material in the pipe wall to support the design load in contrast to the regular corrugated-wall pipe. Plastic use efficiency was expressed as the (strength-to-weight) ratio of the pipe structure. The smooth-core corrugated design increased the pipe's strength/weight ratio from 23 to 34% over that for the corrugated-wall design when both had the same depth of corrugation (h). When the corrugation depth for the smooth-core corrugated profile was designed 20% greater, the increase in the strength/weight ratio was even larger, at 58 to 68%. Thus, the combination of the smooth-wall core and a 10 to 20% deeper corrugation significantly increased the stength/weight ratio (plastic-use-efficiency) for the smooth-core corrugated pipe over that obtained for the comparable corrugated-wall design.

Both types of corrugated PE pipes have a significant advantage over other pipe products in terms of relative weight per unit length of pipe and ease of handling light-weight pipe sections. The relative pipe weights of smooth-core corrugated and corrugated-wall PE example pipes were estimated as 13 to 45% less than that for corrugated steel pipe, an average of 75% less than the unit weight of smooth-wall PE pipe, and 16 to 27 times less than that for concrete culvert pipe.

The full flow capacity of the smooth-core corrugated pipes was from 24 to 83% greater than that for regular corrugated-wall pipes, with the greatest differences for the larger pipe diameters because of the higher n-values. The estimated higher flow capacity for the smooth-core corrugated pipes indicated the following "equivalent" pipe diameters: a 381-mm (15-in.) smooth-core corrugated pipe was equivalent in flow capacity to a 457-mm (18-in.) corrugated-wall pipe, a 610-mm (24-in.) smooth-core corrugated equivalent to a 762-mm (30-in.) corrugated-wall, and a 762-mm smooth-core corrugated exceeded the capacity of a 914-mm (36-in.) corrugated-wall pipe. Thus, the pipe diameter requirements or specifications as stated in some standards may need to be revised, to reflect these large differences in flow capacities for corrugated-wall and smooth-core corrugated pipes of the same diameter.

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APPLICATION OF A METHOD FOR DERIVATION OF REGIONAL DRAINAGE FUNCTIONS FOR THE AGROHYDROLOGICAL MODEL DEMGEN (DEMAND GENERATOR) ON DATA FROM THE DRENTSE AA WATERSHED IN THE NETHERLANDS.

P. S. Grashoff*

A method to determine regional drainage function terms for the Demgen (DEMand GENerator) model is applied to data from the Drentse Aa watershed in the Netherlands. The method used is based on regression analysis of average calculated drainages per groundwater class. This method for determination of regional drainage functions proves to be practical and reliable.

A shortcoming noticed in previous studies of the Demgen model is the overestimation of the yearly runoff. It is shown that the overestimation of the yearly runoff in Demgen is not caused by the drainage function of Demgen.

The terms for a polygonal drainage function and a linear drainage function are determined using the averaging method. It is shown that a drainage function of polygonal form in Demgen gives better results with respect to the calculated high groundwater levels than a linear function. Also the distribution of the overestimation of the runoff during the year is more even when using the polygonal function in Demgen.

INTRODUCTION

Demgen has been developed within the PAWN study (Policy Analysis Water Management for the Netherlands [1]) for evaluation of water demands and drought and salinity damages in agricultural areas. Demgen is used on regional or national scales to calculate the water demands by agriculture, the actual evapotranspiration, the amount of drainage water, drought - and salinity damages and groundwater levels. Demgen has been under validation since 1980 and has been used in various studies both at regional and national scale (e.g. [2, 3, 4]).

Previous studies indicated that the drainage concept could be in error for the highlands part of the Netherlands. The extreme high groundwater levels are overestimated and an overestimation of the drainage is found. The first objective of the present study is to improve the drainage concept in Demgen. Furthermore the drainage functions were calibrated in the past by trial and error on results of an unsaturated Demgen version, using measured groundwater levels as input. On a regional or national scale this requires a serious effort. The second objective of the present study is therefore to find a reasonably cost-effective method for the determination of drainage functions on a regional or national scale.

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The present study deals with a method based on computation results of the unsaturated version of Demgen. The method consists of regression analysis on averages of calculated drainages per groundwater class . The method is applied to data of the Drentse Aa watershed in northern part of the Netherlands.

OVERVIEW OF THE DEMGEN MODEL

A short summary of the main concepts in Demgen is given here. A more detailed description of Demgen is given in [5]. In Demgen a study area will typically be divided in districts, subdistricts and plots. The district is a hydrological unit as far the surface water is concerned. Furthermore districts are mutually indepent, except with respect to the surface-water flows to and from the main distribution system. Horizontal groundwaterflows between districts are not taken into account. Districts contain surface water, urban area and vegetation-covered areas, which are called subdistricts.
Subdistricts are characterized by soil type and landform. Subdistricts contain plots which are characterized by their crop and type of sprinkling. Demgen simulates the hydrological cycle for mutually indepent plots and for the surface water of the districts. Plot flows are schematized as shown in fig. 1.

Apart from the climatical input (precipitation P and potential evaporation E_p) Demgen needs the following input on physical characteristics:

1. The drainage function D(y) representing saturated groundwater flow.
2. The soil moisture retention curve $\Theta(\varphi)$ and the hydraulic conductivity function $K(\varphi)$ for root zone and subsoil.
3. Crop parameters of the evapotranspiration and drought damage concept.

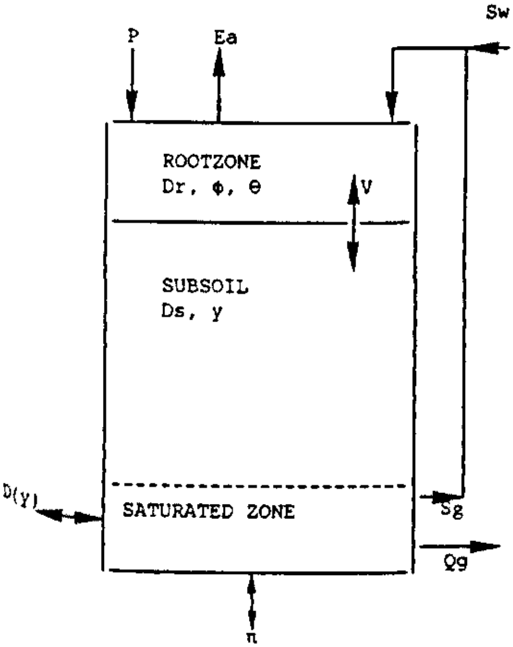
The computation is characterized by the following points:

1. Simulation takes place in ten day (decade) timesteps with steady state flow.
2. Actual evapotranspiration E_a is a function of E_p and φ. E_a is reduced when the suction φ in the rootzone exceeds the reduction point φ_r. Drought damage is a function of the ratio E_a/E_p.
3. Unsaturated flow is based on the stationary scheme of [6]. Upward capillary rise V is calculated as a function of the watertable depth y and the suction in the rootzone φ, while rootzone loss is calculated as the excess moisture above field capacity of the rootzone. The field capacity is defined as the amount of water that can be held in the rootzone against gravitational force.
4. Drainage D(y) is a function of the watertable depth y.

THE DRAINAGE FUNCTION CONCEPT

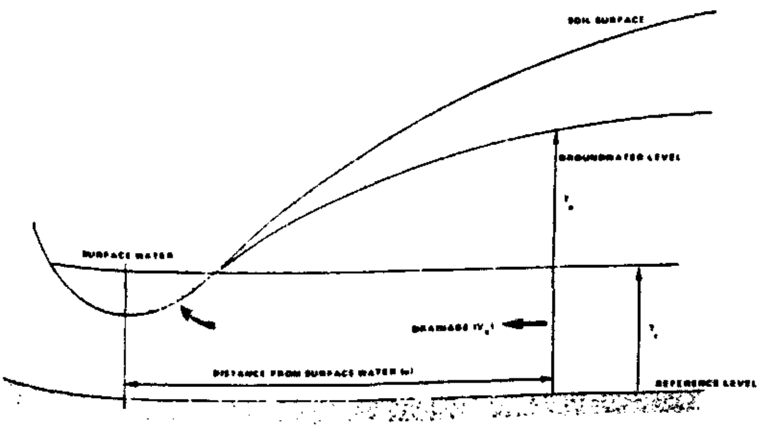
The force of gravity acts on water in the soil, causing it to flow from places with a higher hydraulic head to places with a lower head. The re-

FIGURE 1 OVERVIEW OF THE WATERFLOWS IN A DEMGEN PLOT.



P : precipitation
Ea : evapotranspiration
Sw : sprinkling from surface water
Dr : soil moisture deficit in the rootzone
Φ : suction in therootzone
Θ : moisture content of the rootzone
V : capillary rise(rootzone loss when negative)
Ds : moisture deficit in the subsoil
y : water table depth
Sg : sprinkling from groundwater
D(y): drainage from subsoil
Qg : groundwater extraction
π : up- / downward seepage

FIGURE 2 SOIL PROFILE ILLUSTRATING WATER FLOWS DUE TO DRAINAGE



sulting flow is called drainage when it moves water from the subsoil to the surface water (fig. 2). Drainage flow is governed by a differential equation called Darcy's law:

$$V_x = \frac{y'_x}{K_x} \qquad (1)$$

where

x : Horizontal distance from an arbitrary datum (mm)

V_x : Drainage velocity (mm/day)

K_x : Drainage resistance (days)

y'_x: Deritave with respect to x of the groundwater level y (mm)

The drainage resistance may consist of horizontal and radial components. Solutions to the above above equation define the drainage function D(y). For the highlands part of the Netherlands a simple steady state solution is written in the following linear form:

$$D(y) = \alpha + \beta \cdot y \qquad (2)$$

where

$D(y)$: Drainage (if positive) or infiltration (if negative) (mm/day)

α : Constant term of the drainage function (mm/day)

β : Coefficient term of the drainage function (1/day)

y : Depth to groundwater table (mm)

The drainage function in the highlands is a linear equation with respect to groundwater levels. In the PAWN study the highlands part of the Netherlands is subdivided in 17 drainage-regions. For each region the terms have been determined.

OBJECTIVES AND SCOPE OF THE PRESENT STUDY.

In general the performance of the linear drainage function is found to be satisfactory, considering the fact that it represents the whole saturated zone with all its complex interactions. The following shortcomings have been identified in previous studies [3,4,5]:

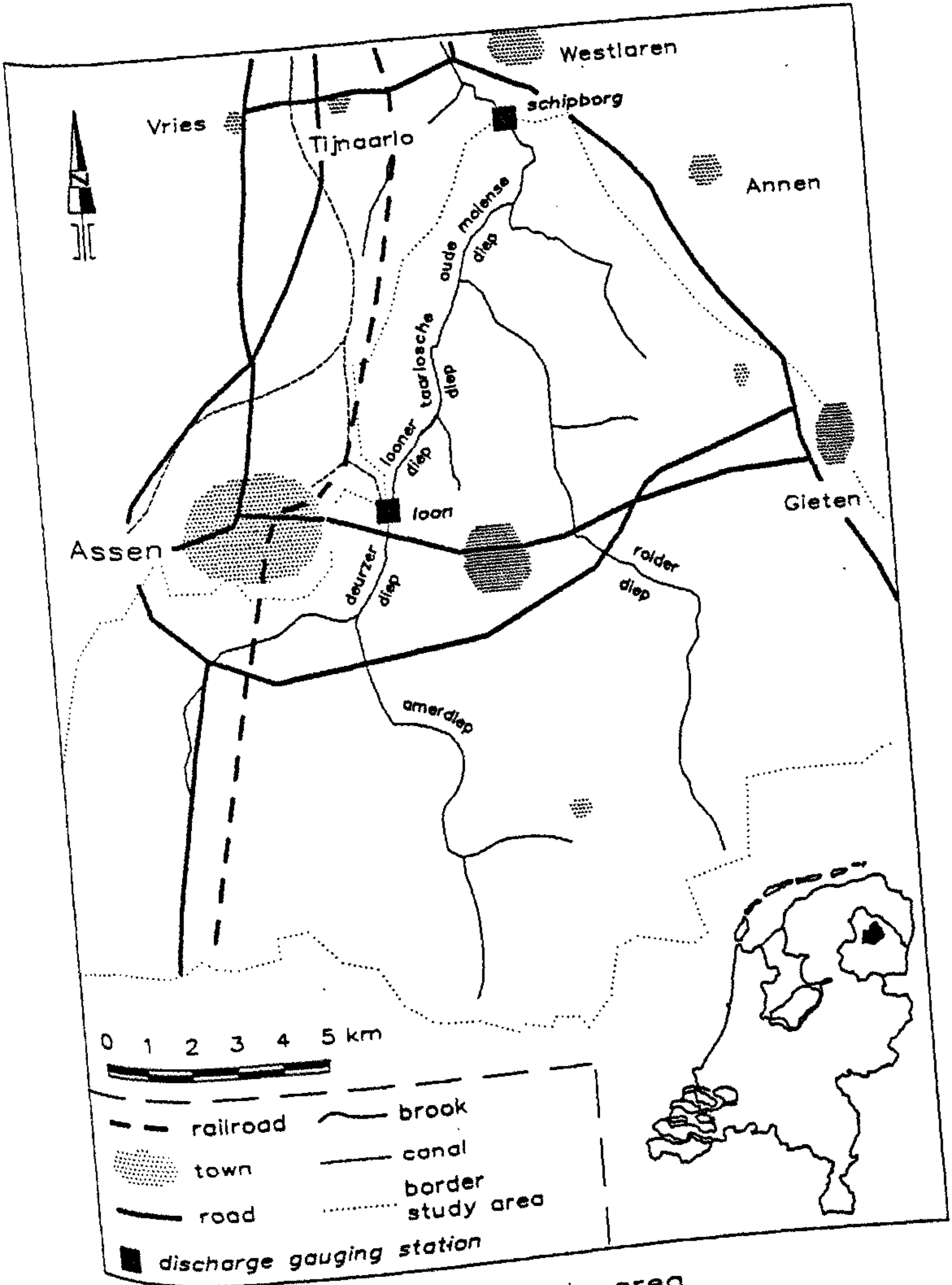


Figure 3. Drentse Aa study area

1. The average runoff is overestimated by about 60 mm/year (2.4 inches), both in summer and in winter. Overestimation in summer is of importance when calculating drought damages.

2. Extreme high groundwaterlevels tend to be overestimated. Proper description of high groundwater levels is of importance for determination of capillary rise and for determination of damages due to extremely wet conditions.

3. The method used for determination of the terms in the linear drainage functions of the PAWN study required a serious effort. This is due to the fact that the drainage-functions were more or less obtained by trial and error. On single plot level this is not a serious shortcoming, but for national and regional applications it is.

The objectives of the present study are to improve the drainage function concept so as to enhance the performance of Demgen with respect to the above mentioned points 1. & 2., as well as to test a new method to determine drainage function terms on a regional scale.

The study area is the Drentse Aa watershed and the study period is 1979-1984. In this area and period adequate data are available to compare the measured values with the calculated groundwater levels and discharges.

THE DRENTSE AA WATERSHED

The Drentse Aa watershed is located in the northern part of the Netherlands. The total area of the watershed is about 260 km^2, in the present study 223 km^2 are taken into account. 28% of the area is covered by natural vegetation, 25% by arable crops, 43% by grass and the remaining 4% consists of surface water and urban areas.

The brooks in the Drentse Aa watershed originate in south-eastern part of the area and flow roughly towards the north. The longest brook is 45 km. long with an average bed gradient of 36 cm per kilometer.

The soil types in the area can be classified in four groups:
1. well permeable medium coarse sand;
2. less permeable sandy clay loam;
3. brook valley wetlands;
4. peat.

In the sixties and seventies the drainage of the less permeable soils has been improved, causing problems of waterexcess in the lower lying parts of the watershed. To alleviate this problem a diversion for excess water has been created near the town of Loon. The rest of the water flows through the Drentse Aa river to the Noord-Willemskanaal (see also fig. 3).

The areal average yearly precipitation is 84 cm. (33.1 inches) during the study period. In fig. 4 an overview is given of the areal average precipitation and potential evaporation. The average yearly runoff of the study area is estimated to be equal to 36 cm. (14.2 inches) per annum. In fig. 5 average decade discharges during the study period are shown and in fig. 6 the areal averaged depths to groundwater table can be found. The areal

FIG. 4 POTENTIAL EVAPORATION AND PRECIPITATION

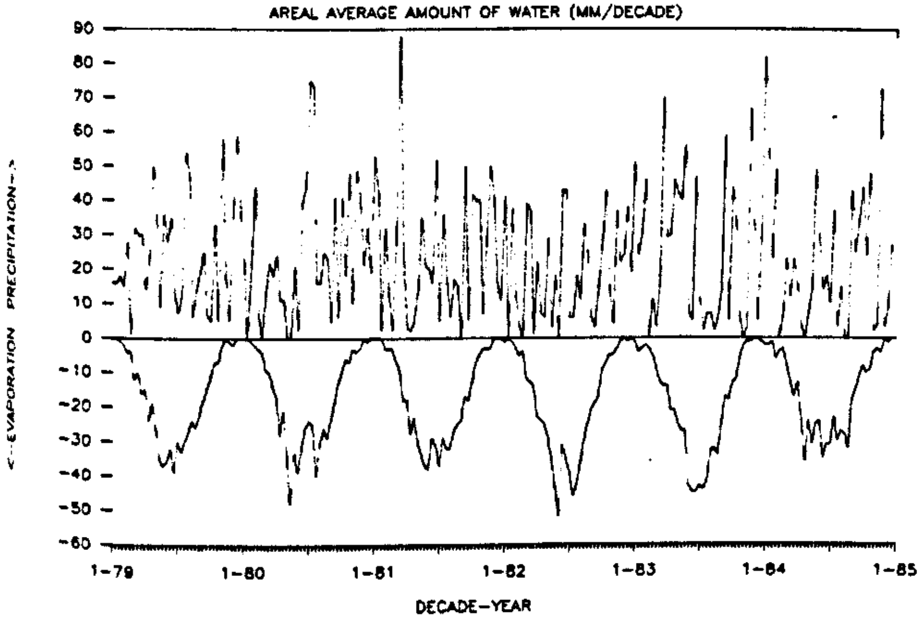


FIG. 5 TOTAL DISCHARGE DRENTSE AA STUDY AREA

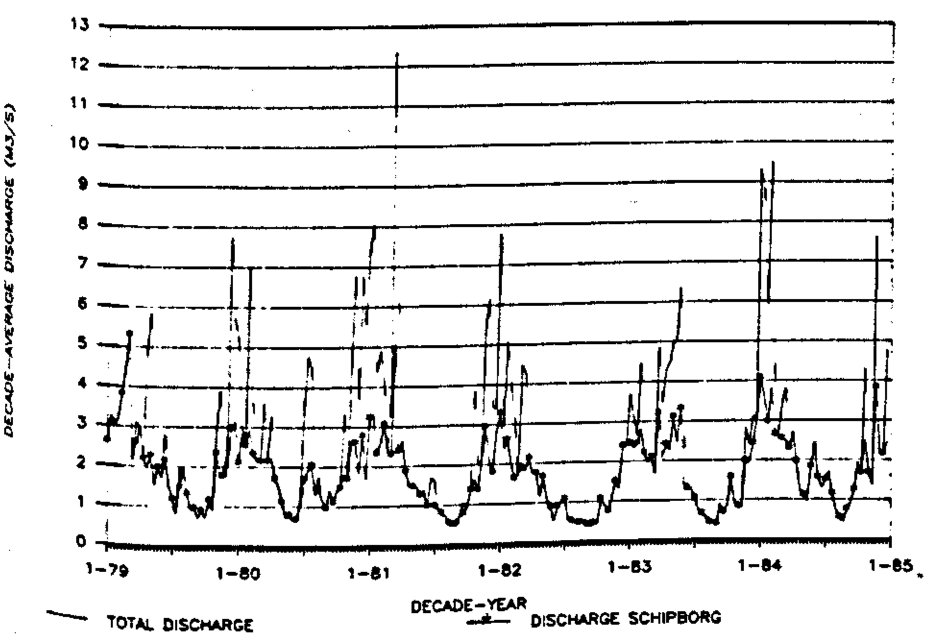


FIG. 6 MEASURED GROUNDWATER TABLE DEPTHS

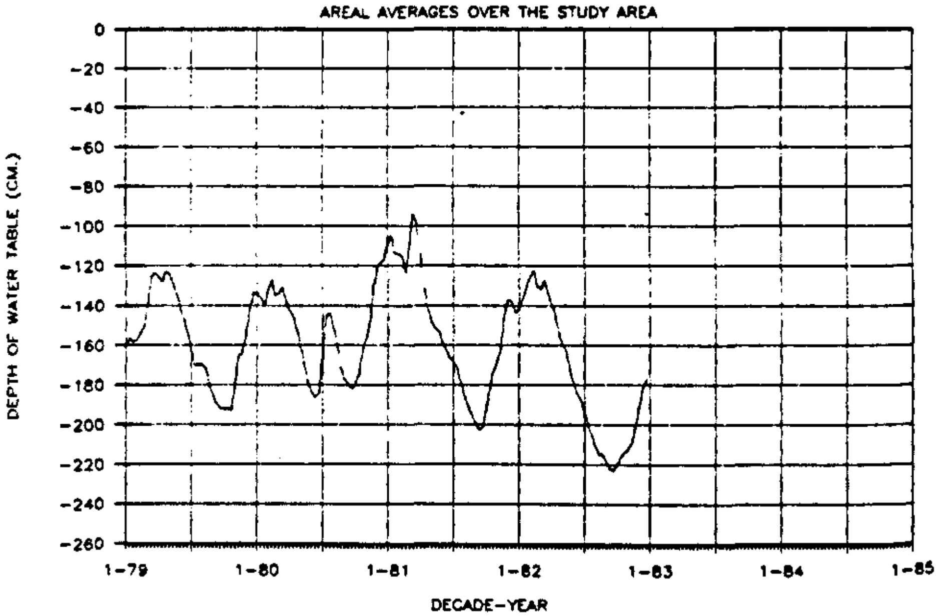
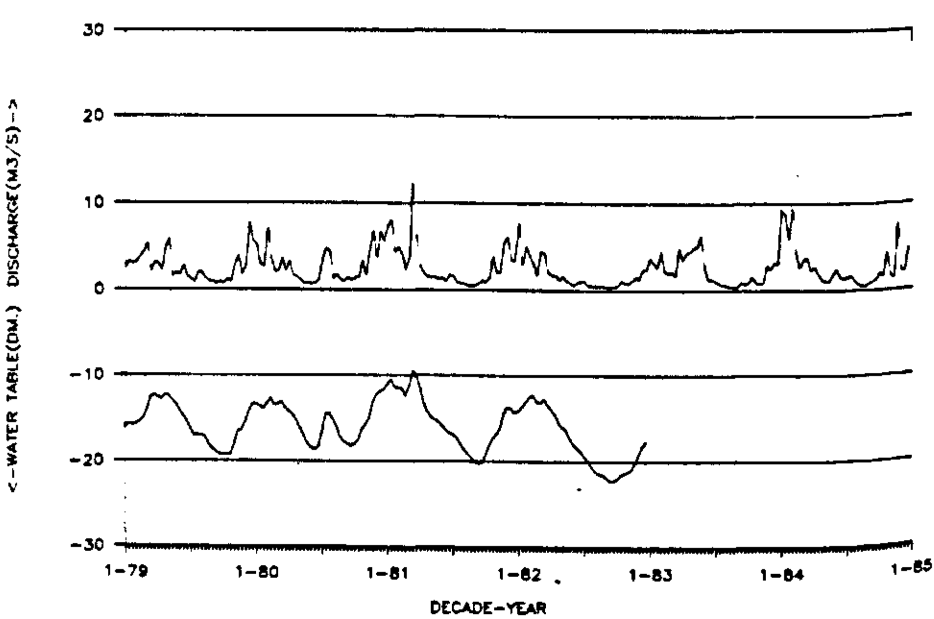


FIG. 7 COMPARISON OF DISCHARGES AND WATERLEVELS



averaged depth of watertable varies during the study period between 90 and 220 cm. (about 20 - 85 inches) below the soil surface.

When comparing the measured discharges to the measured groundwater levels in fig. 7 it is obvious that there is some relation between large discharges and high watertables (and vice versa) in the area under study.

DETERMINATION OF THE DRAINAGE FUNCTIONS WITH UNSATURATED DEMGEN

The unsaturated version of Demgen doesn't use drainage functions to represent the saturated zone. It uses measured groundwater levels as an input to the model and it calculates the amount of drainage that is needed to reach this level for each timestep. It is possible to determine the terms of the drainage function by correlating the calculated drainages with the measured groundwater levels. A problem however is that there is a tremendous amount of scatter in the individual timestep values. In fig. 8 the individual timestep values for drainage and groundwaterlevels are shown, based on results from an unsaturated Demgen calculation for the period 1979-1982. As can be seen in fig. 8 the drainage shows strong and apparantly unrealistic fluctuations. Regression analysis using these data points would be unreliable.

The fluctuations are caused partly by the poor description of the subsoil deficit by Demgen and by the occurence of non-steady state situations and hysteresis effects, which are not taken into account in Demgen. Scatter caused by the latter two phenomena are independent of the Demgen model performance and will make it more difficult to find the proper drainage function for Demgen.

On physical grounds it can be shown that there must be a relation between discharges and groundwater levels (as can be seen in fig. 7). To be able to establish the drainage-function in a reliable way van Vuuren [4] proposes a method based on averaging. In this method regression analysis is based on average values for drainage and groundwater levels rather than the individual timestep values. Groups of 6-10 timestep values are divided in classes of increasing water table depth and then for each class the average value for drainage and watertable depth is computed. Of course averaging doesn't increase the reliability of the regression analysis, but it does increase the chance of finding the proper physically based relation that is underlying the data.

In this way a time averaged value for drainage and water table depth is obtained for each groundwater level class. The result of this approach for the data from fig. 8 is shown in fig. 9. Regression analysis of the time averaged values results in a drainage function that is more in line with what can be expected on physical grounds. In general it can be argued that for higher groundwater levels larger parts of the drainage system will contribute to the total discharge. If that is the case the drainage function will be of a non-linear form.

The data points in fig. 9 show that this phenomenon occurs in the Drentse Aa watershed. By regression analysis for two ranges of groundwater levels the terms for the polygonal drainage function shown in fig. 9 have been found. For comparison purposes the terms for a linear drainage function

FIG. 8 WATERLEVELS VS. CALCULATED DRAINAGE D(y)

D(y) COMPUTED USING UNSATURATED DEMGEN

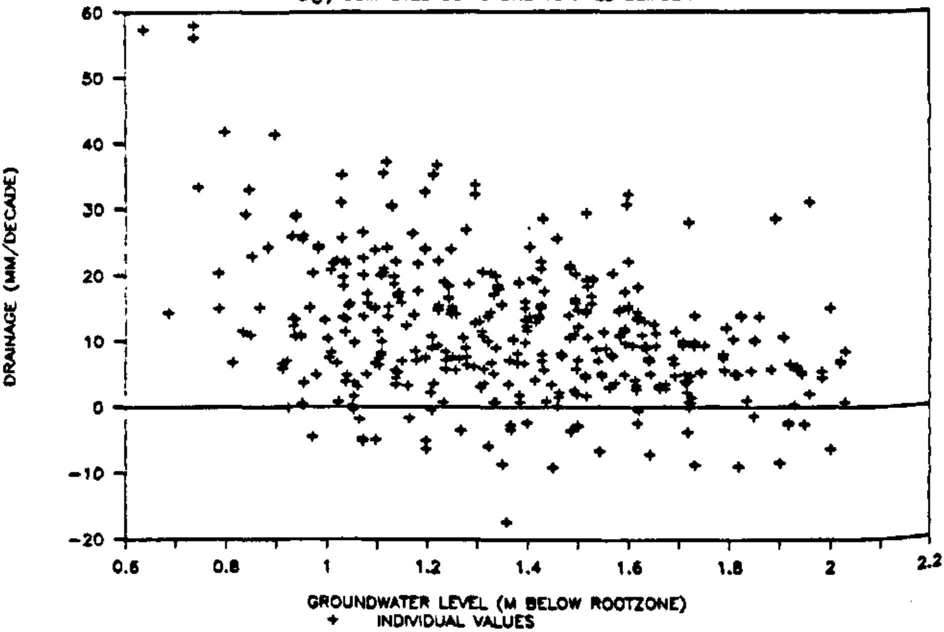


FIG. 9 ANALYSIS OF CLASS-AVERAGE VALUES

AVERAGE OF 10 TIMESTEP VALUES PER WATERLEVEL CLASS

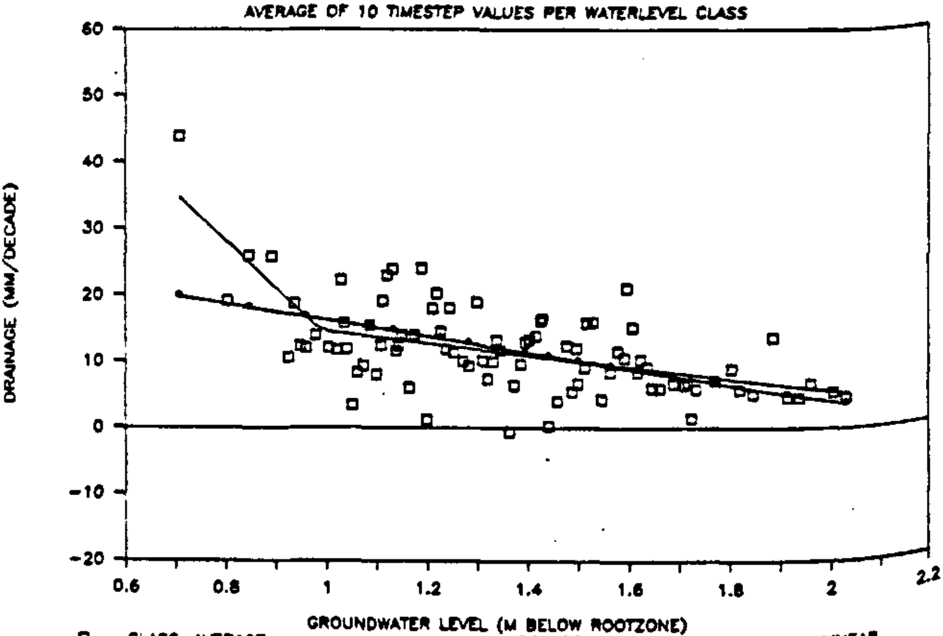


FIG. 10 CALCULATED DEPTHS OF WATER TABLE

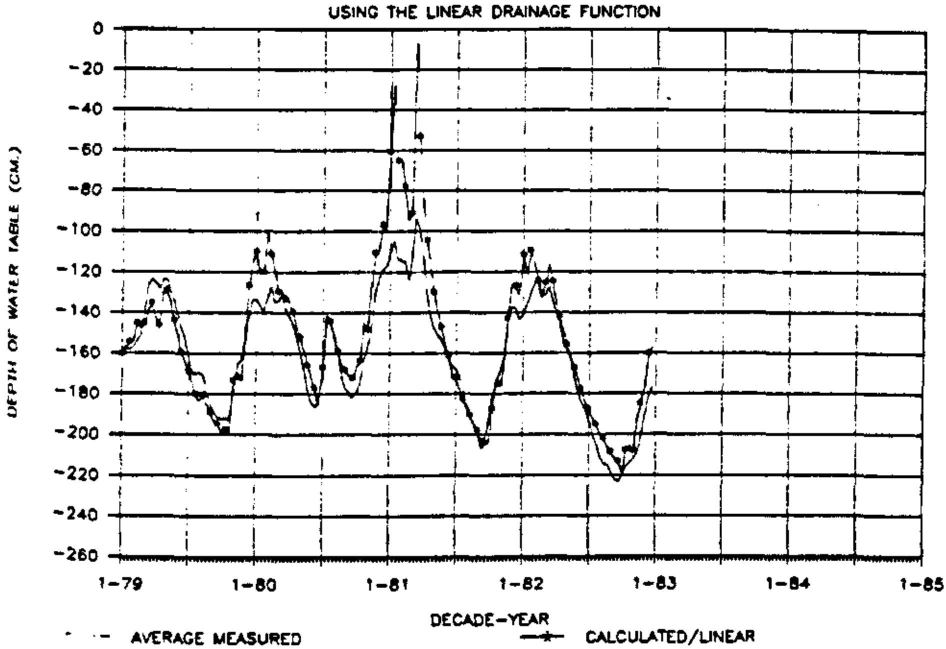
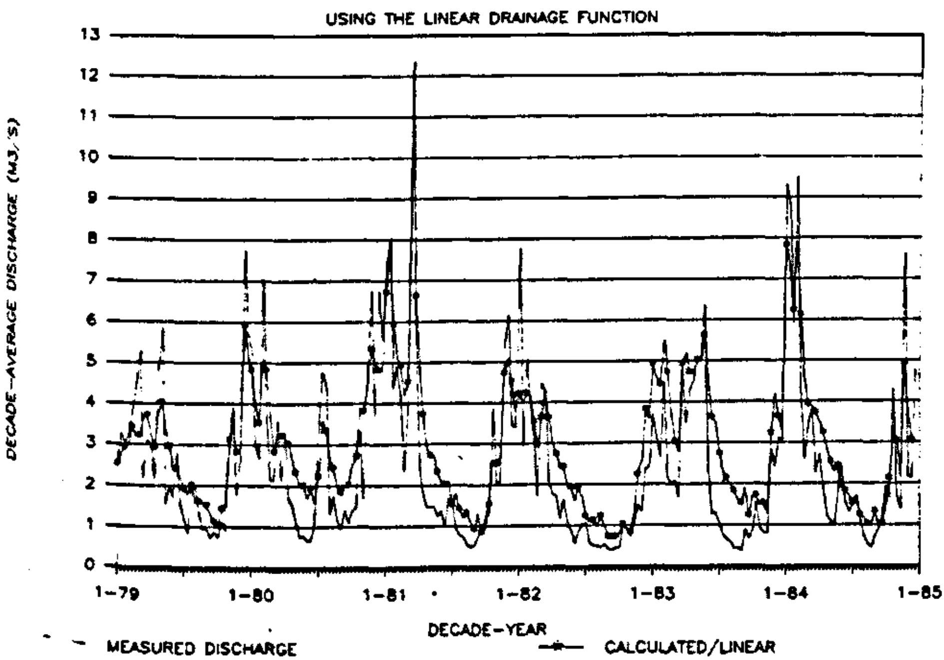


FIG. 11 MEASURED AND CALCULATED DISCHARGES



have also been computed. The formulas for the computed drainage functions are listed below:

linear : $D(y) = 2.86068 - 0.00121 \cdot y$ (all y)

polygonal: $D(y) = 8.41719 - 0.00705 \cdot y$ ($y < 989$ mm)
$D(y) = 2.30651 - 0.00087 \cdot y$ ($y \geq 989$ mm)

where

D(y): Drainage (if positive) or infiltration (if negative) (mm/day)

y : Depth to groundwater table (mm)

The average annual runoff calculated with the unsaturated Demgen version is 436 mm. (17.2 inches) for the period 1979-1982. This is about 80 mm. (3.1 inches) more than the measured runoff. Overestimation appears to be independent of the drainage concept since in the unsaturated Demgen version no use is made of this concept. In the northern part of the study area there is a horizontal groundwater flow in the upper aquifer towards the north, that is out of the study area. This might be the cause for the calculated overestimation of the runoff, since in Demgen it is assumed that there is no horizontal groundwaterflow out of the districts. Unfortunately it is not known at present how large this flow is, otherwise the runoff calculated by Demgen could be reduced accordingly.

VALIDATION OF THE DRAINAGE FUNCTION CONCEPT

The linear and polygonal drainage functions have been used in the normal Demgen version to simulate the saturated zone. The periods used for validation is 1979-1982 for the groundwater levels and 1979-1984 for the discharges. The results of the Demgen calculations are compared with the measured values for water table depths and discharges. In fig. 10 and 11 the result for the linear drainage function is shown for respectively the water table depths and for the discharges. In fig. 12 and 13 the results for the polygonal drainage function can be seen.

Looking at fig. 10 it is obvious that the linear drainage function concept is not adequate in the beginning of 1981. In that period the calculated groundwaterlevels are almost 1 meter (40 inches) higher than the measured levels. In summer periods the measured levels are reproduced quite smoothly. With the linear drainage function the measured discharges are reproduced fairly well as can be seen in fig. 11. This figure also shows that discharges in summer are overestimated.

With the polygonal drainage function both high and low groundwater levels are reproduced well (fig. 12). The summer discharges however are also overestimated by Demgen using the polygonal drainage function (fig. 13). The big advantage of the polygonal drainage function compared to the linear one is the more accurate prediction of high groundwater tables.

FIG. 12 CALCULATED DEPTHS OF WATER TABLE

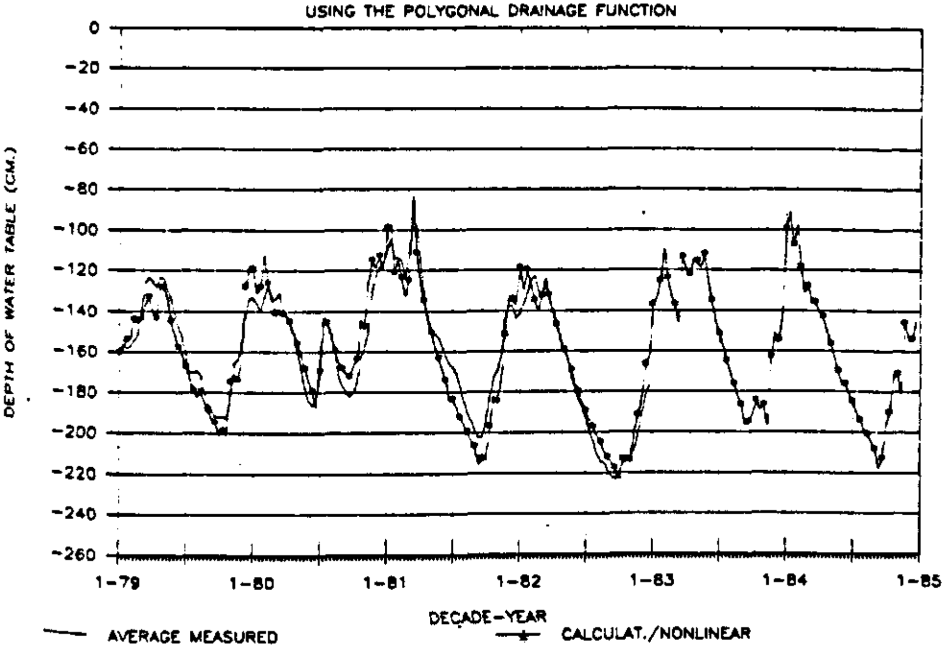


FIG. 13 MEASURED AND CALCULATED DISCHARGES

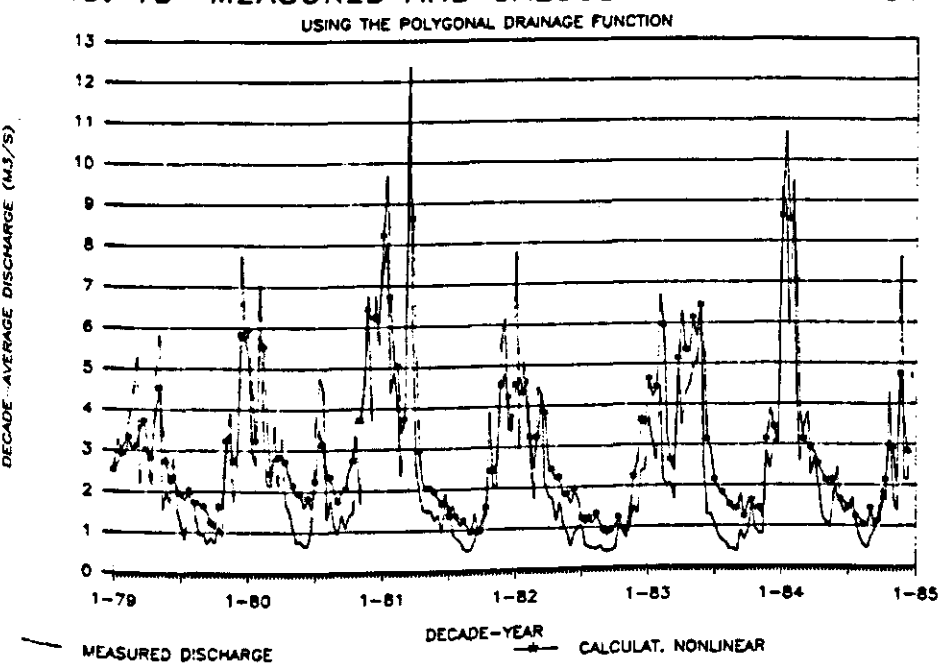


FIG. 14 AVERAGE DEVIATION OF WATERTABLE DEPTHS

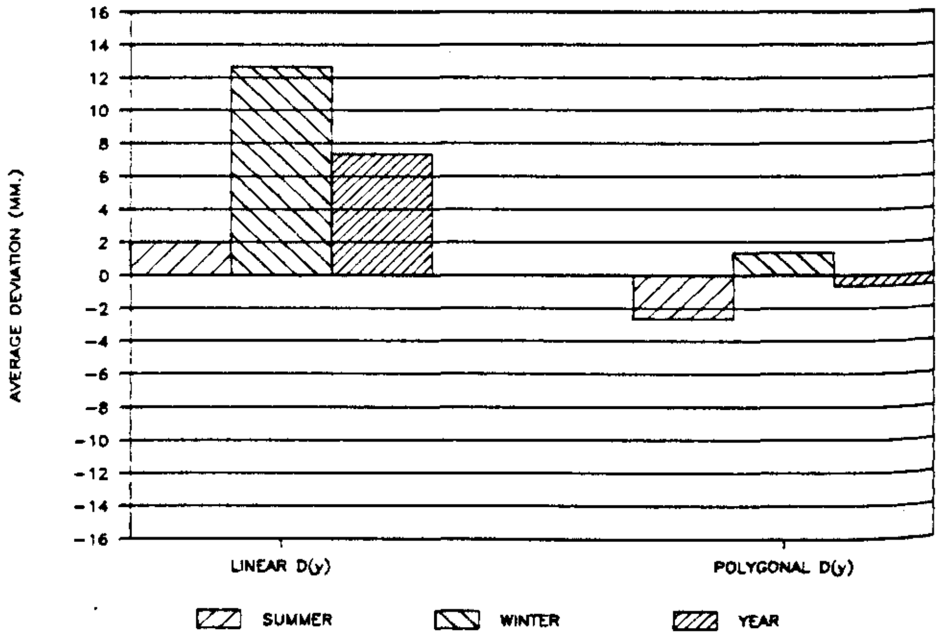
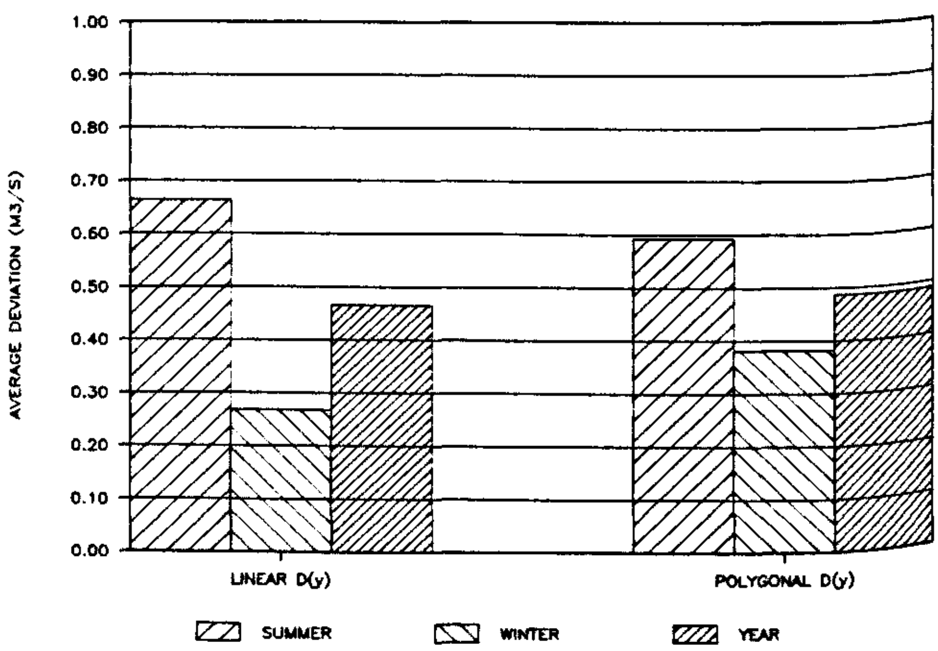


FIG. 15 AVERAGE OVERESTIMATION OF DISCHARGES



Statistical analysis of the differences between the measured and calculated values shows that both drainage functions overestimate drainage not only in summer, but also in winter. The calculated average yearly runoff is 424 mm. (16.7 inches), that is 68 mm. (2.7 inches) more than the average measured runoff. The overestimation is about the same as for the computation using the unsaturated Demgen version. This is not surprising, when it is assumed that the overestimation is caused by the horizontal groundwater flow out of the study area.

The overestimation by the polygonal function for the summer period is somewhat less than for the linear one. In the winter period the picture is reversed. An advantage of the polygonal function is the more even distribution over the year of the overestimation.

The standard error for the groundwater levels is only 9.6 mm (0.38 inches) for the polygonal drainage function. Comparing the measured with the computed values shows that Demgen using the polygonal function performs better for groundwater levels but not significantly for discharges. The average deviations from the measured values are shown in fig. 14 and 15.

CONCLUSIONS

The following conclusions can be drawn from this study:

1. Overestimation of the runoff by Demgen is not related to the drainage concept. The overestimation might be caused by the assumption in Demgen that there is no horizontal groundwaterflow out of the district. In the northern part of the Drentse Aa there is a horizontal groundwaterflow out of the watershed of an unknown magnitude.

2. A polygonal drainage function gives a better prediction of high groundwater levels than a linear drainage function. The distribution over the year of the overestimation of the runoff is more even with the polygonal drainage function.

3. The method used to determine the drainage function terms is based on regression analysis of average drainages per groundwater class, as computed with the unsaturated Demgen version. The method proved to be reliable. No significant improvement of the drainage functions by the "trial and error method" could be found. It proved to be time-consuming to determine the areal average groundwater levels, needed as input for unsatured Demgen.

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Measure of Alfalfa Persistence on Marine Sediments with Shallow Subsurface Drains

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ABSTRACT

Alfalfa persistence responded favorably to shallow subsurface drainage at three spacings (3, 6, and 12 m) compared to no drainage on silty clay loam marine soils after three winters. There were four replications each of four treatments of 7.6 cm diameter drain tubing at 60 cm depth. Surviving alfalfa plants were counted in transects across the plots at right angles to the drains. Alfalfa plant survival on non-drained plots was 0.4 plants m^{-2}. Average persistence on drained treatments was 31.0, 29.1, 13.2 plants m^{-2} for 3, 6, and 12 m drain spacings. Hay yields were higher on the drained vs the non-drained plots, but did not differ among the three drained treatments. Alfalfa plant survival also varied as a function of distance from the drain. The population for the 12 m treatment dropped from 32 plants m^{-2} at the drain to 5.1 plants m^{-2} 6 m from the drain. Extrapolation of the plant population prediction equation for the 12 m treatment would estimate 0.4 alfalfa plants m^{-2} 11 m from the drain.

INTRODUCTION

The New England-Northern New York State region is characterized by short growing season, generally cool climate, and adequate annual rainfall. This region is well adapted for the production of perennial grass and legumes on the well drained soils. Large acreages of poorly drained soils could be highly productive if effectively drained. Clay and silty clay marine and lacustrine sediments occur in Northern New England on fairly flat topography and are similar in drainability to the lacustrine clays found further west and south in the region. Random subsurface drains installed in the past have provided some drainage improvement but are inadequate to protect stands of quality legume forage from high water table in spring and fall, and from winter frost heaving.

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Contribution from the Maine Agricultural Experiment Station, University of Maine, and the New England Plant, Soil and Water Lab, USDA-ARS, Orono, ME 04469

Bornstein et al. (1985), have shown significant increases in yield, alfalfa as percent of hay, and alfalfa plant counts with shallow drains. There were no significant differences associated with the drainage spacings of 3, 6, and 12 m.

Bornstein and Hedstrom (1982) have demonstrated greatly improved trafficability associated with 3, 6, and 12 m drain spacings in comparison to no drain. In 1981 trafficable conditions occurred three weeks earlier in the spring on drained vs undrained plots, although there were no significant differences among the three drainage treatments. Bornstein and Scott (1982) also reported that while there may have been some deformation in these shallow drains, (60 cm deep), they continued to function satisfactorily.

This paper addresses the question of alfalfa plant persistence as a function of shallow drains, and the pattern of such persistence in relation to the drains.

MATERIALS AND METHODS

A 2.4 ha research site located in Brewer, Maine on silt loam marine sediments mapped as Buxton (fine, illitic, frigid Aquic Dystric Eutrochrepts), Scantic (fine, illitic, nonacid, frigid Typic Haplaquepts) and Biddeford (fine, illitic, nonacid, frigid Histic Humaquepts) soils that are moderately well, poorly and very poorly drained, respectively, was used for this experiment. The slope of the site was less than 3 percent. Four drainage treatments in a randomized complete block design with four blocks were installed in 36 x 36 m plots. Treatments were no drainage, 12, 6, and 3 m drain spacing. Average hydraulic conductivity (K) for the B horizon determined by the auger hole method was 1.6 cm/h. Plot drains were perforated, corrugated plastic tubes, with a diameter of 7.6 cm. The drains were placed at a depth of 60 cm with indirect flow to 1.5 m deep main drains installed outside the plot boundaries.

Alfalfa (<u>Medicago sativa</u> L, cv. Iroquois) was planted in early June, 1981. All plots were fertilized with 1.12 Mg ha^{-1} of 5-20-20 B (B=borated) at planting and a split application of 1.12 Mg ha^{-1} of 0-10-40 B in both 1982 and 1983 split after first and last harvests. Lime was applied at 4.48 Mg ha^{-1} both in 1978 and 1981 after soil test. Hay was harvested from the plots twice in 1981, three times in 1982, four in 1983 and three in 1984.

In July 1984, counts of alfalfa plants were obtained from 2 transects across each plot, one third the distance from each end of the plot. Each transect was divided into 36 subplots each 1 m by 0.25 m. The specific location of each subplot could thus be transversely related to the drains.

The original plant counts were converted to logs to normalize the data for variance analyses and the calculation of treatment means. The log means were then retransformed back to the arithmetic scale for use in the discussion. Logical and polynomial contrasts were employed to partition treatment sums of squares into single degree of freedom contrasts. The

0.05 significance level was used to assess differences. The SAS-GLM program was used for data analyses (SAS 1982).

RESULTS AND DISCUSSION

Alfalfa plant survival by drainage treatment is presented in Table 1. The hay yields in Table 2 are from Bornstein et al. 1985. The May and July plant counts were similar, even though the May counts are based on only 4 randomly selected 0.38 m^2 quadrats per plot. The July data, however, are from 2 transects each 36 m long by 0.25 m wide located at right angles to the drains. Bornstein et al. (1985) showed a gradual drop in alfalfa plant populations from 1981 through 1983 with a large drop from 1983 to May 1984 for the drained plots. The undrained control exhibited a large drop in population from the fall of 1981 to the spring of 1982 with a more gradual decline to almost no alfalfa plants in 1984.

Hay yield did not show a trend during the four years, Table 2. The drained plots average a 57 percent yield increase over the undrained treatment. The percent alfalfa in the hay dropped to 11.3 for the undrained treatment. The percent alfalfa in hay averaged over 90 percent for the drained ploats over the four years, with a drop to 70.5 percent the fourth year. Thus alfalfa populations of 13 to 31 plants m^{-2} produced a 70% alfalfa hay.

Without drainage the alfalfa population was 0.4 plants m^{-2}, Table 1. Of the 288 0.25 m^2 no drainage subplots, 83 percent contained no alfalfa plants, showing that at this site, drainage is essential for alfalfa survival.

Plant counts as functions of drainage treatment and distance of the subplot from the drain, are given in Figure 1. A line for the no drainage control is not included since there were no trends or differences in alfalfa population across these plots. The alfalfa persistence was different for the three drainage treatments. In the 3 m drain spacing, no significant decrease in alfalfa population occurred from the drain to 1 m away. The 6 m spacing exhibited a decrease from 36 plants at the drain, to 24 plants 3 m away. The response to the 12 m drain spacing was linear with a decreasing population from 32 plants over the drain to 5 plants 6 m away, when the number of plants are plotted as logs. Thus, if the data were plotted on the arithmetic scale the decrease would be geometric.

These data demonstrate different alfalfa plant populations and patterns of persistence associated with the different drain spacings and distance from the drains. In retrospect, it might have been more informative if yields had also been obtained within the drainage plots from subplots different distances from the drain. The yields, Table 2, represent the average effect over the entire plot. Statistical analyses, including trend analysis, did not reveal yield or percent alfalfa differences among the 3 drainage treatments. The possibility exists, therefore, that a wider drain spacing than 12 m could prove to be satisfactory under commercial field conditions.

Table 1. Effect of drain spacing on the number of plants m^{-2} following the third winter after planting.

Drain Spacing m	Plants m^{-2} May 1984	July 1984 Log (No.+1)	July 1984 Retransformed
No drain	1	0.1604	0.4
12	17	1.1527	13.2
6	37	1.4791	29.1
3	31	1.5055	31.0
Contrasts			
Drainage (+/-)	*	*	
Among 3 drains			
Linear	*	*	
Quadratic	*	ns	

May reading from 4 0.37 m^{-2} random quadrats per plot.
July data from 72 0.25 x 1 m subplots transecting the drains in each plot.
* Significant at level P = 0.05
ns Not significant

Table 2. Alfalfa Hay Yield and Percentage of Hay (Bornstein et al. (1985)

	1981	1982	1983	1984	Mean
	Yield dry weight, Mg/ha				
No drainage	5.82	4.84	6.97	5.23	5.72
All drained	8.53	9.74	9.61	8.13	9.00
	*	*	*	*	*
	Alfalfa percent of hay				
No drainage	86.8	80.8	11.3	2.8	42.2
All drained	94.3	99.3	89.1	70.5	90.8
	ns	*	*	*	*

No differences among the 3 drainage spacings (3,6,12 m)
* Significant at level P = 0.05
ns = Not significant

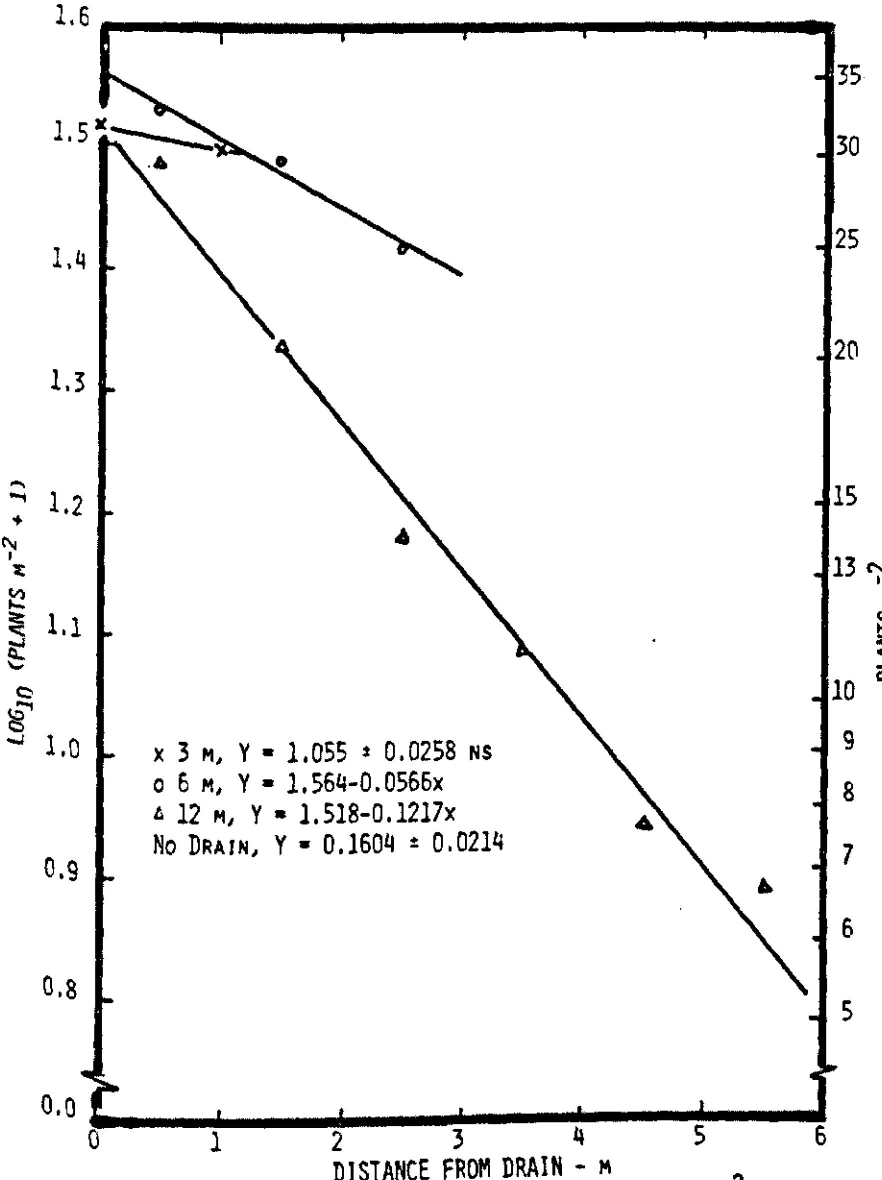

FIGURE 1. RELATIONSHIP OF THE NUMBER OF ALFALFA PLANTS M^{-2} TO THE DISTANCE FROM THE DRAIN FOLLOWING 3 WINTERS AFTER PLANTING

Solving the 12 m drain equation for the control plant population of 0.4 plants m^{2} estimates that no effect of the drains on alfalfa plant population would be encountered at 11 m, or a drain spacing of 22 m. The estimated average alfalfa plant population for drain spacings of 14 and 16 m would be 11.4 and 9.7 plants m^{2} respectively. These estimates are beyond the design of the experiment and assume a continued linear function between 6 and 11 m from the drain. This should be investigated.

Bornstein et al. (1986) have shown that installation of a subsurface drainage system on representative silty clay loam soils spaced at 12 m is economically feasible. The data on alfalfa plant population presented here show differences in population as an interactive function of drain spacing, and distance from drain. However, since there are no differences in yield associated with the drain spacings, from 3 to 12 m, it would be beneficial to know at what drain spacings a reduction in yield and percent alfalfa in the hay would occur.

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SOME ASPECTS ON A JOINT FINNISH-SOVIET EXPERIMENTAL DRAINAGE PROJECT

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Scientific-technical cooperation between Finland and U.S.S.R. has been continuous in practice since 1955 by joint working groups, which cover several fields of science and industry. One of these altogether 40 groups is the joint working group on land reclamation and water economy. The group is primarily concentrating on improvement of drainage technologies inclusive such themes as subsurface drainage practices, materials, machinery and work management, polder construction, economical evaluation, etc.

Although matters related to drainage are primary within the group's activities the other main theme, i.e. water economy, is covering some very important subjects as effects of drain water on water bodies, restoration of river basins, economically use of water reservoirs and protection of their water quality, improved use of effluents from cattle farms, etc.

Common interest in joining efforts for the development of improved drainage method, which may be applied in our climatic conditions particularly on heavy clay soils with very low hydraulic conductivity, led finally to the agreement on construction of a joint experimental drainage field. Indicative of the good cooperation between the experts of both countries is the short time needed for the preparatory and "bureaucratic" procedures, i.e. as the agreement was signed in April 1986 a Finnish team of experts visited the selected site already in May 1986 for field measurement. Both parties prepared their drainage plans by the December 1986 and the final construction schedule could be confirmed in May 1987. Actual work was started on the Finnish part of the field in mid-July and on the Soviet part early August.

DESCRIPTION OF THE EXPERIMENTAL AREA

Physical Description: The experimental area Zaytsevo is located 36 km SSW from the city of Leningrad (approximately 59°35'N, 30°05'E). it is lying along the the main highway leading to Kiew and it forms a rectangular shape with dimensions of about 800 m x 800 m which is divided into two equal halves by the main drainage canal in the middle.
The main canal drains its water into river Verevo at 1.5 km distance. Because slope of the river is rather small at this stretch considerable rise of the watertable in the canal may be expected at heavy rains and during the peak snow melt period in the spring.

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The area is generally flat slightly sloping to south-western direction. Surrounding areas are cultivated (cereals and pastures).

Geohydrological Conditions: Whole area has been previously used for peat mining. Thus in the top soil the thickness of peat formation varies from 0.1 to 0.5 m. In general terms the soil consists of glacial-lacustrial fine-textured loam or clay loams down to 3-5 m with silt loam thereunder. Soil may be described as aciduous with pH values ranging from 3.5 to 4.8. Iron content of the groundwater has a very wide range with 0.1-100 mg/l (mainly 5-10 mg/l).
Groundwater level was very high during the first field measurements when the hydraulic conductivity of the soil was defined. The first results gave such values as 0.03 m/day (top soil, 0.1 m) and 0.07 m/day (depth 0.3 m). The high groundwater level was due to the badly blocked main canal. Due to the clearing and deepening of the canal in September 1986 or predrainage of the area geohydrological conditions changed considerably. As the observations and the measurements done during the work and immediately after its completion are at present (September 1987) still to be processed more exact values will be obtained only later.

Climatological Conditions: Zaytsevo lies in the humid zone with annual precipitation as an average 700 mm, which is rather evenly distributed throughout the year with slightly higher amount of rainfall in the autumn and lower in the late spring. Temperature ranges widely from winter minimum of -40°C up to 30°C as summer maximum peak values. Snow cover prevails from mid December until mid April.

APPLIED METHODS OF SUBSURFACE DRAINAGE

The general final target of the project being jointly prepared recommendations for the defining optimal drainage parameters and techniques applicable in these climatic conditions obviously some years of research are needed. Exchange of data from observations will take place twice a year. At the meetings necessary modifications or changes concerning the ongoing research will be discussed and taken up accordingly into account.

If we consider design and construction as the first phase of the project, so the second phase will consist of various observations and follow-up of technical capacities of both the drainage systems. The latter has been agreed to last initially for five years (1987-91) after which some conclusions could be drawn.

When assessing the initial expectations set for the project, it is worthwhile presenting both the layouts separately. Some fundamental differences exist between the Finnish and the Soviet way of applying methods for drainage. Common mutually conditions included that both areas will be divided into equal plots of 1.5-2.5 ha. Each variation will be replicated thrice and the amount of variations was agreed as 6 i.e. altogether 18 plots were thus formed.

Finnish Approach: On the Finnish side the design criteria applied in practice in Finland were used. The choice of methods was finalized and follows:

- Five variations are drained by PVC plastic pipes (Ø 40 mm). One of them by trenchless digger and the other 4 by trenching machine. Either gravel or sawdust was used as envelope material and drain spacing 10 m and 13 m on both materials;

- May be more by tradition than by practice one sequence was drained with clay tiles (Ø 40 mm) with gravel as envelope material, drain spacing 10 m and the drains were laid by trenching machine (make Ukko-Mara, Finnish made);
- Additionally an area of 4 ha was drained by trenchless digger with sawdust envelope and 10-13 cm spacing;
- All but two systems are connected by a collector to an outlet well. Remaining two systems consist of individual laterals draining directly to the main canal mostly because of high iron content of water in this area.

Soviet Approach: In U.S.S.R. up till recent years a trenching equipment with trench width approximately 50 cm wide has been and still is used extensively. Nowadays equipment for narrower trench width is becoming available in quantities. At the same time use of trenchless diggers is steadily increasing.

As gravel is the predominant envelope material in Finland its in U.S.S.R. is very scarce. This is mainly due to simply unavailability of suitable materials. This is why mostly synthetic materials are being developed with parallel use of local materials such as straw, sawdust, moss, etc.

Soviet variations are as follows:
- Trenching digger with synthetic envelope, backfill with top soil from the drain depth up till soil surface, drain spacing 10-30 m;
- The same as above with gravel envelope;
- One variation with a wide 0.5 m trench with synthetic envelope (spacing 10 m);
- Trenchless drainage with synthetic rope or chainlike envelope material which reaches from drain upto top soil (Ø 50 mm). This type of material is being used in soils with low permeability in order to improve the excess of water from top soil top the drain. It is laid simultaneously with the drain;
- Drain pipes are of PE-plastic material and by Ø 50 mm.

It may be seen from the above that the amount of variables is not very extensive. There is a whole lot of reasons for this, laborous methods of observations being one, but quite a few others that I shall not elaborate here. Only one of basic meaning deserves to be mentioned. Namely, the target of finding out possible effects caused by the applied different technologies including the quality of work itself and management. These effects could be confused, if there would be more variables at the start of the experiment.

OBSERVATION PROGRAMME

Programme for observation and collection of information considered relevant, when we wish to evaluate and compare functional capacities of various which will be followed. It is by no means a rigid one, but may be adjusted whenever necessary by mutual agreement.

It should be pointed out that all measurements will be carried out by the Soviet Institute for research of hydrotechniques and land reclamation techniques of the northern areas (SevNIIGiM) situated in Leningrad. Finnish side is entitled to control the measurements on site and will receive all the results of observations for further studies. The results will be discussed every year jointly.

General contents of the annual reports will include the following data:

1. Meteorological data;
   - Precipitation (rainfall/snowfall);
   - Wind velocity and direction;
   - Evapotranspiration and evaporation (by water balance);
   - Daily temperatures;
   - Depth of frost in soil;
   - Depth of density of snow cover;
2. Results of observations;
3. Evaluation of the functional capacities of drainage systems;
4. As an annex in tabular form data on drain discharge, elevation of groundwater table, soil moisture, soil bearing capacity (soil mechanics), and crop yield.

The methods for different measurements are as follows:

- Drain discharge will be measured manually at about 10 days interval, when no particular reasons for increased flow may be expected. At times of thawing frost, heavy summer rains and autumn measurements will be done 1-2 times a day;
- Soil moisture will be measured by gravimetric method at 0.1 m, and 0.4 m depths below soil surface once every ten days from the snow melt until autumn, when temperature will permanently drop below 0°C. Groundwater depths will be observed by piezometers every day, when GWL $<$ 0.7 m from soil surface and once every five days, when it lies deeper;
- Load bearing capacities of the field will be estimated by the depth of tracks caused by tractors and other machineries. Effects of the same equipment will be measured on every plot. Suitable penetration methods will be checked simultaneously;
- Hydrophysical capacities of the soil will be checked twice a year of undisturbed samples. Actual density of soil will be defined with pycnometers. Hydraulic conductivity of both soil and backfill materials will be measured in-situ;
- Depth of frozen soil will be defined immediately before snow melt and following it every 3-5 days until the soil has thawed completely;
- Amount of crop yield, including standard agronomic observations, will be measured from every plot on a defined area. It may be worthwhile notifying that any conclusions by crop may be drawn only after several different growing seasons;
- Technical quality estimation of the drain system has been done initially during the construction work;
- The complex of measurements will be carried out following the above descriptions, which have been indicated in details by Byshof et al. (1983).

OBSERVATIONS FROM CONSTRUCTION PERIOD

By the time of this report only preliminary results are available. An extremely rainy early summer (rainfall in June 150% of normal) threatened seriously the whole construction work. The fixed starting date (14.07) was somehow preceeded by a relatively dry period of 10 days, which enabled the commencement of construction. During the Finnish work period of 6 weeks two stops of 2-3 days due to rain were experienced, but the work was completed as scheduled. Despite the difficulties faced with transport of gravel on some of the wettest plots, our wheel equipped machinery managed rather well in carrying out the work. Deviations in pipe slope were observed to have remained within ± 0.01 m.

On the Soviet side work was started a bit later and finished in approximately with the same period of time as on the Finnish side. As they are using caterpillar tractors, no particular complications due to weather conditions were observed. General quality of work was stated as good.

SUMMARY

Based on the long-term scientific-technical cooperation between Finland and U.S.S.R. a field experiment on drainage has been started in 1986. The field construction works were completed in September 1987 in such a way that on one half of the area only Finnish design methods, materials and technologies were applied and on the other Soviet practices respectively. Total area of the Zaytsevo experimental field is 74 ha and it is located 36 km south-west from the city of Leningrad in U.S.S.R.

The project will enable direct comparison of various technologies applied within each experimental plot and between the two halves, common main interest being in the suitability of diverse envelope materials on heavy clay soils. Experiences from both countries will be carefully taken into account in the future extensive research work according to the agreed joint programmes.

ACKNOWLEDGEMENTS

The project of Zaytsevo experimental field is mainly financed by the Ministry of Agriculture and Forestry of Finland with the Ministry of Land Reclamation and Water Economy of U.S.S.R. and the respective Ministry of R.S.F.S.R.

Main cooperating parties in Finland are the Drainage Centre, the Centre of Agriculture Research, the Institute for Agricultural Technology of Helsinki University and the States Institutes for Agricultural Technology. In U.S.S.R. Lengiprovodhoz (Design Institute), Lenmelioratsiya (Construction Cooperation) and SevNIIGiM (Research Institute) all located in Leningrad are the actively participating bodies.

The good cooperation of all the above mentioned units, which only enabled the launching of this project, deserves the greatest gratitude.

REFERENCE

Byshof, E.A., T.I. Daishev, and J.A. Kentshyber. 1983. Methodological instructions for measurements related to drainage systems (in Russian). SevNIIGiM 93. Leningrad.

PRODUCTION INSPECTION AND TESTING OF CORRUGATED PVC DRAIN TUBING FOR THE MARDAN SCARP, PAKISTAN

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The Mardan Salinity Control and Reclamation Project (Mardan SCARP) is located in the Northwest Frontier Province of Pakistan. The project area covers a net irrigated area termed Culturable Command Area (CCA) of 50,000 ha (123,600) of the 54,500 CCA serviced by the Lower Swat Canal irrigation distribution system. About 29,600 ha of the CCA of the project is affected by water logging due to high water tables. To alleviate and control these high water tables provisions were included in the project of design and instal horizontal suburface drains on the affected lands.

To carry out the projects activities funding assistance to the Government of Pakistan was provided jointly by a loan of U.S. $60 million from the International Development Association of the World Bank and a grant of Cdn $30 million from the Canadian International Development Agency. The Water and Power Development Authority (WAPDA), a Government of Pakistan agency under the Ministry of Water and Power was delegated the responsibility to implement the projects activities.

PVC DRAIN TUBING PRODUCTION

As part of the activities supporting this subsurface drainage work the capabilities of manufacturing polyvinyl chloride (PVC) corrugated drainage tubing was developed by the Federal Chemical and Ceramics Corporation, Ltd. (FCCCL) of Pakistan, a GOP Corporation under the Ministry of Production. This facility was installed at Nowshera, Pakistan, a city close to the project area, and set up as the Nowshera PVC Factory (PVC Factory), a subsidiary company of FCCCL.

A formal Purchase Order for the Nowshera PVC Factory to supply PVC corrugated drainage tubing and fittings for Mardan SCARP was signed by WAPDA and the Nowshera PVC Factory in February 1984. This Purchase Order formally established the quantity, quality, and schedule of supply, and the payment for furnishing the tubing and fittings at The Nowshera Factory.

Table 1 shows the requirements and production of the different diameters of PVC tubing, for the Mardan SCARP the subsurface drainage system.

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Table 1. PVC Tubing Requirements and Production

Nominal diameter	Quantity required	Quantity produced[a]
	(meters)	(meters)
100 mm	3,575,610	3,682,700
160 mm	284,145	252,250
200 mm	116,770	171,540
10 inch	210,365	137,794
12 inch	311,585	211,004

[a] Production through September 30, 1987.

NOWSHERA PVC FACTORY

The Nowshera PVC Factory, utilizes two complete production lines to manufacture the PVC tubing and auxiliary PVC cutting and welding equipment to produce the required fittings of couplers, tees, elbows, and endcaps. The equipment components and arrangement of each production line is shown by Fig. 1. Also shown on Fig.1 is the crusher unit utilized to recycle rejected pipe. In addition the factory has installed equipment and facilities for handling and storing the raw materials used in the manufacturing process, and short term storage of produced tubing and fittings.

Production Lines

Initially tubing with one production line which used equipment obtained from the WAVIN Company in the Netherlands. This equipment had the capability of producing 100, 160 and 200 mm nominal diameter tubing to DIN specified dimensions. Under project support this equipment was enhanced to produce 10 and 12 inch nominal diameter tubing to ASTM specified dimensions.

Because of the overall tubing requirements for the project a second production line was obtained from Corma, Inc. of Canada and installed in the summer of 1985. This production line had the capability to produce the full range of tubing diameters used in the Mardan SCARP subsurface drainage system.

Drain Tubing Materials

It was recognized that most of the corrugated plastic drainage tubing produced and installed in North America is manufactured from polyethylene (PE) rather than polyvinyl chloride (PVC) resin. But due to the lower cost of PVC resin in Pakistan it was selected as the basic ingredient for the tubing manufacture.

Although the factory manufactures the tubing and fittings the raw materials are imported. They have been imported from various countries, but mainly from United Kingdom, France, West Germany and Romania. The materials are shipped in 3 to 5 ply paper bags, and generally transported by ocean vessels to Karachi, Pakistan then transshipped to Nowshera by truck.

The actual production of the PVC tubing requires blending a number of other ingredients with the resin.

The manufacturing process is illustrated on Fig. 1 and briefly described in the following items of this section.

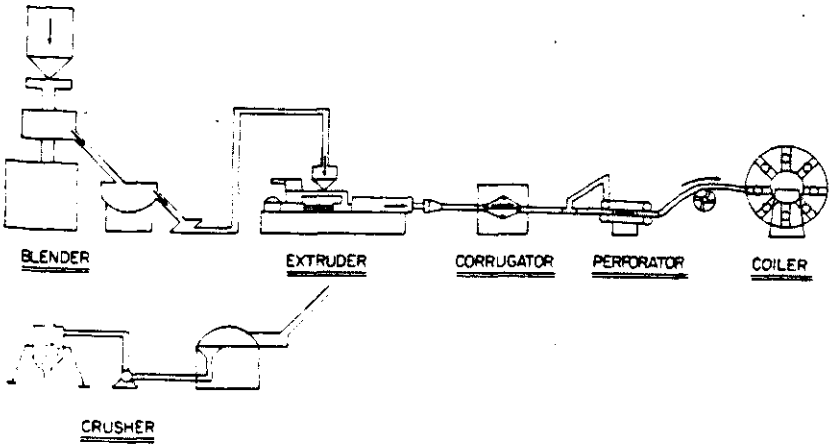

Fig. 1. Arrangement of Nowshera PVC Drain Tubing Production Line.

Blending

The PVC resin is mixed with other additives in a blender where a mixing temperature of 100° to 110°C must be maintained. All ingredients are mixed homogenuously 5 to 6 minutes and then automatically transferred into a cooler where the mixed recipe remains for 4 to 5 minutes under a cooling temperature of 50° to 55°C.

Extrusion

The blended compound is fed in to the barrel of the extruder via a feed screw coupled with a dosage meter. Strip band heaters are distributed around the die heads and the barrel zones in order to maintain the temperature from 170° to 210°C inside the barrel. The blended compound is then plasticized inside the barrel zones and extruded through the die by means of two screw conveyors.

Corrugation

The die fitted at the end of the extruder head delivers the pipe in plain round shape. The plain PVC tubing about 3 cm thick is then inflated by means of a stream of hot air blowing inside the tubing between the extruder and the corrugator.

In order to shape the corrugations on the pipe, a corrugator is attached at the die end of the extruder. The mold blocks of the corrugator are cooled by means of heat exchange with chilled water and cold air. Special care is taken to keep proper alignment between the corrugator and the extruder.

Table 2. List the Ingredients Blended together before the Extrusion Process to Produce the Tubing.

Item no.	Ingredient	Properties
1.	Polyvinyl Chloride	Resin
2.	Omayalite 95-T	Filler
3.	Tribasic Lead Sulphate	Heat stabilizer
4.	Dibasic Lead Sulphate	Heat stabilizer plus lubricant

Table 2. List the Ingredients Blended together before the Extrusion Process to Produce the Tubing. (Cont'd)

Item no.	Ingredient	Properties
5.	Glyceral Mono Stearate	Internal lubricant
6.	Calcium Stearate	Internal lubricant
7.	G-8286	External lubricant
8.	Kane Acc B-288	Impact modifer
9.	Titanium Dioxide	U.V. stabilized
10.	P.V. Yellow	Color

Drain Tubing Production

The tubing manufacturing process is similar for both production lines where the ingredients are blended as required to produce the tubing. The blended materials are then conveyed to the extruder where they are heated and extruded to the correct diameter. The tubing is then molded into the corrugated shape by the corrugator, followed by perforating the tubing, and finally coiled or cut into appropriate lengths for transporting and installing in the field.

The perforators for the two lines use different methods for perforating the tubing. The WAVIN perforator uses punches or needles while the Corma perforator uses rotary knives to perforate the tubing. The produced PVC drainage tubing is either coiled or cut in straight lengths for handling. The lengths of tubing used for Mardan SCARP are given in Table 3.

Table 3. Unit Lengths of PVC Tubing Produced for Mardan SCARP

Nominal diameter	Unit lengths	Status
	(meters)	
100 mm	100	Coiled
160 mm	50	Coiled
200 mm	30	Coiled
10 inch	6	Straight
12 inch	6	Straight

Although the 200 mm diameter tubing was coiled it was found that the coiling induced a memory in the PVC tubing that made uncoiling for field use somewhat difficult. Therefore, the use of 6 meter straight lengths of 200 mm diameter PVC drainage tubing rather than 30 meter length coils is recommended.

As the tubing is produced it is continually inspected and tested by the manufacturer as well as the engineer. The tubing that is rejected may be recycled by crushing it into small granules and blending it with other raw ingredients. A maximum of 5 percent of the recycled material is allowed to be mixed with the other blended ingredients to produce the Mardan SCARP tubing. Successful use of recycled material requires that it not be contaminated with foreign materials or dust.

PVC Factory Production Staff Training

Due to the lack of available personnel with experience in the production of PVC drainage tubing training of the staff was essential. Both training of key individuals outside of Pakistan, and training of staff at the plant was used to develop the required production, inspection and testing capabilities.

Off-site Training: The Production Manager of the Nowshera PVC Factory was sent to Canada, under the sponsorship of the Canadian International Development Agency, to observe the production of plastic tubing and associated quality control procedures at several different production plants in Canada. The trainee was also introduced to the technology used in Canada for producing plastic tubing as well as on-going research in the field of plastics.

Additional off-site training was sponsored by the Nowshera PVC Factory to observe tubing manufacturing, plant maintenance, plant equipment manufacturing, research and development at the facilities of the WAVIN Company in the Netherlands and the Battenfeld Extrusion Company in West Germany.

Local Training: The parent company FCCCL provided three months of initial training to selected Nowshera PVC Factory staff in manufacturing PVC tubing at their subsidiary, Pakistan PVC Ltd. located in Karachi prior to the start up of production at Nowshera. They followed this with one month of training by selected personnel from the Karachi factory in the operation and maintenance of the Nowshera factory staff during the initial stages of production. During this one month period a specialist from WAVIN Overseas Holland also assisted in the start up training program.

Later, with the arrival of new equipment specialists from Corma, Inc., Canada also provided training in the operation and maintenance of their equipment. They also provided intermittent assistance in trouble shooting specific problems that arose during production.

INSPECTION AND TESTING FOR QUALITY CONTROL

An important aspect of the manufacturing and supply of PVC drainage tubing and fittings for Mardan SCARP was the continual inspection and testing required for quality control of the tubing and fittings supplied to the Project. The Nowshera PVC Factory installed a testing laboratory as part of their production facilities. The Engineer, Harza/NESPAK Consultants for Mardan SCARP were charged with the responsibility of acceptance of tubing and fittings to assure they complied with the technical specifications of the Purchase Order between WAPDA and the PVC Factory.

Training

Since the Engineer's available personnel was inexperienced in the inspection and testing of PVC drainage tubing and fittings appropriate training was required. Training programs both off-site and at the Factory were carried out to develop the necessary skills.

Off-site Training: A Senior Engineer, seconded to the Harza/NESPAK Consultants for Mardan SCARP by WAPDA, was sponsored by CIDA for training in quality control at selected locations in Canada. The training was conducted during November and December 1983. The training program consist of; 1) theoretical and laboratory testing training by the Agricultural Engineering Department of McGill University, 2) on-the-job training in carrying out quality control testing by participating in conducting the inspections and tests, and preparing the associated quality control reports for 10 and 12 inch diameter polyethylene produced in Canada for the East Khaipur Drainage

Project in Pakistan; and 3) visiting selected plastic tubing manufacturing plants to observe the production processes and quality control laboratory procedures.

Local Training: A training short-course in quality control inspection and testing was conducted by two CIDA sponsored specialists at the Nowshera PVC Factory in March 1984. The trainees were inspection personnel seconded to Harza/NESPAK by WAPDA and technicians from the Nowshera PVC Factory. The short course included both classroom and laboratory activities. The classroom lectures were supplemented by demonstrations of conducting tests on samples of tubing, after which the trainees carried out the inspections, conducted tests and prepared the test reports under the directions of the short course instructors.

Quality Control Responsibilities

The responsibilities and duties for carrying out the inspections and testing leading to acceptance of the tubing and fittings were set out in the specifications of the Purchase Order between WAPDA and the Nowshera PVC Factory. Both the supplier and the Engineer had specified duties and responsibilities for the quality control program.

Supplier Responsibilities: Contractually, under the Purchase Order, it was the supplier's responsibility to inspect and test the raw materials, maintain and operate the manufacturing equipment and carry out tests to assure the tubing and fittings met the requirements and standards specified in the Purchase Order. The Purchase Order specified that the tubing and fittings would meet the requirements of the U.S. Soil Conservation standards set out in SCS 606 (1980).

The supplier, to carry out the above activities, was responsible for providing the laboratory facilities and the personnel to conduct the required testing of quality. In addition the supplier was required to prepare and submit reports on all laboratory testing to the Engineer.

Engineer Responsibilities: The Engineer was responsible for final acceptance of the tubing and fittings. The Engineers's duties as specified in the Purchase were to "watch and observe the production of the tubing and fittings and to test and examine the material and workmanship employed in connection with the production".

For that purpose, an inspector was stationed at the factory to observe production, observe and verify laboratory tests, select test samples and recommend rejection or acceptance of the tubing and fittings to assure they were in accordance to the minimum requirements of SCS 606.

Standards

As noted above the quality standards applicable to acceptance of the tubing and fittings were promulagated by SCS 606, except that tubing dimensions for the 100, 160 and 200 mm diameter tubing were as specified in DIN 1187 (1971), and the 10 and 12 inch diameter tubing to the dimensions specified in SCS 606. All other requirements were in accordance with SCS 606.

SCS 606 refers to a number ASTM standards applicable to drainage tubing and fitting quality control. Pertinent ASTM standards used as applicable to the inspection and testing for quality control for drainage tubing and fittings supplied to Mardan SCARP are as follows:

1. ASTM D-618 — Methods of Conditioning Plastics and Electrical Insulating Materials;

2.	ASTM D-933	Definition of Terms Relating to Plastics;
3.	ASTM D-1784	Rigid Polyvinyl Compounds;
4.	ASTM D-2122	Methods of Determining Dimensions of Thermoplastic Pipe and Fittings;
5.	ASTM D-2512	Quality of Extruded Polyruny/Chloride Pipe by Acetone Immersion;
6.	ASTM D-2412	Method of Test for External Loading Properties of Plastic Pipe by Parallel-Plate Loading; and
7.	ASTM D-2444	Impact Resistance of Thermoplastic Pipe and Fittings by Means of a Tup (falling weight).

Inspection and Testing

The Nowshera PVC Factory continuously produced tubing and fittings 24 hours a day seven days a week, and each day was divided into three 8 hour shifts. Inspection by the Engineer was provided on a continuous basis to visually observe the tubing and fittings as they were produced to detect manufacturing defects, and to collect random samples for laboratory testing. The Engineer's inspector also observed and verified the laboratory tests as they were carried out.

The laboratory tests carried out on the collected samples were: measurements of dimensions and perforations; stiffness; elongation; joint separation; impact; and bending and straightening. At the time of delivery at the factory the Engineer's inspectors performed a final visual inspection to detect any previously unobserved defects. Any tubing or fittings which did not meet the specification were rejected by the Engineer and remained the property of the supplier.

Frequency of Inspection and Testing: The specifications in the Purchase Order, including SCS 606, did not include the frequency of inspections and testing that would be carried out such as specified by the U.S. Bureau of Reclamation in their Tentative Standard Specifications for PVC Drainage Tubing (1976). Although this could have been corrected by an addendum to the Purchase Order, a mutually agreed frequency of sampling was developed and adhered to by the PVC Factory and the Engineer. The frequency of sampling adhered to is shown in Table 4.

Table 4. Sampling Freuqency of PVC Corrugated Tubing

Test	Samples (no.)	Frequency
Stiffness	6	Once a day at any shift
Impact	10	Once a shift
Bending	3	Once a day at any shift
Straightening	3	Once a shift
Elongation	3	Once a day at any shift
Water Opening	2	Once a day at any shift
Dimensions	6	Once a day at any shift
Acetone	3	Every new batch of materials

EXPERIENCE WITH PVC TUBINC PRODUCTION

The development, management, operation and maintenance of the Nowshera PVC Factory to successfully produce PVC corrugated drainage tubing and fittings resulted in encountering a number problems. Various solutions were developed the overcome these problems. These problems, the solutions used and recommendations for anyone considering such production are presented in the section.

Material Handling and Storage

The materials for producing the drainage tubing and fittings are delivered by truck to the factory in bags which are unloaded manually and stocked in the materials stores in designated areas for each separate material. Initially these stores were directly accessible to the blender and kept open, but to avoid any mishandling or adulteration a boundary wall was constructed between the stores and the blending section. Now, except for the issuance of the raw materials for each days production, the stores are closed and locked.

When handling the raw materials the blender operators must wear goggles and face masks for safety since some of the materials contain lead which can be injurious to humans. During the initial stages of production occasionally foreign materials were present in the blended materials used for the tubing. This caused defects or interrupted production. This problem was essentially eliminated by installing a sieve on the blender bin to separate out such foreign materials.

Ultra Violet Light Stabilization

Some tubing showed rapid degradation under sunlight exposure during the initial stages of production. The cause was identified as an insufficient amount of titanium oxide, known as an ultra violet light stabilizer, in the blended materials being used. This problem was detected at the beginning of production and was corrected by increasing the amount of titanium oxide in the blended mix.

Perforators

Several problems associated with the perforations in the drainage tubing were encountered by the factory. The specifications required that perforations be adequate to provide 21.2 square cm of openings per lineal meter (1 sq. in. per lineal foot) of tubing.

The WAVIN perforator was originally set up to meet the DIN Standards of 10 sq. cm. of opening per lineal meter of tubing. The specified area was achieved by selecting larger punches and modifying the punch holders accordingly.

The specifications also required the perforations to be clearly cut and free of burrs. Continuous production, of course, wears and dulls the punches and knives which, after some sharpening, must be replaced. Due to costs and problems of importing new punches and knives for the perforators the factory attempted to manufacture them locally.

The initial manufacture produced punches and knives that resulted in perforations with extensive burrs, which of course caused the pipe to be rejected. The problem was evaluated as improper selection of materials, and efforts were directed to locating suitable materials of proper hardness and other properties for the punches and knives. Success was achieved and adequate perforator punches and knives have been manufactured locally.

The burrs, caused during the perforation process is a continuing problem. Even slight imperfections and adjustment of the punches and knives, or slight dimensional problems with the tubing leaves a few internal burrs around the perforations. A special ovaloid shape mandrel was obtained and run through the coiled pipe by rotating the coil while it is attached to the coiler. This has removed the internal burrs effectively.

Incomplete perforations also caused rejection of some tubing during the initial stages. This mostly occurred due to in accurate adjustments of the punches and knives which prevented then to accurately place a perforation in the vallies of the tubing. The solution was careful training of the technicians in making the correct adjustments of the perforator punches and knives.

Another noteworthy achievement was the local manufacture of a successful spare perforator head to perforate 100 mm diameter tubing. This was done because of its need to assist in the required production of 3.6 million meters of 100 mm diameter tubing.

Although evolutionary in nature the modifications, local production of replacement punches and knives, application of a burr cleaning mandrel, and training of technicians has resulted in successfully producing perforated PVC tubing to specifications.

Equipment Compatability

The experience of the Nowshera PVC Factory in obtaining and modifying equipment highlights some concern about compatability of equipment components supplied by different manufacturers. The initial production line obtained by the factory was supplied by WAVIN Overseas Holland. This equipment was supplied with dies and molds for the production of 100, 160 and 200 mm diameter drainage tubing. The required tubing for the project included 10 and 12 inch, or equivalent diameter tubing.

Under CIDA sponsorship the management of Corma, Inc., Canada evaluated the equipment and proposed to furnish Corma dies and accessories for the WAVIN Extruder and a corrugator, mold blocks and a perforator to adapt the WAVIN extruder for production of 10 and 12 inch ASTM specified dimension tubing.

This auxiliary equipment was furnished, but problems were encountered in actual production. The first set of dies furnished were so called "offset dies", which were found to incompatible with the extruder. These were returned and one month later straight dies were furnished and successfully mounted on the WAVIN extruder.

Initial use of this equipment to produce 10 and 12 inch tubing resulted in a very short run time when after a few hours the plastic burnt and adhered to the extruder equipment and dies. With assistance from Corma specialist various adjustments and modifications were made extending the run periods from 4 to 6 hours to 20 to 30 hours before shut down was required.

Not only was short run periods a problem from this application, but each time 10 and 12 inch diameter tubing was to be produced, the WAVIN corrugator was shifted to the side and the Corma corrugator placed in line with the extruder then moved out when the production was adequate. With the available capabilities of staff and methods for making the corrugator switches, the moves of this heavy 10 to 15 ton equipment was not only time consuming and tedious, but hazardous to personnel.

It was recognized when signing the Purchase Order that one additional production line would be required to produce the scheduled Mardan SCARP requirement of drainage tubing. WAPDA assisted the factory to obtain the equipment by utilizing IDA loan funds through international competitive tendering to obtain equipment for a second production line.

The winning tenderer was Corma, Inc. of Canada. This equipment arrived and was erected and commissioned in June 1985, and was capable of producing 100, 160 and 200 mm, and 10 and 12 diameter tubing. To handle reject tubing a second crusher was locally developed and assembled at the plant.

The final arrangement of equipment is fully in production and has successfully produced the major amount of the drainage tubing and fittings required for the project.

Corrugations

Frequently tubing has been produced with incomplete corrugations and, although the frequency has not escalated the problem has not been completely solved, therefore, incomplete corrugations still randomly show up at times.

Laboratory Testing

Basic laboratory test equipment was purchased and imported by the Nowshera PVC Factory. The air conditioning and cold chambers have been provided from locally available parts and materials.

Conditioning: A laboratory room temperature of 22° C has continued to be maintained throughout the production with only minimal deviations. But in the smaller refrigerated cold chamber it has been found difficult to maintain a temperature of plus or minus 1° C at all times.

Initially it was recognized that the above cold chamber had inadequate size to condition 10 and 12 inch diameter samples for the bending and straightening tests. Therefore, the Nowshera PVC Factory obtained and installed a large volume chilled brine tank. This tank can accommodate up to a 12 inch diameter bending and straightening mandrel along with test specimens.

Elongation and Separation Tests: The laboratory equipment available adequately performs the elongation and separation tests on all the tubing and fittings, except for the tees. To date the laboratory does not have appropriate equipment to perform separation tests on tees.

Bending and Straightening Tests: For carrying out the bending and straightening test the SCS 606 standards specify the use of a cylindrical mandrel 3 times the nominal diameter of the tubing. The mandrels for the 100, 160 and 200 mm are easily operated but those for the 10 and 12 inch diameter PVC drainage tubing are difficult to manage.

COMMENTS AND RECOMMENDATIONS

The modern technology of using perfarated corrugated plastic tubing for subsurface drainage tubing is largely appreciated and accepted by the people of Pakistan. The Government of Pakistan places a high priority on Salinity Control and Reclamation Projects. PVC corrugated drainage tubing has proved to be an ideal for subsurface drainage on these projects. The following comments and recommendations are not only specific to Pakistan but should also be given serious considerations in other developing countries.

Storage and Carriage

A total storage area of 75,000 square feet was recommended by the Engineer. This was to provide a three months supply for storage based on the projected use by the project's contractors. The supply of pipe and fittings was then determined from the anticipated demand for installation under two separate construction contracts. Murphy's law then prevailed; what could not go wrong did go wrong. The award of contract and consequently the construction work in the contract went far behind schedule and the corrugated tubing required considerably greater storage.

To avoid such problems, it is recommended to make the Contractor responsible for the supply of all materials including the drainage tubing and fittings for the work under a subsurface drainage contract. The Contractor should also be responsible for the carriage of all materials. The Engineer should still be responsible for the quality control. In order to promote local plastics industries, it might be wise in such contracts to prevent the Contractor from importing the tubing.

Selection of Equipment

A simple recommendation but of gold value: DO NOT COUNT ON INTERCHANGING EQUIPMENT FROM DIFFERENT COMPANIES especially in developing countries. Problems of incompatibility between percentage of scrap and time loss. It is often necessary to spend considerable effort and money in designing the manufacturing process to maintain a very low waste level.

During Blending Operations Beware of Contamination

In opening bags by tearing the top, care should be taken not to drop paper shreds into the product. A sieve fixed to the bin reduces considerably potential problems of contamination from this potential source.

Maintenance and Lubrication Plans are Essential

Spare parts are very difficult to obtain in developing countries. A good maintenance program is essential and saves a lot of troubles. The Annual Preventive Maintenance and Lubrication Plans adopted by the Nowshera PVC Factory are shown in Appendix I and II.

Standards for Quality Control

Until now, SCS-606 standards have been applied for the testing of the materials as well as for the inspection, testing and acceptance of the tubing. These standards have been found to not be completely applicable to Pakistani Conditions. For instance, the high temperature impact resistance should be tested as per the Australian Standards (AS 2439, Part 1-1981). Methods for testing the stretch resistance for fittings should also be specific to local conditions.

In order to make the best use of time available resources, it is normal and advisable to adopt standards from other countries with similar economic conditions and climate, but the United Nations Industrial Development Organization leaves no doubt as to what should be done next.

"Every country that plans industrialization and rapid economic growth through the introduction of standarization and quality control must consider establishing a central national standard body".

Among all functions of such a national standard body are the following:

- Prepare and promote the general adoption of standards at the national level in cooperation with other interested organizations working to improve industry, agriculture, domestic and foreign trade in a country.

- Undertake tests for industry and issue certificates of compliances with standards.

- Implement national standards through the administration of a national certification mark scheme or the inspection of goods.

"It is not an exageration to say that the establishment and promotion of a plastics industry should be the most important consideration in planning industrialization in developing countries".

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4. World Bank. 1979. Staff Appraisal Report Pakistan Salinity Control and Reclamation Project (SCARP) Mardan.

APPENDIX I

UNIT: NOWSHERA PVC — ANNUAL PREVENTIVE MAINTENANCE PLAN — YEAR: 1986

S. NO:	EQUIPMENT	DESCRIPTION OF WORK
1.	BLENDER	1.1 Check Power tightness of Seals on bowel cover and chute covers, replace if damaged. 1.2 Check tightness of all bolts and fittings. 1.3 Check all electric connections. 1.4 Check calibration of thermocouple. 1.5 Check and replace if necessary filter socks on cooler cover. 1.6 Check correct operation of (i) Proximity switches. (ii) Pneumatic valves. 1.7 Clean whole equipment from dirt and dust.
2.	EXTRUDER	2.1 Clean oil filters and replace if necessary. 2.2 Adjust Extrusion Head relative to barrel support. If necessary. Check Extrusion both for Head/Barrel. 2.3 Clean grills of fans & Electric Motor assuring unobstructed flow of Air for cooling. 2.4 Maintain Die parts lying unassembled at workshop. 2.5 Clean filter vacuum pump. 2.6 Check all Electric Connections/Pyrometer/Heaters/Gauges/Valves/Nuts & Bolts, etc. Clean whole equipment.
3.	CORRUGATOR	3.1 Cooling fans of Drive Motor should be kept free from dirt/dust. 3.2 Measure the wear of bronze guide faces of Corrugator chain. 3.3 Check all Bushes/Links/Locks/Washers W.R.T. Wear/Tear. Clean whole Equipment. 3.4 Special attention should be given to the profile of Chains. 3.5 Clean filters, replace if necessary. 3.6 Carry out maintenance of mold blocks lying at workshop.
	PERFORATOR	4.1 Check tension & Wear/Tear. Clean whole Equipment. 4.2 Check Punches/Knives W.R.T. Wear/Tear. 4.3 Check all gears W.R.T. Wear/Tear. Clean whole Equipment from Dirt & Dust.
5.	COILER	5.1 Clean all Levers & Grease them properly. 5.2 Check all Chains/Levers/Bearings/Clutches W.R.T. Wear & Tear. Clean whole Equipment thoroughly.
6.	CRUSHER	6.1 Check all Nuts/Bolts & tighten if necessary. 6.2 Special attention is to be paid to Knives Edges clearance of 0.5-0.3 mm is to be maintained between relating & fixed knives. 6.3 Tighten all screws of Knives at 30 K.P.M. 6.4 Check Edges of Knives & required them if necessary. Clean whole Equipment thoroughly.

APPENDIX I (Cont'd)

UNIT: NOWSHERA PVC ANNUAL PREVENTIVE MAINTENANCE PLAN YEAR: 1986

S. NO:	EQUIPMENT	DESCRIPTION OF WORK
7.	REFRIGERATION	7.1 Check alignment/Proper functioning of all five Centrifugal Pumps.
		7.2 Check & carry out lagging of all brine/NH3/ Chilled Water Lines.
		7.3 Check Tension of V. Belts & tightness of Multi/ Bolts/Fittings of NH3 Compressor.
		7.4 Check & rectify leakage of NH3. Clean whole Equipment thoroughly.

APPENDIX II

UNIT: NOWSHERA PVC LUBRICATION PLAN

S. NO:	EQUIPMENT	TYPE OF LUBRICANT	CYCLE	METHOD OF LUBRICATION
1.	BLENDER	Axshell - 17	M1	Grease Gun
		-do-	M2	Grease Gun
		Alvania R.A.	Y1	Grease Gun
		Axoshell - 17	M1	Grease Gun
		Macoma R - 220	M1	Manual
2.	EXTRUDER	-do-	M2	Manual
		-do-	M2	Manual
		Alvania - 2	M2	Grease Gun
		Alvania EP - 2	Q1	Grease Gun
		Voluta Oil A	M2	Manual
3.	CORRUGATOR	Macoma R - 220	M3	Manual
		Alvania EP - 2	W1	Grease Gun
		Alvania - 2	W1	Grease Gun
4.	PERFORATOR	-do-	W2	Grease Gun
		-do-	Q2	Grease Gun
		-do-	Q2	Grease Gun
		Macoma R - 220	M3	Manual
		Macoma R - 220	m3	Manual
		Alnania EP - 2	Q3	Grease Gun
5.	COILER	Alnania - 3	Q3	Grease Gun
6.	CRUSHER			
7.	REFRIGERATION	Vitrea 69	M4	Manual
		Alnania - 3	Q4	Grease Gun