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Land Use Planning in Denmark:

The Use of Soil Physical Data in Irrigation Planning

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The present paper deals with a model developed and used at the Danish Ministry of Agriculture, Bureau of Land Data, for calculation of the amount of water needed for irrigation. The model incorporates information on soil types and their geographical distribution, soil water retention and root development in relation to soil types, and climatic conditions such as water deficits.

Introduction

In Denmark the yield of different crops has increased significantly during the last century due to better fertilization and drainage. As a consequence water deficit during the growth season is today one of the most limiting factors for plant production, especially on sandy soils.

Consequently, an increasing part of the agricultural land has been irrigated during the last decades, normally with groundwater. Because of the increasing demand for groundwater for irrigation, industry and private use, the groundwater level may fall in some part of the country. This might give raise to environmental problems as decreasing discharge in the rivers and a decrease in the area of wetlands. Therefore it has been necessary to establish a water planning system for Denmark taking into account the demand of water for irrigation.

Table 1 – The definition of the Danish soil types.

Map Colour Code	SOIL TYPE	JB-nr.	Percentage by weight: Clay < 2 µm	Silt 2-20 µm	Fine Sand 20-200 µm	Total Sand 20-2000 µm	Humus 58,7 % C
1	Coarse Sand	1	0-5	0-20	0-50	75-100	≦10
2	Fine Sand	2			50-100		
3	Clayey Sand	3	5-10	0-25	0-40	65-95	
		4			40-95		
4	Sandy Clay	5	10-15	0-30	0-40	55-90	
		6			40-90		
5	Clay	7	15-25	0-35		40-85	
6	Heavy Clay or Silt	8	25-45	0-45		10-75	
		9	45-100	0-50		0-55	
		10	0-50	20-100		0-80	
7	Organic Soils	11					> 10
8	Atypic Soils	12					

Soil Maps

At the Ministry of Agriculture, Bureau of Land Data, a nation-wide soil classification of Denmark was initiated in 1975. In 1980 approximate 400 soil maps (scale 1:50,000) were available covering the entire Danish area.

The soil maps are based on texture analyses of samples from approximately 35,000 sites and the geological origin of the soil in 1 metre depth, where this information is available. Samples were taken at all sites from a depth of 0-20 cm and at selected sites also from a depth of 35-55 cm. Texture, organic matter and calcium carbonate were measured in all samples, and the results were stored in a computer system (Mathiesen 1980).

The agricultural land was divided into 8 soil types according to the texture in 0-20 cm depth, Table 1. These soil types correspond to the mapping units, named map colour code 1-8. In the soil maps the agricultural land is divided into these 8 soil types, while the remaining areas are divided into urban areas and forest areas. Table 1 shows that the above mentioned 8 soil types are further subdivided into 12 soil classes, JB 1-12.

All soil maps have been digitized in order to provide facilities for the production of computer drawn soil maps in different scales and with different combinations of parameters (Platou 1983 a,b). This has further more facilitated e.g. statistical treatment of the data and calculation of the area distribution of regions such as counties, catchment areas, etc.

Soil Water Retention

For a calculation of the demand for irrigation by means of the soil maps it is necessary to establish a relationship between soil texture and soil water retention. For that purpose detailed soil profile investigations were carried out in Northern Jutland in November 1981. During this time of the year the soil water content will be at field capacity.

The profiles were located in the landscape with the intention of getting represented soils developed in sediments of different geological origin. From each profile undisturbed samples were taken in 4 to 5 horizons for a determination of the soil water retention. Samples were also taken for texture analysis.

The water content at pF1.0, pF1.5, pF2.0, pF2.5, pF3.0 and pF4.2 were measured in the laboratory by the pressure-membrane-apparatus method, and the porosity and bulk density were calculated. The texture was determined by the hydrometer method, and the organic matter was measured in a Leco-IR-apparatus (Mathiesen and Nørr 1976).

The available water content for plant production (AWC) is defined as the water content between field capacity (FC) and the permanent wilting point (PWP). It is generally accepted that the water content at PWP is equal to the water content at pF4.2 (Wiklert 1964), whereas the water content at several pF-values such as 1.7, 2.0, and 2.3 have been suggested equivalent to the water content at FC (Reeve et al. 1973, Salter and Williams 1965, River and Shipp 1977, Madsen 1979). The soil water retention data from the investigation in Northern Jutland shows a close correlation between the water content at pF2.0 and FC, except for horizons with very low water content at FC, Fig. 1. These horizons are coarse sandy subsoils in which root development are impeded. It is therefore reasonable to use the water content at pF2.0 as a measure of FC. Thus AWC is defined as the water content between pF2.0 and pF4.2.

On the basis of the samples from the investigated profiles in Northern Jutland, regression analyses have been worked out combining the water content at pF2.0 and pF4.2 with texture and organic matter. The following classes have been used in the regression analyses: clay 0-2μ, silt 2-20μ, fine sand 20-200μ, coarse sand 200-2000μ and organic matter. The variation in texture was 0-70% clay, 1-50% silt and 0-7% organic matter.

$$\text{pF 2.0 (vol\%)} = 2.888 \times \%\text{organic matter} + 0.490 \times \%\text{clay} + 0.455 \times \%\text{silt} + 0.164 \times \%\text{fine sand} + 2.376 \qquad r = 0.894, \quad s = 4.32 \tag{1}$$

$$\text{pF 4.2 (vol\%)} = 0.758 \times \%\text{organic matter} + 0.520 \times \%\text{clay} + 0.075 \times \%\text{silt} + 0.42 \qquad r = 0.970, \quad s = 1.63 \tag{2}$$

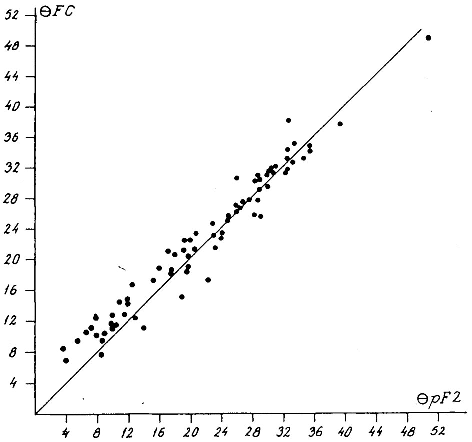

Fig. 1.
Relationship between water content at pF2.0 and field capacity determined as the water content at sampling time in November 1981. Only results from well drained soils have been used.

By means of Eqs. (1) and (2) and the mean textural composition of the soil types in a given region such as a county, it is possible within the region to calculate the mean AWC (vol %) in the topsoil (0-20 cm depth) and in the subsoil (35-55 cm depth) for the different soil types. The mean textural composition of map colour code (MCC) 1-5 for the entire country are listed in Table 2 together with the water content at pF2.0, pF4.2 and AWC as calculated for the topsoil and the subsoil.

Table 2 shows that the water content at pF2.0 and pF4.2 increases with increasing MCC number. AWC on the contrary is almost constant for MCC2 to MCC5, and only MCC1 has notable lower values in AWC. The slight decrease in AWC from MCC2 to MCC3 is due to the fact that MCC3 is a mixture of fine sandy and

Table 2 – Mean textural composition and water content for soil types represented by map colour code 1-5 as average for the entire Danish area. o = topsoil, u = subsoil

map colour code (MCC)	clay 0-2 μ	silt 2-20 μ	Texture f.sand 20-200 μ	c.sand 200-2000 μ	org matter	Water content vol% pF2.0	pF4.2	AWC	number of observ
1	o 3.4	4.5	30.3	58.3	3.5	21.1	5.2	15.9	8224
	u 3.1	3.3	28.6	63.2	1.8	15.3	3.6	11.7	1287
2	o 3.4	6.1	59.1	28.0	3.4	26.3	5.2	21.1	3301
	u 3.4	4.6	61.4	29.0	1.7	21.1	3.8	17.3	504
3	o 7.1	9.7	43.5	36.3	3.4	27.2	7.4	19.8	11327
	u 7.0	8.4	45.2	37.4	1.9	22.5	6.1	16.4	1517
4	o 11.9	14.0	43.9	27.4	2.8	29.8	9.8	20.0	9237
	u 12.2	12.6	45.6	28.6	1.6	26.1	8.9	17.2	916
5	o 17.1	16.9	40.8	22.0	3.1	34.1	12.9	21.2	3286
	u 18.4	15.0	42.4	22.8	1.4	29.2	12.2	17.0	802

coarse sandy soils with 5 to 10% clay, while MCC2 is only fine sandy soils with 0 to 5% clay. A mixture of fine sandy and coarse sandy soils with less than 5% clay (MCC1 and MCC2) will have a much lower AWC than MCC3.

Root Zone Capacity and Effective Root Depth

The root zone capacity (RZC) is defined as the amount of water in the soil profile, which can be utilized by the plants before wilting due to lack of water supply. At this point the soil water tension will be about pF4.2 in the upper part of the soil profile, because of a high root density there.

This means that AWC in this part of the profile is completely utilized by the vegetation. In deeper sections of the profile the root density is lower and only parts of AWC have been utilized by the vegetation, when wilting occurs.

By means of the simulation model »Heimdal« (Hansen 1975, Hansen et al. 1976) the following relationship has been established between root density and soil water retention at the point of wilting (Madsen 1979).

1.0 cm root/cm^3 soil	pF4.2
0.1-1.0 cm root/cm^3 soil	pF3.0-pF4.2
0.1 cm root/cm^3 soil	pF2.0-pF3.0

In order to investigate the relationship between root development and soil water rentention in different soil types, more than 100 profiles have recently been studied (Madsen 1979, 1980, 1983). From every soil profile approximately 10 samples were taken for root investigation. The root length was measured on a grid and the root density was determined as cm root/cm^3 soil.

For the estimation of RZC it has been necessary to define the effective root depth (ERD). ERD is defined as the depth of the soil in which AWC is equal to the amount of soil water utilized by the plants until wilting occurs due to lack of water. ERD corresponds roughly to the thickness of soil layers which have root densities greater than 0.1 cm root/cm^3 soil, Fig. 2.

In Fig. 2 the amount of transpirated water is calculated by the simulation model "Heimdal". In this simulation climatic data from a typical drought period in May and June in Denmark was used, and the vegetation was barley. The soil water retention curves from all distinct soil horizons in the profile and the maximum root density for every 10 cm down through the profile were furthermore used as basic inputs in the model. The plants were considered dead when the leaf-water-potential did not exceed -20 bar during the night.

It is obvious that the thickness of soil layers with more than 0.1 cm root/cm^3 soil is only a rough estimate of ERD, and in soils where atypic root profiles are developed, great differences between true and calculated RZC may arise.

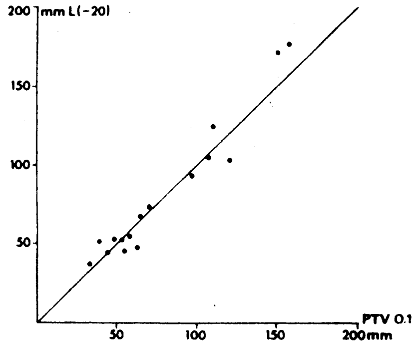

Fig. 2.
Relationship between the summed-up available water content in the soil layers with more than 0.1 cm root/cm^3 soil (PTV 0.1) and the summed-up transpirated water until leaf water potential at night does not exceed -20 bar, L(-20), determined by simulation.

Based on the above mentioned investigations of root development and the root investigations of Wiklert (1962), Vetter and Sharafat (1964) and Böhm (1978) the ERD-values listed in Table 3 are used for map colour code 1 to 5.

In MCC1 the effective root depth (ERD) is shallow and equal for all crops. This is due to the root impeding sandy subsoil poor in clay and silt. In MCC2 and MCC3, ERD is a little deeper for cereals than for grass, and ERD is normally a little shallower in MCC2 than in MCC3. There are great differences in ERD within the same crop because of great differences in the content of clay, silt and fine sand in the subsoils. Some MCC2 soils do not have a deeper ERD than MCC1, especially those soils having subsoils poor in clay and silt. Within MCC3 big differences in ERD are found between soils of coarse clayey sand (JB3) and soils of fine clayey sand (JB4). The first mentioned type is often developed in diluvial sand having subsoils poor in clay and silt whereas the latter is often developed in clayey tills with clay-rich subsoils. Thus ERD is normally shallower in JB3 than in JB4. In MCC4 and MCC5 root development is very deep, especially for winter-sown crops, barley, etc. Also in these soil types great differences are found, due to acid subsoils, compacted soil layers and poor internal drainage.

RZC is calculated for the different map colour codes in relation to crops by using the mean textural composition of the soil types, Eqs. (1) and (2) and ERD

Table 3 – The effective root depth (cm) in Denmark for different map colour codes and selected crops.

Map colour code	grass	spring-sown cereals	winter-sown cereals	beets
MCC1	45	45	45	45
MCC2	55	65	75	65
MCC3	60	75	85	75
MCC4	60	90	110	90
MCC5	60	90	110	90

Table 4 – The average root zone capacity RZC (in mm) for various crops related to map colour code 1-5.

Map colour code	grass	spring-sown cereals	winter-sown cereals	beets
MCC1	63	63	63	63
MCC2	105	122	139	122
MCC3	107	132	148	132
MCC4	110	162	196	162
MCC5	113	164	198	164

listed in Table 3. In the calculation of RZC the mean textural composition of the topsoil represents the uppermost 25 cm of the profile, whereas the mean textural composition of the subsoil represents the deeper part of the profile between 25 cm depth and ERD. In Table 4 the average RZC for map colour code 1-5 is listed for the entire country.

Table 4 shows that MCC1 has a significantly lower RZC than the other soil types, and RZC is equal for all crops. MCC2 and MCC3 have nearly equal RZC, and it is highest for winter-sown crops and lowest for grass. MCC2 and MCC3 are considered as medium soils according to RZC. MCC4 and MCC5 are the best soil types according to RZC. Also in these soil types RZC is highest for winter-sown cereals and lowest for grass.

Calculation of the Amount of Water Needed for Irrigation

For grass, barley and beets the relationship between root zone capacity and the average potential need of water for irrigation (APW) is listed for different parts of Denmark (Table 5). The APW is defined as the amount of irrigation water needed to keep a plant production not limited by lack in the water supply throughout the growth season in years with mean climatic conditions. Thus in dry years APW will not be sufficient to keep optimal plant production throughout the growth season.

The APW is reached by modeling (Gregersen and Knudsen 1980, 1981) using a modified form of the model described by Johansson (1974). The calculations of APW in relation to RZC are based on the daily precipitation and the weekly measured evaporation in Denmark during the period 1957-78.

Table 5 shows that at equal RZC great differences in APW occur between different parts of the country. The greatest demand for irrigation at equal RZC is found in the western part of Zealand due to low precipitation during the growth season, whereas little demand for irrigation is found in some parts of Jutland. In spite of this the greatest demand of irrigation is found in Western Jutland where sandy soils are dominating.

Table 5 – Relationship between root zone capacity, (RZC) and the average potential need of water for irrigation (APW) in the growth season.

County	Grass Root zone capacity, mm 60	80	100	120	140	160
Nordjylland	161	144	132	90	87	82
Viborg	176	158	154	111	102	97
Århus	182	168	153	113	104	100
Vejle	134	121	112	73	78	69
Ringkøbing	181	165	154	107	105	89
Ribe	156	135	127	76	69	63
Sønderjylland	152	138	122	93	74	71
Fyn	155	141	131	91	81	75
Vestsjælland	205	197	188	133	130	117
Østsjælland	171	154	149	106	96	93
Lolland-Falster	152	137	128	89	79	81
Bornholm	171	160	155	102	101	100
Mean	166	152	142	99	92	86

County	Barley, etc. Root zone capacity, mm 60	80	100	120	140	160
Nordjylland	86	72	68	46	36	29
Viborg	77	71	62	40	46	36
Århus	85	79	72	49	36	35
Vejle	62	60	48	29	28	19
Ringkøbing	85	79	72	49	36	35
Ribe	73	67	56	36	23	23
Sønderjylland	77	67	62	35	28	24
Fyn	73	66	55	32	36	26
Vestsjælland	94	87	83	50	49	49
Østsjælland	75	70	64	45	36	29
Lolland-Falster	69	59	53	31	28	18
Bornholm	84	80	65	45	39	36
Mean	78	71	63	41	35	30

County	Beets Root zone capacity, mm 60	80	100	120	140	160
Nordjylland	93	78	73	50	39	31
Viborg	83	77	67	43	50	39
Århus	92	85	78	53	39	38
Vejle	67	65	52	31	30	21
Ringkøbing	92	85	78	53	39	38
Ribe	79	72	60	39	25	25
Sønderjylland	83	72	67	38	30	26
Fyn	79	71	59	35	39	28
Vestsjælland	102	94	90	54	53	53
Østsjælland	81	76	69	49	39	31
Lolland-Falster	75	64	57	33	30	19
Bornholm	91	86	70	49	42	39
Mean	84	77	68	44	38	32

Table 6 - The average potential need of water for irrigation APW (in mm) for map colour code 1 to 5.

Map colour code	grass	spring-sown cereals	winter-sown cereals	beets
MCC1	164	77	77	83
MCC2	131	39	35	43
MCC3	127	37	33	40
MCC4	120	30	–	31
MCC5	114	29	–	31

The average APW in the different soil types for the entire Danish area (Table 6), can be calculated by combining Tables 4 and 5.

Table 6 shows that MCC1 has a significantly higher demand of irrigation than the other soil types. Among the other soil types the greatest differences are found in grass but only small differences occur.

By means of the digitized soil maps it is possible to combine the values in Table 6 with given areas and e.g. calculate the total demand of water (in m^3) for irrigation within a region.

Summary

On the basis of digitized soil maps based on 35,000 texture analyses in combination with information on soil-water retention, root development and climatic conditions a model for the calculation of the demand for irrigation within different regions in Denmark has been established. The available water content in soil layers, the root zone capacity and the effective root depth are defined and used as basic parameters in the model.

The calculations show that APW is very high for grass in all soil types and especially in the coarse sandy soils. For winter-sown cereals, spring-sown cereals and for beets the APW is very low except in the coarse sandy soils. This is especially due to a shallow effective root depth for crops in the coarse sandy soils.

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