Methods of Predicting Salinization and Alkalinization Processes due to Irrigation on the Hungarian Plain

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One of the most significant human soil forming factors is irrigation. Irrigation is a question of vital importance in many countries in the arid and semiarid regions of the world. It is significant also in the more humid regions for; the procurement of high yields, the production of water loving crops, the effective use of high rates of fertilizers, etc. [15]. That the effect of irrigation is, however, not always favourable has been proved by a thousand year's irrigation experience and newer scientific information [1, 15, 32].

Well planned and executed irrigation supplies the plants with an adequate amount of water, favourably changes the soil forming processes, and increases the potential fertility of the soil. Poor irrigation practices not only directly damage the plants (poor aeration) and limit their metabolism and nutrient uptake (unfavourable nutrient mobilization), but also destroy the soil structure. Deterioration of the physical and water properties of the soil results in the initiation, extension and/or deepening of the harmful soil processes (peat formation [32], salinization, alkalinization, solodization [30, 31, 32, 35] etc.) which markedly decrease soil fertility. Among these processes salinization and alkalinization are the most extensive and harmful [1, 2, 3, 4, 9, 21, 25, 32, 34].

Most irrigation works are in the arid and semiarid regions of the world. The very high potential evaporation and transpiration here favour salt accumulation processes [15, 25]. The concentration of the mixed salt solutions results in the accumulation of the relatively most soluble Na-salts in the liquid phase and consequently in the soild phase, partly on the soil adsorption complex [22]. Therefore, in these regions there exists the potential danger of salinization and alkalinization.

Secondary salinization and alkalinization processes may take place mainly in the following situations:

1. Accumulation of salts from poor quality irrigation water [11, 15, 25, 46].

2. Increase in the level of ground water and:

a) the ground water's salt content accumulates in the affected layers;

b) the rising ground water transports the salts from deeper soil layers to the surface or surface layers, or

c) the rising water table limits natural drainage and hinders the leaching of salts.

The seriousness of the threat to agriculture posed by these situations is determined by the following factors:

1. Climatic factors such as: temperature, rainfall, humidity, vapour pressure, evaporation and their fluctuations and dynamics;

2. Geological, geomorphological, geochemical, hydrological, hydrogeological and hydrochemical factors such as: natural drainage, depth and fluctuation of the water table, the direction and velocity of horizontal ground water flow, salt content and composition of the ground water, etc.

3. Soil factors such as: soil profile, texture, structure, saturated and unsaturated water conductivity, soluble salt content, salt composition and salt profiles, exchangeable cations, pH, etc.

4. Agrotechnics such as: land use, crops, cultivation methods, etc.

5. Irrigation practices such as: the amount of irrigation water, method, frequency and intensity of irrigation; salt content and composition of the irrigation water; natural and artificial drainage, etc.

In arid lands with deep ground water tables the salt added with the irrigation water (often brackish or salty) often causes salt accumulation as in North Africa and some parts of Central Asia [11, 19, 25]. In lowland basins, depressions or delta areas with no outlet or with very unfavourable natural drainage the high and rising water table and stagnant, salty ground waters cause salinization and alkalinization even under such relatively humid climatic conditions as found in the Carpathian Basin [1, 2, 3, 4, 9, 14, 17, 21, 25, 28, 32, 47, 48].

Leaching salts, accumulated by irrigation, is a relatively simple problem in the case of neutral Na-salts ($NaCl$, Na_2SO_4) in light textured soils. Heavy leaching can be used, but it is rather expensive because of the high water consumption and the need for appropriate horizontal and vertical drainage, etc. and it is not always effective [10, 15, 25, 51]. Soda salinization of heavy irrigated soils is even more dangerous as it results in the following soil processes: saturation with Na^+ and deterioration of the soil structure, permeability and other water properties. After salinization of heavy soils, soil improvement is not possible or more exactly it is possible only by very expensive complex melioration methods [1, 2, 3, 4, 32]. Therefore, the most important and most economic solution to the problem of secondary salinization and alkalinization is prevention. In the planning of extensive irrigation all kinds of technical and agrotechnical conditions must be provided to avoid (at least to a certain degree) these harmful processes of salinization and alkalinization.

The tasks of soil science are to determine these conditions (e.g. critical depth of water table, quality of irrigation water, etc.), to determine the preconditions and possibilities of irrigation and to predict possible secondary salinization and alkalinization processes that might result from irrigation.

To develop a reliable method of predicting salinization and alkalinization the following problems must be solved:

1. The main sources of water soluble salts (irrigation water, ground water, surface waters, salty deep soil layers, etc.) must be identified [1, 12, 14, 16, 18, 19, 28, 32, 33, 47, 48].

2. The main features of the salt regime must be characterized (salt balances); and the whole range of natural factors influencing the salt regime must be analysed [5, 6, 7, 8, 17, 19, 20, 25, 26, 28, 34, 36, 37, 38, 45, 51].

3. The effect of irrigation on the water and salt regime of the soil must be determined [5, 6, 8, 11, 15, 26, 36, 37, 46, 50, 51].

Consequently an exact salinity prognosis must be based on an evaluation of many natural and human factors and a knowledge of the existing soil processes.

The potential danger of salinization and alkalinization on the Hungarian Plain

The Hungarian Plain is the lower part of the geologically, geomorphologically, hydrologically and hydrogeologically closed Carpathian Basin (Central Europe). The climate of the Hungarian Plain is semi-humid. The annual potential evaporation exceeds the annual precipitation. During the summer months there is a considerable water deficit [49] as shown by the following data (50 years average):

Main climatic features of the Hungarian Plain

	Jan.	Feb.	March	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Temperature C°	−1,8	0,1	5,8	11,1	16,7	20,0	22,2	21,3	16,9	11,2	4,9	0,4	10,7
Precipitation mm	27	29	31	43	58	60	52	49	40	47	50	32	524
Potential evaporation mm	7	14	24	54	95	116	133	109	71	37	14	7	680

Under such climatic conditions the main reasons for the occurring of extensive salt affected areas and the potential danger of salinization and alkalinization of the Hungarian Plain (Fig. 1) are the geological and hydrological conditions:

1. Closed character of the basin [32, 33, 47, 48].

2. Thick, salty Tertiary and Quaternary layers in the geological profile [32, 33].

3. Stagnant, salty ground waters with a high (or easily and rapidly rising) water table with very slow horizontal flow because of the negligible slope [23, 24].

The situation is aggravated by the predominance of sodium carbonate and bicarbonate and the thick basin deposits of heavy (fine-texture) clays, clay-loams and loess-like clays that contain mostly illite and montmorillonite type clay minerals.

Many authors have shown that, in the Hungarian Plain, the main sources of Na-salts are the subsurface waters [1, 23, 27, 29, 32, 33, 44, 47, 48]. Consequently, the main effect of irrigation on the salt regime appears to be through its influences on the ground water regime. Under irrigation, the control of the depth of the water table (or rather the control of the various factors influencing it) is of critical importance.

The ground waters near the surface are not only direct salt sources, but they limit downward water movement, and thus leaching. In such cases, after many years' irrigation salt accumulation may occur even if the irrigation water is of good quality and would not cause salt accumulation in well drained land.

In Hungary — because of water quality laws — surface salinization and alkalinization due to poor quality irrigation water is rather rare. Some exceptions occur with irrigation from deep wells in the region between the rivers Danube and Tisza, and because of changes in the salt content and composition of irrigation water in uncovered reservoirs and temporary irrigation canals [1, 32, 46].

Unfortunately salinization and alkalinization due to irrigation has

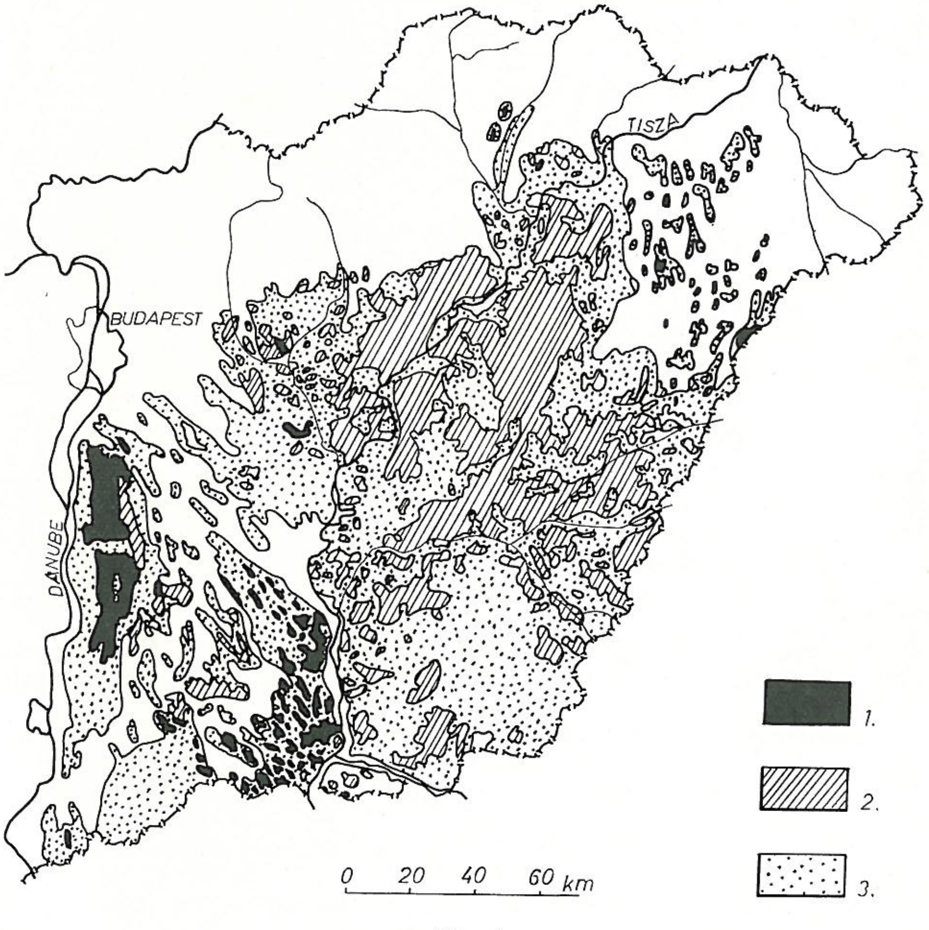

Fig. 1

Salt affected soils in the Hungarian Plain. 1. Alkali soils without structural B-horizon; 2. Alkali soils with structural B-horizon; 3. Potential salt affected soils occurred in some parts of the Hungarian Plain. After World War II, and especially after the start of the Tisza—I (Tiszalök) Irrigation Project (1953), irrigation was started on large territories of the Transtisza (Eastern) part of the Hungarian Plain. Although, at that time the harmful soil processes that could occur due to irrigation were known (at least generally) from Hungarian and foreign data and experiences, proper attention was not paid to them in the territorial installation and technical planning of the project and in irrigation practices. Consequently, on the territory of the Tisza—I Irrigation Project about 120 000 hectares were affected by undesirable soil

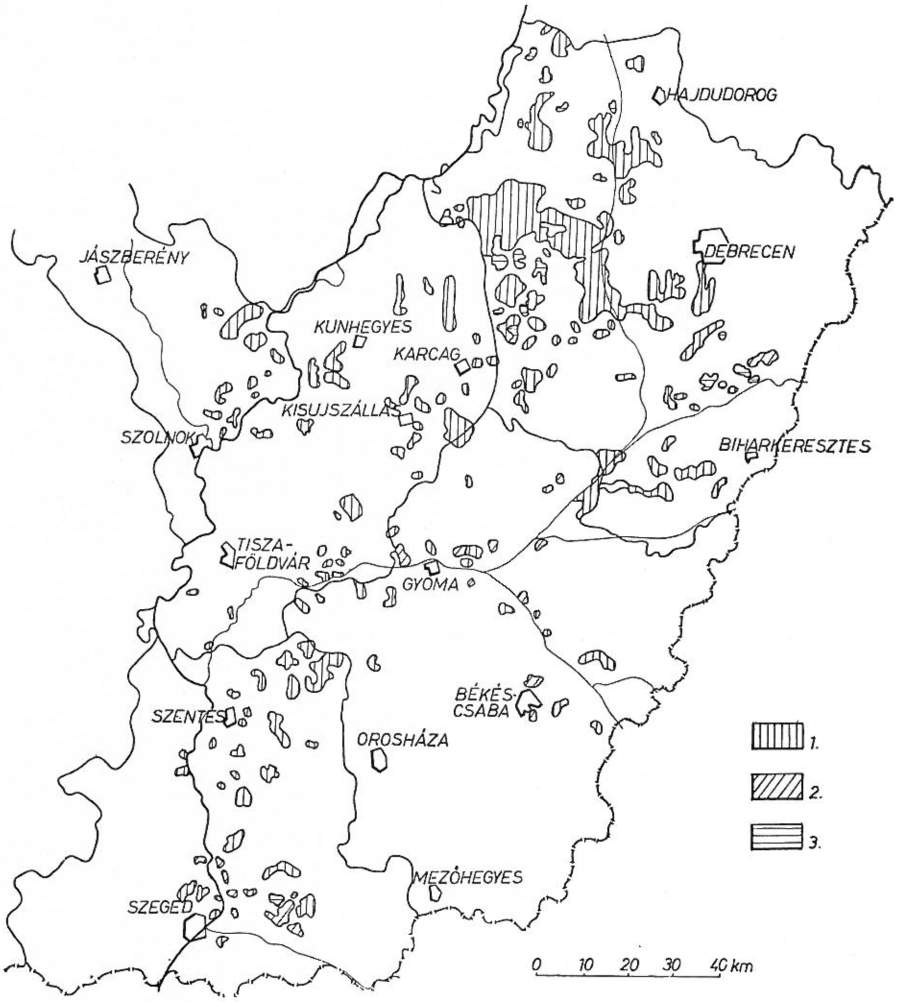

Fig. 2

General possibilities of effective irrigation from the viewpoint of soil conditions in Szolnok, Hajdú-Bihar, Békés and Csongrád counties (Eastern part of the Hungarian Plain). 1. Areas tobe irrigated; 2. Areas that may be irrigated conditionally; 3. Areas not to be irrigated processes such as peat formation (about 6000 hectares), salinization and alkalinization (about 100 000 hectares) and a combination of these processes (about 20 000 hectares [1, 2, 3, 4, 9, 32, 39]. These territories are shown in Fig. 2 (1968 data of the National Institute for Agricultural Quality Testing). Probably these unfavourable effects of irrigation were even more widespread than realized, because of the salinization and alkalinization of deeper soil layers which are not shown on this map.

The data prove that salinity is a real danger on the Hungarian Plain. For this reason the planning and installing of the new Tisza Irrigation Projects must be preceded by detailed, thorough, and exact scientific investigations including careful soil survey and research. The results of these studies must be taken into consideration in the course of the territorial installation, technical planning and practices of irrigation. The main aim of these soil investigations is to determine the possibilities and preconditions of effective irrigation in this region covering an area of about 25 000 square kilometres.

In this paper the results and conclusions of the research work that has been carried out by the authors, are summarized. The possibilities and preconditions of irrigation on the territories of the Transtisza (Eastern) part of the Hungarian Plain belonging to both the present irrigation projects and the ones to be installed in the future have been studied. The present soil processes existing in this area have been analysed. An attempt has been made to establish a salinity prognosis system and to elaborate measures to guarantee beneficial effects of irrigation, increased soil fertility and the prevention of harmful soil processes [39, 40, 41].

The possibilities and preconditions of irrigation, and methods of predicting salinization and alkalinization due to irrigation on the Hungarian Plain

Four steps are considered:

1. The determination of the possibilities of effective irrigation from the viewpoint of general existing soil conditions on the Hungarian Plain (shown on a map with a scale of 1 : 100 000) [39].
2. The determination of the possibilities and preconditions of effective irrigation from the viewpoint of more specific existing soil conditions on smaller areas within the territories in question (shown on maps with a scale of 1 : 25 000) [40, 41].
3. The determination of the possibilities and preconditions of effective irrigation from the viewpoint of soil conditions on a detailed basis on specific farms (shown on maps with a scale of 1 : 10 000).
4. The elaboration of a follow-up salinity control system for present and future irrigated areas based on systematic soil surveys.

General possibilities of effective irrigation from the viewpoint of soil conditions on the Hungarian Plain [39]

Because of irrigation effects on the areas under irrigation and surrounding land (the whole geographical region, catchment area, etc. may be affected) the integrated (complex) effect of irrigation must be studied not only for irrigated fields, irrigated farms and irrigation districts, but also for the whole irrigation project. Having a detailed knowledge of the natural conditions of the region (geography, geology, geomorphology, hydrology, hydrogeology, soils, etc.) and the present soil processes the relationships between these factors and irrigation can be analysed. The probable changes in soil conditions after different kinds of irrigation can be forecasted and thus the best irrigation practices including all kind of technical, culturtechnical and agrotechnical measures necessary for the prevention of undesirable soil processes can be suggested.

Accordingly — as a first step — the natural factors of the area in question were measured and analysed. For Szolnok, Hajdú-Bihar, Békés and Csongrád counties a series of maps were prepared or adapted with a scale of 1 : 100 000 as follows:

a) Genetic soil map (soil type and subtype);

b) Map of the average depth of the ground water level — in meters (0—1, 1—2, 2—3, 3—4, 4—6, more than 6 meters);

c) Map of the highest ground water level — in meters (0—1, 1—2, 2—3, 3—4, 4—6, more than 6 meters);

d) Map of the average salt content of the ground water — in gram/litre (0—0.5, 0.5—1, 1—2, 2—4, 4—8, more than 8 g/l).

e) Map of the chemical composition of the ground water (dominating cations and anions).

The following information was used as well:

a) Map of the absolute height of the water table (above sea level) with a scale of 1 : 400 000 [23];

b) Map of the water properties of soils in Hungary with a scale of 1 : 500 000 [6];

c) Geological map of Hungary with a scale of 1 : 200 000;

d) Data from ground water level observation wells in the region in question (more than 400 wells have been observed for over ten years).

On the basis of the above mentioned materials a map was prepared (with a scale of 1 : 100 000) indicating the general possibilities of effective irrigation from the viewpoint of soil conditions. This map is shown in Fig. 3.

On the map three categories were distinguished:

I. Areas to be irrigated. In these areas irrigation will not result in hydrological and soil processes that significantly decrease soil fertility or adversely affect soil properties if:

a) Good quality irrigation water that meets present Hungarian water quality standards (taking into account water and soil properties, land use, etc.) is applied,

b) No significant changes in natural conditions are induced or occur by natural phenomena or human activities (flood control, establishing of large reservoirs, fish ponds, etc.) on the whole geographical region (even outside the Hungarian part of the basin), and the rise in the water table does not exceed 2 metres above the forecasted level.

To this group belong:

1. The flood plains and recent alluvial terraces of the larger rivers, especially the Tisza river,

2. The sand plateaus (except the spots of solonchak and solonchak-solonetz soils that occur in the depressions among sand dunes):

a) Sand plateau of Jászság,

b) Sand plateau of Nyírség,

c) Sand plateau of the region between the rivers Danube and Tisza, if:

aa) the total salt content of the ground water is lower than 0.5 g/litre, or

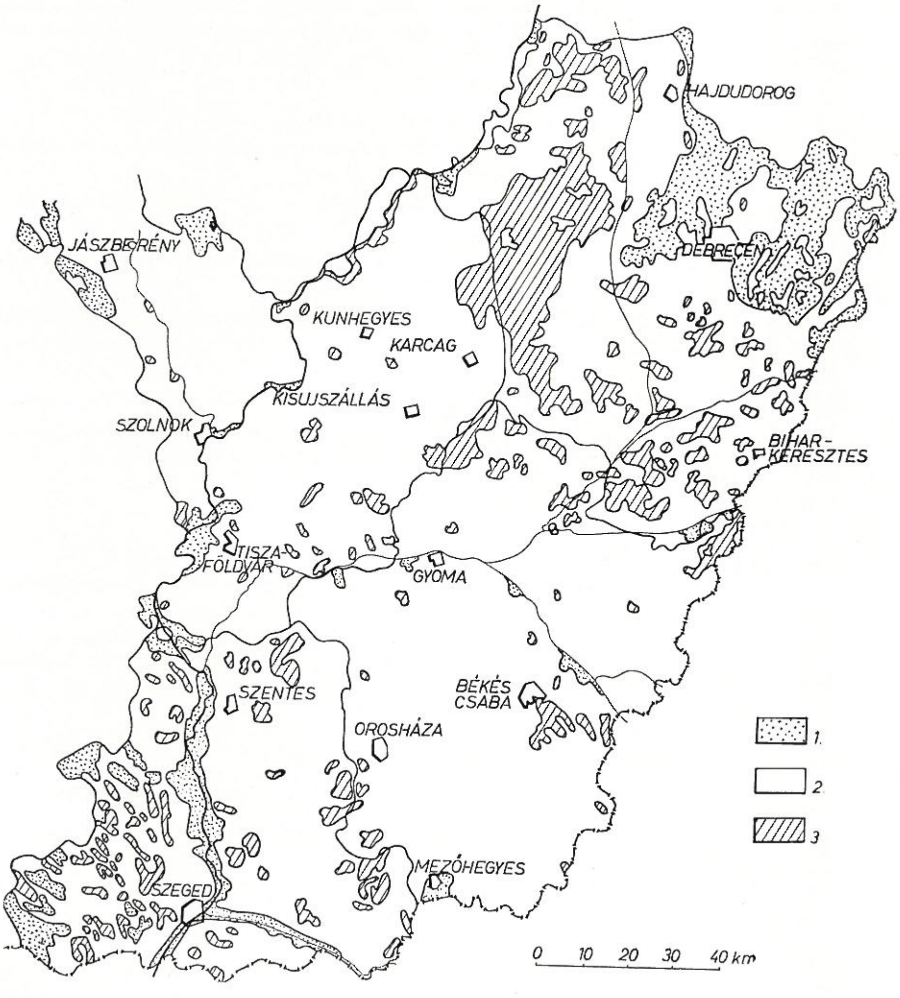

Fig. 3

Existing undesirable soil processes due to irrigation in Szolnok, Hajdú-Bihar, Békés and Csongrád counties (Eastern part of the Hungarian Plain). 1. Peat formation; 2. Salinization and alkalinization; 3. Combination of these processes *bb)* the total salt content of the ground water is 0.5—1 g/litre and the average depth of water table is 2—3 metres with a minimum of 2 metres, or

cc) the total salt content of the ground water is 1—2 g/litre and the average depth of water table is 3—4 metres with a minimum of 2 —3 metres.

3. Some parts of the loess plateaus:

a) Calcareous chernozem territories of the Debrecen loess plateau, if the average depth to the water table is more than 7—8 metres and the minimum is more than 5 metres.

b) Calcareous chernozem territories of the Békés—Csanád loess plateau around Mezőhegyes, if the average depth to the water table is more than 7—8 metres and the minimum is more than 5 metres.

II. Areas that may be irrigated conditionally. In these areas harmful hydrological and soil processes — decreasing soil fertility and unfavourably influencing the soil properties — may be prevented *only* by fulfilling the following requirements:

a) The water table must be kept below the "critical depth". The determination of the critical depth of the water table will be discussed later in this paper.

b) Good quality irrigation water — meeting present Hungarian water quality standards — is applied [6].

Special attention must be paid in this relation to the salt content and composition of different irrigation waters (originating from rivers, reservoirs, ponds, lakes, wells, etc.) and the changes in water quality in uncovered, temporary irrigation canals.

To this group belong the areas not specifically belonging to categories I and III.

III. Areas not to be irrigated. In these areas, for the time being, irrigation is not advisable because it would result in the development or intensification of undesirable hydrological and soil processes that decrease soil fertility. To prevent these phenomena expensive technical and meliorative measures are required.

The exceptions are as follows:

a) If these lands are utilized as grassland with halophytic vegetation (e.g. *Puccinellia limosa* or a mixed halophytic pasture association), they can be irrigated even with salty water. But the irrigation of these areas is permissable *only* if the irrigation does not cause undesirable phenomena (rise of water table, secondary salinization and alkalinization) in the surrounding territories.

b) If these lands are utilized as rice fields, they can be irrigated with water of proper quality. The criteria mentioned above e.g. water table, etc. must be met here also.

c) If after several years the soil properties constantly and considerably improve as a result of melioration and proper agrotechnics, the soil survey can be repeated and on the basis of the results of these investigations the soil can be re-classified into group II.

To this group belong:

1. Territories covered by solonchaks, solonchak-solonetzes and shallow meadow solonetzes.

2. Territories covered by soils strongly deteriorated by salinization and alkalinization due to irrigation (in the 0—50 cm layers).

3. Certain 1—1.5 kilometer wide strips of land around large reservoirs. On these areas, before and after building the establishments, special detailed and regular soil surveys will be necessary to study the water and salt regime.

The 1 : 100 000 scale map (Fig. 3) gives a good scientific basis for high level planning, for the territorial installation of the irrigation project, for locating the irrigation districts and for the determination of the necessity, importance and scheduling of measures to guarantee a beneficial effect from irrigation.

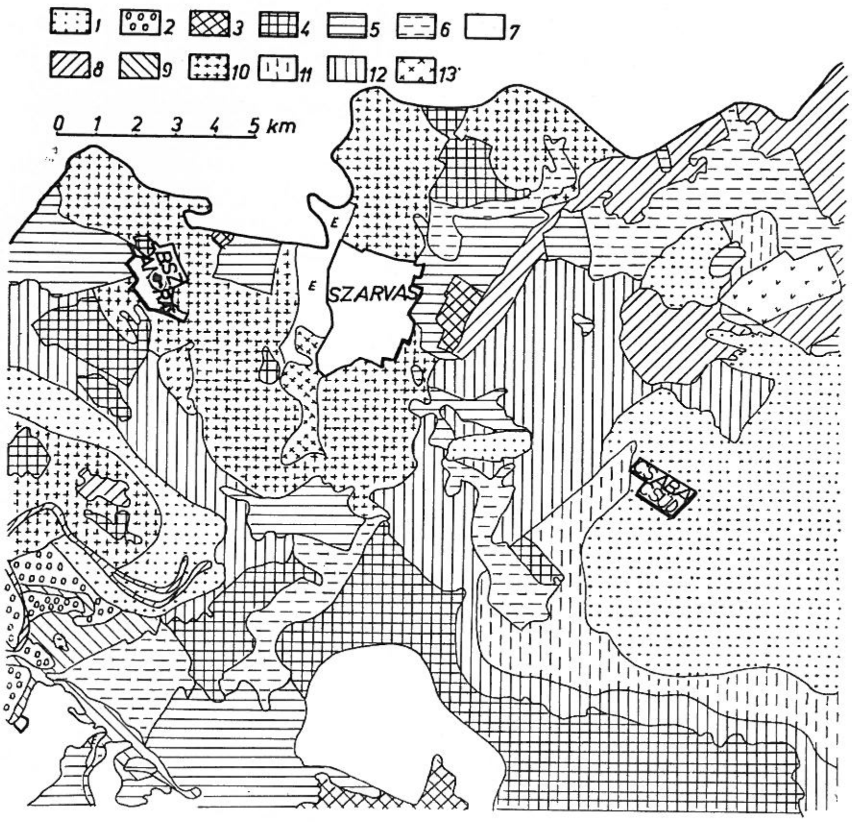

Fig. 4

Soil map. 1. Calcaraous meadow chernozem soil; 2. Meadow chernozem soil, solonetzic in deeper layers; 3. Shallow meadow solonetz soil; 4. Medium meadow solonetz soil; 5. Deep meadow solonetz soil transitional to steppe formation; 6. Solonetzic meadow soil; 7. Strongly solonetzic meadow soil; 8. Meadow soil; 9. Meadow soil, salty in deeper layers; 10. Alluvial meadow soil; 11. Calcareous chernozem meadow soil; 12. Chernozem meadow soil, salty in deeper layers; 13. Humous alluvial soil

Possibilities and preconditions of effective irrigation from the viewpoint of soil conditions in smaller areas [40, 41]

Having a general knowledge of the natural conditions, ground waters, soils and irrigation waters of a large irrigation massive (including present and future irrigation projects) a more detailed survey was necessary for the planning of irrigation districts, technical establishments, drainage systems and other main irrigation practices. For this purpose a more detailed survey was elaborated including the preparation of a series of maps with a scale of 1 : 25 000. On these maps the possibilities of irrigation were indicated more thoroughly and exactly and more detailed information was given about the preconditions and measures necessary to guarantee the prevention of undesirable soil processes.

As a first step the following maps were prepared with a scale of 1 : 25 000

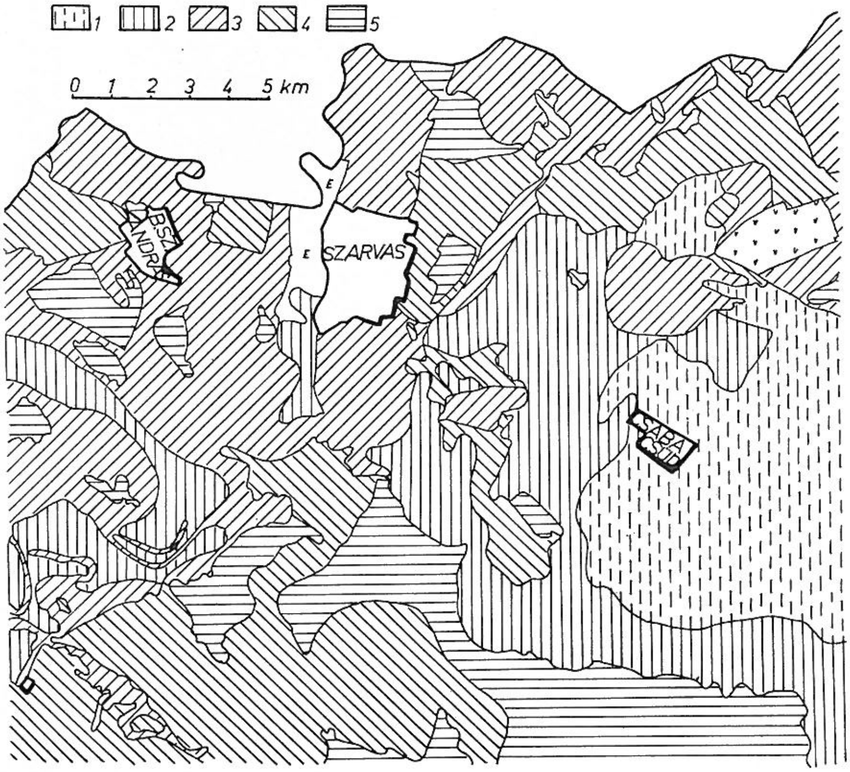

Fig. 5

Map of soil texture and water properties. 1. Soils with medium water holding capacity and high permeability; 2. Soils with high water holding capacity, a high available moisture content and medium permeability; 3. Soils with high water holding capacity, a low available moisture content and medium permeability; 4. Soils with very high water holding capacity and low permeability; 5. Soils with very high water holding capacity and very low permeability

(See Figs. 4, 5, 6 and 7 containing maps prepared — as an example — for a South-Transtisza region, near Szarvas):

Soil map (Fig. 4). This map indicates the soil type and subtype and shows a general picture of existing soil processes. The map is necessary for the interpretation and evaluation of soil properties and for forecasting prospective changes in soil conditions due to irrigation.

Map of soil texture and water properties (Fig. 5). This map indicates the soil texture (sand, sandy loam, loam, clay loam, clay and organic soils) and the categories of soil water properties on the Hungarian Plain as follows:

I. Soils with very low water holding capacity and very high permeability. To this group belong the blownsands and loose, slightly humous sandy soils.

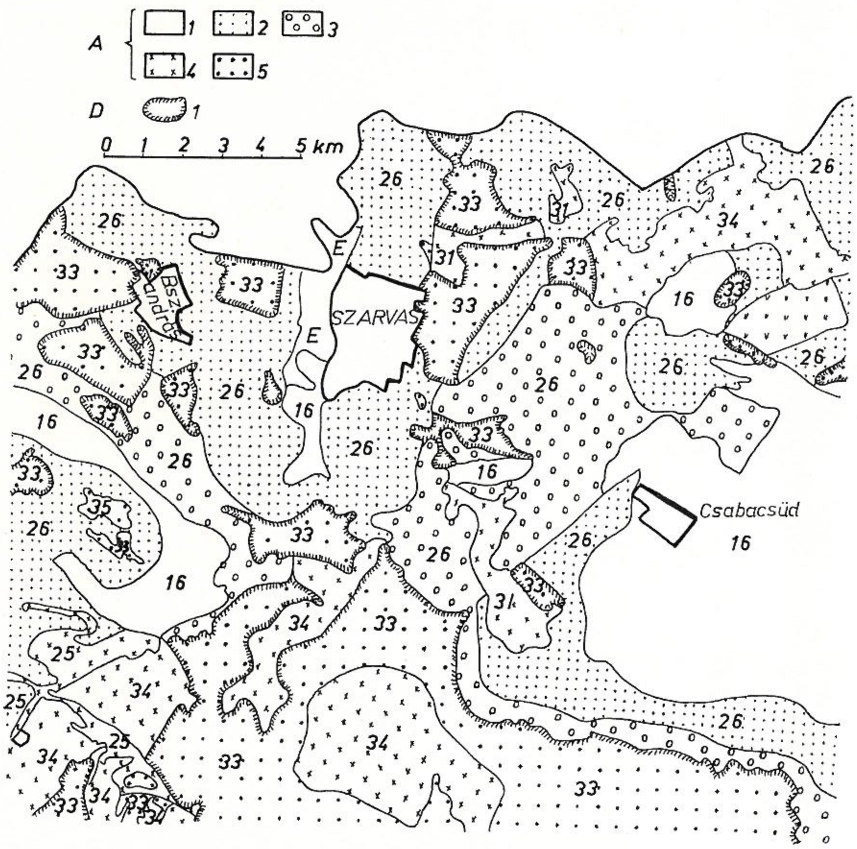

Fig. 6

Map of salinity status. A) Average total salt content in the soil between the surface and the water table, in percentage: 1. 0.050—0.075%; 2. 0.075—0.10%; 3. 0.10—0.15%; 4. 0.15—0.20%; 5. More than 0.20%. B) Maximum total salt content of the soil profile, -in percentage. (The first cipher of the two-figure numbers on the map): 1. Less than 0.10%; 2. 0.10—0.20%; 3. 0.20—0.40%; 4. More than 0.40%. C) Depth to the salt maximum in the soil profile, in cm. (The second cipher of the two-figure numbers on the map): 1. 0—5 cm; 2. 5—25 cm; 3. 25—50 cm; 4. 50—100 cm; 5. 100—150 cm; 6. More than 150 cm. D) Soil reaction of the B_1-horizon. 1. pH above 9; 2. pH 8—9

II. Soils with low water holding capacity and high permeability. To this group belong the humus sandy soils, light textured meadow, meadow-alluvial and meadow-chernozem soils.

III. Soils with medium water holding capacity and high permeability. To this group belong the chernozem and meadow chernozem soils of the Transtisza region, the meadow-chernozem soils of the region between the rivers Danube and Tisza and some alluvial-meadow and meadow-alluvial soils.

IV. Soils with high water holding capacity, a high available moisture content and medium permeability. To this group belong the fine textured (clay, clay loam) meadow-alluvial soils and the loamy meadow soils.

V. Soils with high water holding capacity, a low available moisture content and medium permeability. To this group belong some meadow soils of the Transtisza region (clay loam, clay) and some meadow soils that are solonetzic in deeper horizons.

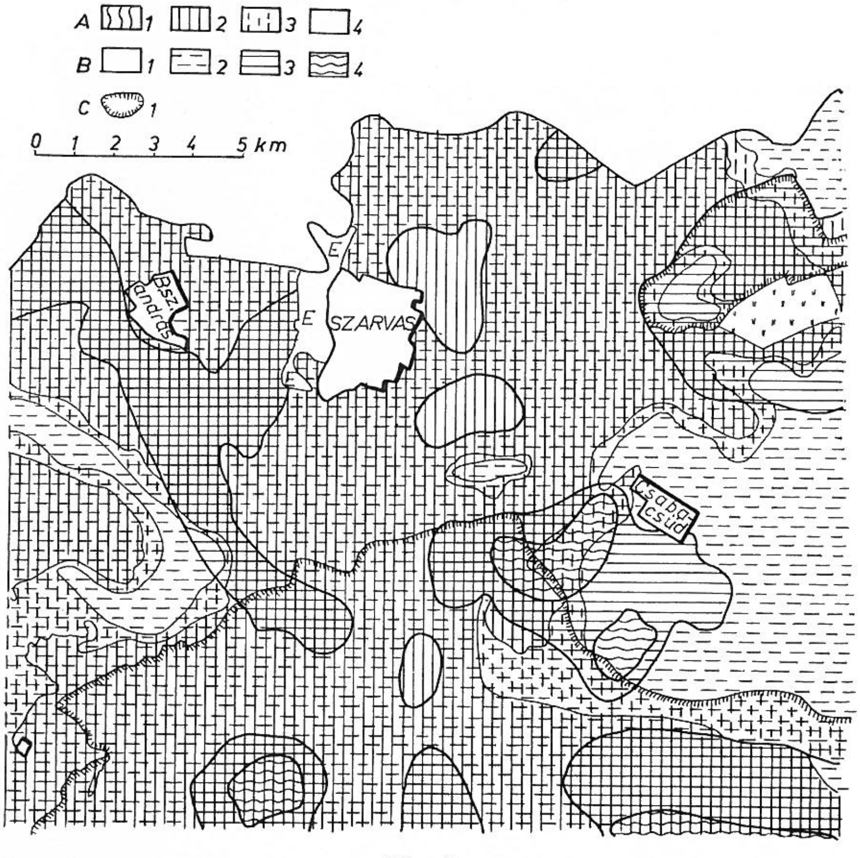

Fig. 7

Map of ground water conditions. A) Average depth to the water table, in m 1. 1.5—2.5 m; 2. 2.5—3.5 m; 3. 3.5—4.5 m; 4. 4.5—6.0 m. B) Average salt content of the ground water, in g/litre; 1. 0—1; 2. 1—2; 3. 2—4; 4. 4—8 g/litre. C) The Na-percent of the ground water, 1. above 75; 2. below 75

VI. Soils with very high water holding capacity and low permeability. To this group belong the solonetzic meadow soils and the deep meadow solonetzes that are transitional to steppe formation.

VII. Soils with very high water holding capacity and very low permeability. To this group belong the shallow meadow solonetzes and the solonchak-solonetzes.

The criteria of these categories (water holding capacity, available moisture content and permeability) are given in Table 1.

Map of salinity status (Fig. 6). This map indicates:

a) average total salt content in the soil between the surface and the water table — in percentage (0—0.05, 0.05—0.075, 0.075—0.10, 0.10—0.15, 0.15—0.20 and more than 0.20%),

b) maximum total salt content of the soil profile — in percentage (0—0.1, 0.1—0.2, 0.2—0.4 and more than 0.4%),

c) depth to the salt maximum in the soil profile — in centimeter (0—5, 5—25, 25—50, 50—100, 100—150 and more than 150 cm),

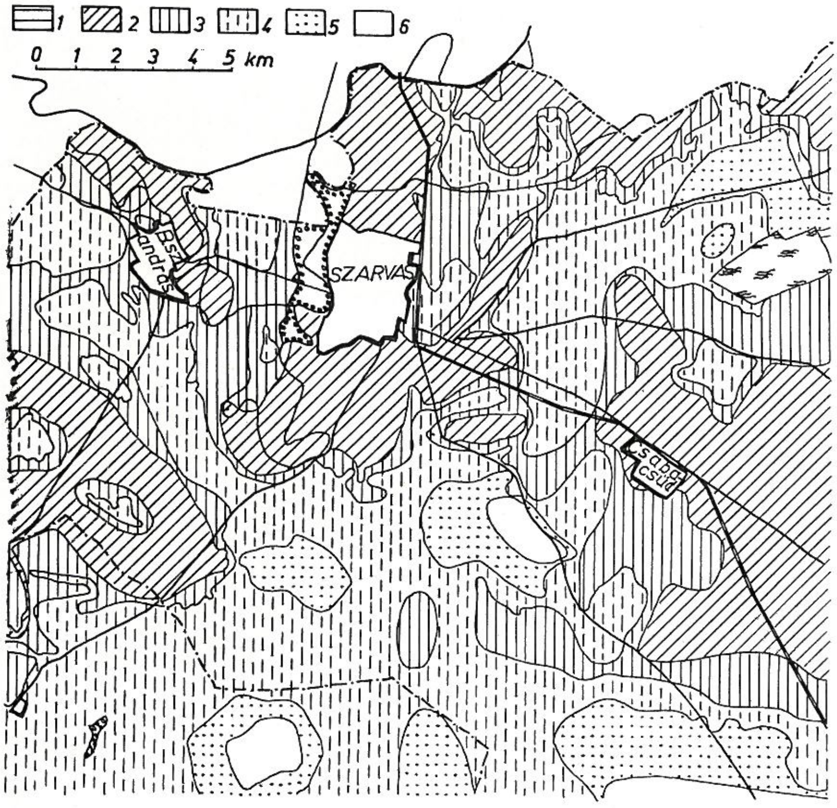

Fig. 8

Map of the critical depth of the water table, in m. 1. 2.0 m; 2. 2.5 m; 3. 3.0 m; 4. 3.5 m; 5. 4.0 m; 6. 4.5 m *d)* soil reaction of the B_1 horizon (pH below 8, 8—9 and above 9).

Map of ground water conditions (Fig. 7). This map indicates:

a) average depth to the water table — in metres (0—1.5, 1.5—2.5, 2.5—3.5, 3.5—4.5, 4.5—6 and more than 6 metres),

b) average salt content of the ground water — in grams/litre (0—1, 1—2, 2—4, 4—8 and more than 8 g/l).

c) Na content of the ground water — in percentage (Na%):

$$Na\% = \frac{Na^{+}}{Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}} \cdot 100$$ (expressed in me/l). On the basis of the the above mentioned maps two more maps were prepared with the same scale (1 : 25 000):

Map of the "critical depth" to the water table — in metres (2.0, 2.5, 3.0, 3.5, 4.0, 4.5 meter) (Fig. 8).

The main source of water soluble salts in the soils of Hungary is the ground water and irrigation causes salinization and alkalinization mainly by raising its level. The possibility and intensity of salt accumulation from the ground water depend on capillary rise. This is closely related to, among other factors (capillary conductivity, climatic conditions, etc.), the depth of the water table. To prevent these undesirable soil processes a certain water table level must not be exceeded. The determination of this "critical" water table depth is very important in the technical planning of irrigation works and drainage systems and for the determination their parameters. Thus may be decided the real possibilities of effective and economical irrigation. The critical depth of the water table is influenced by many factors:

a) precipitation and potential evaporation,

b) soil texture, structure and water properties (especially the water holding capacity, wilting point, available moisture content, permeability, hydraulic and capillary conductivity, etc.),

c) present salt content, salt profile and salt composition of soils and the harmful salinity limit,

d) salt content and composition of the ground water,

e) stagnancy, supply and horizontal flow of the ground water,

f) human factors (irrigation, drainage, melioration, agrotechnics, etc.) influencing the above mentioned factors and water movement in the soil.

There is no appropriate method for the calculation and prediction of ground water salinization even though some authors have published data about a computer method for predicting the salt concentration of waters percolating through stratified substrata [42, 43]. The problems mentioned above are farther complicated by the fact that the determination of the critical depth of the water table is not possible using only hydrological-hydrophysical-hydrochemical calculations. Other factors (land use, system of irrigated farming, agrotechnics, etc.) must also be taken into consideration. The evaluation of these factors includes, in addition to exact calculation, a series of conventional estimates and subjective assumptions. Consequently, the determined values of the critical depth to the water table are always approximations, and show a special periodically fluctuating dynamism.

During our calculation method, given below, for the determination of the critical depth to the water table we assume, that:

a) the ground water rises to the capillary zone of the soil and the soil solution migrates within the soil profile without changes in their salt concentration and composition,

b) the soil solution in the whole soil profile is saturated with Ca and Mg salts and essentially only sodium salts migrate within the soil profile. The capillary flow (amount of water rising from the ground water into the unsaturated soil layers) was taken as a simple function of the depth to the water table. It was a rather rough estimation because, for the exact determination of the capillary flow, at least two more factors must be taken into account: capillary conductivity as a function of suction, and the suction profile. Substitution of measured values for these factors instead of the estimated averages whould improve the calculation considerably. Furthermore, other factors affecting the capillary flow (precipitation, evaporation, soil texture, structure, porosity, water holding capacity, permeability, available moisture content, etc.) may be taken into consideration through their determining or modifying effect on capillary conductivity or on the suction profile. The effect of human activity (irrigation, melioration, agrotechnics, etc.) on capillary rise and through it on the water and salt regimes of soils may also be evaluated.

In our present calculation we took the following factors as variables:

a) amount of irrigation water,

b) salt content of irrigation water,

c) "salt regime coefficient", or the annual salt balance of unirrigated soils i.e. the quantity of salts leached out or accumulated per year [5, 6, 8, 36, 37, 38, 47],

d) thickness of the capillary zone,

e) categories of soil water properties (volume weight, water holding capacity, available moisture content and permeability),

f) average total salt content of the soil between the surface and the water table,

g) salt content of the ground water,

h) soil reaction and the Na percentage of the irrigation water. We used calculation method "a" if the Na percentage of the irrigation water was below 75, or the pH in the B_1 horizon was below 9, and method "b" if the Na percentage of the irrigation water was above 75 or the pH in the B_1 horizon was above 9.

The consecutive steps of the calculations in the "a" method are given below:

$$(1)\quad x = \frac{c_1 \cdot w_1}{D_1 \cdot v} \cdot 10^{-5}$$

x = quantity of salts added by the irrigation water — as percentage of soil

c_1 = concentration of the irrigation water in g/litre

w_1 = amount of irrigation water used in m^3/hectare

D_1 = thickness of the soil layer between the surface and the capillary fringe (upper boundary of capillary zone), m

v = volume weight of the soil — g/cm^3

(2) $y = \frac{c_2 \cdot w_2}{D_2 \cdot v} + a$

y = quantity of salts in the capillary zone — per cent of soil

c_2 = concentration of the ground water in g/litre

w_2 = quantity of available moisture in the capillary zone (m^3/hectare)

D_2 = thickness of the capillary zone — m

a = average original salt content of the soil before irrigation – per cent ofsoil

(3) $c_3 = \frac{y}{W_k} \cdot 10^3$

c_3 = concentration of the soil solution in the capillary zone (g/litre)

W_k =field capacity (weight per cent)

(4) $z = \frac{c_3 \cdot w_3}{D_1 \cdot v}$

z = quantity of salts transported by capillary flow from the ground water and the capillary saturated soil layers to the unsaturated zone of the soil (per cent of soil)

w_3 = capillary flow (amount of water rising from the ground water into the unsaturated soil zone) — m^3/hectare

(5) $b_{10} = (a + x + z + d) \cdot 10$

b_{10} = average salt content of the soil after 10 years' irrigation (assuming that the above mentioned factors are constants during this period) — per cent of soil

(6) $b_{10} - a = (x + z + d) \cdot 10$

d = "salt regime coefficient" i.e. the quantity of salts leached out or accumulated under natural conditions per year (annua) salt balance of non-irrigated soils — per cent of soil [5, 6, 8, 36, 37, 38, 47]

$b_{10} - a$ = change in the average salt content of soil (salt balance) due to ten years' irrigation — per cent of soil

The calculation procedure of the "b"-method is the same except that only the equivalent quantity of sodium (alkali) salts in the irrigation water, ground water, soil solution and the "salt regime coefficient" rather than the total soluble salt content must be calculated.

If we assume the following situation:

c_1 = 0.4 g/litre
w_1 = 2500 m^3/hectare/year
v = 1.3 g/cm^3
} $x = 0.0033\%$/year

c_2 = 2.0 g/litre
w_2 = 1500 m^3/hectare
D_2 = 1 m
a = 0.10%
W_k = 21.5%
d = −0.03%
w_3 = 1000 m^3/hectare

then the calculated values as a function of the depth to the water table will give the following figures:

	Depth to the water table, meter				
	1.5	2.0	2.5	3.0	3.5
D_1-in m	0.5	1.0	1.5	2.0	2.5
y-percent of soil	0.123	0.123	0.123	0.123	0.123
c_3-g/litre	5.7	5.7	5.7	5.7	5.7
z-percent of soil	0.176	0.0658	0.0292	0.0219	0.0175
b-percent of soil	0.2614	0.1435	0.1043	0.0960	0.0910
b_{10}-percent of soil	1.714	0.535	0.143	0.057	0.005
b_{10}-a -percent of soil	1.614	0.435	0.043	−0.043	−0.095

The data show that, if the depth to the water table is less than 3 m, salt accumulation will occur. Consequently, to prevent salinization and alkalinization the water table must be maintained at a depth of at least 3 m (critical depth in this case).

Having adequate data on the influencing factors and using the described calculation method the prospective rate of salt accumulation at different depths to the water table may be forecasted. The critical depth of the water table may be estimated in this way.

Calculations were made for areas of the Tisza Irrigation Projects on the Eastern part of the Hungarian Plain assuming the following factors as constants:

$c_1 = 0.4$ g/litre, $w_1 = 2500$ m^3/hectare, $d = -0.03\%$

Moreover we considered the following variables (shown in Figs 4, 5, 6 and 7):

a) categories of soil water properties (Fig. 5) including D_2, w_2 and W_k values (Table 1),

b) average total salt content of the soil between the surface and the water table — in percentage (Fig. 6),

c) average salt content of the ground water — in g/litre (Fig. 7),

d) Na per cent of the ground water and the pH of the B_1 horizon.

The final results of these calculations are summarized in Tables 2 and 3. Using these tables and the maps shown in Figs. 4, 5, 6 and 7, a 1 : 25 000 scale map was prepared to indicate the critical depth to the water table. This map is shown in Fig. 8.

Map of the possibilities and preconditions of irrigation (Fig. 9). First this map shows the possibilities of effective irrigation from the viewpoint of detailed soil conditions. Using the same evaluation basis as used for the general map (1 : 100 000) the following were distinguished on the 1 : 25 000 map:

I. Areas to be irrigated
II. Areas that may be irrigated conditionally
III. Areas not to be irrigated.

Table 1

Soil categories according to the water soil properties

Soil categories		Water holding capacity, in volume percentage	Available moisture content in the percentage of the water holding capacity	Permeability in mm/hour
I	Soils with very low water holding capacity and very high permeability	below 16	above 60	above 300
II	Soils with low water holding capacity and very high permeability	16—24	50—60	above 300
III	Soils with medium water holding capacity and high permeability	24—32	50—60	100—300
IV	Soils with high water holding capacity, a high available moisture content and medium permeability	32—40	40—50	70—100
V	Soils with high water holding capacity, a high available moisture content and medium permeability	32—40	20—40	70—100
VI	Soils with very high water holding capacity and low permeability	above 40	20—40	30— 70
VII	Soils with very high water holding capacity and very low permeability	above 40	below 20	below 30

Second, this map indicates — on the basis of a comparative evaluation of the ground water map (Fig. 7) and the map of the critical depth to the water table (Fig. 8) — the following measures that must be taken for ground water control to prevent salinization and alkalinization processes due to irrigation:

A) Lowering of the water table. In the areas having a higher average ground water table than the "critical" one, the precondition of effective irrigation, land use and soil amelioration is a lowering of the water table below the critical depth. Comparing the present water table (Fig. 7) with the critical depth to the water table (Fig. 8) the amount of lowering may be calculated, and on this basis the necessary technical measures can be planned and established. Without lowering the water table in these areas irrigation results in the beginning, strengthening or deepening of undesirable soil processes — consequently, irrigation is not advisable. After ground water regulation — parallel with complex amelioration — these territories may be irrigated. However, this is not always economical because the necessary technical measures are very expensive.

B) Prevention of a rise in the water table level (ground water level stabilization). In areas having an average water table level not more than 1 m deeper than the critical depth, a precondition of effective irrigation, to prevent harmful soil processes, is ground water level stabilization (the prevention of a rise in the water level).

Comparing the present water table (Fig. 7) with the critical depth (Fig. 8) the maximum allowable water table rise may be determined. On this basis, having a knowledge of the main parameters of future irrigation practices (amount of irrigation water per irrigation and per year, the frequency and method of irrigation, etc.) appropriate technical measures can be decided and outlined to prevent an desirable rise of the water table.

Table 2

The critical depth to the water table as a function of water soil properties categories, ground water and soil salinity (calculated by method „a")

The concentration of the ground water g/liter	The average total salt content of soil between surface and the water table, percentage	Water soil property categories						
		I	II	III	IV	V	VI	VII
1	0.050	2.0	2.5	2.5	2.5	2.0	—	—
	0.075	2.5	3.0	2.5	2.5	2.5	2.5	—
	0.100	3.0	3.5	3.0	2.5	2.5	2.5	2.5
	0.150	—	—	—	3.0	3.0	3.0	3.0
	0.200	—	—	—	—	3.0	3.0	3.5
2	0.050	2.5	2.5	2.5	2.5	2.5	—	—
	0.075	3.0	3.0	2.5	2.5	2.5	2.5	—
	0.010	3.0	3.5	3.0	3.0	2.5	2.5	2.5
	0.150	—	—	—	3.5	3.0	3.0	3.0
	0.200	—	—	—	—	3.5	3.5	3.5
4	0.050	3.0	3.0	2.5	2.5	2.5	—	—
	0.075	3.5	3.5	3.0	3.0	3.0	3.0	—
	0.100	3.5	4.0	3.5	3.0	3.0	3.0	3.0
	0.150	—	—	—	3.5	3.5	3.5	3.5
	0.200	—	—	—	—	3.5	3.5	3.5
8	0.050	3.5	3.5	3.5	3.5	3.5	—	—
	0.075	4.0	4.0	3.5	3.5	3.5	3.5	—
	0.100	4.0	4.0	4.0	3.5	3.5	3.5	3.5
	0.150	—	—	—	4.0	4.0	4.0	4.0
	0.200	—	—	—	—	4.0	4.0	4.0

If, in these areas, the water table rises above the critical level — lack of adequate technical and agrotechnical measures — there is a real danger of unfavourable soil processes in the irrigated territories or their surroundings. Consequently, in such cases irrigation is not advisable.

C) Regular study of the water table. In areas belonging to class II (from the viewpoint of irrigability) and having an average water table level more than 1 m below the critical depth, effective irrigation needs no special ground water regulating measures. Here attention has to be paid to a regular study of the water table. In case of a considerable and permanent water table rise due to irrigation (on the irrigated territories or on their surroundings) necessary preventive measures must be taken early. If the water table rises to within 1 m of the critical depth, the area should be assigned to group (B).

In addition to the above mentioned information, the map (Fig. 9) gives some general directives concerning irrigation:

1. Frequent irrigation is advisable with low water application rates. To this group belong soils with the soil water properties of categories I, VI and VII.

2. Medium frequent irrigation is advisable with medium water application rates. To this group belong soils with soil water properties of categories IV and V.

Table 3

The critical depth to the water table as a function of water soil properties categories, ground water and soil salinity (calculated by method „b")

The concentration of the ground water g/liter	The average total salt content of soil between surface and the water table in percentage	Water soil property categories						
		I	II	III	IV	V	VI	VII
1	0.050	2.5	3.0	2.5	2.5	2.5	—	—
	0.075	3.0	3.0	2.5	2.5	2.5	2.5	—
	0.100	3.5	3.5	2.5	2.5	2.5	2.5	2.5
	0.150	—	—	—	3.0	2.0	2.5	2.5
	0.200	—	—	—	3.0	3.0	2.5	3.0
2	0.050	2.5	3.0	2.5	2.5	2.5	—	—
	0.075	3.5	3.5	3.0	2.5	2.5	2.5	—
	0.100	4.0	4.0	3.0	3.0	3.0	2.5	2.5
	0.150	—	—	—	3.5	3.0	3.0	3.0
	0.200	—	—	—	—	3.5	3.5	3.5
4	0.050	3.0	3.5	3.0	3.0	3.0	—	—
	0.075	4.0	4.0	3.5	3.0	3.0	3.0	—
	0.100	4.0	4.5	3.5	3.5	3.5	3.0	3.0
	0.150	—	—	—	3.5	3.5	3.5	3.5
	0.200	—	—	—	—	4.0	4.0	4.0
8	0.050	3.0	3.5	3.5	3.5	4.0	—	—
	0.075	4.0	4.5	4.5	4.0	4.0	4.0	—
	0.100	4.0	4.5	4.5	4.5	4.5	4.0	4.0
	0.150	—	—	—	4.5	4.5	4.5	4.5
	0.200	—	—	—	—	4.5	4.5	4.5

3. One (or infrequent) irrigation is advisable with a high water application rate. To this group belong soils with the soil water properties of categories II and III.

It must be emphasized that the above mentioned grouping gives only general information for irrigation practices (frequency, intensity, rate, methods, etc.) because these factors finally must be determined by a detailed, complex, technical and economic study of future irrigation projects, districts and farms.

Using the presented method, 1 : 25 000 maps were prepared for the whole of the Eastern part of the Hungarian Plain by the National Institute for Agricultural Quality Testing, Budapest, Hungary.

Possibilities and preconditions of the effective irrigation of individual farm from the viewpoint of soil conditions

The third step of our work is a detailed study of the possibilities and preconditions for the effective irrigation of individual farms, from the viewpoint of soil conditions. The results of this study are to be summarized on a series of large scale maps. These will give more detailed information about soil conditions, soil processes (present and future) as well as more detailed recommendations for land use, planning and practices in irrigation and irrigated farming.

The greater scale will require further investigations: evaluation of more factors; exact experimental determination of the present, more or less roughly estimated factors; more detailed analysis (even the use of computers) of interrelationships. The following major factors must be characterized more exactly:

a) horizontal ground water flow and stagnancy of ground water,

b) capillary rise (capillary conductivity and the suction profile and factors influencing them, especially salinity),

c) effect of salt composition on the water and salt regimes of the soil,

d) concentration and salt composition of the soil solution in soils of different texture and soil water properties,

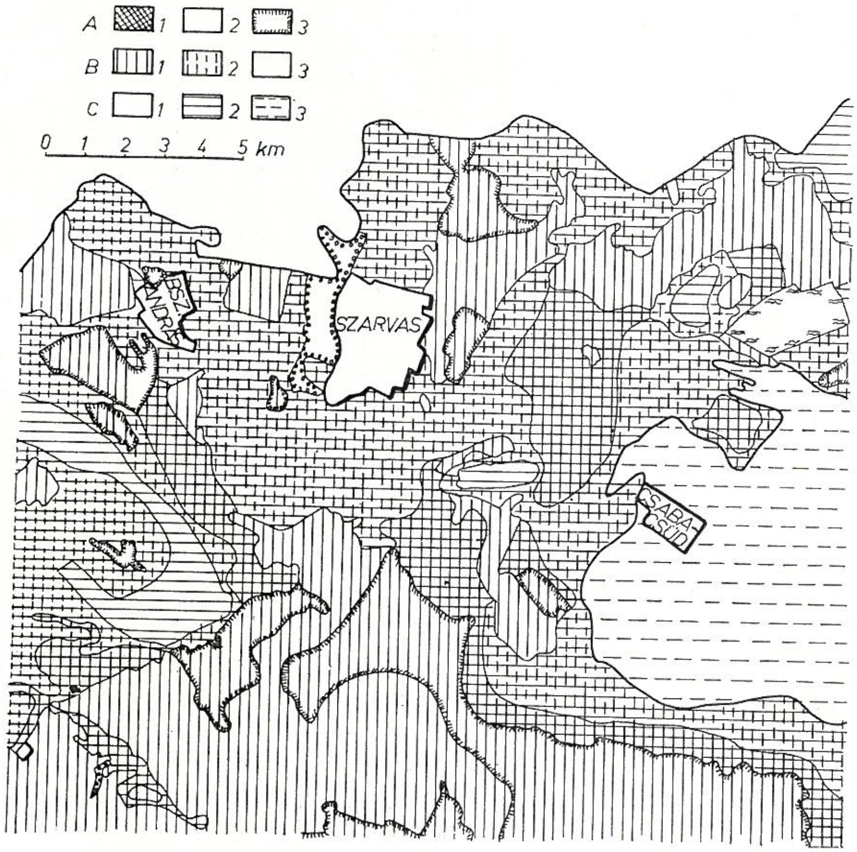

Fig. 9

Map of possibilities and preconditions of irrigation. A) The possibilities of effective irrigation from viewpoint of soil conditions: 1. Areas to be irrigated; 2. Areas that may be irrigated conditionally; 3. Areas not to be irrigated. B) The necessary ground water control: 1. The lowering of the water table; 2. The prevention of a rise in the water table; 3. The regular study of the water table. C) The general directives concerning irrigation: 1. Frequent irrigation is advisable with low water application rates; 2. Medium frequent irrigation is advisable with medium water application rates; 3. One (or infrequent) irrigation is advisable with a high water application rate *e)* harmful limit of salts for different plants on different soils (salt tolerance).

The detailed maps and explanatory booklets are to be prepared for farming units.

Water and salinity control system for present and future irrigated areas

A detailed, follow-up survey system is necessary to regularly measure water and soil processes during the operation of the irrigation project — even though planning may have been perfect and as much caution as possible taken to prevent soil damage. The survey system should indicate the measures that must taken to control the water and salt regimes.

Even with severe precautionary measures, it might happen that one or more factors unexpectedly exceeds its limit. In this case the preconditions of effective irrigation would not be completely fitted and harmful soil processes might occur and depress soil fertility. For example, even the forecasted depth to the water table and the predicted salt balances based on a detailed and complex analytical study can not exactly and surely forecast the integrated effects of natural factors (climatic, hydrological, hydrogeological, etc.) and irrigation, especially for the whole area of the irrigation project (irrigation massive) during long periods.

Thus an adequate water and salinity control system is necessary in which the following factors have to be outlined and thoroughly determined:

— aim and subject of investigations (the factors and features to be examined),

— sampling (time, frequency, intervals, methods, etc.)

— field and laboratory examinations (including adequate analytical methods),

— evaluation methods (including mathematical procedures, statistical analysis, possibly a computer program, etc.),

— necessary measures must be taken, on the basis of the evaluated results, for water and salinity control. These measures should prevent harmful effects of irrigation such as: peat formation, salinization, alkalinization, solodization, etc.

The elaboration of such a water and salinity control system is necessary not only for the Hungarian Plain but for irrigation projects of other areas as well, where there is an existing hazard of salinization and alkalinization.

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