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Design and operation of drainage-subirrigation systems in Poland

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Abstract. The different techniques used in the design and operation of drainage-subirrigation systems in low-lying riverine areas in Poland are presented. The required groundwater levels used as designing criteria and the applications of the steady state and unsteady state approach to ditch (drain) spacing design in different soil conditions are discussed. The practical application of groundwater level maintenance using the techniques of controlled drainage, subirrigation with a constant water level, and subirrigation with a regulated water level, are shown for three different field sites.

Introduction

Climatic conditions in Poland are characterized by a considerable variability in weather conditions during long periods of time (years) as well as short periods of time (days, weeks). Average yearly precipitation rate is approximately equal to 600 mm, average yearly temperature is from 6°C to 8.5°C, average length of vegetation period is about 200 days. The coldest month is January with average temperature from −1.5°C to −5.5°C, the warmest month is July with average temperature from 17°C to 18.5°C. Because of this, for rational soil water management there is a need for drainage in times of excess rainfall, and for irrigation during periods of drought. For soils with a shallow water table depth in low lying river plain areas this can be achieved using gravitational drainage subirrigation systems. Such systems usually consist of a network of ditches and control structures which can be used on mineral as well as organic soils with sufficient permeability. The total area of grasslands about 0.5 mln ha, in low lying riverine areas in Poland is equipped with drainage-subirrigation systems. The scope of this paper is to discuss the different techniques used in the design and operation of such systems and these are illustrated using the results of field measurements.

Design criteria

A subirrigation system should be designed so that the water level in the field is controlled to a point which allows the root zone of the growing crop to be supplied by an upward movement of water (capillary rise). This groundwater level can be determined using the steady state soil water flow theory.

One dimensional upward steady-state water flow in an unsaturated zone can be described by:

$$q = -K(h)\left(\frac{dh}{dz} + 1\right) \quad (1)$$

with boundary condition:

$$h = 0 \text{ at } z = 0 \quad (2)$$

where:

q – groundwater flux (cm/d),
K – unsaturated hydraulic conductivity (cm/d),
h – the pressure head (cm),
z – vertical coordinate, positively upward and zero at the phreatic surface (cm).

Equation 1 can be solved for any region of z by separating the variables and integrating yielding:

$$\int_{z_1}^{z_2} dz = \int_{h_1}^{h_2} \frac{-1}{1 + \frac{q}{K(h)}} dz \quad (3)$$

For a flow in a layered soil profile, Eq. 3 can be applied for each separate layer. Hence:

$$z = -\int_{0}^{h_1} \frac{dh}{1 + \frac{q}{K_1(h)}} - \int_{h_1}^{h_2} \frac{dh}{1 + \frac{q}{K_2(h)}} - \ldots - \int_{h_{n-1}}^{h_n} \frac{dh}{1 + \frac{q}{K_n(h)}} \quad (4)$$

where $h_1, h_2, \ldots, h_n$ are the pressure heads at elevations of various layers $z_1, z_2, \ldots, z_n$.

As the solution of Eq. 3 or 4, the relationship between the maximum rate of upward water movement and the water table depth below the root zone, i.e.

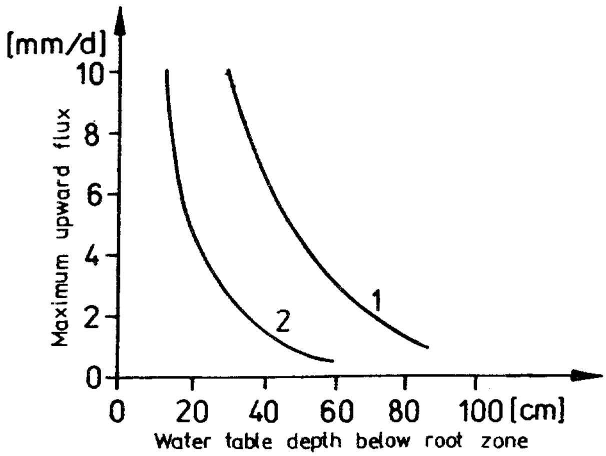


Fig. 1. The relationship between the maximum steady upward flux and the groundwater level below root zone. 1 – soil from the Stara Notec I field site, 2 – soil from the Komorowo field site.

z(q,h) is determined. The required groundwater level is then estimated as the sum of the height of capillary rise z(q,h) for the desired flux and the thickness of the root zone, z_r.

Gardner (1958) obtained analytical solutions for the upward flux in terms of the water table depth for a specific form of K(h) function. In most cases, however numerical methods must be used to obtain solutions for tabulated or functional relationships. These methods can be used for either homogeneous or layered soils. The application of this approach in the designing of subirrigation systems was reported in literature by: Skaggs (1978, 1980, 1982); Brandyk (1985, 1990); Brandyk & Wesseling (1985); van Bakel (1986); Youngs et al. (1989); Wesseling (1990) and others. The relationships for the maximum steady upward flow as a function of water table depth are plotted in Fig. 1 for Stara Notec I peat-muck and Komorowo clay soils. The value of h = 500 cm of water was used as the minimum allowable value of soil moisture content in the root zone of grass. The depth of the water table and the allowable limits within which it should be maintained are soil dependent. The K(h) – function can be evaluated directly from measurements, or approximated from soil water characteristics, h(Θ), and vertical saturated conductivity, Ks, using, for example, methods proposed by Millington & Quirk (1961); Kunze et al. (1968); and van Genuchten (1980).

For design purposes the value of the required flux, q, can be estimated from the analysis of evapotranspiration during periods of drought for a given probability level (for grasslands p = 20% is recommended in Poland) and the available moisture content in the root zone at the beginning of a period of drought,

Table 1. The required groundwater levels for different soil-moisture regime classes according to Szuniewicz (1979).

Required groundwater levels in (cm)	Soil-moisture regime classes			
	B	BC	C	CD
z_1	35	30	25	20
z_2	45	35	30	30
z_{opt}	70	50	35	35
z_3	95	85	60	50

as discussed by Skapski et al. (1992). Values of required groundwater levels estimated from field observations are also used.

Hydrogenic soils in Poland are grouped into so-called soil moisture regime classes according to the similarity of the soil's physical properties. The following soil moisture regime classes have been specified (Okruszko, 1986): A – wet, AB – periodically wet, B – moist, BC – periodically dry, C – dry, CD – periodically semi-arid, D – arid. The required groundwater levels for keeping the soil moisture content in the root zone within allowable limits (i.e. between the minimum allowable moisture content and the maximum allowable moisture content) for soil moisture regime classes B, BC, C and CD (recommended in Poland for subirrigation and controlled drainage), used as permanent grasslands, are presented in Table 1. The values of z_1, z_2 and z_{opt} in Table 1 are defined as groundwater levels corresponding to volumetric air contents of 6%, 8% and 10% in the root zone, respectively. The value of z_3 corresponds to the minimum allowable moisture content which is moisture content of the soil at a tension of 2.7 pF.

Water management techniques

The following three techniques for maintaining groundwater level in subirrigation systems can be distinguished:
- controlled drainage,
- subirrigation with a constant water level,
- subirrigation with a regulated water level.

In Poland so-called controlled drainage technique is applicable in small watersheds with very limited water resources available for subirrigation. The available flux during the vegetation period is lower than 0.35 $l\ s^{-1}\ ha^{-1}$ (~ 3 mm/day). This technique assumes drainage during spring to groundwater level (z_1), which assures a minimum air content in the root zone, then the control structures are closed and the position of the groundwater level is determined by the actual rate of precipitation and evapotranspiration.

Subirrigation with a constant water level is applicable when the available flux for subirrigation is in the range of 0.35 to 0.5 l s^{-1} ha^{-1}. This technique assumes drainage during spring to the optimal groundwater depth (z_{opt}). Then an open water level in the ditches is maintained using control structures in such a way that the water table position is kept close to its optimal values. Such a technique assumes drainage in times of excess rainfall and subirrigation during dry periods.

Subirrigation with a regulated water level is applicable when the available flux is higher than 0.5 l s^{-1} ha^{-1} (4.3 mm/day). The water table may be lowered to the minimum required groundwater level (z_3) at the beginning of the growing season, then the control structures are closed and the water table is temporarily raised to level z_1 and then the control structures are opened to allow drainage. This procedure is repeated as often as required during the growing season.

The application of these techniques for three different field sites are discussed below.

Controlled drainage

The results of field investigations from the Pawlowek field site (Brandyk, 1989) are used to illustrate controlled drainage technique. The Pawlowek field site is located in the Bydgoszcz district. It occupies an area of about 100 ha of meadows in low-lying areas of ditch 'F' valley. The scheme of the Pawlowek field site is shown in Fig. 2. The groundwater management in this area depends

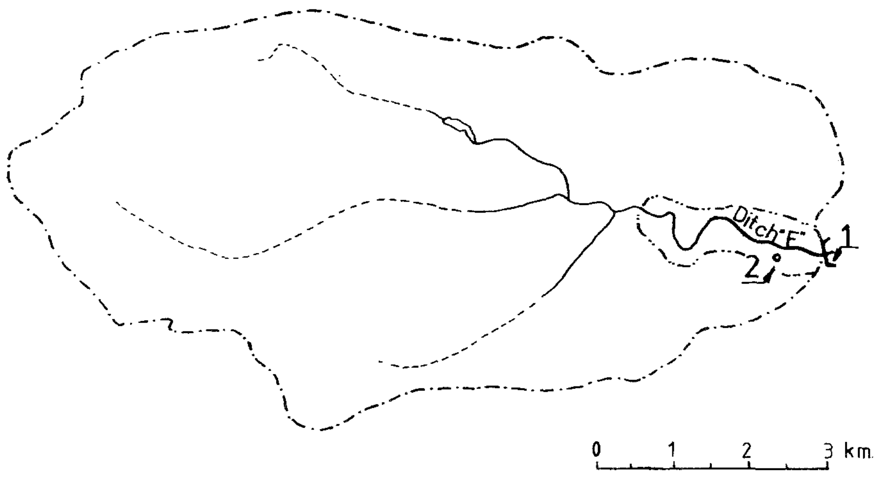


Fig. 2. Scheme of the Pawlowek field site, where: 1 – control structure, 2 – observation well.

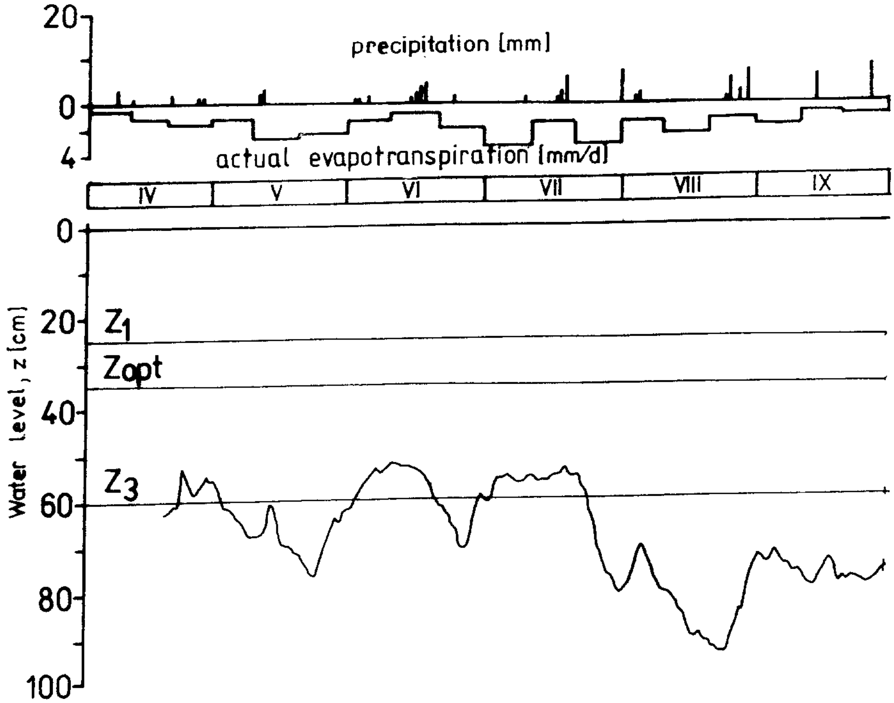


Fig. 3. Groundwater levels recorded in observation well at Pawlowek during the vegetation period in 1989.

on open water levels in ditch 'F', which is regulated by control structure (1). The available water flux for subirrigation is very low and equal to 0.25 l s^{-1} ha^{-1}. As a result after drainage in early spring to groundwater level z_1, the control structure is closed to maintain the groundwater level above the maximum admissible level z_3. This technique of groundwater management gives successful results during years with average and higher than average precipitation rates but can fail during very dry years. In such areas with very limited water resources there is no need to construct a network of drains and ditches for subirrigation. The changes in groundwater levels recorded in control well (2) during the growing season in the year of 1989 are shown in Fig. 3. In the last decade of July the groundwater level fell below the maximum admissible level (z_3) because the growing season in 1989 was very dry. The total precipitation for the vegetation period (April–September) in 1989 was equal to about 90 mm. The average annual precipitation rate for this area is about 550 mm.

Subirrigation with a constant water level

The Stara Notec I field site is an example of a system of subirrigation with a constant water level. This system is also located in the Bydgoszcz district in Poland. It occupies an area of about 900 ha of meadows in the Notec river valley. A typical fragment of the Stara Notec I system of an area of about 125 ha is shown in Fig. 4.

The Stara Notec river is used as the main drainage waters receiver, and also as the main water source for subirrigation in this area. Irrigation water is supplied through the turnout, located near the barrage on the Stara Notec river and then distributed over the area by watercourses B, B-1, B-2, B-3 which supply water to the systematic ditch network. In the designing of such subirrigation systems the proper determination of ditch spacing is very important. This can be done when soil properties are determined. The soils in this area are peat-muck soils. A typical soil profile consist of a layer of peat-muck underlain at an average depth of 1.3 m by sand to the depth of 6.1 m. The saturated hydraulic conductivity of the upper layer is equal to 0.5 m d^{-1} and the saturated hydraulic conductivity of the lower layer is equal to 2.6 m d^{-1}.

In subirrigation systems with a constant water level the steady state formulae can be applied for ditch spacing determination. In considered cases the formulae of Toksoz and Krikham (1971), modified for subirrigation by Krikham and Horton (1986) and the formulae of Ernst (1975) for layered soils, can be applied. Also an approximate method based on D-F assumptions as described by Skaggs (1981) after averaging the saturated hydraulic conductivity and applying Hooghoudt's equivalent depth concept can be used. Using the above mentioned formulae, ditch spacings from 80 to 100 m for Stara Notec I soil conditions were obtained. The following values of the parameters were assumed in the calculations: ditch depth – 0.9 m, ditch bottom width – 0.5 m, water level in the ditch – 0.75 m, steady rate of evapotranspiration – 0.005 m d^{-1}.

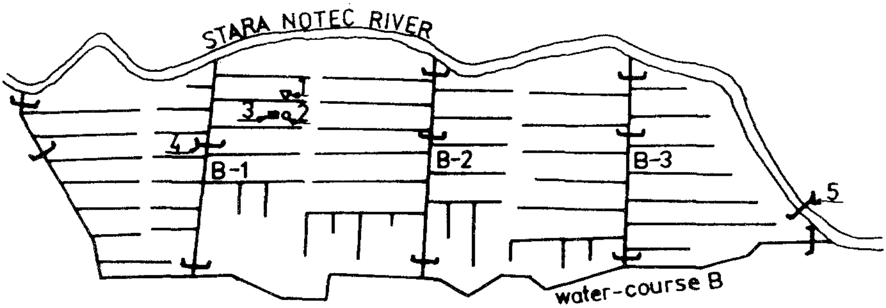
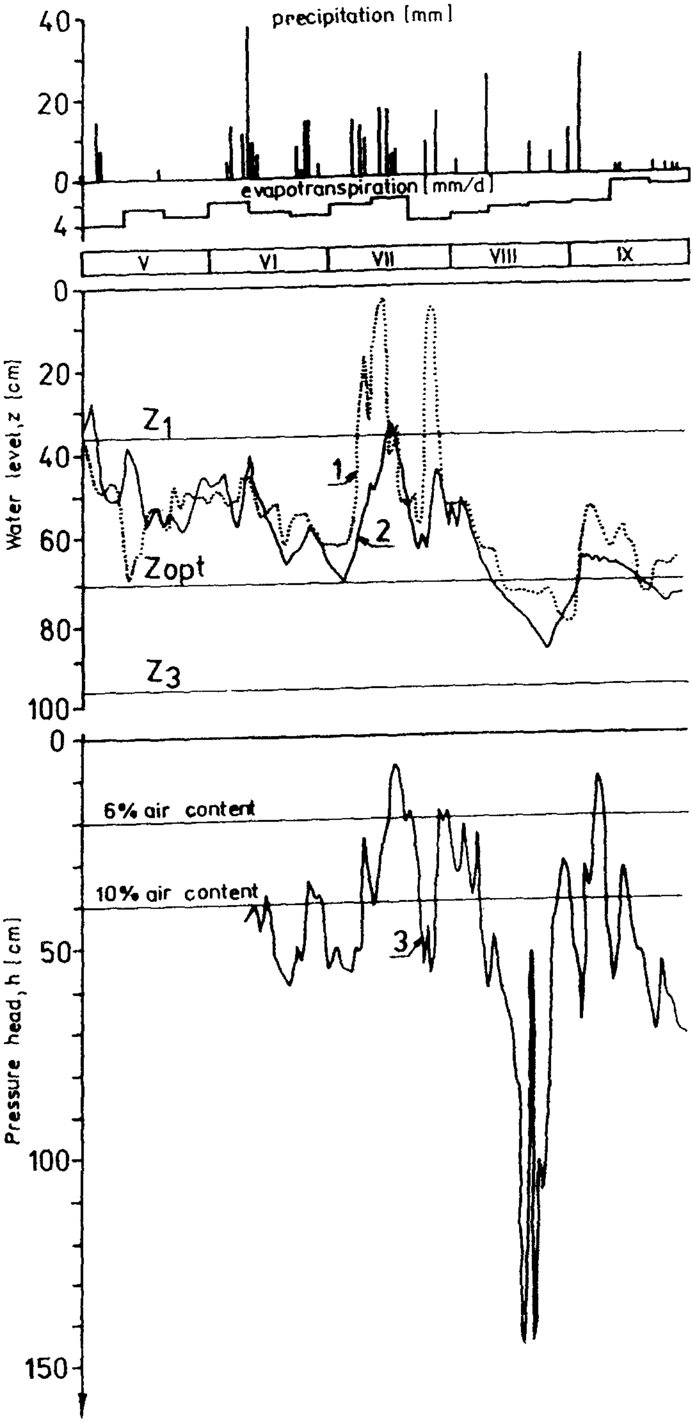


Fig. 4. A typical fragment of the Stara Notec I drainage-subirrigation system, where: 1 – ditch open water gauge, 2 – observation well, 3 – soil tensiometers, 4 – control structures, 5 – barrage.



precipitation [mm]
40
20
0
evapotranspiration [mm/d]
4
V
VI
VII
VIII
IX
0
20
40
60
80
100
Water level, z [cm]
Z1
Zopt
Z3
1
2
0
6% air content
10% air content
50
100
150
Pressure head, h [cm]
3

For the field site whose scheme is presented in Fig. 4 the ditches were designed with spacing of 80 m. In Fig. 5 the results of the groundwater level and ditch open water level measurements at Stara Notec I during the vegetation period in 1988 are presented. The values of both evapotranspiration and the precipitation, as well as the required groundwater levels are also shown in this figure. From the groundwater level changes it can be seen that during nearly the whole of the considered period of time the groundwater level was between the minimum (z_1) and the maximum (z_3) admissible levels. Only during the short periods of time with intensive rainfalls in May and July did the groundwater level exceed the lower admissible limit (z_1). The results of tensiometric soil moisture pressure head measurements in the root zone during the vegetation period in 1988 are also shown in Fig. 5. The values of soil moisture pressure heads during nearly the whole of the considered period of time were within allowable limits, i.e. h = 20 cm, which corresponds to 6% of air content in the root zone, and h = 500 cm which corresponds to the minimum allowable moisture content for grasslands on peat-muck soils. Because water management of peat-muck soils. Because water management of peat-much soils should fulfill plant water requirements and also requirements for protection against peat organic matter losses in the mineralization process, soil moisture pressure heads were kept closer to the maximum allowable moisture content (h = 20 cm).

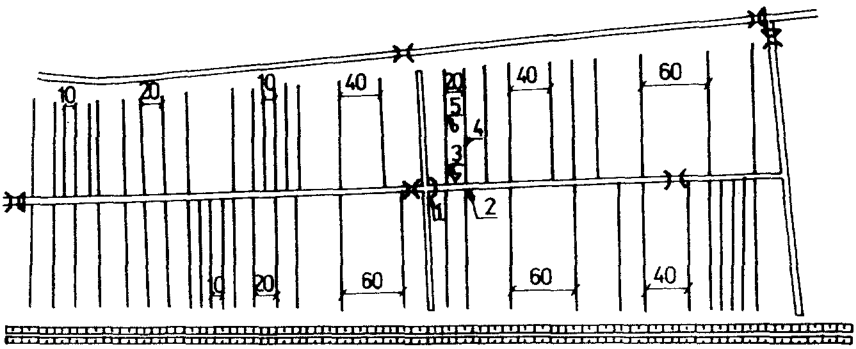


Fig. 6. Scheme of the Komorowo drainage-subirrigation system, where: 1 – control structures, 2 – ditches, 3 – ditch water level gauge, 4 – tile drains, 5 – observation well.

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Fig. 5. Results of ditch open water levels (1), groundwater levels (2), and soil moisture pressure head measurements in the root zone (3) during the vegetation period in 1988. Stara Notec I field site.

Subirrigation with a regulated water level

The Komorowo drainage-subirrigation system can be used as an example to illustrate subirrigation using the regulated water level technique. This system is located in the delta of the Vistula river near the city of Elblag. The scheme of Komorowo system is presented in Fig. 6. This system was designed for experimental research on different spacings between tile drains in a combined ditch-drain network. There are alluvial clay soils in this area. A detailed investigation of the hydrogeological and soil conditions showed that the upper soil layer (thickness 1 m) consists of clay soils with saturated hydraulic conductivity values from 0.2 to 0.4 m d^{-1} and the lower soil layers (thickness 4 m) consists of sands and sandy clay loams with saturated hydraulic conductivity ranging from 0.8 to 2.5 m d^{-1}. These layers overlay heavy clay, assumed as an impermeable layer because of its very low permeability $k = 0.04$ m d^{-1}. In such alluvial clay soils to allow a upward water movement by capillary rise with an average intensity of 3 mm/d during periods of drought, the groundwater level should be kept no deeper than 25 cm below the lower boundary of the root zone (Fig. 1). The value of average daily water deficit of 3 mm/d is recommended for the designing of irrigation systems in these areas. Because the average effective depth of the root zone was estimated as 20 cm, the required groundwater level in this case is equal to 45 cm below the soil surface. On the other hand to assure more than minimum allowable air content in the root zone in this soil the groundwater level should be lowered to a position of about 1 m during periods of excess rainfall.

Thus the operation of the drainage-subirrigation system should allow for

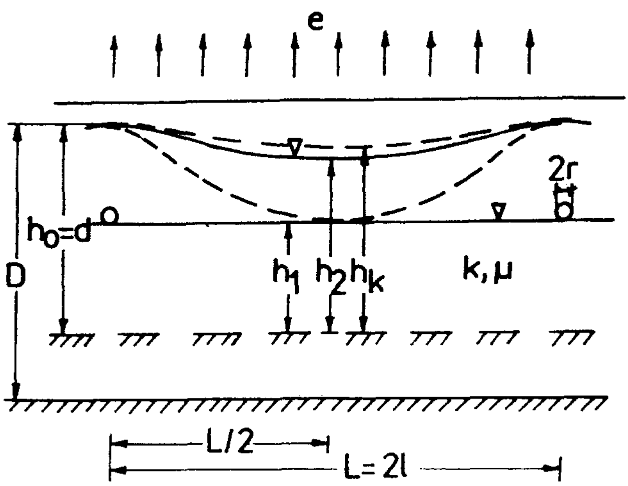

Fig. 7. Scheme of the water level positions during subirrigation used in Ostromecki's method.

change in the groundwater table position under changing weather conditions within an acceptable period of time. So the unsteady state approach to the design of ditch or drains spacing, based on an acceptable time criterion, is required in this case. This can be achieved using the formulae of Ostromecki (1969) or Skaggs (1981). As the method developed by Skaggs is well-known and described in detail in the literature, in this paper only the method of Ostromecki (1969), which is widely used in Poland, is discussed briefly below. This method is based on a semi-analytical solution of the Boussinesq equation using D-F assumptions, and the Hooghoudt equivalent depth concept. The schematisation used in Ostromecki's method is shown in Fig. 7. The Ostromecki method permits us to determine the time period required for raising the groundwater level to the desired depth. This period of time is the sum of two components T1 and T2, where T1 is the time period when water infiltration from the ditch reaches the middle of the ditch spacing, T2 is the period of time required to raise the groundwater level from an initial position (h_1) to the desired position (h_2) in the middle of the ditch spacing. These time periods can be calculated as:

$$T1 = -\frac{\mu\, m(h_0 - h_1)}{2e} \ln\left[\frac{h_k^2 - h_1^2}{h_0^2 - h_1^2}\right] \tag{5}$$

and

$$T2 = \frac{\mu\,(1-m)\, l^2}{2\, n\, k\, h_k} \ln\left[\frac{h_k + h_2}{h_k - h_2}\,\frac{h_k - h_1}{h_k + h_1}\right] \tag{6}$$

where:

μ – specific yield (-),
k – average saturated hydraulic conductivity (m/d),
m – coefficient which depends on the shape of the phreatic surface (-),
e – average daily water deficit value (m/d),
n – coefficient which is equal to 2 according to Ostromecki (-),
h_0, h_1 – as shown in Fig. 7 (m),
h_2 – groundwater level in the middle of the ditch spacing at the end of subirrigation (m),
$h_k^2 = h_0^2 - \frac{e\, l^2}{n\, k}$ – maximum possible height of groundwater level in the middle of the ditch spacing (m).

Calculations of the ditch spacing according to Ostromecki's and Skaggs methods were made using the following values of the parameters: specific yield $\mu = 0.15$, average daily water deficit e = 0.003 m/d, initial groundwater level

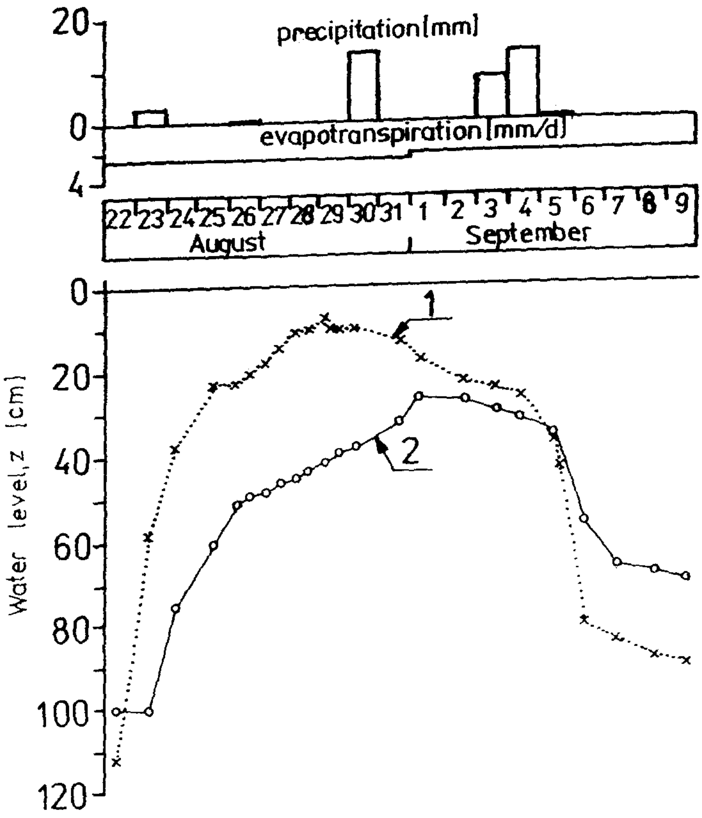

Fig. 8. Changes in water levels during one subirrigation-drainage period in 1988, where: 1 – open ditch water level, 2 – groundwater levels in the middle of the drain spacing.

−0.8 m, desired groundwater table position below the soil surface at the end of subirrigation −0.45 m. As the designing criterion for drain spacing determination a time period not exceeding 7 days to raise the groundwater level was chosen. This criterion is fulfilled for Komorowo conditions by drain spacing of 20 m, for which the calculated period of time using Ostromecki formula, is about 7 days; whereas calculated by using Skaggs formulae it is about 6 days. These results are confirmed by the results of the field measurements presented in Fig. 8.

The results of water level measurements at the Komorowo field site for 20 m drain spacing during the growing season in 1988 are shown in Fig. 9. These data are illustrative of subirrigation with a regulated groundwater level where rapid changes in groundwater level are maintained under changing weather conditions. The results of systematic soil moisture content measurements using the gravimetric method confirms the efficiency of such groundwater management

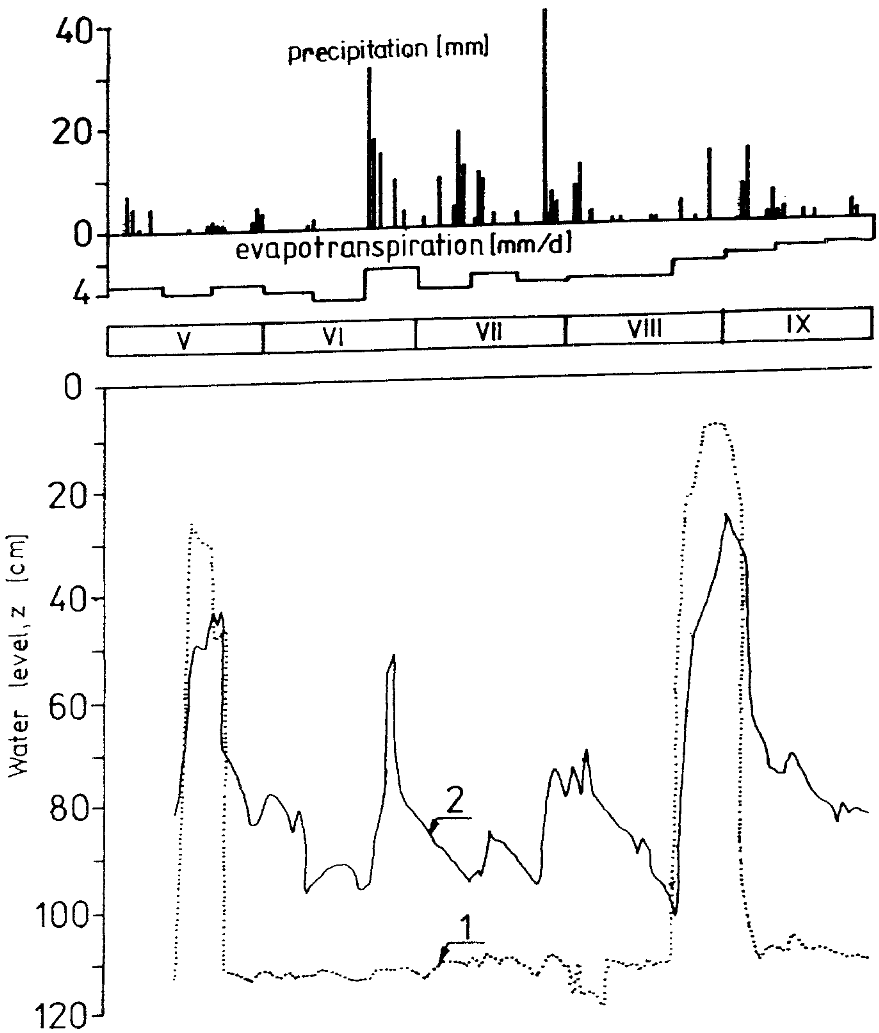

Fig. 9. Results of ditch open water levels (1) and groundwater levels (2) during the vegetation period in 1988. Komorowo field site.

technique because the values of the soil moisture content in the root zone were within the admissible range.

Conclusions

Three different techniques of groundwater management in drainage – subirrigation systems are presented.

Controlled drainage technique is applicable in small agricultural watersheds with very limited water resources. The main advantages of such technique are the low cost because only one control structure in the ditch or small river needs to be constructed and this kind of water management technique is easy to perform in the field. The main disadvantage of this technique is that during very dry periods it is not possible to maintain groundwater level to the desired position.

Subirrigation with a constant water level is based on keeping the groundwater level in a position which is close to its optimum value, by the proper maintenance of the open water levels in the ditch network using control structures. This technique is recommended in Poland when the available flux for subirrigation is greater than 0.35 l s^{-1} ha^{-1}, and for such soils where it is possible to assess the optimal groundwater level which guarantees both the required air content in the root zone during periods of excess rainfalls as well as sufficient capillary rise during periods of drought. The results of calculations of ditch spacing using three different steady state methods, which were confirmed by the results of field investigations, showed that subirrigation requirements in peat-muck soil at the Stara Notec I field site can be satisfied with an 80 m ditch spacing.

Subirrigation with a regulated water level assumes the groundwater level changes according to weather conditions by rapid open water level changes in the ditch-drain network. It is possible to implement this technique when the available flux in the irrigation water source is higher than 0.5 l s^{-1} ha^{-1}, and recommended for soils which require groundwater level changes under changing weather conditions. The results of drain spacing calculations using the unsteady state method of Ostromecki (1969) and Skaggs (1981) agreed quite well with the results of field investigation in the Komorowo field site at drain spacing equal to 20 m.

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