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An Assessment of Controlled Drainage Efficiency in Sandy Loam Soils

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Abstract

Field studies on the effectiveness of controlled drainage in sandy loam soil were carried out in the Lowland of Middle Lithuania. The plot, which has existing subsurface water removal systems operated as conventional drainage was readjusted for groundwater table management. A water level control structure was installed and two separate systems - free drainage (FD) and controlled drainage (CD) were arranged. The groundwater table level was allowed to rise to a maximum of 68 cm above the drains. Measurements to record groundwater table depth, drain outflow quantity and quality were performed through the period 2000-2007.

It was determined that in the CD system annual drainage outflow lasted shorter by 40-62%, at the same time it was reduced by 25% and nitrate leaching – by 20-28% lower in comparison with drainage operating in an ordinary regime. These quantities varied depending on weather conditions. Groundwater table control in single-acting drainage system is feasible and has positive hydrological and environmental impact.

Key words: controlled drainage, groundwater table management, drainage water quality, inorganic nitrogen

Introduction

In the past, drainage systems were designed for a long life, on the assumption that climatic conditions would not change in the future. This will not be so in the years to come, due to global warming and the greenhouse effect. Therefore, planners and designers need to systematically re-examine planning principles, design criteria, operating rules and management policies for new infrastructures (De Wrachien and Feddes, 2004). Some of the existing drainage systems may be rebuilt and equipped with new technical facilities, which would pay more attention to the impact of tile drainage on stream and groundwater quality (Maticic and Steinman, 2007).

Intensive drainage systems, necessary to provide trafficability during extreme wet periods, often remove more water than necessary during drier periods, leading to temporary overdrainage. Problems with drought on drained soils have resulted in a transition from conventional drainage methods to groundwater table management systems (Evans et al., 1995). Especially controlled drainage and subirrigation was developed in the USA, where it has been widely applied over the last 20 years because of its environmental benefits and increased yields (Skaggs, 1999).

Most existing subsurface drainage systems can be retrofitted for controlled drainage (Brown et al., 1997). However, based upon previous research, the possibilities for applying this method are strictly limited by soil texture and topography (Evans et al., 1995; Wahba et al., 2002). Controlled drainage is best suited for flat or gently sloping lands (less than 1% slope) as it is much easier to maintain the groundwater table at a uniform depth. On the sandy soils studied, controlled drainage did not effectively raise the groundwater table to a greater degree than observed on the free drainage treatment due to uneven deep of impermeable layer (Dukes et al., 2003). A field with considerable surface undulation could result in excessive variation of the depth to the groundwater table within the field. For this case, proper groundwater table management may require more water control structures resulting in increase the cost of the system installation.

In Lithuania the maintenance of large-scale drainage systems installed during the former period needs a lot of organisational and financial support (Maziliauskas, 2004). Many existing drainage systems were not designed for drainage water management making retrofitting expensive. Therefore such drainage practice, with the exception of several research and demonstration sites, was not applied because there are practical limitations on a portion of suitable areas and that the practice is economically challenging on slopes greater than 1% (Morkūnas and Ramoška, 2001). However, on the plains with intensive farming and high pollution levels drainage control shows promise by reducing the influence of agricultural activities on the environment. Despite some inconsistencies, the primary benefit of controlled drainage is a reduction of the total outflow and nutrient loading (Mejia and Madramootoo, 1998; Ramoška et al., 2011). The reductions at individual sites were influenced by locality conditions.

Surface water quality problems are of great concern in Lithuania. The strong upward NO_3-N trend in the Nemunas River and its major tributaries was detected in Lithuania of later years (Sileika et al., 2006). The studies on feasibilities of controlled drainage as one of the means to reduce the non-point source pollution from drained agricultural areas are relevant at such circumstances.

The aim of the studies was to research drainage control possibilities and the effectiveness from the point of view of hydrology and environmental protection. The factors determining the effect of groundwater table management on water quality were investigated.

Experimental site. The locality where the investigations were carried out represents a region of intensively developed agriculture in the Middle Lithuania Lowland with typical soils and topography. An area, which has existing composite subsurface water removal system operated as conventional drainage, was chosen for the research. Tile drains with a radius of 40 mm were placed in a regular herringbone pattern at a depth of 0.9-1.1 m and spacing at 20-24 m. Two separate systems - free conventional drainage (FD) and controlled drainage (CD) were arranged (Fig. 1). A water level control device with riser column and hand operated rigid flap door was installed in the outlet of drainage collector in the manhole. Elevation of outlet allowed to raise groundwater table to a maximum of 68 cm above the drains. This level was chosen in consideration of the site relief (the slope 0.2-0.9%) and the required groundwater table depth favourable to crop growth – 0.60-0.70 m below the soil surface. The area impacted by groundwater table management covered 2.8 ha, or 52% of the CD treatment plot. The results of eight-year studies (2000-2007) are analysed in the paper.

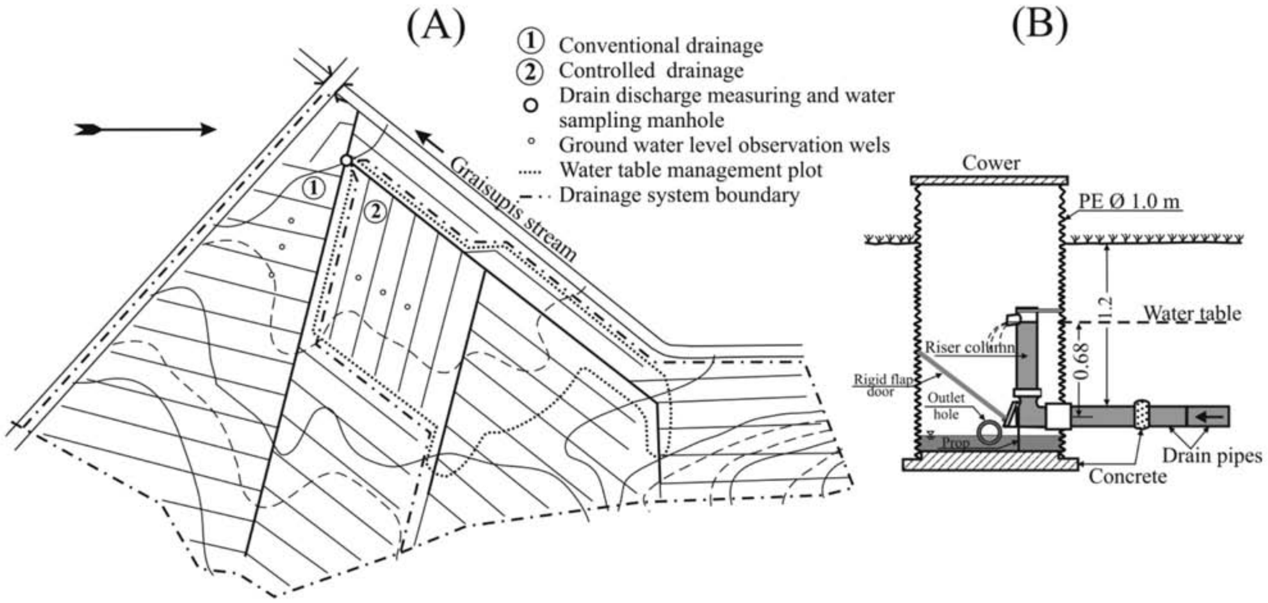

Figure 1. **Layout of the experimental site (A) and groundwater table management structure (B)**

Soil and climate data. Relatively young soils developed under the influence of glaciation *Endocalcari-Endohipogleyic Cambisols* (*CMg-n-w-can*) are prevailing in the site. Sandy loam soil texture was defined throughout the soil profile up to the drains in both treatments. Beneath the drainage depth of the CD treatment, there is sandy clay loam. Such combination of soil horizons is favourable for groundwater table management, as water seepage into deeper soil layers is limited.

Steady-state infiltration method using a ring infiltrometer was applied to determine saturated hydraulic conductivity of the soil. Saturated hydraulic conductivity varies from 1.7 to 2.5 m day^{-1} in the topsoil layer. The statistical mean value at $p \leq 0.05$ equalled 1.7 ± 0.6 m day^{-1}. In the subsoil these values were more than four times lower - 0.4 ± 0.2 m day^{-1} on the average. At a depth of 1.4 m it reaches only 0.01 ± 0.01 m day^{-1}. The organic matter content in the topsoil was 20 ± 2.6 g kg^{-1}, and 1.6 ± 0.3 g kg^{-1} in the subsoil. Soil porosity was 47 and 34% respectively. Mineral nitrogen content determined before treatment was 1.5 ± 0.1 g kg^{-1} in the topsoil layer and 0.5 ± 0.1 g kg^{-1} in deeper layers on the average. Hydraulic conductivity of sandy loam layer, which is the main path of the flow out of drains into the surrounding soil in CD system, was 0.3 ± 0.2 m day^{-1}. Other characteristics of this layer are: the bulk density – 1.9 ± 0.04 g cm^{-3}, particle density – 2.7 g cm^{-3}, porosity – 28%. The water storage capacity of the 1.0 m deep soil profile when the groundwater table was at its maximum height (0.7 m) in CD treatment was 359 mm.

The data of meteorological station, located approximately 5 km from the experimental site were used to characterize weather conditions. According to the total rainfall the years of 2002, 2003, 2005 and 2006 were dry, 2000, 2001 and 2004 – moderate, 2007 – humid, with a precipitation likelihood of 86 - 95%, 53 - 68% and 24% respectively. The years under the study were drier and warmer than usual: the total precipitation was 12% less than the long-term average value and air temperature was +1.4 ^{o}C higher than the annual mean (Table 1). Evapotranspiration exceeds precipitation by about 3 - 6%. It should be noted that dry growing season occurs more often in this region of Lithuania. During the studies the groundwater level rises to 0.84 ± 0.11 m below land surface in early spring (April) and drops to 1.58 ± 0.25 m later in summer (July – August). Available soil water storage in spring were 80 - 100 mm.

Data collection and analysis. The drainage systems chosen for the research were similar in their characteristics: drainage coefficients were 1.1 ± 0.3 and 1.2 ± 0.4 mm d^{-1} respectively. Statistical analysis showed that they were not significantly different at $p \leq 0.05$.

To evaluate the hydrological effect of controlled drainage, drain discharge and groundwater table depth were measured every 1 - 5 days, depending on the drainage intensity during the main drainage season in both systems. Groundwater table depth was measured in three observation wells (PVC Ų50 mm) installed at the midpoint between the parallel laterals to a depth of 1.1 m. Discharges of FD and CD treatments were measured in volumetric way in drainage manhole simultaneously. Drainage coefficients were calculated for each discharge measurement. Monthly and annual drainage outflow for each treatment was calculated too.

Table 1. **Rainfall and air temperature recorded at the meteorological station, located nearby the experimental site**

Index	Year							
	2000	2001	2002	2003	2004	2005	2006	2007
Annual precipitation, mm	563	571	465	456	564	418	465	668
Percentage of the norm*	95	97	79	77	96	71	79	113
Precipitation of the warm period*, mm	396	384	298	328	388	291	338	442
Percentage of the seasonal norm*	99	96	75	82	97	73	85	111
Annual air temperature, ^{o}C	8.2	7.8	8.0	7.1	7.0	7.0	7.7	7.9
Temperature deviation, ^{o}C**	+2.0	+1.6	+1.8	+0.9	+0.8	+0.8	+1.5	+1.7

Note: * the long-term average of annual precipitation - 590 mm, the norm of warm period (April - October) - 399 mm;
** the annual mean temperature +6,2 ^{o}C.

Samples of drainage water were collected for analysis once a week, or twice a month, subject to the drainage intensity. Water was analysed for inorganic nitrogen (NO_3-N and NH_4-N). Concentrations were determined by the spectrometric method, using an FIA Star 5012 analyser, according to the water quality investigation standards (LST EN ISO 13395:2000; LAND 38:2000). The runoff of nitrate nitrogen was calculated on the basis of the linear interpolation method.

A conventional cropping rotation and land cultivation were applied in the site. The beginning of drainage outflow control in spring was chosen taking into account crop requirements and climatic conditions. The control device was opened in case when water level had risen close to the soil surface during spring melting. Drainage outflow was withheld when groundwater table depth in the site dropped to 0.70 m below soil surface.

The reliability of the results was determined by processing them using mathematical-statistical methods. Differences of drainage treatments were tested at the significance level $p \leq 0.05$.

Results and discussion

Groundwater table regime. One of the targets of drainage outflow management is raising groundwater level in a drained area. However, according to the research results, it is not always possible to achieve that. In the experimental site it was impossible to maintain the groundwater table constantly at designed 0.68 m throughout the growing season (not enough rain), therefore, groundwater table fluctuated in response to weather conditions. During the studies the total length of time the groundwater table persisted above the drains level ranges between 28 and 75 days.

According to the data, under the climatic conditions of Middle Lithuania in spring 0.5 to 8.0 mm drainage outflow was retained by controlling water level in the drainage outlet. The retained quantity of water only partially depended on the continuance of groundwater table management throughout the year (r=0.54). Such climatic factors as precipitation and the mean air temperature have a much greater influence on the retained outflow (r = 0.87-0.98). The groundwater table persistence at its highest level (0.40-0.68 m above the drains) correlate with precipitation more significantly, while overall persistence (in the range of 0.0-0.68 m) more significantly correlate with mean daily temperature (as with increased total evaporation less precipitation passes into the drains and due to that water level drops gradually). The strongest logarithmic relationship (r = 0.86) is obtained between the groundwater table persistence above the drains and precipitation likelihood (Fig. 2). In the case of dry or moderate spring (above 25% likelihood) the groundwater table above the drains must be retained for 30–40 days, in the wet period (below 25% likelihood) - up to 2.5 months.

Groundwater table depth in CD treatment was significantly higher in April 2002, February and March 2004 and April 2006, while in November 2006 it was significantly lower than in FD treatment (Table 2). There were no significant differences between drainage treatments during all the other periods. That is partly related with drainage parameters and the climatic conditions of the research period. Due to relatively small diameter of laterals (40 mm) and considerable spacing between drains (20-24 m), lateral seepage was insufficient to elevate groundwater table. As it is referred, controlled drainage requires about 65% of the spacing normally needed for drainage alone. Drain tubing depth should be shallower than the depth for conventional drainage (Belcher and D'Itri, 1995).

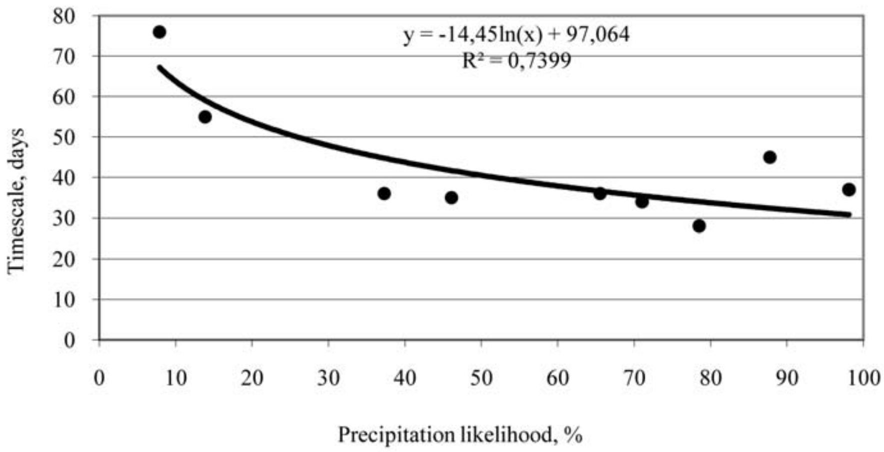

Figure 2. **Relationship between the groundwater table persistence above the drains (*y*) and precipitation likelihood (*x*)**

Table 2. **Groundwater table depth in between the drains of FD and CD systems** (monthly means and confidence intervals)

Date	FD	CD	Date	FD	CD
2001 05	0.84±0.06	0.86±0.06	2004 11	0.51±0.18	0.48±0.17
2001 10	0.52±0.21	0.55±0.19	2004 12	0.41±0.21	0.37±0.15
2001 11	0.39±0.14	0.36±0.14	2005 05	0.98±0.07	1.02±0.08
2001 12	0.77±0.18	0.78±0.14	2006 04*	**0.64±0.15**	**0.56±0.16**
2002 03	0.43±0.20	0.39±0.21	2006 05	1.11±0.05	1.07±0.06
2002 04*	**0.87±0.02**	**0.76±0.01**	2006 11*	**0.38±0.06**	**0.51±0.10**
2003 04	0.48±0.10	0.51±0.06	2006 12	0.40±0.02	0.38±0.05
2003 12	0.41±0.13	0.39±0.11	2007 01	0.39±0.15	0.34±0.14
2004 02*	**0.54±0.21**	**0.41±0.18**	2007 05	0.70±0.34	0.65±0.33
2004 03*	**0.35±0.28**	**0.29±0.26**	2007 10	0.60±0.32	0.62±0.33
2004 04	0.80±0.23	0.83±0.20	2007 12	0.61±0.21	0.53±0.22

* differences statistically significant at $p \leq 0,05$

Drainage outflow. While analysing the drainage activity it was found out that free conventional drainage flow continues nearly two times longer than the controlled one – 1423 and 725 days respectively (Table 3). In a dry year the flow duration of the CD was 2.6 times (by three months on average) in a moderate year – 1.6 times shorter. Statistical evaluation showed that these differences are significant. Accordingly, a statistically significant difference of the annual drainage outflow between treatments was established: it was 25% (184 mm) lower in CD area on the average compared with FD area.

Table 3. **Drainage outflow characteristics during the study period**

Year	Flow duration, days			Annual outflow, mm		
	FD	CD	Δ, days	FD	CD	Δ, mm
2001	232	141	91	174	131	43
2002	140	54	86	63	46	17
2003	159	43	116	46	26	20
2004	262	166	96	153	105	48
2005	127	51	76	64	59	5
2006	167	77	90	37	26	11
2007	336	193	143	193	152	41
Total sum	1423	725	698	730	546	184

Δ – difference between treatments

A warmer and drier than usual growing season in the years of 2002 - 2005 (75 and 73% of long-term precipitation norm) determined greater depletion of soil water supplies and the abatement of ground water into deeper layers, therefore, the non drainage period extended far in the autumn. Under prolonged dry conditions in spring 2000, 2001, 2004 and 2005 there was a shortage of water (from rainfall) to maintain an elevated groundwater table. The ascending water level in the control device did not induce a quick groundwater table level rise and did not have any considerable impact on the formation of depression curve in between drains in CD treatment. The retained outflow spread out in the soil around the drainpipe within an area affected by groundwater table management. Under such conditions CD system will not offer an advantage over a conventional drainage. Under prolonged wet conditions (when wet autumn coincides with warmer than usual winter (2003 –2004 and 2006 – 2007), the water level rose up to the arable layer quicker and was closer to the soil surface in CD treatment. However, the proportion of water retained by elevating the groundwater table was insignificant. The significant water level differences in treatments were established, when the drainage outflow control was started directly after peak period in spring. When the control was delayed, there was not enough water to reach the designed groundwater table level.

Water quality and Nitrogen losses. In the course of the investigations groundwater table management had different impact on drainage water quality and nitrogen losses. In 2001–2005 the average annual concentration of nitrate nitrogen in CD water was 5–13% lower and NO_3–N losses were 31% lower on the average than in FD treatment (Table 4). These results correspond with a common impact of controlled drainage – an elevated groundwater table level creates anaerobic conditions that promote denitrification and decrease in nitrate concentration, herewith nitrate nitrogen leaching is reduced (Twitty and Rice, 2001). According to Evans et al. (1995) controlled drainage may reduce nitrate-nitrogen concentrations in drainage outflow by up to 20%.

Extreme values of nitrate nitrogen in controlled drainage water were found in the years of 2006-2007. NO_3-N concentration of this period in CD water was 29–72% higher in comparison to FD. Extreme value reached 24.7 mg l^{-1} and was 7% higher than MAC (according to Lithuanian standards the maximum allowable concentration of NO_3-N into the natural environment is 23 mg l^{-1}, MAC of NH_4-N - 5 mg l^{-1}). The reason for such high in NO_3-N concentrations was dry summer-autumn season in 2005 and the lack of precipitation in the beginning of summer 2006, when only 35% of the precipitation norm fell. Because of a lack of moisture in the soil plants used fertilizers inefficiently. In that case mineral nitrogen accumulates in soil. When drainage outflow started, better conditions for leaching existed in CD area. Meanwhile, the water in FD system flowed to the drains from deeper layers where less nitrogen compounds accumulated. Due to the impact of meteorological factors a higher NO_3-N concentration in CD drainage water lasted even 11 months (Fig. 3).

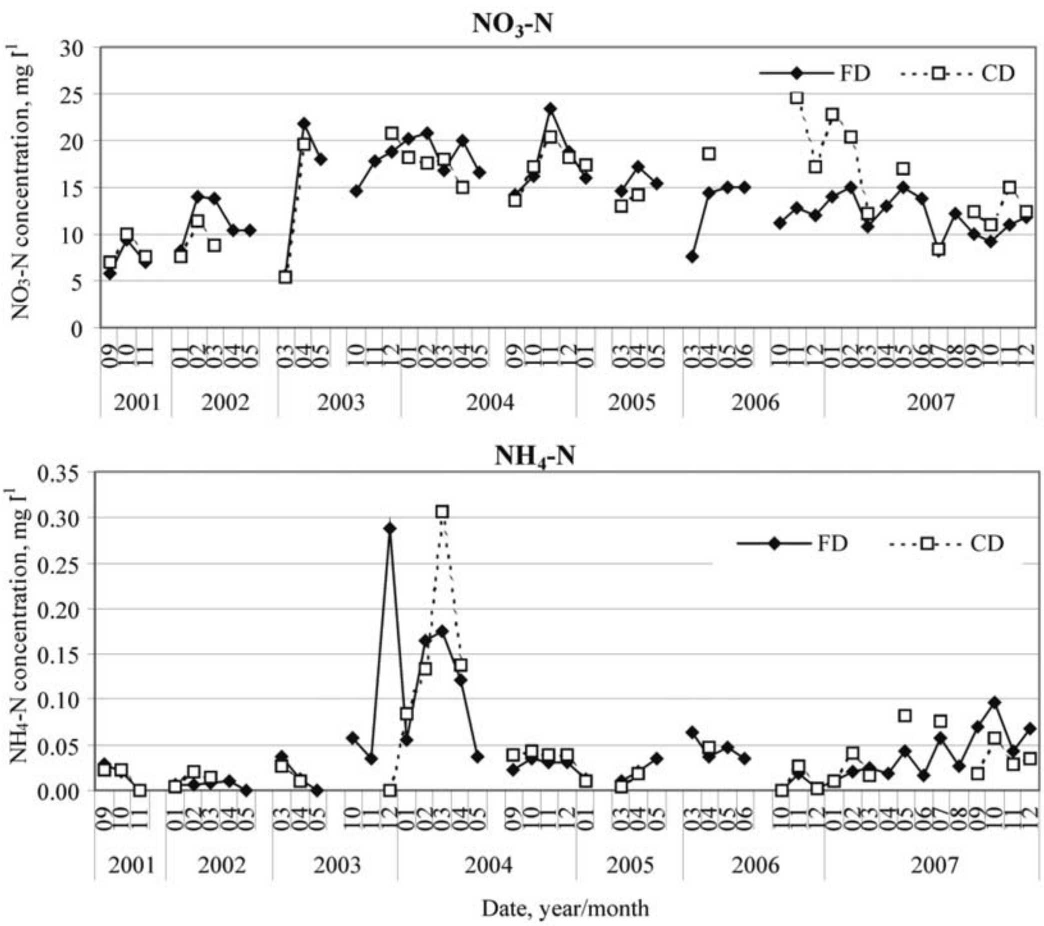

Figure 3. **Dynamics of nitrate and ammonium nitrogen concentration in drainage water**

In recent studies, no statistically significant differences in nitrate concentrations have been found in conventional and groundwater table management systems. The reductions in nitrate nitrogen loads determined in controlled drainage system are conditioned by reduction in drain outflow. Some authors propose that up to 70-90% of drainage outflow can be retained by controlling water level (Lalonde et al., 1996; Wesström et al., 2003; Cooke et al., 2006). Evans et al. (1995) stated that the total drainage outflow might be reduced by 30%. They concluded that controlled drainage reduced nitrogen transport at the field edge, primarily because of the reduction in outflow volume. There is less water leaving the field through the drainpipe, and therefore, less nitrate flowing out of the drain, even if there is no change in nitrate concentration.

The concentration of ammonium nitrogen in FD and CD water varied differently. Extreme values of NH_4-N concentration were related with heavy melting of certain periods, when water level rose to the cultivated layer rich in mineral nitrogen. However, they were lower than MAC. In December 2003 the highest concentration of NH_4-N in FD and CD area reached 0.3 – 0.9 mg l^{-1} and in March 2004 – 0.2–0.3 mg l^{-1} respectively. During autumn 2006 and winter 2007, when a pronounced increase of NO_3-N concentration was recorded in CD drainage water, NH_4-N concentration did not differ significantly: FD – 0.01 mg l^{-1}, CD – 0.04 mg l^{-1}.

The nitrate and ammonium nitrogen losses in the experimental site were related to the drain outflow variation depending on the amount of precipitation. Compared with FD, the annual reduction of NO_3-N in dry years in CD was 28% (Table 4). In moderate years, the corresponding reduction was about 20%. However, statistically these differences are not significant. Contradictory data were found in 2006 and 2007, when despite the decrease of the annual drainage outflow of 30 and 21% in CD area, NO_3–N loses increased slightly compared to FD system. That was related with greater NO_3-N concentration in drainage water in CD treatment. The total nitrate nitrogen losses from CD area were 22% lower compared with FD treatment during the investigations (2001–2007). However, on the basis of *t*-test these differences cannot be regarded as statistically significant at $p \leq 0.05$.

Table 4. **The amount of nitrate and ammonium nitrogen leached from FD and CD systems in the experimental site. Retention '–' and loss '+' presented as difference (Δ), %**

Year characteristic		NO_3-N, kg ha^{-1}			NH_4-N, g ha^{-1}		
		FD	CD	Δ, %	FD	CD	Δ, %
2001	moderate	16.7	14.4	-14	90	22	-76
2002	dry	8.9	4.4	-51	5	8	+60
2003	dry	7.9	4.6	-42	90	167	+86
2004	moderate	29.5	17.9	-39	135	116	-14
2005	dry	10.2	9.0	-12	10	9	-10
2006	dry	4.4	4.5	+2	8	6	-25
2007	humid	23.5	23.8	+1	78	31	-60
Total sum		101.1	78.6	-22	416	359	-14
Average of dry years		7.8	5.6	-28	28	48	+68
Average of moderate years		23.2	18.7	-20	101	53	-44

On the subject of NH_4-N leaching it is difficult to identify any consistent pattern. The values of ammonium nitrogen loss in particular years changed widely in both treatments (variation coefficient CV = 87-125%). Calculating the leached amount of NH_4-N within the entire study period there was a statistically insignificant difference of 14% between treatments.

Conclusions

In the controlled drainage system that was not adapted for subirrigation, the duration of the groundwater table persistence above the drain tubing is conditioned by the beginning of drainage outflow control as well as the period's meteorological conditions. This time is related to the seasonal rainfall, air temperature (r = 0.87-0.98) as well as to the precipitation likelihood (r = 0.74).

When controlling the water level in drainage outlet, annual drainage outflow lasted shorter by 40-62%, at the same time it was reduced by 25% and nitrate leaching – by 20-28% (in comparison with drainage operating in an ordinary regime). These indices varied depending on weather conditions: in dry years the difference between treatments was higher and in moderate years it was lower.

In the drainage systems adapted only for water removing, the maintenance of optimal groundwater table depth for vegetation of agricultural crops is complicated. However, groundwater table control makes more effective use of rainfall and soil moisture supplies, herewith can minimize agricultural pollution. This practice helps to improve water quality of surface water bodies.

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