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Controlled drainage — effects on drain outflow and water quality

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Abstract

A field experimental project was set up in southern Sweden to assess the effects of controlled drainage on hydrology and environment. Controlled drainage makes it possible to vary the drainage intensity with the variation in drainage requirement during season by controlling the height of a riser in the drain outlet and thus to a certain degree control the amount of outflow of solutes via the drainage system. During periods with low drainage demand, the riser in the drain outlet can be raised and the groundwater level in field will rise up to the level of the riser before the discharge takes place. Three plots, each with an area of 0.2 ha (40 m×50 m) were installed on a loamy sand. One plot was drained by conventional subsurface drainage (CD) and two plots were drained by controlled drainage (CWT). The plots contained four lateral drain tubes, at 10 m spacing and placed at 1 m depth. Each plot was isolated by a double layer of plastic sheeting placed in the back-filled trenches to a depth of 1.6 m to prevent lateral leakage and subsurface interactions. Measurements of precipitation, drain outflow and soil and air temperatures were carried out hourly. Groundwater levels were measured and samples of drain outflow were collected twice a month for nitrogen and phosphorous analyses. Mineral nitrogen contents in soil were measured three times a year.

Controlled drainage had a significant hydrological and environmental effect during the 2 years of measurement (1996–1998). Compared with CD, the total drain outflow from CWT was 79% less in Year 1 and 94% in Year 2. The total reduction in nitrate losses with CWT corresponded to the reduced outflow rates. Compared with CD, the total amounts of nitrate in drain outflow were 78% less in Year 1 and 94% in Year 2. The highest concentrations of nitrate were measured at the time of the largest outflow rates. The phosphorous losses were 58% less for CWT as compared to the CD values in Year 1 and 85% less in Year 2. The reduction in nitrogen content in the soil profile during the winter season was 60–70% less in CWT than in CD. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Controlled drainage; Drain outflow; Nitrogen leaching; Phosphorous losses; Mineral nitrogen content in soil

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1. Introduction

Natural drainage processes are not sufficient for agricultural production on most Swedish arable land. Drainage intensity and drainage system design are based on the requirement for drier soils with better accessibility and greater bearing capacity, an extension of the period in which tillage operations can take place and protection of crops from excessive soil water conditions. Besides creating a favourable crop growing environment, good subsurface drainage (CD), compared to natural drainage, generally increases peak outflow rates. It also brings about a decreasing surface run off and thereby reducing losses of sediment, phosphorus, organic nitrogen and pollutants attached to sediments. In Sweden, peak nutrient losses occur during the winter and early spring due to both, a precipitation surplus and the limited demand of a crop for available nutrients during this period. Heavy N fertilizer rates and current cropping patterns are also contributing factors.

The rates of nitrogen leaching range from 5 to 100 kg ha^{-1} and year (SNV, 1997a). About 45% of the anthropogenic nitrogen loads reaching the seas come from arable land. Based on an international agreement, the Swedish government determined an environmental goal of a 50% reduction of nitrogen loads to the seas during the period 1985–1995. In 1995, the reduction of nitrogen loads only reached 20%. It is estimated that about 10% of this reduction was due to a decrease in total arable land area, about 50% to a change in crop rotation (mainly increasing areas of temporary pasture and fallow land and decreasing areas of cereals) and about 40% to an increased nitrogen use efficiency by improved fertilisation and increased crop harvests (SNV, 1997b). A new goal has recently been set. The nitrogen loads from arable land to the seas are to be reduced by 40% as compared to the 1995 level and this goal should be obtained within one generation (Svenska Miljömål, 1997).

Nitrogen leaching from arable land in Sweden has been studied in subsurface drained plots and lysimeters. The research has focused on evaluating alternative cropping and soil management practices to reduce nitrogen leaching (Lindén et al., 1993; Torstensson et al., 1996; Stenberg et al., 1997; Weslien et al., 1997) and has contributed to the formulation and implementation of guidelines for farmers concerning cropping (e.g. catch crops, soil cover in winter), soil management practice (e.g. timing and methods) and fertilisation practices (e.g. timing of manure application). Despite progress in decreasing the amounts of nitrogen available for leaching, the fact still remains that the outflow of nutrients from agricultural land is highly dependent on the amount of run off, which in turn depends on the amount of rainfall. The great variability in annual run off leads to great variability in annual losses of nutrients between years within a small geographical area.

The need for drainage varies with soil type, site conditions, crop, time of season and variation in precipitation between years. Once the installation of a drainage system is completed, the land is drained, thereafter, according to the pre-designed drainage intensity. However, a new variable drainage water management technique to reduce off-site environmental impacts has been extensively researched in the USA and Canada (Skaggs et al., 1992; Lalonde et al., 1996). The technique is simple and involves using different heights of riser in the drain outlet. During periods of peak drainage requirement, the water level in the field rises up to the level in the riser. The concept of controlled drainage (CWT) makes it possible to vary the drainage intensity with the variation in drainage demand and thus to control the amount of outflow from the drainage system and thereby the amount of soluble nutrient losses. An analysis of 14 studies in North Carolina showed that CWT reduced total annual nitrogen losses at the field edge by an average of 45% (10 kg ha^{-1}) and total phosphorus losses by 35% (0.12 kg ha^{-1}). The total drain outflow was reduced by 30% (Evans et al., 1992). Because of the environmental benefits of CWT, it has been accepted as 'best management practice' by the regulatory agencies in North Carolina. The technique has been introduced on 800 000 ha in humid regions of the US (Evans et al., 1995).

When the riser in the drain outlet is raised, the drainage intensity decreases and any excessive rainfall will cause the groundwater level in the field to rise up to the level of the riser before the discharge begins. As a result, a larger part of the subsoil is submerged. The retention time of water in soil increases, leaving more water available for evapotranspiration and for interim storage of soluble nutrients. The decreased drainage intensity reduces the outflow through the drain and, depending on the drainage system management and site conditions, may increase surface run off and lateral and deep seepage. The anaerobic conditions created in the submerged soil will affect both chemical and biological processes. Depending on the soil type, site, season and climate, the fate of nitrogen present as nitrate in the soil will be affected. The nitrates, whether added as fertilisers or formed by nitrification, may be taken from the soil in one of four ways; (i) incorporated into micro-organisms, (ii) assimilated into higher plants, (iii) lost in drainage, and (iv) lost to the atmosphere in gaseous form. Nitrification is an aerobic process, generally carried out by autotrophic bacteria that oxidise ammonium to nitrate with oxygen as an electron acceptor. Nitrification is retarded by high soil water contents and in the absence of oxygen, nitrate is subsequently reduced to dinitrogen gas by denitrifying bacteria that use the NO_x^- as an alternative electron acceptor to oxygen. Recently, a new process producing dinitrogen gas was discovered (Mulder et al., 1995). This is an anaerobic process in which ammonium is oxidised by autotrophic bacteria that use nitrate as the electron acceptor under anaerobic conditions (Anammox). Mineralisation, in which organic N is converted to ammonium, will take place to some extent under almost any conditions but the magnitude of gaseous N losses will greatly increase under favourable anaerobic conditions. This prevents pollution of groundwater but is a waste of resources and so the outcome of these contrasting effects must be balanced against each other.

In 1996, a pilot field experimental project was initiated to assess the effects of CWT on hydrology and environment under the climatic conditions and soils of southern Sweden. The study included watertable strategies subjecting the subsoil to various degrees of water status. The effects on drain outflow, nutrient losses, soil aeration, nitrogen flow and crop performance were measured. In this paper, results are presented from 2 years of field experiments on drain outflow and nutrient losses.

2. Materials and methods

2.1. Field plots

A field trial was established at Månstorp (southwest Sweden 56°29′N, 13°0′E, in the County of Halland) and run over two periods, September 1996 to June 1997 (Year 1) and

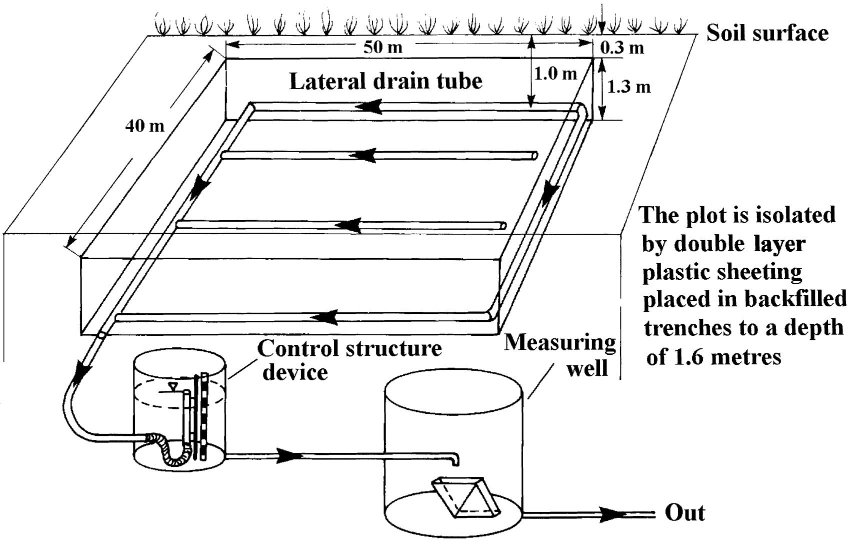

Fig. 1. CWT plot design.

July 1997 to June 1998 (Year 2). The criteria for selection of the site were level topography and homogeneous soil with high saturated hydraulic conductivity in the topsoil and low saturated hydraulic conductivity in the subsoil, the latter a barrier to deep seepage. Three plots were installed, each with an area of 0.2 ha (40 m×50 m). One plot was drained with conventional CD drainage and two duplicate plots were drained with controlled drainage (CWT1 and CWT2) (Fig. 1). In the following, CWT denotes the arithmetic mean of CWT1 and CWT2. Each plot contained four lateral drain tubes (diameter 50 mm), at 10 m spacing and 1 m depth. The circumference of each plot was isolated by double layer plastic sheet placed in back-filled trenches to a depth of 1.6 m to prevent lateral leakage and subsurface interactions. The drain outflow from CWT plots was collected in a control structure device and then conducted further to a measuring well. The control structure was used to restrict drain flow by raising the outlet and allowing the groundwater level to rise to a pre-selected maximum height (60–70 cm below the soil surface in Year 1 and 30–40 cm in Year 2). Drainage water from the CD plot was collected into a measuring well.

During 1996, the plots were planted with potato (*Solanum tuberosum* L.), a crop that leaves a high amount of nitrate available for leaching (Madramootoo et al., 1992). In the same year, the plots were sown with winter barley (*Hordeum vulgare*) in late autumn (failed crop) and then re-sown in the spring of 1997 with a spring barley cultivar (*Hordeum distichum*).

2.2. Climate

Månstorp has a cold, semi-humid climate with an annual mean temperature of 7.2°C. Two months (January and February) have a mean temperature below 0° (Alexandersson

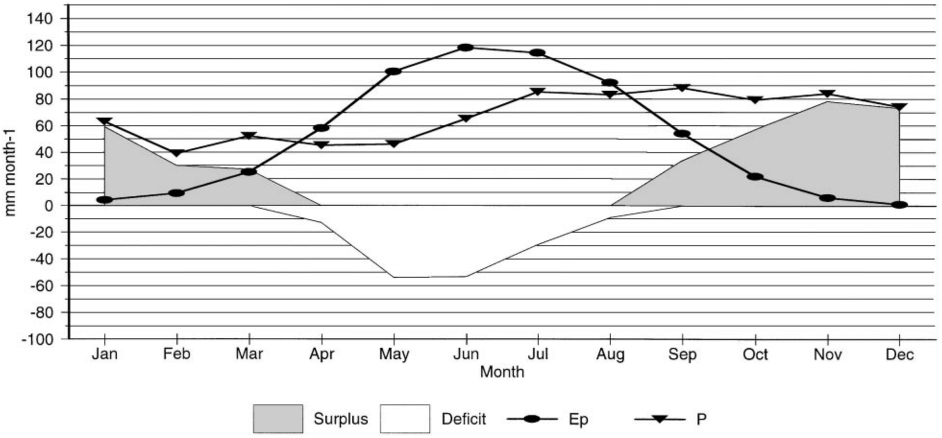

Fig. 2. Mean (30-year average) monthly precipitation (P), potential evapotranspiration (Ep) and periods of surplus and deficit precipitation during the year.

et al., 1991). The mean annual precipitation is 803 mm and the mean annual potential evapotranspiration estimated from the Penman equation is 585 mm, using data from Halmstad 1961–1990, 30 km north of Månstorp (Eriksson, 1981). Between September and March there is an average precipitation surplus calculated, as precipitation minus potential evapotranspiration, of 358 mm (Fig. 2).

The annual precipitation of 603 mm for Year 1 (Table 1) and 602 mm for Year 2 (Table 1) was below the mean annual precipitation.

Table 1
Monthly drain outflows and precipitation

Month	Year 1				Year 2			
	CD (mm)	CWT1 (mm)	CWT2 (mm)	Precipitation (mm)	CD (mm)	CWT1 (mm)	CWT2 (mm)	Precipitation (mm)
July	–	–	–	44.0	0	0.01	0.01	43.9
August	–	–	–	60.6	0	0	0	10.4
September	–	–	–	66.9	0	0	0	44.5
October	1.1	0	0	47.9	0	0	0.01	76.2
November	64.2	12.3	11.2	67.2	2.5	0.2	0.4	28.4
December	39.3	14.4	18.6	38.7	43.7	0.3	2.3	56.5
January	0	0.01	0.01	4.9	47.2	0.1	2.8	41.4
February	11.9	0.1	0.1	60.5	76.8	0.3	1.6	63.2
March	30.0	3.1	8.5	29.2	39.6	8.5	7.6	38.8
April	5.0	0.03	0.03	36.6	19.9	0.3	2.5	56.5
May	20.9	0.1	4.3	70.1	1.6	0.1	0.02	8.3
June	0.01	0.2	0.5	76.6	8.2	0.1	1.2	133.4
Total	172.4	30.2	43.2	603.2	239.5	9.9	18.4	601.5

2.3. Soil

Soil texture was determined using methods of sieving and pipetting (Ljung, 1987). The topsoil (0–20 cm) at the site was a weakly structured loam (FAO, 1990) with an organic matter content of 6%. The subsoil (20–70 cm) was a single grained loamy sand with zero organic matter content. A glacifluvial clay layer was found at a depth of 1 m.

Saturated hydraulic conductivity and soil water retention characteristic data were determined on undisturbed 10 cm high (7.2 cm diameter) soil cores in steel cylinders (four replicates) from each 10 cm level of the profile down to 1 m depth. The average values of saturated hydraulic conductivity determined by a constant head method in the laboratory (Andersson, 1955) varied between 8.2 m per day in the topsoil and close to 0 m per day at a depth of 90–100 cm. Drainage equilibrium relationships were calculated from soil water retention characteristics. Porosity was on average 41% (33.4–53.5%) for the entire soil profile and the maximum water storage capacity of the soil profile to 1 m depth was 412 mm. At a drainage equilibrium of a water table depth of 1 m (calculating from progressive water tensions in each 10 cm layer above the water table) the water storage capacity of the soil profile to 1.0 m depth was 306 mm. At a water table depth of 0.6–0.7 m, the water storage capacity of the 1.0 m deep soil profile was 356 mm and at a water table depth of 0.3–0.4 m was 385 mm.

Precipitation and capillary rise can replenish the water storage near the soil surface, which is depleted by evaporation. The capillary rise potential was measured in the laboratory (three replicates) by a method described by Beskow (1929). The average capillary rise was approximately 20 cm for the 0–50 cm layer and 35 cm for the deeper part of the soil. Thus, when the water table was at its maximum height in CWT treatments, capillary rise brought the top of the capillary fringe to within 30 cm of the soil surface in Year 1 and almost to the soil surface in Year 2.

3. Measurements and sampling

3.1. Water flow parameters

Precipitation was measured hourly near the site with a tipping-bucket rain gauge connected to a multichannel data logger (CR10X, Campbell Scientific). Air and soil temperatures were recorded hourly with thermoelement cables connected to the same logger.

Five groundwater observation wells (4 cm diameter) were installed in each plot. Two wells were installed over the central lateral drains to a depth of about 0.8 m and three midway between the drains to a depth of 1.1 m. Groundwater levels were measured twice a month during winter seasons by inserting a sonic water sensor mounted on a graduated rod. The groundwater levels outside the plots and the water levels in the control structure devices were monitored with pressure transducers (BTE2000G, Sensor Technics) connected to data loggers (ACR/SR7, Status Instrument Ltd) (data not reported).

The drain outflow from each plot was measured in the measuring well by means of tipping buckets, calibrated twice a year. The tipping buckets were wired to a multichannel data logger (CR10X, Campbell Scientific). The data stored in the logger was downloaded once a month with a laptop computer.

3.2. Nutrient parameters

Mineral nitrogen contents in the soil profile were measured three times a year; in early spring, at harvest and in late autumn by a method described by Lindén (1981). Soil sampling depths were 0–30, 30–60 and 60–90 cm. Pooled into two samples were 20 subsamples, analysed from the topsoil (0–30 cm) of each plot. Subsamples (10) were pooled into one sample and analysed from each layer of the subsoil (30–60 and 60–90 cm) of each plot. The samples were stored frozen (−20°C). After thawing and extraction with 2 M KCl, nitrate and ammonium were determined with automatic colorimetric methods (Tecator, 1983, 1984). The values obtained were transformed to kilogram per hectare using values of average dry bulk densities and gravimetric water contents measured under field conditions.

Samples of drainage water were collected for analysis twice a month during flow periods. Water was analysed for nitrate, ammonium, total nitrogen, phosphate and total phosphorous according to Swedish Standards. The concentrations of nitrate were determined with the colorimetric cadmium reduction method (Grasshoff, 1964; Wagner, 1974). Concentrations of total nitrogen were determined in the same way after oxidising organic and inorganic nitrogen compounds to nitrate. The concentrations of phosphate were determined with the colorimetric ascorbic acid reduction method. Concentrations of total phosphorous were determined in the same way after oxidising organic and inorganic phosphorous compounds to orthophosphate. Daily values of concentrations were obtained by linear interpolation of the measured values. Daily leaching was calculated by multiplying daily drain outflow values by daily concentration values.

4. Results and discussion

4.1. Groundwater levels

The groundwater levels (three replicates per plot) fluctuated more in CWT than in CD (Fig. 3). The groundwater level between tile drains in CD rose, due to recharge to the groundwater from excess rainfall, to a maximum value of 80 cm below soil surface. The groundwater level in CWT was generally higher than in CD (Fig. 3). The level in CWT reached the same level as in the riser in November 1996. After a decline in January 1997, the CWT groundwater level rose again in March. In Year 2, the groundwater level fluctuation followed the same pattern of winter and spring peaks as in Year 1 with a smaller trough in between, but the peaks were considerably higher due to a higher preselected groundwater level in Year 2.

The fluctuations in groundwater levels can partly be explained by the climatic conditions and partly by the coarse soil texture. During periods of soil temperatures below zero (January and February), water is drawn towards the freezing layers and the groundwater level declines (Håkansson, 1960). It was not necessary to artificially lower

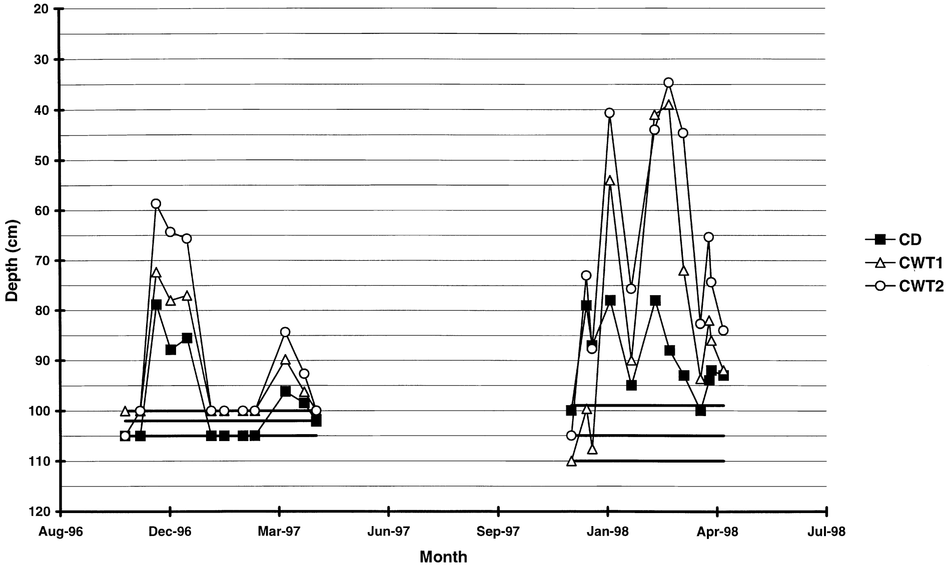

Fig. 3. Groundwater levels in observation well midway between the tile drains in CD and CWT during the winter season of Years 1 and 2.

the groundwater level in CWT to provide trafficable conditions at the time of spring tillage. This suggests a high evaporation rate from CWT, supported by a capillary rise from a declining groundwater level that, prior to spring tillage, brought the waterfront to within 30 cm of the soil surface in Year 1 and almost to the soil surface in Year 2. It was shown in lysimeter trials conducted in a greenhouse on sandy soil during a winter period of 87 days that the difference in evapotranspiration between a water table at 40 cm and a water table at 1.0 m was 120 mm (Benz, 1987).

4.2. Drain outflow

Surface run off from rainfall or snowmelt was not observed during the 2 years of measurement. Controlled drainage had a significant hydrological and environmental effect during the 2 years of measurement (Fig. 4). For CD, total drain outflow for the winter was 172 and 240 mm in Years 1 and 2, respectively. The discrepancy is due to a difference in precipitation during these periods (432 and 503 mm, respectively) and perhaps also to a longer period of soil frost in Year 1 (Table 1). In comparison, the total drain outflow from CWT was reduced by 79% in Year 1 and by 94% in Year 2.

In October of Year 1, all three field plots had the same water content in the soil profile. The drain outflow began at the end of October from CD and 1 week later from CWT (Fig. 4). During the first year of measurement there were two distinct periods of outflow, coinciding with the peaks of groundwater levels, with a period of soil frost between. In year 60% of the total outflow from CD was measured, during November to December, with a maximum peak flow of 5.3 mm per day (Table 1). Around 79% of the total outflow

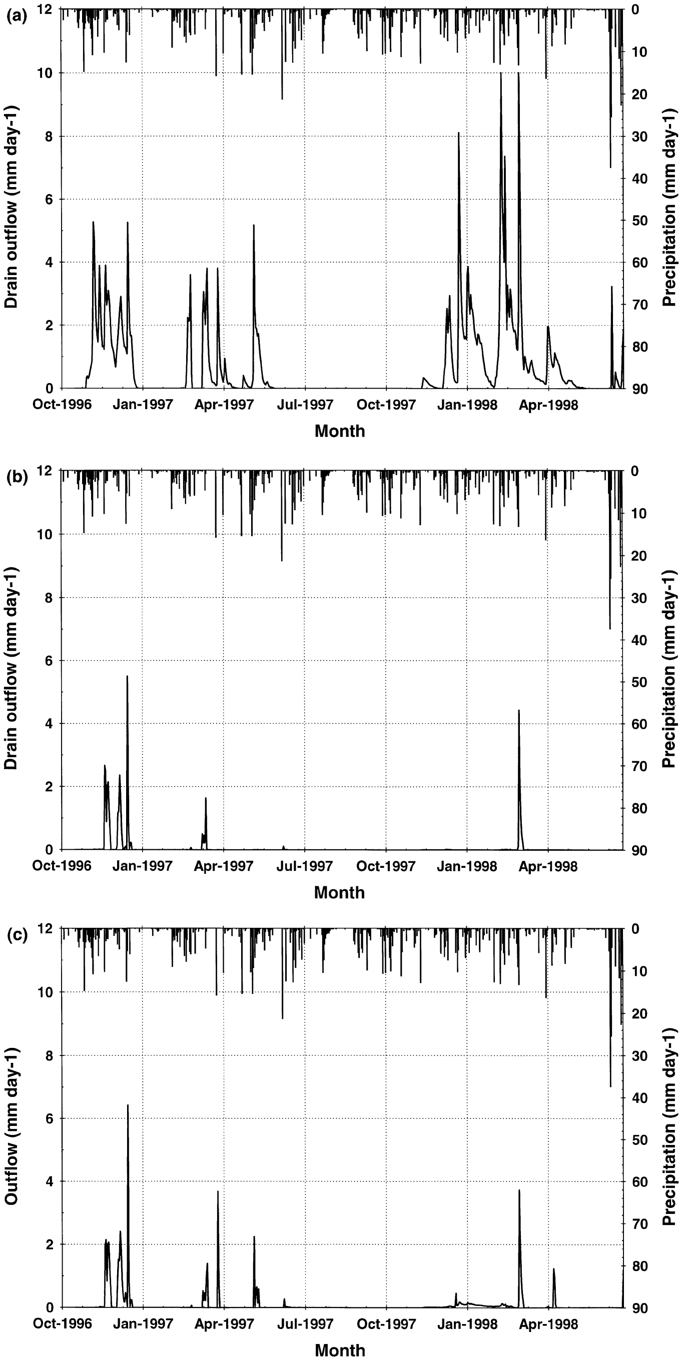

Fig. 4. Daily drain outflow (bottom lines) for (a) CD, (b) CWT1 and (c) CWT2 and daily precipitation (upper bars).

Table 2
Monthly values of losses in nitrate (NO_3^-) and phosphorous (P-Tot) in the drain outflow

Month	CD		CWT1		CWT2	
	NO_3^- (kg ha^{-1})	P-Tot (kg ha^{-1})	NO_3^- (kg ha^{-1})	P-Tot (kg ha^{-1})	NO_3^- (kg ha^{-1})	P-Tot (kg ha^{-1})
Year 1						
October	0.22	0.0003	0	0	0	0
November	14.85	0.0093	3.06	0.0045	2.21	0.0030
December	9.82	0.0024	3.59	0.0052	3.50	0.0047
January	0	0	0	0	0	0
February	2.16	0.0031	0.02	0	0.02	0
March	5.71	0.0105	0.65	0.0010	2.11	0.0046
April	0.81	0.0004	0	0	0.01	0
May	4.08	0.0021	0	0	1.01	0.0005
June	0	0	0.01	0.0001	0.11	0
Total	37.65	0.0281	7.33	0.0108	8.97	0.0128
Year 2						
October	0	0	0	0	0	0
November	0.30	0.0003	0.01	0.0001	0.06	0
December	5.08	0.0046	0.04	0.0001	0.24	0
January	6.36	0.0013	0.02	0	0.47	0.0006
February	10.31	0.0114	0.03	0.0001	0.20	0.0006
March	5.02	0.0056	1.04	0.0022	0.96	0.0005
April	2.33	0.0020	0.03	0	0.33	0.0023
May	0.18	0.0001	0.01	0	0	0.0010
June	1.22	0.0001	0	0	0.16	0
Total	30.80	0.0254	1.18	0.0025	2.42	0.0050

from CWT occurred during the same period, with a maximum peak flow of 5.9 mm per day.

During Year 2, in contrast to Year 1, there was an outflow from the CD drains all the time from November to June. Considerable outflow was observed in the period from December to April, with one-third of the total outflow measured in February when the maximum peak flows of 10 mm per day were recorded (Table 1). In CWT, most of the outflow (64%) occurred in March with a maximum peak flow of 4.0 mm per day.

4.3. Nutrient losses

The total reductions in nitrate losses (Table 2) were related to the reductions in outflow (Table 1) for both measuring periods. Compared with CD, the reduction in Year 1 for CWT was 78%. In Year 2, the corresponding reduction for CWT was 94%. This represents a potential saving on fertiliser of about 30 kg nitrate per ha and year or the prevention of this amount of pollution for the same period. About 90% of total amounts of nitrogen measured in the drain outflow were nitrate, and the rest were ammonium and organic nitrogen. The time of peak losses varied with treatment and year. In Year 1, 66% of the total nitrate was lost in the outflow from CD and 77% from CWT during

Table 3
Monthly mean values of ammonium (NH_4^+) and nitrate (NO_3^-) concentrations in the drain outflow

Month	CD		CWT1		CWT2	
	NH_4^+ (mg l^{-1})	NO_3^- (mg l^{-1})	NH_4^+ (mg l^{-1})	NO_3^- (mg l^{-1})	NH_4^+ (mg l^{-1})	NO_3^- (mg l^{-1})
Year 1						
October	–	–	–	–	–	–
November	0.013	22.8	–	–	–	–
December	0.016	25.0	0.065	25.3	0.088	20.7
January	–	–	–	–	–	–
February	0.018	18.2	0.013	19.6	–	–
March	0.016	20.0	0.162	21.3	0.192	23.2
April	0.124	16.0	0.157	10.3	0.026	26.2
May	0.031	20.3	0.103	5.9	0.030	24.5
June	–	–	–	–	–	–
Year 2						
October	–	–	–	–	–	–
November	–	–	–	–	–	–
December	0.018	11.2	0.052	12.4	0.079	11.9
January	0	13.7	–	–	0.177	10.9
February	0.018	13.4	0.094	8.4	0.213	13.5
March	0.022	12.2	0.032	13.9	0.064	13.3
April	0.074	11.6	–	–	0.022	12.5
May	0.054	11.5	–	–	–	–
June	0.045	15.5	0.312	0.7	0.120	12.0

November–December (Table 2). In Year 2, one-third of the total losses from CD occurred in February, while well over half (64%) of the total losses from CWT plots were measured in March.

The nitrate concentration in the drain outflow from CD fluctuated between 16 mg l^{-1} (April) and 25 mg l^{-1} (December) during Year 1 (Table 3). In CWT, the nitrate concentrations in the drain outflow were roughly the same as in CD up to March. However, in April and May, the nitrate concentration was much lower in CWT1 (5.9 mg l^{-1}) and higher in CWT2 (24.5 mg l^{-1}) compared with CD (20.3 mg l^{-1}). In Year 2, the nitrate concentrations were initially lower than in Year 1 (Table 3) but still exceeded 10 mg l^{-1} in all plots. During Year 2, CD and CWT2 had similar fluctuations in nitrate concentrations, while those in the drain outflow from CWT1 followed the same pattern as in Year 1 with a remarked drop in nitrate concentration in late spring. At the end of June in Year 2, the nitrate concentration in CWT1 decreased to 0.7 mg l^{-1}.

The nitrate concentration is clearly affected by the water content and the temperature in the topsoil. Rapid fluctuations in groundwater levels create rapid fluctuations in nitrate concentration in drain outflows. An elevated groundwater level creates anaerobic conditions that promote denitrification (Gambrell et al., 1975; Gilliam and Skaggs, 1986). The rapid decrease in nitrate concentration in the late spring in the outflow from CWT1 suggests anaerobic conditions in the topsoil caused by capillary rise induced by heavy rainfall (Fig. 4) that raised the groundwater level and led to subsequent denitrification. Drying and rewetting and freezing and thawing cycles in a soil can result in a peak rate of

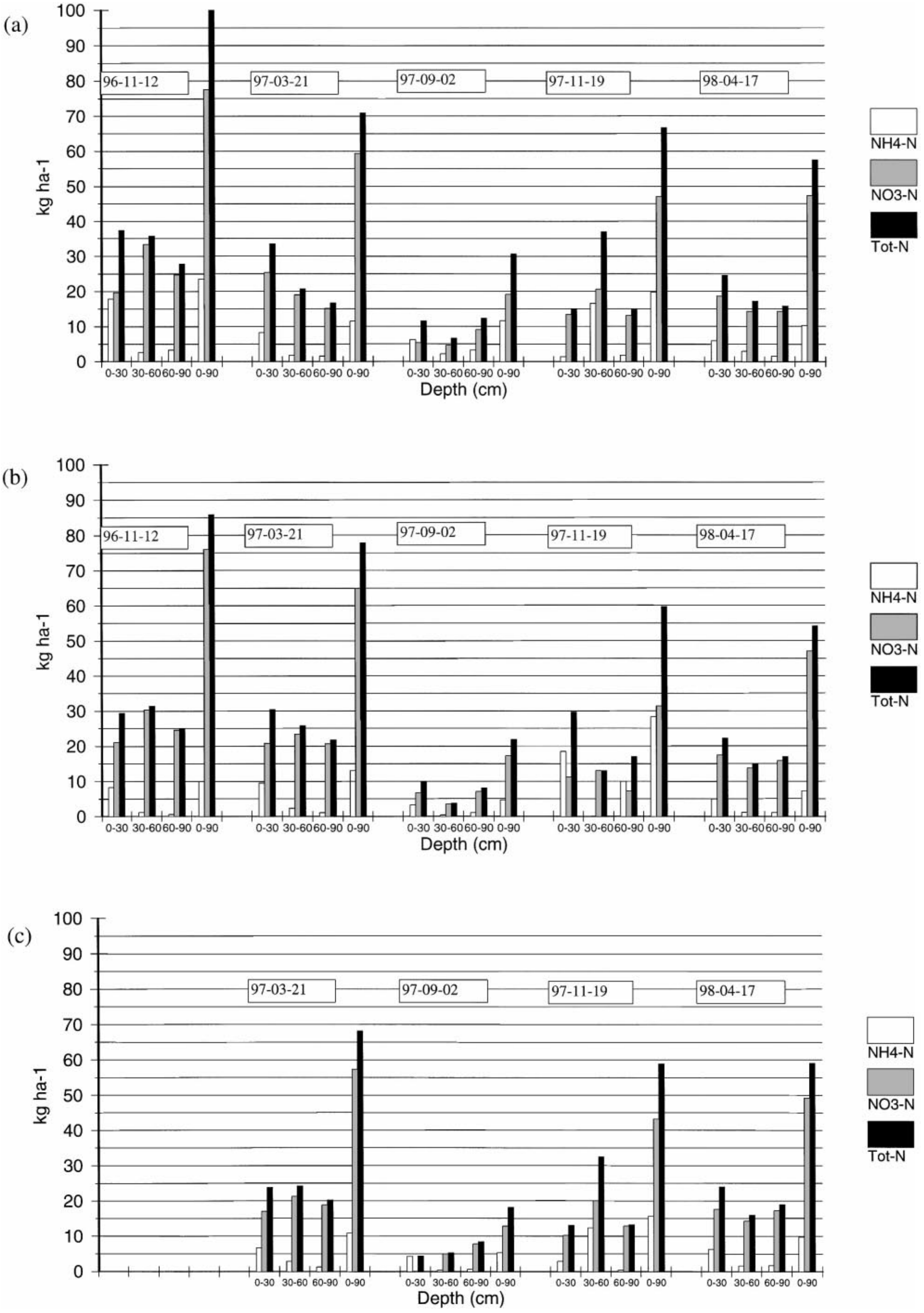

Fig. 5. Total nitrogen (Tot-N); nitrate (NO_3-N) and ammonium (NH_4-N) contents in soil in (a) CD, (b) CWT1 and (c) CWT2 on five different occasions.

decomposition of the soil humus, following a flush of ammonium and then of nitrate (Mack, 1963; Harding and Ross, 1964). Due to a low outflow rate from CWT, the sampling interval was too long to draw any conclusions but in both measuring periods there were still occasions of rapid rises in ammonium concentrations followed by rises in nitrate concentrations (March, April and December 1997) (Table 2). A similar phenomenon was observed in CD during springtime.

In Year 1, 0.028 and 0.012 kg ha^{-1} of phosphorous was lost from CD and CWT, respectively (Table 2). This corresponds to a reduction in phosphorous losses of 57% for CWT. In Year 2, the reduction in phosphorous losses was even greater, 85% for CWT (0.0038 kg P ha^{-1}) compared with CD (0.025 kg P ha^{-1}).

4.4. Mineral nitrogen content in soil

After the potato crop, the total mineral nitrogen content in soil in late autumn of 1996 was very high, 101 kg N ha^{-1} in CD and 86 kg N ha^{-1} in CWT1 (no soil samples were taken from CWT2 in late autumn of Year 1) (Fig. 5). A similar pattern was observed after harvest of the barley crop in 1997. In CWT, much (90–95%) of the mineral nitrogen present in the soil in late autumn was retained in the soil over the winter (Fig. 5). This was a period when 14–30% of the mineral nitrogen in CD was leached to the drainage water or otherwise lost from the soil. This represents a saving of 6–22 kg (losses from soil) N fertilisers per ha and year, or the prevention of this amount of pollution for the same period. By March 1997, the total nitrogen mineral content in soil had decreased by 30 kg N ha^{-1} in CD and 8 kg N ha^{-1} in CWT1. This corresponded to nitrate losses recovered in the drain outflow (Table 2). Around 10 kg ha^{-1} more nitrate was found in the subsoil (30–90 cm) in CWT1 than in CD (Fig. 5). In April 1998, the total mineral nitrogen content in the soil had decreased during the winter by 9 kg N ha^{-1} in CD and by 3 kg N ha^{-1} in CWT (arithmetic mean of CWT1 and CWT2), probably due in part to denitrification. CWT plots had a higher nitrate content in the lower subsoil (60–90 cm) than CD.

5. Conclusions

The CWT had a significant hydrological and environmental effect during the 2 years of measurement (1996–1998). Compared with CD, the total drain outflow from CWT was 79% smaller in Year 1 and 94% smaller in Year 2. The reductions can partly be explained by increased soil water storage due to a raised groundwater level and partly by climatic factors, e.g. soil frost and evaporation.

The annual precipitation was the same for both years but 200 mm below the mean annual precipitation. Despite this, there were large differences in monthly precipitation, reflected in different outflow characteristics from CD between years. The total drain outflow from the control plot for the winter was 172 mm in Year 1 and 240 mm in Year 2. This discrepancy was due to a difference in precipitation during the measurement periods (432 and 503 mm, respectively) (Table 1). Furthermore, a period of soil frost in Year 1 temporarily increased the soil water storage volume.

The total reduction in nitrate losses in CWT corresponded to the reduced outflow rates. Compared with CD, the total nitrate losses in drain outflows from CWT plots were 78% smaller in Year 1 and 94% smaller in Year 2. The highest concentrations of nitrate were measured at the time of largest outflow rates. A high water content in the topsoil and an increasing soil temperature in spring clearly decreased the nitrate concentration in the drain outflow. The nitrate concentration in drain outflow from CWT1 decreased rapidly after heavy rainfall in late spring of both years. This was probably an effect of anaerobic conditions in the soil, inhibiting nitrification and promoting denitrification.

Compared with CD, phosphorous losses in drain outflow in CWT were 58% smaller in Year 1 and 85% smaller in Year 2.

The CWT system also affected the distribution and the total content of mineral nitrogen in the soil. In CWT, most (90–95%) of the mineral nitrogen present in the soil in the late autumn was retained in the soil over the winter. In Year 1, the reduction in mineral nitrogen content in soil over the winter corresponded quantitatively to the nitrogen losses in the drainage water in both CD and CWT. In Year 2, the difference in mineral nitrogen content in soil between late autumn and spring sampling was quantitatively smaller for CD than the amount of nitrogen recovered in the drain outflow from the plot during the same time period. Only 28% of the nitrogen losses in the drainage water from CD can be referred to the reduction in mineral nitrogen content in soil during the winter season. For CWT, the reduction in mineral nitrogen content in soil during the winter season was 67% higher than the nitrogen losses in the drainage water from CWT. Once again the variation in soil temperature and water content in soil between the 2 years was reflected.

Further investigations are needed on the management of a CWT system to optimise the benefits for both environmental and agricultural production aspects. Water balances for the conventional and controlled drained plots must be established before it is possible to separate and quantify the reasons behind the differences in outflow patterns. Measurements of nutrient concentrations of soil water at different levels in the soil profile are necessary to estimate leakage to the groundwater if deep seepage occurs. Measurements of mineralisation and nitrification rates and denitrification fluxes are needed to explain differences between years and treatments in nitrogen content in soil.

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