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Research Paper

Impact of Seasonality on Artificial Drainage Discharge under Temperate Climate Conditions

key words: discharge generation, drainage water recovery, lag time, response time, tile drainage discharge

Abstract

Artificial drainage systems affect all components of the water and matter balance. For the proper simulation of water and solute fluxes, information is needed about artificial drainage discharge rates and their response times. However, there is relatively little information available about the response of artificial drainage systems to precipitation. To address this need, we analysed 11 datasets from artificial drainage study sites (daily or hourly resolution), one daily dataset from an open ditch system, and three datasets from rainfall simulations on tile-drained fields.

When we considered all 11 artificial drainage study sites, we found that artificial drainage discharge responded to 70% of all rainfall events during the year, and that the response rate differed significantly between 56% summer and 84% in winter. A median of 23% of the yearly precipitation rate is discharged by artificial drainage systems, varying from 9% of the precipitation in summer to 54% of the precipitation in winter. The artificial drainage systems usually started to respond within the first hour under rain fed conditions, and the response time increased at lower rainfall intensities (< 1 mm h^{-1}). The peak outflow normally occurred within the first two days. The influence of soil texture and land use on artificial drainage discharge rates could not be reproduced properly, due to the spatial high variability caused by other site-specific properties.

Abbreviations

DRAINMOD: Model for Artificially Drained Soils, PVC: Polyvinylchloride, WFD: European Water Framework Directive

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1. Introduction

Artificial drainages comprise sub-surface (tile) drainage systems made of PVC- or clay tubes which are mainly installed on arable land, and open ditch systems (surface drainage systems) which are mainly used in grasslands and forests. Artificial drainage systems are installed to avoid saturated water conditions in soils, thus improving trafficability soil aeration, and thereby agricultural production and soil cultivation. Such drainage systems are mainly situated in (1) lowland landscapes with a relatively high groundwater table and relatively permeable sandy soils, to control the water level, (2) landscapes with relatively impermeable soils with a stagnant horizon or underground with temporary perched water tables, to rapidly remove stagnant water, and in (3) wetlands with organic soils such as fens and bogs which are drained to allow cultivation of these soils.

In Europe, there is a marked decrease in the utilization of tile drainage from north to south, for example 91% of the total agricultural land is tile drained in Finland, 90% in Lithuania, 80% in Latvia (DE LA CUEVA, 2006), 16% in Germany (WERNER *et al.*, 1991; WODSAK and WERNER, 1994), and only 0.3% in Portugal (DE LA CUEVA, 2006). Most of the tile drainage systems were installed in the 1960's to the 1980's. In the US, there are about 170 M ha of cropland, 26% (43 M ha) of which require tile drainage (PAVELIS, 1987).

Artificial drainage systems affect all components of the water and nutrient balance of a landscape (AMATYA *et al.*, 2006; ARABI *et al.*, 2006; KONYHA *et al.*, 1992, MCLEAN and SCHWAB, 1982; PENNING-ROSWELL *et al.*, 1986; SKAGGS *et al.*, 2005a, b; WESSTRÖM *et al.*, 2000; WISKOW and VAN DER PLOEG, 2003). The shortened nutrient discharge pathways, and the reduced denitrification capacity, mean that the tile drainage systems beside the groundwater systems are the main pathways for diffuse nitrogen input into rivers (AMATYA *et al.*, 2004; FERNANDEZ *et al.*, 2002). In addition, agro-chemicals such as pesticides are rapidly transferred to surface water via tile drainage systems (KALITA *et al.*, 2006; KLADIVKO *et al.*, 1999; RÖPKE *et al.*, 2004).

A reduction in nutrient inputs into rivers, especially of nitrogen and phosphorus, is needed in order to achieve the environmental objectives of the European Water Framework Directive (WFD). To reduce the nutrient discharges arising from tile drainage systems, the outflow must be reduced. In order to determine appropriate measures for the reduction of such emissions, information is needed about the seasonal course of the tile drainage discharge rates, and the influencing factors controlling the water fluxes in tile drained arable land. Several authors have shown that tile drainage discharge follows a seasonal course (ABBASPOUR *et al.*, 2001; ALGOAZANY *et al.*, 2007; KAHLE *et al.*, 2007; LARSSON and JARVIS, 1999), although this has only been described for single study areas, rather than deriving a general valid correlation. Therefore, the risk for ground and surface water posed by contaminative solute fluxes is still not rateable, especially the seasonal danger after fertilization and application of agro-chemicals. The aim of this study is therefore to understand the temporal course of artificial drainage discharge under different site conditions.

The main questions are: (1) to which percentage of rainfall events did the tile drainage systems respond, (2) which is the lag time between a rainfall event and the beginning of the artificial drainages discharge, (3) which is the seasonal proportion of artificial drainage discharge in relation to seasonal precipitation rates, and (4) are the tile drainage discharge rates controlled by site conditions, such as soil texture or land use.

2. Material and Methods

2.1. Data Acquisition and Processing

A total of 263 scientists and scientific institutions were contacted, to request monitoring data on artificial drainage discharge rates for areas under temperate climate conditions. We received 23 datasets from 9 countries, covering a period from 1989 – 2005. Thus we had a positive outcome rate of approximately 10%.

Because 8 of these 23 datasets had a low temporal resolution, we did not use them, and we ultimately studied 15 datasets with daily or higher temporal resolution: 11 tile drainage discharge sites, 1 open ditch discharge site under natural rainfall conditions (Table 1a), and 3 tile drained discharge sites under irrigation conditions (Table 1b). For three study sites (Dumfries, Infeld und Taastrup) discharge rates from more than one tile drainage tube were monitored. The data set with the open ditches (USA) was included, because the behaviour of this ditch is comparable to tile drainage systems. Site specific properties, such as precipitation rates, soil texture, and land use, were extracted from the corresponding publications, or were requested from the authors directly.

Data were divided into those from study sites under natural rainfall conditions, and those under irrigation conditions. The precipitation rates were either obtained from climatic station situated in the test area, or from the nearest meteorological station. Depending on the temporal resolution of the artificial drainage discharge data, the precipitation rates were either summarized to daily values covering a 24 h period (starting at 7 a.m.) or to hourly values. The irrigation rates ranged from 30 mm to 83 mm per irrigation (irrigation intensity between 13 and 36 mm h^{-1}, see Table 2a, b). Precipitation and discharge data under natural rainfall conditions were then corrected to their cross-sectional area of artificial drained land, and referred to in mm h^{-1} or mm d^{-1}.

2.2. Calculation of the Artificial Drainage Discharge Reaction Rates

To get information on the proportion of precipitation events to which the artificial drainage systems responded, we calculated the artificial discharge response rates under natural rainfall conditions as a quotient of the number of daily precipitation events and the number of daily discharge events, which were realized on the same and the following day; this was done for 12 artificial drainage data sets. In order to determine the influence on the rainfall intensity on the artificial drainage reaction rate, the precipitation events were grouped into five classes ranging from < 5 mm to > 30 mm.

2.3. Calculation of the Artificial Drainage Discharge Response Time (Lag Time)

For assessment of the discharge response time (lag time), we used only data with hourly resolution (l'Orgeval study site) or half-hourly resolution (Bokhorst study site) under natural rainfall and under irrigation conditions. The lag time was calculated as the elapsed time between a rainfall event and the start of the artificial drainage discharge, which was in turn characterised by an increase in discharge rate compared to the pre-discharge event. To account for the influence of the rainfall intensity, the lag times were further calculated for 5 rainfall intensity classes ranging from 0.001 mm to 10 mm. All available data within each rainfall intensity class were set to 100%, and the percentage of response within each time frame was calculated. We did not account for response times greater than 8 h, or for rainfall events that were not associated with changes in the tile discharge rates. Therefore the sum of percentage within each rainfall intensity class did not always reach 100%.

2.4. Calculation of the Proportion of Artificial Drainage Discharge from Precipitation

The proportion of artificial drainage discharge from precipitation was calculated as the quotient between precipitation rates to the artificial drainage discharge rates. In calculating the proportion of artificial discharge, we did not account for the precipitation losses via evapotranspiration or soil water storage.

Table 1. Site description.

Study site	Country	Location	Measured period		Area	Drain		Drain & Rainfall solution	Land use	Data source
			date	number of years		depth	space			
					ha	m	m			
Tile drainage study sites										
Lindhof	Germany	near Eckernförde, Schleswig-Holstein	3.12.1998 to 31.12.2005	7	1.0	no data	no data	daily	arable land sugar beats, potatoes, perennial ryegrass (catch crop)	University of Kiel, Institute Hydrology and Water Resources Management of the Ecology Centre Kiel, lead-managed by Prof. N. Fohrer; Fohrer and Deunert (2005); Deunert and Fohrer (2005).
Infeld	Germany	near Nordenham, Lower Saxony	1.01.1989 to 31.12.2000	12	field 1 0.22; field 2 0.24; field 3 0.16	field 1 1.28; field 2 1.01; field 3 0.96	field 1 16; field 2 18; field 3 12	daily	grassland perennial ryegrass	University of Rostock, Institute for Landuse, Professorship Soil physics and Resource Protection; the longtime measurements conducted by chamber of agriculture (Landwirtschaftskammer) Lower Saxony, Oldenburg; Bechtold *et al.* (2007); Köhne *et al.* (2006).
Dummerstorf	Germany	near Rostock, Western-Pomeranian	1.11.2001 to 31.10.2006	5	4.16	1.1	12 to 14	daily	arable land maize,wheat, rape, sugar beats	University of Rostock, Institute for Agriculture and Environment Sciences, lead-managed by Prof. B. Lennartz; Kahle *et al.* (2005, 2007); Lennartz *et al.* (2006); Tiemeyer *et al.* (2006, 2008).
Bokhorst	Germany	near Kiel, Schleswig-Holstein	11–18.10; 29.11–6.12.1993; 10–17.1; 28.2–7.3; 14–21.3; 11–18.4;’ 16–27.5; 14–21.11; 26-31.12.1994; 1–2.1; 13.1–20.2; 6–20.3; 27.3–3.4; 17–24.4.1994	2 winter	F0,5 with 0.5 and F50 with 50.0	1.1 to 1.2	11 to 14.5	half-hourly	arable land barley, wheat, rape (3 yr cycle)	University of Kiel, Institute of Landscape Ecology and Institute of Hydrology and Water Resources Management of the Ecology Centre Kiel; Göbel (1997); Lennartz *et al.* (1999).
Otelfingen	Switzerland	near Otelfingen	23.08.1995 to 7.08.1997	2	1.6	1.0	20	daily	arable land wheat, sugar beats, sunflowers	Federal Office for Water and Geology, Hydrological Survey, 3003 Bern, Switzerland; Kohler *et al.* (2005).

l'Orgeval	France	near Paris, Département Seine-et-Marne	1.11.1998 to 16.06.2002; 1.10. to 31.03.2002–07	4 years and 5 winter	130	0.1 to 1.0	8	hourly	arable land basically cereals (50% wheat)	Unité de Recherche „Hydrosystèmes et Bio-procédés“ Research Unit „Hydrosystems and Bio-processes“ Cemagref; Augeard *et al.* (2005).
Lanna	Sweden	South-west Sweden, Lanna plain	1.10.1994 to 31.11.1995	1.5	0.4	1.0	13.5	daily	no data	Swedish University of Agricultural Sciences, Department of Soil Sciences, lead-managed by M.H. Larsson and N.J. Jarvis; Larsson and Jarvis (1999).
Taastrup	Denmark	near Copenhagen	1.10.1998 to 31.3.2002	4 winter	4 fields per 0.16	1.1	8	daily	arable land wheat	The Royal Veterinary and Agricultural University, Taastrup, Denmark; Petersen *et al.* (2004).
Cockle Park	Great Britain	near Morpeth, Northumberland	1.10.1989 to 30.9.1991	2	0.25	3	13.5	daily	grassland (1989) arable land wheat (1990) barley (1991)	Department of Agricultural and Environmental Science and Department of Agriculture, University of Newcastle und ADAS Soil & Water Research Centre; Beulke *et al.* (1998).
White Hill	Ireland	near Hillsborough	1.05.1989 to 31.10.1991; 1.05.1997 to 31.10.2005	11	1.6	1.0	20	daily	grassland (92%) arable land (8%)	UK Agricultural Development and Advisory Service, Filed Drainage Experimental Unit (FDEU); Watson (2000).
Dumfries	Great Britain	in Dumfries, Scotland	28.01. to 29.04.1994	4 month	4 fields per 0.4	0.7	7	daily	grassland perennial ryegrass	Hooda *et al.* (1999).
Open ditch system										
Carteret County	USA	North Carolina	1.01.1988 to 31.10.2004	17	0.2	0.8 to 0.1	10	daily	pine forest	North Carolina State University in collaboration with USDA Forest Service (D.M. Amatya); Amatya *et al.* (2006) and Weyerhaeuser Company.
Rainfall simulation										
Neuenkirchen	Germany	Northern Pre-Harz	with irrigation	–	0.1	no data	no data	minutes	arable land wheat, sugar beats	Worreschk (1985)
Eixendorf reservoir	Germany	Upper Palatinate	with irrigation	–	no data	0.7 to 1.3	no data	minutes	arable- and grassland	Diepolder and Raschbacher (2007); Diepolder *et al.* (2005)
Kanawha	USA	Iowa	with irrigation	–	8 × 0.00045	1.2	no data	minutes	arable land	Czapar *et al.* (1992)

Table 2a. Properties of the study sites under natural rainfall conditions.

Study sites	Tile drainage discharge	Precipitation	Temperature	Soil data			Land use
	mean yr	mean yr	mean °C	clay %	silt %	sand %	
Bokhorst F0,5[1]	–	825	8.3	10	25	63	arableland
Bokhorst F50[1]	–	825	8.3	15	25	60	arable land
Lindhof	252	613	8.5	15	25	60	arable land
Infeld 1	370	834	9.0	30	40	30	grassland
Infeld 2	280	834	9.0	30	40	30	grassland
Infeld 3	330	834	9.0	30	40	30	grassland
Dummerstorf	141	665	8.2	10	28	63	arable land
Otelfingen	407	889	9.0	24	62	14	arable land
l'Orgeval	111	706	9.7	18	76	6	arable land
Lanna	326	676	6.9	55	39	6	no data
Taastrup[1]	–	–	8.5	14	21	65	arable land
Cockle Park	180	577	Min 5.3; Max 11.9	29	34	37	arable land 1989); grassland (1990–91)
White Hill	509	852	8.7	21	35	44	arable land (8%); grassland (92%)
Dumfries	546	1054	Min 8.6; Max 12.4	40	40	30	grassland
Carteret County	541	1370	18.3	21	45	34	forest

[1] For the study sites Bokhorst and Taastrup no mean tile drainage discharge could be calculated due to not continuously measured tile drainage discharge (see Table 1).

Table 2b. Properties of the study sites under irrigation conditions.

	Irrigation intensity mm/h	Irrigation amount l/m^2	Number of irrigations	Temperature (mean) °C				
Neuenkirchen	36	30 to 59	5	–	–	–	–	arable land
Eixdorfer reservoir	13–20	30–50	78	–	4–24	25–57	19–65	arable land, grassland
Kanawha	18	79 to 83	8	–	24	57	19	arable land

For the assessment of seasonality, the proportion of artificial drainage discharge from precipitation was divided into the winter period (November to April) and the summer period (May to October). Additionally, the monthly proportion of artificial drainage discharge from precipitation was assessed. The seasonal trend was evaluated within each study site, in order to account for possible effects of site-specific properties on the proportion of artificial drainage discharge from precipitation.

2.5. Description of Study Sites

The artificial drainage study sites under natural rainfall conditions (*N* = 12) were situated on arable land (*N* = 7), grassland (*N* = 3, Lanna no information) and forest land (*N* = 1) under sub-humid to humid climatic conditions, with mean annual precipitation rates ranging from 577 to 1531 mm, and mean annual temperature of 9.9 °C. The study sites were located on sandy (*N* = 2), loamy (*N* = 6), silty (*N* = 2) and clayey (*N* = 2) soils. Because the artificial drainage discharges were drained from the B-horizons, soil texture data were derived from these horizons. Basic site properties (precipitation rate, temperature, land use and soil texture) are given in Table 2a, b.

2.6. Statistical Analysis

Means, medians, standard deviations (SD), analysis of variance, and correlations were computed with the statistical analysis programme SPSS. Parametric (independent-samples t-test, paired-samples t-test) and nonparametric (Wilcoxon signed-rank test, Mann-Whitney u-test) statistical tests were used because the data were only partly normally distributed (Kolmogorov-Smirnov statistic, Shapiro-Wilk statistic). Statistical tests were performed to determine significant differences in seasonal course and site specific distribution of artificial drainage reaction rates, artificial drainage reaction times, and proportions of artificial discharge from precipitation. The probability level (p) of all tests was 95%.

3. Results

3.1 Percentage of Rainfall Events to which Artificial Drainage System Responds

Analysis of the precipitation intensity revealed no significant difference in the precipitation distribution between summer and winter (Fig. 1). Some 43% of the year was precipitation-free, and the annual precipitation distribution was dominated by daily precipitation

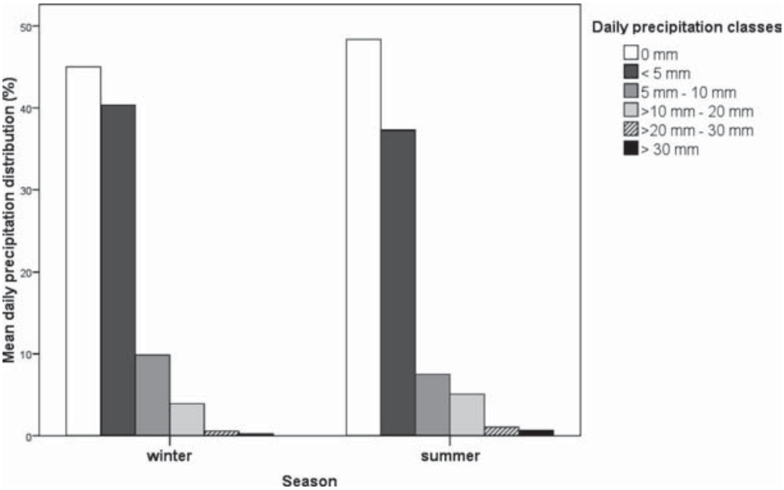

Figure 1. Daily precipitation intensity, in 5 classes, in winter and summer.

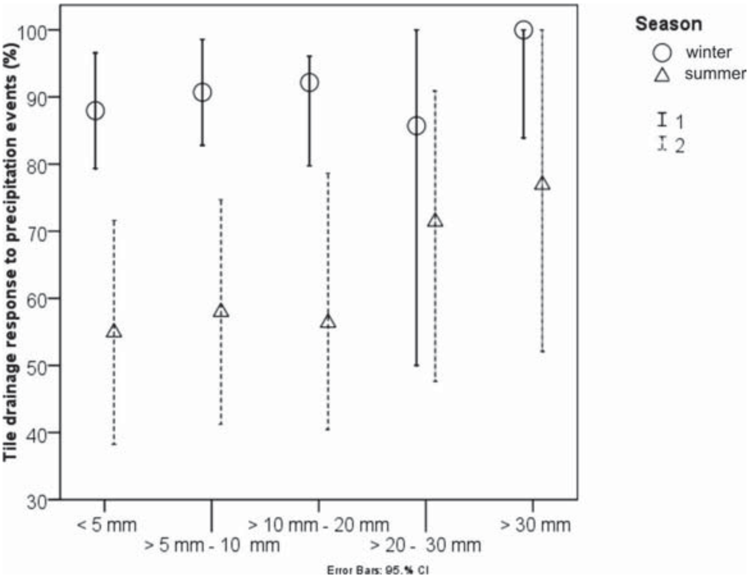

Figure 2. Seasonal artificial drainage response to precipitation events according to rainfall intensity.

intensities lower than 5 mm d^{-1} (37% (winter) to 32% (summer)). Strong rainfall intensities > 30 mm d^{-1} were very rare, occurring only 0.3% (winter) and 0.6% (summer).

Based on the defined rainfall classes (ranging from > 0 mm to > 30 mm d^{-1}), we assessed whether the artificial drainage systems responded within the first two days after a rainfall (event day, or on the next day). For all precipitation classes considered together, the artificial drainage systems responded to 70% (*SD* 21%) of the rainfall events.

There was a significant difference in the proportion of artificial drainage response to precipitation, with a median of 50% in summer and 88% (*SD* 18%) in winter. For rainfall events < 20 mm/d, the reaction rates were statistically significantly lower in summer (mean 44%, *SD* 27%) than in winter (mean 82%, *SD* 16%). No significant seasonal differences were found for precipitation intensities > 20 mm d^{-1}, with a mean of 80% (*SD* 80%) (Fig. 2).

3.2. Lag Time, and Time of Peak Artificial Drainage Response after Rainfall Events

The lag time for precipitation events > 0.001 mm was less than one hour for 76% (mean, *SD* 27%) of the discharges from the study site l´Orgeval (France), and 50% (*SD* 15%) of the discharges from Bokhorst (Germany) (Fig. 3, Fig. 4, respectively). With decreasing precipitation intensities, the proportion of drainage reaction to precipitation events decreased, and the lag time response increased. The proportion of discharge reaction to precipitation events > 5 mm h^{-1} was an average of 76% for both sites.

Similar to the results obtained under natural rainfall conditions, the drainage discharge reaction time using high irrigation intensities (18 mm h^{-1} to 53 mm h^{-1}), showed that tile drainage systems responded to 83% (Eixendorf), 25% (Kanawha) and 100% (Neuenkirchen) of events within the first hour, and had a maximal response time of 118 min (Eixendorf), 270 min (Kanawha) and 36 min (Neuenkirchen), respectively. In two of the three locations,

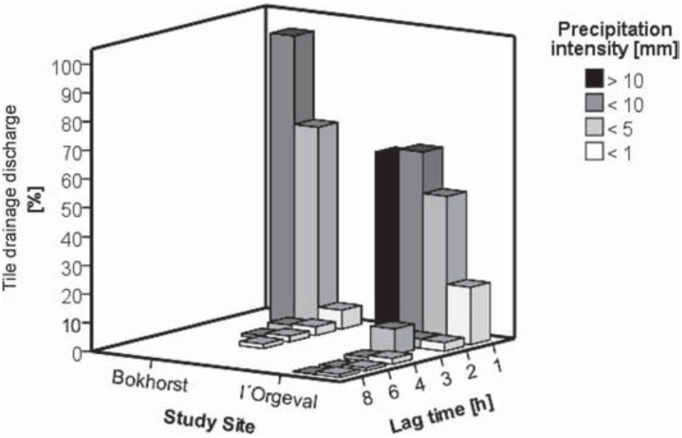

Figure 3. Lag time of artificial drainage reaction after precipitation (mean values) for two study sites.

the sites were pre-irrigated until the soil water content was near to field capacity before the simulated rainfall was started. However, the tile drainage systems response time under pre-irrigation condition was similar to that without pre-irrigation.

The highest artificial drainage discharge (peak) (considering the discharge data with a daily resolution) usually occurred within the first two days after a precipitation event. For higher temporal resolution data, such as that for Bokhorst, it could be seen that the peak discharge was realized within the first day (Fig. 4). Although most of the water was discharged through the artificial drainage systems within the same day, in some cases discharge continued over a 10 day period.

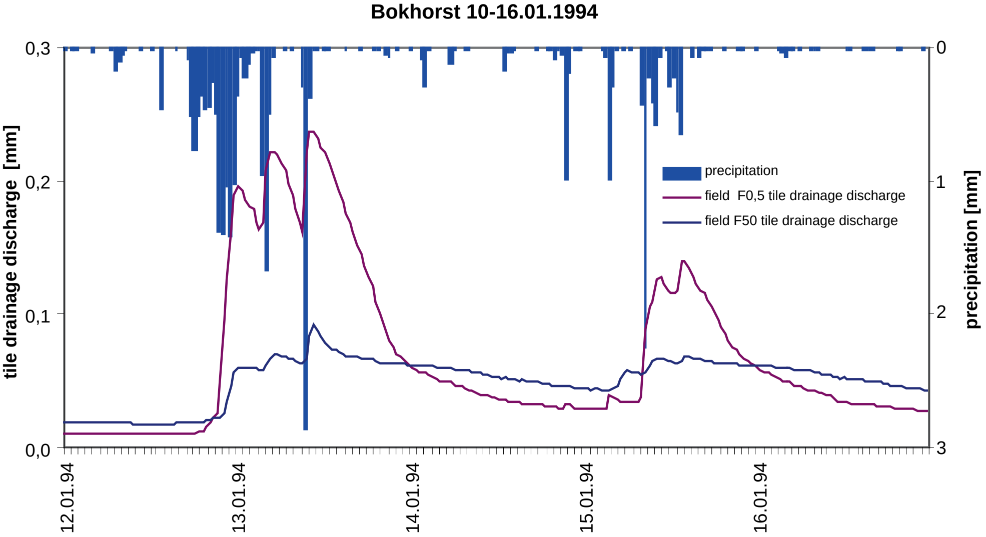

Figure 4. Example of temporal changes in the tile drainage discharge response after high precipitation events in Bokhorst.

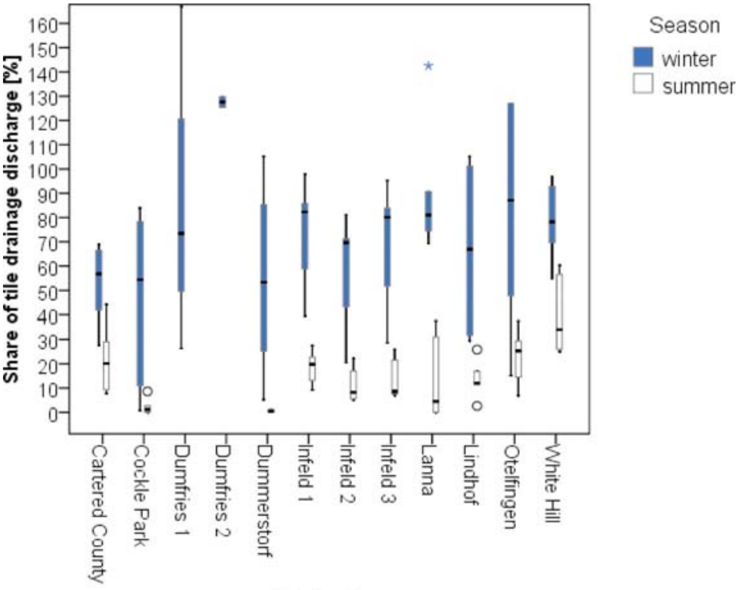

Figure 5. Proportion of the site specific artificial drainage discharge from precipitation differentiated for summer and winter for 12 sites.

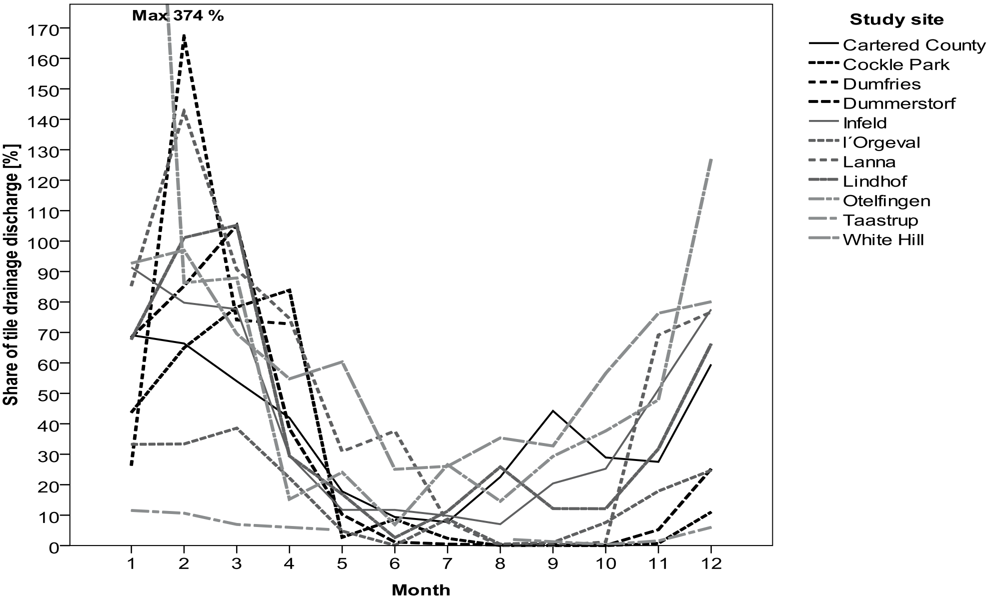

Figure 6. Monthly percentages of artificial drainage discharge from precipitation for 11 sites.

3.3. Proportion of Artificial Drainage Discharge Derived from Precipitation

Over all study sites ($N = 12$), a mean of 23% (*SD* 37%) of the annual precipitation was discharged through the artificial drainage systems. The percentage in winter (median 54%, $N = 11$, Fig. 5) was significantly higher than in the summer (median 9%). Hence, artificial drainage discharge rates were positively correlated with precipitation rates within each season (for both seasons: $r^2 = 0.5$). In winter, there were no significant differences among monitoring sites in the percentage of artificial drainage discharge from precipitation, however in summer, these among site differences were statistically significant.

The monthly proportion of artificial drainage discharge from precipitation ($N = 11$) varied within the year, and decreasing from March to May, stayed on a low level in June and August, and then increased again from September to February (Fig. 6). Some of the monthly variations between monitoring sites were accounted for, at least in part, by the amount of data available. For example Infeld (Germany) and Carteret County (USA) with long duration data (11 and 17 years), showed a decrease in tile drainage discharge in early summer and an increase at the beginning of autumn, consistent with the overall trend. In contrast, sites with monitoring data of short duration (*e.g.*, from Dumfries with data of four months) were more affected by extreme climatic events than sites with long duration data. Thawing periods in the winter increased the percentage of artificial drainage discharge from precipitation at some sites to values > 100% (such as occurred at Dumfries, Lanna, Otelfingen), while a low percentage of artificial drainage discharge from precipitation is attributable to high evapotraspiration rates during the summer period.

3.4. Influence of Soil Texture

The mean artificial drainage discharge rate from study sites with perennial and continuous data collection separated by the main soil texture groups (sandy, loamy, silty and clayey

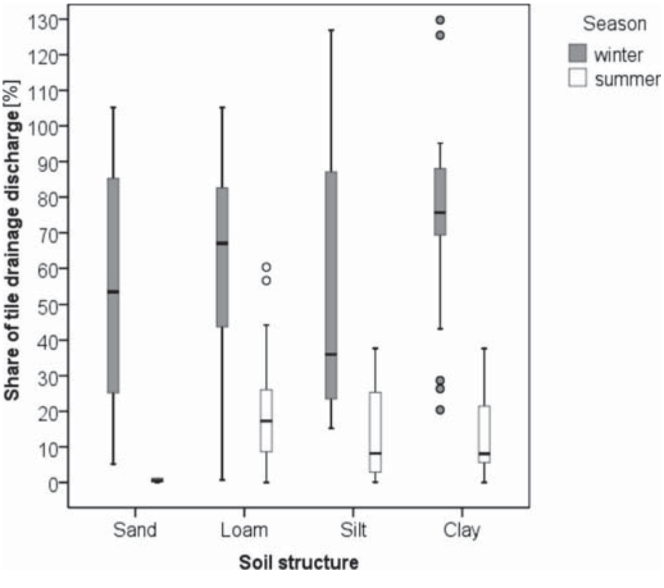

Figure 7. Proportion of artificial drainage discharge from precipitation for the main soil texture groups in different seasons.

soils) revealed no significant differences between the soil texture groups in the winter, with a mean artificial drainage discharge rate of 70% (*SD* 49%) (Fig. 7). In contrast, in summer, significantly lower mean artificial drainage discharge rate were found for sandy soils (2%, *SD* 4%, $N = 1$), compared to the remaining soil groups, (within which no differences were found (mean 15%, *SD* 13%, $N = 11$)). These results must be interpreted with caution because we had only one monitoring site with sandy soils.

3.5. Influence of the Land Use on Artificial Drainage Discharge

The mean proportion of discharge rates from precipitation was highly variable between study sites on arable land, and less variable between study sites on grassland. This high variability was affected by two study sites (Taastrup, L'Orgeval) with very low proportions of drainage discharge from precipitation. Extreme values at these study sites were caused by short monitoring times. Therefore, the proportion of discharge from precipitation was significantly higher under grassland compared to that under arable land. The proportion of discharge from precipitation of 71% for grassland (*SD* 12) and 61% for arable land (*SD* 41) was not significantly different when these two study sites (Taastrup and l'Orgeval) were excluded from statistical analysis.

4. Discussion

Our comprehensive data acquisition efforts showed that monitoring data from artificial drainage discharge were rare. No information was available about tile drained organic soils which cover a large proportion of agricultural land in the humid climate zone. Thus, due to the lack of replications in soil and site conditions, it is difficult to generalize our findings. The following discussion about the main aspects of our findings includes commentary on the limits of the study and considerations in its interpretation that must be kept in mind when drawing conclusions.

4.1. Percentage of Rainfall Events to which Artificial Drainage Responds

In summer, high evapotranspiration rates and agricultural land use during the growing season decreased the net infiltration rates in the soil compared to those in the non-growing season. These boundary conditions led to low soil water contents, and a low percentage of artificial drainage response to rainfall events at rainfall intensities < 20 mm d^{-1} (44%), compared to the twice as high percentage of artificial drainage response encountered in the winter season (82%) with a low evapotranspiration demand. In contrast, at high rainfall intensities > 20 mm d^{-1}, the net infiltration amount is sufficient either to saturate the entire soil matrix or to allow the creation of saturated preferential flow pathways, leading to a similar percentage of artificial drainage response to rainfall events between the summer and winter season.

4.2. Lag Time and Time of Peak Artificial Drainage Response after Rainfall Events

Short artificial drainage reaction times after precipitation events were observed for all study sites, covering different classes of land uses and soil textures. For the study sites with only daily data resolution, conclusions regarding artificial drainage reaction times are of limited value. Usually one can only detect that a response occurs the same day or the next day, due to different times of measuring precipitation and artificial drainage discharge.

However, from study sites with hourly discharge data we can conclude that the response is visible within the first six hours after the precipitation event. This short time contrasts with the saturated calculated hydraulic conductivity for these sites, which is 7.7 days (L'Orgeval) and 1.9 days (Bokhorst) for a tile drainage depth of 1 m. For heavy rainfall events with more than 10 mm d^{-1} precipitation rate, the artificial drainage discharge usually starts to drain within the first hour, independent of the season. That means that the artificial drainage response for heavy rainfall events is also quick if the soil moisture is low. This may again indicate that high rainfall intensities accelerate water fluxes through preferential flow pathways (GISH *et al.*, 2004). Also KUNG *et al.* (2000) reported that 90% of the tracers were found during the first day in a leaching experiment in Indiana (USA). LENNARTZ *et al.* (2006) found short lag times of 5–16 hours after precipitation events on different scales (for a tile drained plot, a ditch and a brook in Northern Germany), which indicate that short lag times could be found even on a catchment scale.

4.3. Proportion of Artificial Drainage Discharge Derived from Precipitation

The proportion of artificial drainage discharge from precipitation varied seasonally due to high evapotranspiration rates in summer. In summer the probability of a reaction of the artificial drainage systems is increased by high rainfall intensities and in winter the frequency of the artificial drainage reaction is generally high. Thus the overall nutrient discharge risk to rivers is generally reduced in the summer months. However, single high rainfall events in the summer may increase the risk of pollution, due to the high levels of fertilizer and agro-chemicals in the soil during the growing period.

Our results clearly indicate that high rainfall intensities accelerate the water fluxes through preferential flow pathways in the soil, in agreement with previous studies (GERKE and KÖHNE, 2004; GÖBEL, 2000; JAYNES *et al.*, 2001; KÖHNE *et al.*, 2006; KOHLER *et al.*, 2005; PETERSEN *et al.*, 2004). Hence, these water fluxes reach rapidly the tile drainage system, and are therefore less available for crop water uptake in the summer.

4.4 Influence of Soil Texture

Our results indicate that the behaviour of the artificial drainage systems was not significantly dependent on the soil texture. We could not determine whether the significant lower proportion of discharge for a sandy soil in the summer within one study site (Dummerstorf), was caused by low and homogeneous distributed soil water contents compared to those of other study sites with more structured soils or by other factors. The lower proportion of discharge for sandy soils contrasts with the results of common water seepage models, which calculate a higher seepage rate for sandy soils than for finer structured soils (loamy, silty and clayey soils). Higher seepage rate for sandy soils are also calculated by using models such as DRAINMOD (AMATYA *et al.*, 2004; FERNANDEZ *et al.*, 2002; SKAGGS, 1978). The artificial drainage discharge data covering study sites with different soil textural classes that we now present, diverges from Darcy's law assuming homogeneous flow conditions, in that the sites start to drain rapidly after precipitation events.

These results are comparable to those from KAMRA and LENNARTZ (2005), who stated, that the preferential solute movement for displacement studies under unsaturated steady state flow conditions in 24 undisturbed soil columns (from northern Germany) was not notable related with any soil property. Also, CZAPAR (1992, Kanawha, Iowa, USA) reported that tile drainage discharge rates for four sand backfills (precipitation 82–84 mm) were significantly lower than for four loam backfills (precipitation 79–83 mm) and that the mean lag time was longer in the sand backfills (161 min) than in loam backfills (69 min). Also, WORRESCHK

(1985) found in a tracer experiment, that measured flow velocities were significantly higher than the saturated water conductivity. It is possible that cracks, worm or root channels in more structured soils accelerated the water fluxes through preferential flow pathways (Hendrickx and Flury, 2001; Kladivko *et al.*, 1991; Köhne *et al.*, 2006; Lennartz *et al.*, 1999), and hence the tile drainage discharge rates compared to those in the sandy soils during the summer season.

At present it is still difficult to use the more complex dual-permeability model (involving matrix and preferential flow, such as used by Jarvis (2007) and Kohler *et al.* (2001)), because the use of these models has been restricted to theoretical applications and laboratory studies carried out under well-defined and controlled conditions (Jarvis, 2007; Simunek *et al.*, 2003), which require much more input data than models assuming homogeneous flow conditions.

4.5 Influence of Land Use on Artificial Drainage Discharge

It is assumed that besides the precipitation rate, (which was the major factor positively controlling the percentage of artificial drainage discharge (Fig. 6)), the land use – and hence the evapotranspiration rates – have a pronounced influence on the discharge rates in the summer. Contrary to our expectations, and to the referred trend in literature (arable land > grassland > forest land) consistent with Skaggs *et al.* (2011), the percentage of artificial drainage discharge between the different land use classes were comparable. We assume that land use specific discharge rates can only be compared under comparable site conditions. Moreover grassland sites are often unsuitable for arable land use due to high ground-water levels, which in turn increase the capillary rise of water from the groundwater, and the hence the percentage of artificial drainage discharge.

5. Conclusion

Artificial drainage systems have a short response time to rainfall events combined with a fast increase to peak discharge rates. This effect is independent of land use and soil texture. The shortened nutrient discharge pathway leads to a reduced denitrification capacity of tile drained landscapes and high values for nutrient or pesticide emission into surface waters (Flury, 1996; Gärdenäs *et al.*, 2006; Jarvis, 2007, 2002; Macrae *et al.*, 2007; Tiemeyer *et al.*, 2008, 2009). Measures to reduce this high level of agricultural emissions are often discussed (*e.g.*, Kreins *et al.*, 2010; Mander *et al.* 2000; Savchuk *et al.*, 2008; Thieu *et al.*, 2010). In addition to a reduction via agricultural measures, further measures are needed in order to enhance water quality, especially from tile drained areas, which are detected as a major source of nutrient and pesticide emission into surface waters. Possible solutions are constructed wetlands or purification ponds (Kovacic *et al.*, 2000; Mitsch *et al.*, 2001; Stachowicz *et al.*, 1994), and controlled tile and open drainage systems (Amatya *et al.*, 1998; Sands *et al.*, 2008; Skaggs and Chescheir, 2003; Skaggs *et al.*, 2005b).

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