ENVIRONMENTAL ENGINEERING

The 8th International Conference
May 19–20, 2011, Vilnius, Lithuania
Selected papers

ISSN 2029-7106 print / ISSN 2029-7092 online
ISBN 978-9955-28-828-2 (2 Volume)
ISBN 978-9955-28-827-5 (3 Volume)
http://enviro.vgtu.lt

SEASONAL CHANGES OF PHOSPHORUS CONCENTRATIONS IN LIME FILTER DRAINAGE WATER

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Abstract. The drainage outflow may be identified as the leading source of water quality in agricultural regions. Phosphorus concentrations above background levels increase the risk of eutrophication in water bodies. Various technologies are currently being developed to reduce non-point source pollution. Chemical amendments to the soil are one of the means to reduce movement of phosphorus via subsurface tile drainage systems. The field studies were performed to determine if the chemical treatment with lime could increase P retention in drainage backfill and reduce P transport to receiving waters. The site was located in the South-West Lithuania. Composite subsurface drainage systems with drain spacing of 16 and 24 m were installed in heavy-textured clay loam soils, drainage trenches were backfilled with soil mixed with 0.6% CaO. This paper reports the results of eleven-year studies (1999 – 2009). Water samples were analysed for total phosphorus (TP) and phosphate phosphorus (PO4–P). Concentrations were determined by the spectrometric method, according to the water quality investigation standards (LAND 58:2003). The reliability of the results was determined by processing them with the help of mathematical-statistical methods and using MS Excel 2000 Data Analysis Tool Pack. The significant differences between phosphorus concentrations in control drainage water and in the treatments with lime added into the trench backfill were estimated within winter-spring period (November – May). During the summer–autumn months (June – October) the mean concentrations differed insignificantly. Phosphorus concentrations in control drainage water exceeded the concentrations determined in stream water during the entire year. The highest amounts of phosphorus from drainage systems are transported in winter and spring.

Key words: lime, drainage, phosphorus, trench backfill, water quality.

1. Introduction

In all the countries of Northern Europe, agriculture is estimated to be responsible for the greatest contribution of phosphorus to inland and coastal waters (Heiskanen 2004). The Baltic Sea is suffering from an unacceptably high nutrient load (Bergström *et al*. 2007). Curonian Lagoon is one of the most polluted and eutrophicated water bodies in Lithuania. Šileika *et al*. (2005) found that 46% of phosphorus comes mainly from settlements and agriculture. Phosphate losses from a watershed can be increased by a number of human activities. There are large regional differences and great variations in the amounts of P lost from agricultural land as a result of differences in soils, soil hydrology and agricultural production (Valsami-Jones 2004). Critical levels of phosphorus in water, above which eutrophication is likely to be triggered, are approximately 0.03 mg l^{-1} of dissolved phosphorus and 0.1 mg l^{-1} of total phosphorus. Dissolved P can enter waterways via surface and subsurface flow paths and through agricultural tile drains (Akhtar *et al*. 2003). Dissolved reactive phosphorus can constitute 20–70% of total P in water (Ulen 2007).

Phosphorus flows from the soil are complex and difficult to predict. One of the ways it does move through the soil profile is through the series of macropores, cracks and earthworm and root channels, also known as preferential flow paths. Preferential flow has always been conceived to have a detrimental impact on water quality because it moves solutes beyond the soil zone where both biotic and abiotic chemical reactions are usually at their highest potentials (Ryan 1998; Ekholm *et al*. 1999; Van den Eertwegh 2006). In fine-textured soils macropore preferential flow is generally considered more significant in contrast to coarse-textured soils.

The disturbed backfill soil over a tile drain represents a good pathway for generating rapid P transport in the soil similar to the flow through macropores, especially in the first few years after drain installation (Heckrath *et al*. 1997). Based on the assumption that 2.5% of the soil volume in a newly tile-drained clay soil is made up of backfill (0.5 m wide pipe trench and 20 m drain spacing), it is obvious that the backfilling method has a great impact on P losses from drained arable soil (Bergström *et al*. 2007). As in the clay soil the largest part of runoff discharges through more permeable drainage trenches, for these soils additional measures should be considered to reduce leaching of phosphorus (Van der Salm *et al*. 2007).

Various technologies are currently being developed to reduce concentrations of phosphorus in tile effluent (Foy and Dils 1998). A method developed for clayey soils in Finland involves incorporating burnt lime (CaO) with the backfill material in drains (Weppling and Palko 1994). The lime filter drain, as the method is often known, thus acts as a mini chemical treatment plant. The result is a stable and porous backfill that efficiently binds the phosphorus in percolating water (Curtin and Syers 2001; Šaulys and Bastiene 2006). In addition to P removal, the lime filter drain can also lead to improved drainage in impervious clay soils and can thus contribute towards decreasing erosion (Bell 1996). The average lifetime for the lime filter drain has been shown to exceed 10 years without any loss in treatment effect. In Sweden, the method has only been tested at one experimental site (Ulén 2003) and the long-term effects have not been monitored.

Calcium can react with phosphate to form insoluble compounds (Rhoton and Bigham, 2005). It is assumed that phosphate binding capacity increases from sand to clay because of the adsorption of phosphorus to soil particles (Djodjic *et al*. 2004). In natural conditions phosphates are removed by sorption with clay minerals in the soil matrix and by chemical precipitation. The sorbed phosphates are held tightly and are generally resistant to leaching until the soil absorptive capacity for phosphates becomes saturated. Chemical precipitation with calcium (in soils with neutral or alkaline pH) or with iron or aluminium (at acid pH) occurs at a slower rate than sorption, but is also an important removal mechanism (Murphy and Stevens 2010). Phosphorus binding to minerals and ion exchange capacity in different clay fractions has been examined in Sweden (Bergström *et al*. 2007).

Scientists from many countries have noted the lack of knowledge about the efficiency of preventive measures to reduce phosphorus inputs to the surface waters (Foy and Dils 1998). The reported investigations have been conducted in order to evaluate the impact of lime admixture to trench backfill in clay soils in regard to seasonal changes of phosphorus concentrations in subsurface drainage water. The field studies have been performed to determine if the lime filter drainage could reduce P transport to receiving waters all-year-round irrespective to meteorological conditions.

2. Methods

Experimental site. The study was carried out on a heavy-textured soil in the experimental site Kalnujai located in the Jūra river catchment of the South-Western Lithuania, Raseiniai district (Fig 1). The Jūra catchment drains middle part of Žemaičiai Upland, the surface of which is covered with humus rich but poor in labile phosphorus clay loams (80% of the basin area). High concentrations of suspended matter in the Jūra and its tributaries show the phosphorus loads to be formed there by soil erosion in the catchments. Almost half of average annual precipitation amount (47%) turns to runoff. Such conditions stimulate soil outwash and inflow of adsorbed phosphorus.

The area is attributed to an agricultural non-point source pollution zone. Drainage water from the main collectors discharges into the modified (deepened and straightened) reach of the Šilupė stream. This stream (length – 4.4 km, basin area – 4.0 km^2) is a fourth-range tributary of the River Nemunas. Monitoring on water quality in the site has been ongoing since 1999. Results of eleven-year studies (1999 – 2009) are reported in this paper.

The site is drained by composite subsurface lime filter drainage systems where calcium oxide is mixed with the excavated earth material to increase permeability of clayey soils and to improve drainage water quality.

Three drainage treatments have been installed with four replications of each:

I – drainage trench backfill mixed with lime (0.6% CaO), drain spacing L = 16 m;

II – the same, L = 24 m;

III (control) – drainage trench backfilled with disturbed clay loam soil, L = 16 m.

The shale ashes from Estonia containing 21.5% CaO are used as liming material. The amount of lime needed depends on soil quality. The amount of shale ashes (24 kg m^{-1}) is calculated according to the optimal amount of the lime that needs to be mixed with clay soil in order to enhance its best hydraulic conductivity (Šaulys, 1999).

Perennial grasses for hay were grown in the period of four years (1999-2002). In autumn of 2002, the plot was tilled and since 2003 it has been used under crop cultivation. Principal crops are cereals.

Soil and climate data. Lithuanian soils are attributed to low phosphorus retention class; the definition is based on soil climate and soil classification. *Orthi-Haplic Luvisols* (*LVh-or*) and *Hapli-Epihypogleyic Luvisols* (*LVg-p-w-ha*) with soaking features prevail in the site. The soils are a sandy clay / clay loam and are maintained at about pH 6.9-7.5. The texture of the subsoil varies from over 60% to 34% of clay. Subsoil containing such quantities of clay should absorb P strongly. In the beginning of the investigations mean phosphorus content in the plough-layer (0–23 cm) ranges from very low to medium (27–144 mg kg^{-1}).

The data of Raseiniai Meteorological Station was used to characterize meteorological conditions (Fig 2). The mean air temperature of the study period was 7.1°C and exceeded the seasonal norm (5.9°C) by about 1.2°C. In the warmest years – 2000, 2002 and 2008 – it was by about 2°C higher than the norm (higher temperatures were frequent in winter–spring months – December–April and July).

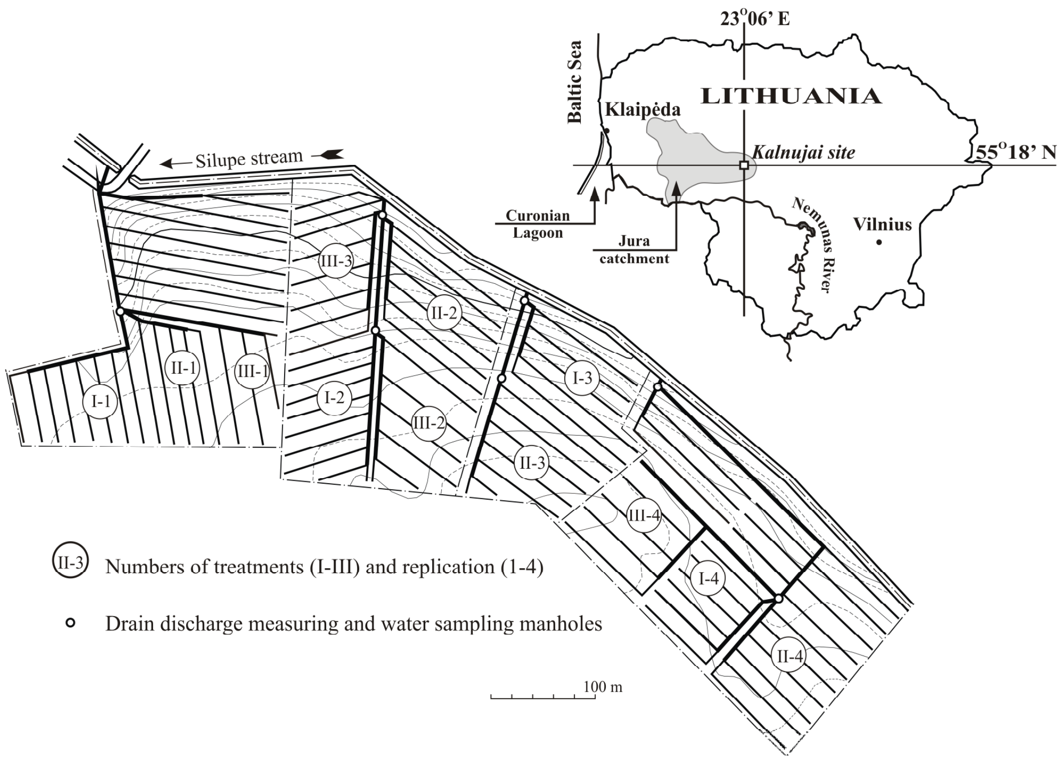

Fig 1. Geographical location and experimental layout of Kalnujai site

Comparison with seasonal norm of annual precipitation the years 2001 and 2007 attributes to humid ones (precipitation likelihood 14 and 2%). In the dry year (2005) precipitation likelihood was 93%. The remaining period may be considered as moderate: annual precipitation was close to seasonal norm (665 mm). Drainage runoff occurred during the entire year of 2001 and 2007, in 2005 dormant period of the drainage lasted even for ten months. Significantly uneven precipitation distribution was observed in April and May (variation coefficient V = 68–73%). In some years precipitation in January, May and October made 2.5–3 of monthly norm, while the average of April made only 60% of the multi-rate.

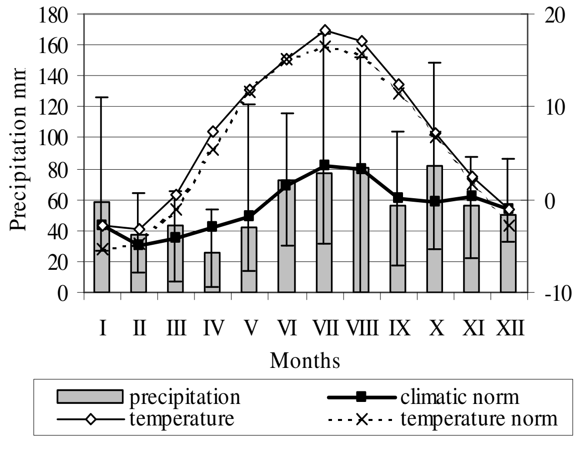

Fig 2. The means of monthly precipitation and air temperature, 1999–2009 (error bars show data range)

Data collection and analysis. To evaluate the effect of lime filter drainage on water quality the phosphorus content was measured from 1999 to 2009. Drainage water samples were collected at the drain outlets in manholes where drain discharges were measured, periodicity of sampling was once a month. Water samples from the Šilupė stream were taken simultaneously. Concentrations of total phosphorus (TP) and phosphate phosphorus (PO_4–P) were determined by the spectrometric method with FIA Star 5012 system analyser according to the water quality investigation standards (LAND 58:2003). The reliability of the results was determined by processing them with mathematical-statistical methods, using MS Excel 2000 Data Analysis Tool Pack. Differences of drainage treatments were tested at the significant level p = 0.05 and p = 0.01. To test the statistical significance of the difference between the means was fulfilled by estimation of data variation (F-Test Two-Sample for Variances), after that t-Test Two-Sample Assuming Equal/Unequal Variances was made. Correlation between phosphorus concentrations in the drainage treatments and meteorological indices (precipitation and temperature) was established.

3. Results and discussion

The highest average concentrations of TP and PO_4–P were determined in the drainage outflow of the control treatment (Table 1). They reached 0.044±0.006 and 0.032±0.004 mg l^{-1} respectively. Summing-up of all study period shows that the mean value of PO_4–P was 1.8 times higher than its average concentrations in the Šilupė stream water (0.018±0.003 mg l^{-1}) and 3.2 times higher than its average concentrations in the outflow of lime filter drainage treatments (0.010±0.001 mg l^{-1}). Extreme annual values of PO_4–P (0.049 mg l^{-1}) were quantified in the dry year of 2003, when the lowest annual drainage runoff was observed (33 mm). These values were partly caused by changes in land use when grassland was tilled.

Table 1. The mean concentrations of phosphorus in drainage and stream water in 1999–2009

	I	II	III	stream
	TP			
mean	0.021	0.021	0.044	0.039
max	0.035	0.034	0.060	0.062
min	0.012	0.012	0.028	0.026
SD	0.007	0.007	0.009	0.012
V %	33	33	20	31
Conf $_{95}$	0.004	0.004	0.006	0.007
	PO_4-P			
mean	0.010	0.010	0.032	0.018
max	0.013	0.015	0.046	0.027
min	0.008	0.007	0.022	0.012
SD	0.001	0.002	0.006	0.005
V %	13	22	19	26
Conf $_{95}$	0.001	0.001	0.004	0.003

In the outflow of drainage treatments I and II, where trench backfill was mixed with lime (0.6% CaO for the soil mass), TP concentrations were by 52.3% and PO_4–P concentrations – by 68.7% lower than those in the control drainage water. The dispersion analysis of the data has determined the differences to be statistically significant at p =0.01. So, it can be concluded that lime filter drainage may reduce phosphorus concentrations considerably.

TP concentration in the Šilupė steam varied between 0.026 and 0.062 mg l^{-1} during the period of 1999–2009 (the mean value 0.039±0.007 mg l^{-1}). Phosphates content increased from the lowest values in spring (0.012 mg l^{-1}) to 0.027 mg l^{-1} in August (the mean value 0.018±0.003 mg l^{-1}). According to the rates approved in Lithuania, maximum admissible concentrations (MAC) in river water are 0.1 mg l^{-1} of TP and 0.0653 mg l^{-1} of PO_4–P (LR Aplinkos… 2006). Consequently, the water of the Šilupė stream can be considered as uncontaminated with phosphorus because the concentrations do not exceed Lithuanian surface water quality standards. However, in the EU, surface water quality is considered to be good when TP concentrations do not exceed 0.025 mg l^{-1} (The Harmonised…, 1996). Therefore, the risk of eutrophication in the Šilupė stream still exists.

The investigation data shows that seasonal fluctuations with respect to phosphorus content are characteristic to the differences between conventional drainage and lime filter drainage (Fig 3). The lowest concentration of TP is determined in September, whereas the highest one – in January. Total phosphorus in drainage water from the plot with lime filter drainage shows more variability between different sampling times (V = 33%) versus phosphate phosphorus (V = 13–22%). Dils and Heathwaite (1999) appeal to field experiments in mixed agricultural catchment in the UK and state that phosphorus concentrations in drain discharge are low (<100 μg TP 1^{-1}) and stable during base-flow periods (<0.5 1 min^{-1}), and generally lower than the ones in the receiving stream. In contrast, temporary (hours) elevated P peaks are measured in drain-flow during high discharge periods (>10 1 min^{-1}). Large sediment-associated particulate P losses are measured during the first major drain-flow events of the autumn. Results of the investigations conducted in the Kalnujai experimental plot give a different picture. The highest PO_4–P concentrations in control drainage water are fixed during the entire year with extreme values in January. In the Šilupė stream water increased PO_4–P concentrations are observed in summer, decreased ones – in spring. However, in all months the phosphate content in surface water is lower than that in the conventional drainage water but exceeds that in the water from lime filter drainage. This shows that in cultivated areas drainage water has a significant influence on phosphate phosphorus content in surface water and such means as admixture of lime to drainage trench backfill in heavy clay soils can reduce this negative impact.

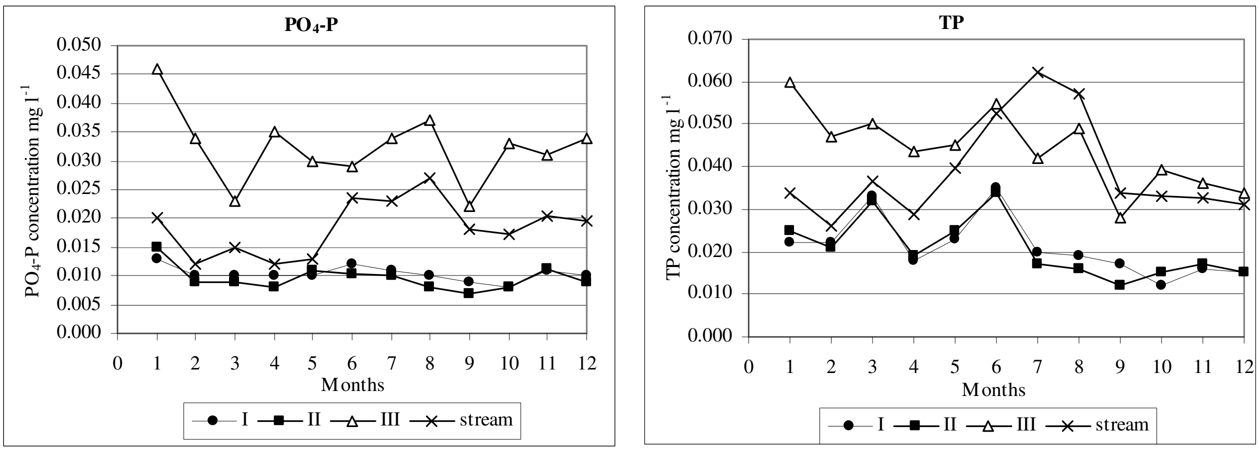

Fig 3. Seasonal changes of mean phosphorus concentrations in drainage outflow and stream water during 1999–2009 (I-II – lime filter drainage, III- control drainage)

In stream water the inflow of TP increases in warm season. The strongest increase is observed in April – July period, then concentrations gradually decrease. The highest phosphorus concentrations and their variation are observed in summer time (June–August) when runoff is low and intensive release of dissolved phosphorus from the sediments takes place. In July – October period the TP content in the stream water is higher than that in the drainage water. A. Povilaitis (2004) states that trends in the change of phosphorus concentrations in Lithuanian rivers are strongly affected by fluctuations of runoff and phosphorus content in streambed sediment. Taking into account the fact that high quantities of phosphorus can be transported with suspended sediments, the significantly increased loads of suspended matter during the heavy rains in summer can result in the increased particulate phosphorus content.

The changes in predominating phosphorus forms in the Šilupė stream water depend on the season of the year. The portions of phosphate phosphorus amounts make from 33% to 63% of total phosphorus amount there. The largest ones were detected in winter months. Thus, the water outflowing from the conventional drainage systems can influence the total phosphorus content in the recipient stream in cold season only. This influence may vary.

Comparison of lime filter drainage (I and II) and control drainage (III) water gives ambiguous results, which show that significant differences develop only in certain months (Table 2). Hence, the effectiveness of lime filter drainage depends on the meteorological conditions of the season. It has been established that in cold season (November–January) TP concentrations decrease by 56–63% in the water of lime filter drainage (significant differences at p=0.01), differences are less significant in February – May period (p = 0.05), and no significant differences have been established for the June – October period due to high variation of data. Similar are fluctuations of PO_4–P concentrations. According to the data of wet year, phosphate phosphorus content in lime filter drainage treatments is significantly lower than that in conventional drainage (p = 0.01) in all months, with exception of June – October period, when drainage usually does not work.

Table 2. Statistical estimation of phosphorus concentrations in drainage water and in the Šilupė stream in the period of 1999–2009

	Months											
	1	2	3	4	5	6	7	8	9	10	11	12
	TP											
I-II	–	–	–	–	–	–	–	–	–	–	–	–
I-III	++	+	+	+	+	–	–	–	–	–	++	++
II-III	++	+	+	+	+	–	–	–	–	–	+	++
I-str.	+	–	–	–	–	–	++	+	+	++	+	++
II- str.	–	–	–	–	–	–	++	++	++	+	+	++
III-str.	+	–	–	–	–	–	–	–	–	–	–	–
	PO_4-P											
I-II	–	–	–	–	–	–	–	–	–	–	–	–
I-III	++	+	++	++	++	–	–	–	–	–	++	++
II-III	+	+	++	++	++	–	–	–	–	–	++	++
I-str.	–	–	–	–	–	–	–	–	–	–	++	–
II- str.	–	–	–	–	–	–	+	–	+	–	++	+
III-str.	+	+	–	+	+	–	–	–	–	–	–	–

Note: + significant difference at p=0,05; ++ significant difference at p=0,01; – no differences

Comparison of TP concentrations in lime filter drainage water and in the stream shows that significant differences become distinct in the beginning of July, after the discharge has decreased, and persist until January – in this period TP concentration in the stream increases 2.0–3.6 times. Significant differences between PO_4–P concentrations in the stream water and in drainage outflow are fixed in November (p=0.01), and those at the significance level p = 0.05 – in July, September and December. In the comparison of drainage variants I and II no significant differences between phosphorus concentrations have been established.

Differences between phosphorus concentrations in stream water and control drainage water are observed in some months only. In January – February TP concentration in drainage water is 1.8 times higher than that in the stream water, but statistically significant differences are established only in January. PO_4–P concentration in drainage water significantly increases (2.3–2.9 times) in January – May, with exception of March. In other time of the year the phosphate phosphorus content in drainage water is 1.2–1.5 times higher, than that in the stream water, but differences are not statistically significant.

In the period of observations phosphorus concentrations in lime filter drainage water do not pertain neither to precipitation amount nor to fluctuations of air temperature (Fig 4). This brings to the statement that the effectiveness of lime does not depend on meteorological conditions. In the conventional drainage water correlations between phosphorus concentrations and the amount of precipitation and temperature are very weak. At the same time strong correlation between total phosphorus concentration in surface water and monthly precipitation (r = 0.82), and medium correlation (r = 0.49) between the concentration and the temperature was estimated (Table 3).

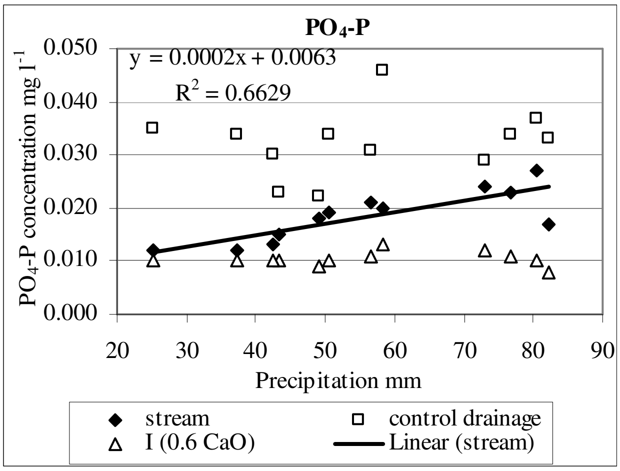

Fig 4. Correlation between monthly precipitation and mean concentration of PO_4-P in drainage and stream water

The distribution of annual average phosphorus concentration in stream water within the period of 1999–2009 shows a slightly decreasing trend of TP (r = 0.49) and PO_4–P (r = 0.84). These results confirm the tendencies established earlier (Šaulys and Bastienė 2008) and correspond to general character of downward trends found in the Lithuanian rivers within agricultural areas (Povilaitis 2004, 2006). Lukianas and Bagdžiūnaitė-Litvinaitienė (2006) comment that these decreases are caused by the changes in agricultural activity during the economic transition period. However, in reality the reasons can be of a very different character. Laws, regulations and economic instruments are used to reduce nutrient losses, together with information campaigns and individual advice. In additional to national regulations and international conventions (e.g. the EU Framework Directive for Water), there is a number of measures that can be adopted at farm and field level to decrease losses of phosphorus.

Table 3. Pirson's correlation coefficients between phosphorus concentration and climate indices

	I	II	III	Stream	Precipitation mm	Temperature °C
			TP			
I	1					
II	**0.827**	1				
III	0.480	0.571	1			
Stream	0.364	0.130	0.211	1		
Precipitation mm	0.058	0.049	0.190	**0.817**	1	
Temperature °C	-0.113	-0.328	-0.236	0.486	0.503	1
			PO_4-P			
I	1					
II	0.935	1				
III	0.655	0.759	1			
Stream	0.301	0.134	0.257	1		
Precipitation mm	-0.084	-0.124	0.112	0.689	1	
Temperature °C	0.071	-0.106	-0.099	0.805	0.503	1

In summary, during the period of 1999–2009 P concentrations in the effluent of the experimental subsurface lime filter drainage were about 1.8 times (46%) lower than those found in the Šilupė stream water at the Kalnujai site, indicating that this improvement may reduce surface water pollution with phosphorus compounds.

4. Conclusions

The drainage water quality monitoring data from the site, where experimental drainage systems with lime backfill were installed 20 years ago (in 1989), brings to the statement that the average lifetime for the lime filter drainage exceeds 20 years without any loss in treatment effect.

Statistically significant differences (at p = 0.01) among drainage treatments affirm that lime admixture in heavy textured soils may reduce phosphorus concentrations in subsurface drainage water considerably. In the outflow of drainage treatments with lime (0.6% CaO for the soil mass), TP concentrations are by 52.3% lower while PO_4–P concentrations are by 68.7% lower than those in the conventional drainage water.

Seasonal fluctuations with respect to phosphorus content are characteristic to the effectiveness of lime filter drainage. It has been established that in cold season (November–January) TP concentrations are 2.3–2.7 times lower in water of lime filter drainage (significant differences at p = 0.01), in February – May period the differences are less significant (1.5–2.0 times, p = 0.05), and no significant differences have been established for the June – October period due to high variation of data. Phosphate phosphorus content in lime filter drainage treatments is significantly lower than that in conventional drainage (p=0.01) in all months, with exception of June – October period, when drainage usually does not work.

In heavy clay soils phosphorus concentrations in lime filter drainage water do not pertain neither to precipitation amount nor to fluctuations of air temperature. This brings to the conclusion that the effectiveness of lime does not depend on these meteorological indices. In the conventional drainage water correlations between phosphorus concentrations and the amount of precipitation and temperature are very weak. Strong correlation has been established between total phosphorus concentration in the stream water and monthly precipitation (r = 0.82), and medium strong correlation (r = 0.49) – between the concentration and the temperature.

Lime filter drainage in heavy textured soils positively affects the quality of drainage water and reduces the transport of phosphorus into open water bodies. This drainage practice can be treated as an effective measure preventing non-point pollution of surface waters in agricultural areas.

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