Effects of artificial land drainage on hydrology, nutrient and pesticide fluxes from agricultural fields – A review

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Abstract

Agricultural intensification has led to a large increase in drained arable land and pastures worldwide over the last two centuries. The installation of land drains not only affects the water balance of a landscape, but also influences the susceptibility to erosion, nutrient cycling, transport of plant protection products (PPPs) and greenhouse gas emissions. Due to the complex nature of environmental systems, the direction in which the substance flows are affected remains unclear, as does the strength of the effects. In this literature review, the focus is on the most relevant site-specific factors that affect the soil moisture regime, erosion, nitrogen (N) and phosphorus (P) fluxes, and PPP fluxes under undrained and drained conditions. The considered factors are the topography, soil characteristics, drainage types, rainfall characteristics and land management. Case studies from temperate climate zones represent the basis of the discussion, with a focus on continental Europe and the USA.

In most cases, drainage enhances the total annual water flows from arable fields, while the effects on peak flows were variable, with the local topography playing a crucial role. There exists a certain level of consensus in the literature that subsurface drainage methods reduce the risk of erosion, while surface drainage may increase erosion at the edge of drainage channels. Nitrogen fluxes are generally enhanced following drainage. This is especially true for organic soils with large stores of organically bound N and, therefore, a high loss potential. For P losses, the trend goes in the opposite direction, with generally reduced losses seen following drainage installation. Similar findings are expected in relation to PPP losses. However, these trends may reverse on flat terrain, where subsurface drainage may reduce the on-site retention of these compounds. Overall, the literature reveals the patterns by which drainage affects hydrology, nutrient and PPP fluxes, although it is also evident that the combination of site-specific factors is influential. This hence needs to be considered as part of any risk assessment or management decisions.

Keywords: Erosion; Nitrogen; Peak flow; Phosphorus; Plant protection products; Preferential flow; Runoff

1. Introduction

It is estimated that approximately 34% of the farmland in northwestern Europe and between 17 and 30% in the USA is artificially drained (Blann et al., 2009; Pavelis, 1987). The majority of drainage systems in Europe were installed within the last 200 years and nowadays many installations are in a bad state (Béguin and Smola, 2010; Davidson, 2014; Gimmi et al., 2011; Holden et al., 2004; Zollinger, 2006). Both policymakers and farmers are therefore forced to consider whether the renovation of old tile drains is always an adequate approach or if other management options may be more sustainable from an agronomic, an ecological as well as an economic perspective (Zollinger, 2006). Contemporary views concerning the ecological effects of drainage systems have changed in relation to the views that were prevalent at the time when such systems were initially installed. It is clearly recognised that the productivity of fields with intact drainage systems is substantially enhanced (Pavelis, 1987). The maintenance of drainage is, however, very costly (Béguin and Smola, 2010), and drainage systems have manifold and complex effects on surrounding ecosystems (Blann et al., 2009). Drainage systems, for example, change the water balance of a landscape, affect nutrient cycling as well as plant protection product (PPP) transport, affect greenhouse gas emissions and threaten the habitats of a series of animal and plant species (Blackwell and Pilgrim, 2011; Blann et al., 2009; Gimmi et al., 2011; Snyder et al., 2009). Due to the complex nature of environmental systems, the direction in which these processes are affected remains unclear, as does the strength of the effects. Some level of consensus can be seen in the literature that subsurface drainage systems reduce erosion, although, depending on the local situation, they can have both reducing or enhancing effects on the hydrological flow components, nutrient and PPP losses, and greenhouse gas emissions (Blann et al., 2009; Holden, 2005). Other possible management alternatives to the renovation of drainage systems include the extensive use of cultures adapted to wet conditions or the complete renaturation of the sites (Joosten et al., 2015).

A trade-off must be made between the ecosystem services that wet (arable) lands can deliver and the potential adverse effects they may have on the environment and the economy (Blackwell and Pilgrim, 2011). In order to make decisions regarding the sustainable use of potentially periodically or permanently wet agricultural fields, which result from high water tables or anthropogenic or natural compaction, the effects of drainage on the different processes need to be understood and weighed against each other. The processes influenced by the artificial drainage of agricultural land include hydrology, soil erosion, nutrient and PPP fluxes, greenhouse gas emissions and biodiversity (Blann et al., 2009; Skaggs et al., 1994). However, the potential effects on CO_2 and CH_4 emissions as well as the effects on biodiversity are outside the scope of the present review.

Several literature reviews dealing with the general effects of drainage on the water balance have been published in recent years, with those concerning mineral soils mainly focusing on US agriculture and those concerning organic soils mostly considering English conditions (Blann et al., 2009; Holden et al., 2004; Holden et al., 2006a; Robinson, 1990; Robinson and Rycroft, 1999; Skaggs et al., 1994). Additionally, some reviews focusing on phosphorus (P) (Blann et al., 2009; King et al., 2015; Sims et al., 1998b), nitrogen (N) (Blann et al., 2009; Jungkunst et al., 2006; Skaggs et al., 1994; Snyder et al., 2009) and PPPs (Brown and van Beinum, 2009; Kladivko et al., 2001) are available.

In this review, we investigate the various effects of drainage on the different fluxes (water flows, erosion and N, P and PPP flows), with a particular focus on how the fluxes differ between artificially drained and undrained sites. More specifically, the interactions with additional relevant site factors that affect the fluxes, such as topography and land management, are analysed. While artificial land drainage affects the physical and chemical properties of all soil types, the effects are expected to be much more significant on organic soils originating from drained peat lands, due to the decomposition of organic matter and the slow transformation into transition forms towards mineral soils. For this reason, this analysis will especially focus on differentiating the effects of drainage on organic and mineral soils. While a range of comparative studies concerning drained and undrained conditions are available with regards to water flows on both mineral and organic soils, comparative studies regarding N, P and PPP fluxes are rare. Regionally temperate climate zones and continental European conditions in particular are preferentially considered. The present review therefore aims to provide a scientific background to support science-based decision making regarding the future use of arable land affected by intermittent water logging. In addition, current knowledge gaps and areas requiring further research are pointed out.

2. Methods

The literature was searched using scientific search engines, namely the ISI Web of Knowledge and Google Scholar. The keywords used are listed in Table S.1. In addition, all references citing the relevant reviews were checked (Blann et al., 2009; Brown and van Beinum, 2009; Holden et al., 2004; Holden et al., 2006a; Holden et al., 2006b; Irwin and Whiteley, 1983; Jungkunst et al., 2006; King et al., 2015; Kladivko et al., 2001; Robinson, 1990; Robinson and Rycroft, 1999; Sims et al., 1998a; Skaggs et al., 1994). Furthermore, the archives of Swiss governmental research into land melioration were searched for studies regarding the effects of drainage on water flows. Only studies that included a detailed description of the applied methods were included in the review. Publications in the German, French and English languages were considered. In total, some 195 articles were included. The number of articles of relevance to the different fluxes and places of origin (four categories: "USA/Canada", "Continental Europe", "UK/Ireland" and "Other countries") are reported in Table S.2.

3. Effects of artificial field drainage on water flows

A series of reviews concerning the drainage effects have previously been published. Some focus on peatlands (Holden et al., 2004; Holden et al., 2006a; Holden et al., 2006b), others mainly cover mineral soils (Blann et al., 2009; Irwin and Whiteley, 1983; Kladivko et al., 2001; Robinson, 1990; Robinson and Rycroft, 1999; Skaggs et al., 1994). These reviews summarise a large number of field studies; however, very often only the drain flow and not the total outflow is measured or else an undrained control is missing, since high quality controls are in practice very difficult to find (Robinson and Rycroft, 1999). The majority of studies have focused on England and the USA (Blann et al., 2009; Robinson and Rycroft, 1999; Skaggs et al., 1994), while studies from continental Europe are comparatively rare (Bullock and Acreman, 2003; Henning and Hilgert, 2007; Robinson et al., 1991; Robinson and Rycroft, 1999; Seuna and Kauppi, 1981). The majority of studies were conducted at the field or small catchment scale and hence very little information is provided regarding the influence of wetland drainage on river floods at larger scales (Acreman and Holden, 2013). Table 1 summarises the effects of drainage on water flows as observed in the studies included in the published reviews, more recent studies as well as older studies not considered in the reviews.

3.1. Surface and subsurface water flows

The results reported with regards to the effects of drainage on water flows from agricultural land are highly variable. While most studies found a small increase (on average, ca. 10%) in the total annual discharge as well as in base flows following drainage installation (Bengtson et al., 1988; Bullock and Acreman, 2003; Evans et al., 1995; Holden et al., 2006a; Robinson, 1990; Schilling and Helmers, 2008; Seuna and Kauppi, 1981), the effects on peak flows during rain events are complex and vary greatly from one study site to another (Blann et al., 2009; Bullock and Acreman, 2003; Kladivko et al., 2001).

The increased total annual outflow following drainage installation can result from decreased water losses due to evaporation (Figure 1) (Blann et al., 2009; Bullock and Acreman, 2003; Henning and Hilgert, 2007). The extent to which drainage systems affect evapotranspiration, however, depends on the season and also varies with site conditions, since, for example, the respective crop may play an important role (Food and Agriculture Organiation of the United Nations, 1998; Khand et al., 2014). Further, the dewatering of peat on organic soils can also contribute to enhanced low flows (Robinson, 1986, 1990).

Peak flows are in general affected by two opposing effects following the installation of land drainage (Figure 1). On the one hand, drains enhance the storage capacity of the soil due to lower water tables, which in turn decreases surface runoff, while on the other hand, it increases the transport velocity of subsurface water towards and through drainage channels (Blann et al., 2009; Heggli, 1954; Robinson, 1990; Skaggs et al., 1994). Yet, surface runoff may not only be caused by saturation excess, since it can also occur under well drained conditions. In that case, it is caused by infiltration rather than saturation excess (Thomas et al., 2016). In humid zones, such as central Europe, saturation excess is more frequent, while in arid zones infiltration excess prevails (Ogden and Watts, 2000; Reichenberger et al., 2007). However, under certain conditions, infiltration excess can also be a relevant process in humid zones (Doppler et al., 2012). For subsurface flows, the process of preferential flow also needs to be considered, since it has been found to significantly enhance flow velocities through the soil profile (Flury et al., 1994) and into drainage systems (Stamm et al., 2002). Preferential flow includes all transport pathways in all types of soil, thereby circumventing flows through the soil matrix. It can occur either through macropore (cracks, fissures, root channels, earthworm burrows) or finger flow in sandy soils (Reichenberger et al., 2007; Stamm et al., 1998).

At any given site, a series of local conditions determine which of the above-mentioned processes are ultimately dominant, as well as whether an increase or a decrease in peak flows is observed. The most relevant factors are the topography, soil characteristics, drainage types, drainage depth and intensity, rainfall characteristics and soil management (Blann et al., 2009; Robinson, 1990; Robinson and Rycroft, 1999). In the following sections, the effects of these site factors in terms of modifying peak flow under drained and undrained conditions are described in more detail.

Table 1. Studies investigating the effect of drainage or land melioration on peak flows. The references in italics represent studies cited in the corresponding review articles and they are not included in the reference list of this article. NA stands for information not available.

Author/Year	**Country**	**Scale/Time**	**Type of drainage**	**Soil**	**Peak flow/surface runoff differences drained vs. undrained**
			Review articles		
Irwin and Whiteley (1983)					
O'Kelly (1955)	GB/IE	Measurements before and after drainage installation	NA	NA	Enhancement
Bailey and Bree (1980)	GB/IE	Twelve watersheds	Surface, subsurface drainage, channel improvement	NA	Enhancement
Eggelsmann (1967, 1971, 1972)	DE	Drained and undrained watersheds	Subsurface drainage	Peat	Reduction
McCubbin (1938)	CA	Before and after melioration works	Land melioration works	NA	No effect (on flooding)
Serrano (1982)	CA	Watershed	NA	NA	No effect
Woodward and Nagler (1929)	US	Watershed study Watershed (four years before and six years after intensive drainage management)/not specified	NA	NA	No effect (on flooding)
Bennet and McGill (1971)	US	NA	NA	NA	No effect (on flooding)
Skaggs et al. (1994)					
Hil (1976)	US	Reginal scale (review)	NA	NA	Enhancement
Campbell et al. (1972)	US	Regional scale	River channelisation	NA	Enhancement

Skaggs et al. (1980)	US	Field scale	Surface and subsurface drainage	NA	Enhancement
Gregory et al. (1984)	US	Watershed	Peat mining	Peat	Enhancement
Gilliam and Skaggs (1989)	US	NA	NA	NA	Enhancement
Starr and Paivanen (1986)	FI	NA	Drainage of forested peat	Peat	Enhancement
Evans et al. (1989)	US	NA	NA	NA	Enhancement
Baden and Eggelsann (1968)	DE	Drained and undrained watersheds	NA	Peat	Reduction
Burke (1972)	IE	NA	NA	Peat	Reduction
Green (1973)	GB	NA	NA	Peat	Reduction
Pereira (1973)	RU	NA	NA	Peat	Reduction
Heikurainen (1976)	FI	NA	NA	Forest soils	Reduction
Heikurainen (1980)	FI	NA	NA	Forest soils	Reduction
Heikurainen (1978)	FI	NA	NA	Forest soils	Reduction
Robinson (1990) and Robinson und Rycroft (1999)					
Robinson (1983), Armstrong (1983), Schuch (1978)	GB/DE	Paired studies/before and after drainage installation	Surface and subsurface drainage	Peat and mineral soils	Enhancement
Arrowsmith (1983), Harris (1984), Armstrong and Garwood (1991), McLean and Schwab (1982), Robinson (1983)	GB/US	Paired studies/before and after drainage installation	Surface and subsurface drainage	Peat and mineral soils	Reduction
Robinson and Beven (1983), Robinson et al. (1987)	GB/IE	Paired studies	Subsurface drainage	Clay soils	Reduction in winter/enhancement in summer
Holden et al. (2004) and Holden et al. (2006a)					
Lewis (1957)	GB	NA	NA	Peat	Enhancement
Oliver (1958)	GB	Watersheds	NA	Peat	Enhancement
Howe and Rodda (1960)	GB	Qualitative observation	NA	Peat	Enhancement

Conway and Millar (1960)	GB	Four small (2 ha) watersheds/two drained and two undrained	NA	Peat	Enhancement
Mustonen (1964)	FI	NA	NA	Peat	Enhancement
Howe et al. (1967)	GB	Watershed	Afforestation and drainage	Peat	Enhancement
Institute of Hydrology (1972)	GB	NA	NA	Peat	Enhancement
Ahti (1980)	FI	Measurements before and after drainage installation	NA	Peat	Enhancement
Robinson (1980, 1986)	GB	Measurements before and after installation in the watershed	Open drainage ditches	Peat	Enhancement
Guertin et al. (1987)	US	NA	NA	Peat	Enhancement
Gunn and Walker (2000)	IE	Measurements in drained and undrained watersheds	Open drainage ditches	Peat	Enhancement
Burke (1967)	IE	Paired study	NA	Peat	Reduction
Baden and Eggelsmann (1970)	DE	Drained and undrained watersheds	Compared to other studies deeper drainage channels/ditches; strong reduction of surface runoff	Peat	Reduction
Heikurainen (1968)	FI	NA		Peat	Reduction
Newson and Robinson (1983)	GB	NA		Peat	Reduction
Moklyak et al. (1975)	Former USSR	Measurements before and after drainage installation		Peat	Enhancement or reduction
		Recent field studies and studies not considered in the reviews			
Tessier (1991)	CH	Catchment/three years before and three years after drainage installation	General melioration works, including drainage channels	NA	No effect on two sites; enhancement of one site
Zollner and Cronauer (2003)	DE	Four watersheds at different drainage intensity (agriculture, forestation, uncultivated)	Subsurface drainage	Peat soil	Enhancement
Tuohy et al. (2016)	IE	Field scale; four replicate plots of each undrained,	Subsurface drainage	Clay loam	Enhancement

		mole drained and gravel-mole drained sites; one year with 12 heavy rain events			
Heggli (1954)	CH	Field/one year	Agricultural subsurface drainage	Peat soil	Reduction
Muma et al. (2016)	CA	Micro watershed (2.4 km^2); CATHY model with calibration and validation of field measurements	Subsurface drainage	Sandy to loamy soils (1–30% clay)	Reduction
Henning and Hilgert (2007)	DE	Regional scale	Mainly subsurface drainage	Mineral soil	NA (only total annual flows reported and they were enhanced)
Schilling and Helmers (2008)	US	Comparison of seven drained and less drained watersheds	Subsurface drainage	Mineral soil	Inconsistent

3.1.1. Effect of topography

Topography may have a crucial impact on the effects of drainage. If surface runoff is caused by saturation excess, drainage systems have the potential to reduce peak flows on slopes with access to open water bodies (Holden et al., 2006a). On flat areas with less than 2% slopes, however, where surface runoff is not relevant in practice (Wohlrab et al., 1992), the faster pathways towards and through drainage pipes tend to increase peak flows, since water otherwise collected in hollows on site can be removed more efficiently (Acreman and Holden, 2013; Lennartz et al., 2011; Scott et al., 1998). These relatively small hollows are of particular importance for small-scale seasonally flooded fields on arable land. For a detailed assessment of the risk of a specific site becoming saturated and surface runoff being caused, estimators such as the topographic wetness index (TWI) may be used. The indices take into account the local surface slope at a specific point in the field and, in addition, the upslope drainage area. The resolution of the digital elevation models and the data processing tools used in this context are decisive, since small-scale elevations and local sinks of less than one metre may determine whether water is retained or surface runoff caused (Thomas et al., 2016; Thomas et al., 2017). This relevant aspect is important in relation to properly reflecting any anthropogenic, small-scale changes of topography, which may have a large effect on connectivity at the landscape level (Doppler et al., 2012; Frey et al., 2009). There are, however, several calculation methods available for the TWI that all differ from each other, especially with respect to the calculation of the upslope contributing area (Sørensen et al., 2006). Further, for flat terrain with poorly defined flow directions, the use of model-based wetness indices (MWI) has been suggested. Such indices take into account the dynamic influences of upstream and downstream conditions. The precondition is, however, that some meteorological and hydrological data are also available (Grabs et al., 2009). Depending on the purpose of the application, the appropriate method should be applied (Grabs et al., 2009; Sørensen et al., 2006).

3.1.2. Effects of soil characteristics

3.1.2.1. Organic soils

Peat soils are generally characterised by high organic matter content (>30%), high porosity and low density. However, large differences exist between the different types of peat, depending on the degree of humification. Peat originating from a well-humified fen might differ greatly in terms of its unsaturated hydraulic conductivity when compared to peat originating from raised bogs (Bölter, 1969). Following drainage, the characteristics of the peat change due to oxidation, compaction and mineral matter additions. That is, the part of a peat bog containing living plants (acrotelm) with generally higher hydraulic conductivity and the part underneath the acrotelm, which mainly consists of dead organic material (catotelm) with lower conductivity, can often no longer be distinguished (Bölter, 1969; Mustamo et al., 2016). Drained peat soils generally show high water retention capacities and reduced hydraulic conductivities as the occurrence of macropores decreases (Liu et al., 2016; Mustamo et al., 2016). Yet, the ability to retain water can also decrease due to hydrophobicity if the peat is drying, depending on the weather conditions (Holden et al., 2006a). These properties, however, are expected to change in the long-term after the installation of drainage due to shrinkage and the decomposition of organic matter (Liu et al., 2016). This means that the water retention capacity may further decrease, again due to the formation of new macropores, thereby enhancing preferential flow paths (Holden et al., 2004; Holden et al., 2006a). The formation of earthworm burrows, for example, has been found to be an important cause of preferential water flow in former wetlands in Switzerland (Kohler, 2004). This implies that the time scale after drainage installation also needs to be considered when describing the outflow patterns from peat soils. In one study conducted in England comparing the annual runoff and peak flows after rain events shortly after surface drainage installation and 40 years later, for example, it has been found that the runoff efficiency (runoff/rainfall ratio) increased over time, although no effect was observed initially. The authors explain this long-term effect by means of the structural changes that occurred in the peat with the development of macropores and pipes. Immediately after the installation of drainage, only shorter lag times and enhanced peak flows were observed, while no changes in the total catchment runoff efficiency were found. The transport pathways also changed over time as the surface runoff decreased (Holden et al., 2006b). Similar results have been found in relation to the Chiemseemoor in southern Germany, where another long-term study concerning organic soil has been conducted. Moreover, in this case, the outflow approximately 60 years after drainage installation (open ditches every 100 m and pipe drains every 15 m at first and later every 6–8 m) was enhanced, both the low flows and peak flows (Robinson et al., 1991). In a different study conducted in northern England, Robinson (1986) found that ten years after the drainage of a peatland, the peak flows were still increased by 10%, while immediately following drainage installation (drainage ditches), the observed increase was about 20%. Additionally, the overall yearly runoff was slightly increased. The increased flood peaks can be explained in this case by faster transport pathways through the drain pipes or channels.

In addition to the reasons mentioned above, Zollner and Cronauer (2003) explain the lower flood peaks observed on intact peatlands when compared to cultivated peatlands in study sites in the southern Chiemsee peatlands (Bavaria, Germany) by means of the rough surface structure of peatlands as well as the presence of hummocks and hollows collecting surface waters. The soil loss from drained peatlands over time may also be a relevant factor, since the potential water storage volume is reduced. However, no studies investigating this hypothesis could be found in the literature.

In a comparable number of other studies conducted mainly on blanket bogs (areas with widespread peat formation not only in hollows, but also on hillslopes), however, the peak discharge rates after storm events decreased following the installation of drainage (Heggli, 1954; Holden et al., 2006a; Irwin and Whiteley, 1983), while the base flows remained the same or increased slightly in most studies (Robinson, 1990). The authors explain the decreasing effect of drainage on flood peaks mainly by means of the enhanced water storage capacity of the soils due to the lower water tables and subsequent reduction in fast surface runoff. However, no long-term observations were made at these sites, although they would be needed to account for any long-term changes in the peat composition.

3.1.2.2. Mineral soils

On mineral soils, drainage systems are needed because of either the natural impermeability of the substrates, anthropogenic soil compaction or high groundwater tables. On heavy clay soils, high surface runoff rates can often be observed under non-drained conditions due to the limited infiltration capacities. On soils with an increasing sand content, high surface runoff is only expected if the groundwater tables are directly at the surface; otherwise, infiltration is normally good. Drainage installation on heavy clay soils does not increase the storage capacity of the soils to any significant extent due to the lack of large pores. However, crack formation following dry periods increases the infiltration capacity (Robinson and Rycroft, 1999) and thus has a reducing effect on the surface runoff.

The factors that ultimately dominate the flow rates strongly depend on the site conditions (Robinson et al., 1985). The majority of studies concerning clay soils identified the reducing effect of drainage installations on peak flows (Robinson and Rycroft, 1999; Schwab et al., 1985; Seuna and Kauppi, 1981). In some studies, for example, in a five-year study concerning grassland drainage on a clay soil, the effects of drainage on the peak flows and overall flows were small. In these studies, only the flow paths differed, which had an effect on the nutrient and contaminant fluxes (Armstrong and Garwood, 1991). In a recent study conducted in Ireland comparing the peak runoff rates from mole-drained and undrained plots in a field experiment on clay loam soil, however, lower peak runoff rates were measured in the undrained than in the drained treatments (Tuohy et al., 2016). Yet, it must be noted that the drainage installation was shallow (0.4–0.55 m), while the average hillslope was only 1.4%. It means that the drainage induced reduction of surface runoff is under these conditions probably not strong enough.

On loamy and sandy soils, the storage capacity following drainage can substantially increase and thus have a reducing effect on peak flows. The subsurface runoff in the pipes, however, is also faster than the natural subsurface flow through the soil matrix, and this factor seems to be dominant in the majority of studies, as enhanced fluxes were often observed (Blann et al., 2009; Henning and Hilgert, 2007; Robinson, 1990). Additionally, preferential flow probably contributed to the enhanced flows observed in some studies. Traditionally, this issue has only been considered to be important on heavy clay soils, although it has also been shown to be relevant in many loamy and silty soils (Flury et al., 1994; Reichenberger et al., 2007).

The findings discussed above show that the texture of mineral soils strongly influences the effects of drainage on peak flows. The trend of generally decreased peak flows seen following drainage installation on clay soils and increased flows seen on more permeable soils has been nicely demonstrated in nine case studies by Robinson and Rycroft (1999).

Not many studies concerning the effects of drainage on water flows at larger than field scales are available. One study conducted in the Swiss Plateau looked into the changes in hydrology three years before and three years after the installation of melioration works at the catchment scale (Tessier, 1991; Tessier et al., 1993). Different results with respect to peak flows following drainage installation were observed in the three case study catchments. While no effect of the melioration works on the peak flows and outflow volumes were found in two catchments, enhanced peak flows and shorter lag times were observed in the third catchment. The authors conclude that melioration works can locally, depending on the drainage intensity and local site characteristics, enhance the risk of small floods following heavy rain events that occur with a return period of <5 years, although they expect no effects of melioration works on floods occurring at lower frequencies (i.e. more than 30 years), since the capacity of the drainage systems would not be sufficient and surface runoff following the topography would be expected. A second study at the regional scale was carried out by Henning and Hilgert (2007) in the plains of Mecklenburg-Vorpommern, Germany, with predominantly loamy soils. They found enhanced variations in the flow rates in the receiving water bodies as well as higher total annual runoff and attributed it to the intensive drainage in the area. Due to the large variation in influencing variables, it is difficult to generalise the findings of these two larger scale studies. Further studies looking into the cumulative effects of agricultural drainages on stream flows are needed.

3.1.3. Effect of drainage types

With regards to the subsurface drainage of crop land, the installation depth of the pipes is of high importance. If the water table is close to the surface, lowering the water table by means of drainage installation can, at least on organic soils and on sandy or loamy soils, increase the water storage capacity of the soil and thereby reduce flood risks (Irwin and Whiteley, 1983; Robinson, 1990). However, this only holds true if the topographic conditions allow it. Controlled tile drainage systems with artificially adjustable water tables at the outflow, when compared to conventional subsurface drainage, have been found to reduce unintended water losses as well as losses of nutrients such as N and P (Evans et al., 1995; Kladivko et al., 2001; Wesström et al., 2001). Controlled drainage means that under dry weather conditions, the outflows can be partly blocked in order to keep the water tables higher, while under wet conditions the water tables can be lowered to reduce surface runoff. Attenuating effects on the total water flows and the flooding of adjustable water tables have also been observed in open ditch drainage systems on agricultural soils in North Carolina (Evans et al., 1995) as well as on forested peat soils in the Czech Republic (Stibinger, 2016).

The distance between two drains is also of relevance, since it has hydrologic effects on the outflow volumes (Holden et al., 2006a; Jin and Sands, 2003). Very closely spaced drains decrease the water retention potential of a soil, as the site discharge becomes very efficient. Yet, if the space between drains exceeds an optimum distance, the relevance of surface runoff increases again (Sloan et al., 2016). The extent of this effect, however, greatly depends on soil characteristics such as the hydraulic conductivity (Sloan et al., 2016; Wiskow and van der Ploeg, 2003). The installation process associated with subsurface drainage tiles or moles may also affect the water flows. In the case of tile drainage systems, for example, the material used as backfill as well as its packing density can be of high importance, since the hydraulic conductivity may differ (Taylor et al., 1980).

3.1.4. Effect of rainfall characteristics and seasonality effects

The intensity and duration of a rainfall, as well as rainfall volumes, strongly affect the hydrology of a catchment. High-intensity rainfalls on dry fields may cause infiltration-limited surface runoff irrespective of the water storage capacity of the soil. On sandy or loamy soils, surface runoff caused by saturation excess is more dominant, while on clay soils infiltration-limited runoff can also be relevant (Reichenberger et al., 2007). Tessier (1991) highlighted how the effects of drainage may be relevant for middle-intensity rain events, but not for heavy rain events causing big floods, since the transport capacity of the drainage systems is exceeded. The impact of drainage systems on water flows after regular rain events, but not on floods after large storms has also been discussed by Sloan et al. (2016) using field data and DRAINMOD simulation in Iowa, USA.

During the summer season, evapotranspiration rates are higher and, generally, a lower proportion of rainfall is lost from the fields through surface or subsurface runoff. Single high rainfall events cause major water effluxes in summer. In winter, the proportion of precipitation found in drainage systems is also high following low-intensity rainfalls (Hirt et al., 2011). In a series of field plots performed at Ballinamore in Ireland, Robinson and Rycroft (1999) reported higher peak flows in summer and lower flows in winter under drained versus undrained conditions. They explain the higher flows seen in summer by means of enhanced cracking and macropore flow. The lower peaks seen in winter can be explained by the surface runoff due to saturation under undrained conditions.

3.1.5. Effect of land management

Land management influences the water regime of a soil and, with it, the strength of the drainage effects. On permanent grasslands, the strongest influence on the soil structure generally results from grazing or irregular cuttings, while arable fields are in general regularly tilled, which causes a larger disturbance of the soil structure and therefore enhances infiltration. Accordingly, lower subsurface drain flows and slightly higher surface runoff have been observed under grassland when compared to a field on which barley was cultivated (Turtola and Jaakkola, 1995). Tilling has been found to accelerate and increase subsurface discharge into drainage pipes due to increased hydraulic conductivity (Moroizumi and Horino, 2004). Especially on clay soils, tilling may substantially enhance the infiltration capacity, thereby leading to enhanced subsurface flow and reduced surface runoff. Yet, macropores and cracks are destroyed by tilling activities, which may temporarily reduce preferential flow (Schelde et al., 2006). It should be noted, however, that there are many different management practices available, ranging from no-till to conservation tillage to conventional tilling (Busari et al., 2015), which can strongly affect the extent to which the peak flows are affected by land management. Additionally, the cultivated crops may influence the effects of drainage due to different evapotranspiration rates (Food and Agriculture Organiation of the United Nations, 1998) or different rooting patterns affecting the preferential flow paths into the drainage pipes (Flury et al., 1994; Reichenberger et al., 2007). In summary, land management has an impact on the effects of drainage mainly by changing the soil structure in a dynamic way, in addition to crop as well as seasonality effects on evapotranspiration.

3.2. Synthesis of drainage effects on water flows

The composition of drainage water from mineral as well as organic soils tends to shift from larger surface flows to more subsurface flows under drained conditions (Sloan et al., 2016). However, the topography, soil characteristics, drainage type, rainfall characteristics and soil management processes all determine the extent to which this shift happens. Furthermore, on organic soils, changes in the structure and composition of organic matter, as well as the soil loss over time, need to be considered.

Although the effects of hydrophobicity on water retention can also be observed on mineral soils, the effects on organic soils are expected to be stronger (Holden et al., 2006a; Ritsema et al., 1997). On mineral soils, the influence of the texture is of greater importance, while on clay soils the peak flows tended to be reduced and on more sandy soils they rather increased (Robinson and Rycroft, 1999). The topography is of particular importance on all types of soils, since, for example, on flat fields (<2% slope) with hollows without natural discharge, the surface runoff is also negligible under undrained conditions. On such sites, the installation of drainage may only enhance the subsurface drainage without reducing the surface runoff, even though the storage capacity of the soil might be enhanced. In Table 2, the relevant site factors are summarised for an estimation of the effects of drainage on water flows on specific fields.

For practical risk estimations of the surface runoff at specific sites, high-resolution digital elevation models at the sub-metre scale combined with hydrological models defining the contributing catchment area and local precipitation may help to more precisely estimate whether overland flow is generated under undrained conditions. Under drained conditions, however, the process of preferential flow into the tiles can enhance the peak flows on all types of soils and it remains unclear exactly which factors are responsible for high preferential flow fluxes, especially on loamy and sandy soils. In their review of the effects of land use management on flood creation, O'Connell et al. (2007) conclude that there is insufficient information available to reach a general conclusion regarding whether small-scale agricultural management changes affect floods at the larger scale or not. They emphasise that multiscale catchment experiments are needed to elucidate the cumulative effects.

Table 2. Summary of the site factors affecting peak flows from drained arable land at the field scale. WT stands for water table.

	Topography	**Soil permeability**		**Organic matter**	**Drainage type**	**Rainfall**
		Low	**High**			
		Clay -- loamy -- sandy				
Enhancing effect on peak flows under drained	Flat areas (<2% slope) or hollows without	If crack formation occurs	If WT rarely at soil surface (before drainage);	Macropore formation on degraded peat	WT still high after drainage (often with open ditches or drainage	Highly variable. Yearly total amount of rain is relevant, but it

conditions expected	natural discharge		preferential flow?	Disappearance of heterogeneous structure and peat layer over time	systems installed at insufficient depths)	also depends on single events: rainfall intensity, total volume and duration.
Decreasing effect on peak flows under drained conditions expected	Slopes with >2% with connection to surface waters	If no crack formation occurs	If WT often at soil surface (before drainage); preferential flow?	Undecomposed peat directly after drainage installation	WT efficiently lowered (subsurface drainage installed at sufficient depths)	

4. Effects of artificial field drainage systems on erosion

There is a consensus in the literature that subsurface drainage reduces the risk of erosion in mineral soils (Bengtson et al., 1995; Bengtson et al., 1988; Blann et al., 2009; Skaggs et al., 1994; Turtola and Paajanen, 1995). However, it should be noted that in some cases enhanced erosion at the river edges of the drainage outflows has been observed due to the higher transport capacities in subsurface drainage systems (Tessier, 1991).

Surface drainage, however, can cause significant erosion at the edges of open ditches (Newson, 1980), depending on the management of the ditch margins. Particularly in the case of peat soils, open ditch drainage is relatively common and high sediment losses have been observed (Holden et al., 2004). Due to their high organic matter content, intact water-saturated peat soils have been found to be much less prone to erosion caused by surface runoff (Carling et al., 1997). The more decomposed a peat soil becomes, however, the more it gets susceptible to erosion by rain splash and runoff, since it loses the fibre-rich peat that has a stabilising effect on the soil (Tuukkanen et al., 2014). In a study investigating the factors affecting peat's erodibility by water, it has been found that the average discharge rates as well as the degree of surface peat decomposition (positive relationships) could best explain the suspended sediment loads seen in the outflow (Tuukkanen et al., 2014). Drained peat surfaces are highly erodible by wind, since the dead plant material dries out and becomes loose. Such soils are especially prone to erosion if the surface is not covered by plants (Evans and Warburton, 2007). For wind erosion, a wind tunnel experiment conducted at high wind speeds showed that the erodibility decreases with increasing peat decomposition (Campbell et al., 2002). The probable reason for this observation is the increased particle density. Further, the formation of surface crusts on bare peat following rewetting and drying strongly decreases the susceptibility of peat soils to erosion (Campbell et al., 2002; Evans and Warburton, 2007).

4.1. Synthesis of drainage effects on erosion

Similar to the effects of drainage on water flows, the topography is also one of the most important factors determining whether a site is susceptible to erosion (Prasuhn et al., 2013). Therefore, only on arable lands with slopes higher than 2% is a reduction in erosion due to drainage installation expected. On such slopes, the long-term risk of erosion at a specific site may be estimated using the Universal Soil Loss Equation (USLE) given by Wischmeier and Smith (1978) or modified versions such as the Revised Universal Soil Loss Equation (RUSLE) or the Modified Universal Soil Loss Equation (MUSLE) (Renard et al., 1997; Williams and Hann, 1978). Based on that, the potential benefit of drainage installation may be estimated. However, in terms of the model selection for practical applications, it must be recognised that the equations are only valid under the conditions they were calibrated for (Renard et al., 1997).

5. The effect of field drains on phosphorus, nitrogen and plant protection product flows

The diffuse losses of nutrients from agricultural fertilisers as well as the losses of PPPs to surface water represent a widespread problem worldwide (Blann et al., 2009; Brown and van Beinum, 2009). The most relevant nutrients are N and P, since they are often limiting factors for algal growth in freshwater and coastal ecosystems (Elser et al., 1990; Gächter et al., 2004). The number of relevant PPPs is high, and treating them individually is beyond the scope of this review. They are instead grouped into compounds strongly or weakly adsorbed into soil surfaces (Brown and van Beinum, 2009).

The reasons for agricultural N, P and PPP fluxes into surface waters can be manifold. The factors that play a role include the application rate, the timing and form of the application and the cultivated crops. Substance losses additionally depend on their chemical properties, such as the water solubility or reactivity, as well as the physico-chemical properties of the soil, such as the organic matter content, texture, iron (Fe), aluminium (Al) or calcium (Ca) content and their combined effects on the sorption strength (King et al., 2015). In addition, artificial drainage systems can significantly alter the substance dynamics of an agricultural soil due to both changes in the water balance and preferential flow paths into the drainage pipes.

5.1. Phosphorus

Since the mobility of P within soils is generally low due to its strong adsorption and inorganic fixation with clay, Fe, Al and Ca (Gächter et al., 2004), P losses through subsurface flows from agricultural fields are considered to be of only limited importance. Instead, for many years the main focus with regards to the loss of P from agricultural landscapes has been on P transport via surface runoff and the prevention of erosion (King et al., 2015). Although the installation of drainage systems tends to increase the water yields from agricultural fields, it is generally concluded that surface runoff and soil loss are reduced at the same time by enhancing infiltration as well as the efficiency of subsurface flow (Dolezal et al., 2001). Accordingly, it is assumed that P losses are reduced following the installation of drainage systems (Blann et al., 2009; King et al., 2015; Simard et al., 2000). However, it is very difficult to find studies directly comparing the loss of P in artificially and naturally drained systems (Radcliffe et al., 2015). Indeed, to the best of our knowledge, only three experiments have been conducted evaluating the net difference in the P loss. Bengtson et al. (1988) and Bengtson et al. (1995) compared four neighbouring plots (two with artificial drainage and two without) in the Lower Mississippi Valley near Baton Rouge on which corn was cultivated and fertilised with commercial granular fertiliser. They found that the plots with artificial drainage showed a reduction in the total P losses between 31 and 36% when compared to the undrained plots, which was related to the reductions in soil loss due to erosion. A reduction of a similar size was found in experiments involving grazed grassland plot lysimeters in the southwest of England (Haygarth et al., 1998). Consistently, the lowest P concentrations were detected in drainage water, as explained by the low Olsen P in the lower horizons resulting in 30% less P loss, when compared to the undrained plot lysimeters. Some comparisons of the P concentrations in the outflows of drained and undrained sites are available in studies investigating the effects of peatland restoration. In one study, peatland restoration was investigated over six years in 24 plots of peatland originally drained for forestry in Finland. In addition, 19 plots of pristine peatland were sampled as controls. Several-fold higher total P concentrations were measured in the outflows of the drained sites when compared to the pristine sites. This finding may be explained by either the inputs of P through fertilisers under drained conditions or by P mobilisation caused by changes in the soil redox potential (Menberu et al., 2017). In a further study concerning peatland restoration in Finland, the differences between the P losses from pristine and drained sites were found to be small (Koskinen et al., 2017).

Although the installation of drainage systems seems to lead to a reduction in the total P losses, at least on mineral soils, the still considerable export of P has been observed in many studies, with significant concentrations seen in the drainage water, which is potentially relevant for eutrophication (Blann et al., 2009; Gentry et al., 2007; Haygarth et al., 1998; Sims et al., 1998b; Smith et al., 2015; Stamm et al., 1998). Many different factors influence the amount of P lost through drainage water. These factors were systematically reviewed and classified in a recent study by King et al. (2015), and they are briefly summarised below. Even though a series of field studies concerning P losses through drainage systems have been published in recent years, Christianson et al. (2016) emphasise the importance of further field studies to also test the effects of cropping systems, nutrient application, soil properties and drainage design on P losses.

5.1.1. Soil characteristics and preferential flow

Preferential flow paths and surface inlets directly connecting the P-enriched topsoils with the drainage system appear to be among the most crucial factors governing the subsurface P loss.

Generally, the P sorption capacity is high in organic and fine-textured soil, while it is lower in coarse-textured soils (Daly et al., 2001; Fox and Kamprath, 1970). Accordingly, one would expect high P losses in the coarse-textured soil types and less losses in fine-textured soils. However, preferential flow paths are very common in well-structured soils (Flury et al., 1994). Thus, Beauchemin et al. (1998) showed that soils with a high clay content generally lose more P when compared to coarse-textured soils. Accordingly, transport via preferential pathways seems in many cases to be of great importance, given that there is a pool of available P. Many studies support this hypothesis by reporting that the presence of preferential flow paths and P-rich soils results in high P export via the drainage system (Chapman et al., 2001; Djodjic et al., 1999; Eastman et al., 2010; Laubel et al., 1999; Paasonen-Kivekäs and Koivusalo, 2006; Van Es et al., 2004). For example, on a drained permanent grassland plot, approximately half the yearly dissolved P load was estimated to be leached from the soil through primarily macropores (Gächter et al., 1998; Stamm et al., 1998). In agreement with that finding, Simard et al. (2000) hypothesised that "if the soil P store is coincident with preferential flow pathways (either artificial mole drainage channels or natural macropores), permanent grassland will be vulnerable to transfer large amounts of P through subsurface pathways."

5.1.2. Drainage system layout

Drainage systems are usually designed to optimise crop production. Two of the most important features of drainage system layout are hence the depth and spacing. Shallow drains typically transport less water when compared to deep drains. By increasing the density of drains (reducing the spacing), higher water yields can be achieved (Hoover and Schwab, 1969). Typically, the P concentrations are higher in shallow drains than in deeper drains (Culley and Bolton, 1983; Duxbury and Peverly, 1978; Gächter et al., 1998; Hausherr et al., 2006; Stamm et al., 1998). However, as deep drainage systems exhibit greater water yields, with respect to P loading, it is generally assumed that deeper drains have greater P losses than shallow ones, even though the water fraction quickly reaching the drains decreases with depth (King et al., 2015; Schwab et al., 1980). Overall, it has been observed that the effect of the drainage depth (0.65 and 0.85 m) on the total P losses is stronger than the effect of the tile spacing (7.5 and 4.2 m) (Tan and Zhang, 2016). This can be explained by the much larger water volume losses achieved through a decrease in the drainage depth.

5.1.3. Soil phosphorus, fertiliser and application

In general, high concentrations of soil test phosphorus (STP) in the topsoil are positively correlated with dissolved P concentrations in the runoff and drainage water (Maguire and Sims, 2002; Pote et al., 1999). Several studies have indicated that there is a STP threshold above which an increase in STP results in a multifold increase in the P concentration in the drainage water (Heckrath et al., 1995; McDowell and Sharpley, 2001; Smith et al., 1995). However, the actual STP threshold varies from study to study, and it is dependent on the STP itself. King et al. (2015) hypothesised that differences in the threshold values could be related to the soil texture. They expect lower threshold values for soils with a high clay content due to the occurrence of preferential flow.

Regarding the type of P applied, there is a consensus in the literature that losses from organic P (e.g. manure) are higher than those from inorganic P (Delgado et al., 2006; Eghball et al., 1996; Macrae et al., 2007; Nayak et al., 2009; Zhao et al., 2001). This is explained by the different sorption characteristics of the P source. While some studies suggest that organic P is less strongly sorbed and therefore more easily leached (Frossard et al., 1989; Simard et al., 1995), other authors argue that applying organic P leads to higher STP than fertilising with an inorganic P source (Kinley et al., 2007; Nayak et al., 2009). In addition, some studies show that the amount of water-extractable P differs widely among the different organic source materials, with swine manure exhibiting the highest values (Elliott et al., 2002; Kleinman et al., 2005; Sharpley and Moyer, 2000).

5.1.4. Tillage

No-till or minimal tillage practices are usually recommended for reducing soil disturbance, erosion and particulate P loss on arable land. However, several studies have shown that these conservation practices actually lead to significantly higher subsurface P losses when compared to conventional tillage practices (Andreini and Steenhuis, 1990; Geohring et al., 2001; Shipitalo and Gibbs, 2000; Zhao et al., 2001). These results can be explained by two processes. As mentioned above, preferential pathways provide a direct link between the P-rich topsoil and the drainage system. Tilling the soil causes these direct connections to be destroyed. In addition, when tilling, the very strong stratification of P in the soil (due to surface application) is attenuated and, typically, less P can be leached (Schärer et al., 2007). However, studies have generally shown that the effects of tillage only last for a short time (Algoazany et al., 2007; Djodjic et al., 2002; Schärer et al., 2007; Schelde et al., 2006). Therefore, the benefits of no-till practices (soil health as well as the reduction of erosion and losses due to surface runoff) must be weighed against the positive short-term effects with respect to subsurface P losses.

5.2. Nitrogen

Nitrogen losses from agricultural fields can occur in various forms, depending on the applied fertilisers as well as the transformation processes occurring within the soil (Haynes, 1986; Heathwaite et al., 1998). Here, it is important to distinguish between losses of organic N, nitrate (NO_3^-), ammonium (NH_4^+), gaseous nitrous oxide (N_2O) and ammonia (NH_3) as the most abundant and relevant forms.

NH_4^+ and organic forms of N generally adsorb strongly into soil particles. Their concentrations are therefore generally reduced in subsurface drains when compared to surface runoff (Haynes, 1986; Skaggs et al., 1994). For NO_3^- losses, the opposite is true. The losses through subsurface waters are generally higher due to its weak sorption into soil particles. High losses of NO_3^- through improved subsurface drainage from mineral soils are well documented. They are often attributed to the enhanced mineralisation and decreased denitrification rates caused by deeper water table depths (Blann et al., 2009; Evans et al., 1995; Grigg et al., 2003; Hirt et al., 2005; Kladivko et al., 2004; Lennartz et al., 2011; Randall and Goss, 2008; Rossi et al., 1991; Seuna and Kauppi, 1981; Skaggs et al., 1994; Williams et al., 2015). Due to its characteristics, NO_3^- losses through preferential flow have also been observed to be a relevant pathway under drained conditions (Kohler, 2004). The effect of subsurface drainage on NO_3^- losses was also demonstrated by comparing fields with different drainage intensities. With increasing drainage intensity (drain depth and spacing), increasing NO_3^- losses were found in a study with a sampling campaign conducted over 15 years in Indiana, USA (Kladivko et al., 2004; Skaggs et al., 2005). In a field study from Illinois, USA, higher N input into surface waters was observed in a intensively drained watershed when compared to one with a comparable climate and cropping conditions with little artificial drainage (Mc Isaac and Hu, 2004). It has also been reported that controlled drainage systems with adjustable water table depths can significantly reduce NO_3^- losses through subsurface drainage (Lalonde et al., 1995; Randall and Goss, 2008). However, there are exceptions to this. For example, in a study concerning a clay loam soil, on average, slightly reduced N exports (20% reduction of yearly exports) were measured under subsurface drained conditions when compared to only surface drained conditions in a six-year study conducted near Baton Rouge, LA, USA (Bengtson et al., 1988). One possible reason for this contrasting finding could be that the application of N fertiliser caused high N concentrations in the surface runoff, while the surface runoff was enhanced in the undrained plots. This notion is supported by the fact that, especially during spring (March–May), enhanced losses were found.

5.2.1. Influence of site characteristics

The total amounts of N lost under drained conditions depend on the soil types. On clay loams, significantly higher N loads were observed than on silt loams in a meta-analysis comparing the N loads from drained fields in 31 studies conducted in the Midwest USA (Zhao et al., 2016). The authors explain the difference by means of the need for more intensive drainage on clay loam soils. Additionally, the precipitation amounts and intensity have a strong influence on N movement in soils. In the same meta-analysis, exponentially increasing N losses were observed with increasing annual precipitation means (Zhao et al., 2016). Directly after rain events, the NO_3^- concentrations in drainage water tend to decrease, since rainwater is generally about ten times lower in terms of the NO_3^- concentration than groundwater, while only small amounts of NO_3^- are stored in the topsoils. Later on, when a bigger portion of the drained water originates from groundwater, peaks in the NO_3^- concentrations are observed (Gächter et al., 2004). For the NO_3^- losses from drained arable land, the cultivated crops and the cropping systems also play an important role (Randall and Goss, 2008). The NO_3^- concentrations measured in drainage water have been found to be lower for cereals such as wheat, perennial crops such as alfalfa and pasture than for corn, soy beans, peas and, generally, crops with a short growing season (Blann et al., 2009; Ernstsen et al., 2015; Randall and Goss, 2008). The highest NO_3^- losses are accordingly often observed during the winter months due to a lack of surface cover (Kladivko et al., 2004).

5.2.2. Organic versus mineral soils

In soils with a high organic matter content, a larger portion of the soil N occurs in organic forms when compared to mineral soils, and it represents a large pool of mineraliseable N (Schmied, 2001). In terms of the rate actually mineralised, the water table depth is a particularly important factor, since lowering the water table enhances the aeration of the organic material (Hacin et al., 2001; Martin et al., 1997; Olde Venterink et al., 2002; Tiemeyer et al., 2007). This explains why there is a particularly high risk of N losses from drained organic soils, and it could also explain the enhanced N concentrations often observed in drainage outflows (Holden et al., 2004; Kohler, 2004; Menberu et al., 2017; Tiemeyer et al., 2007). Schmied and Kohler (1999), however, conclude from a study conducted in the Swiss Furttal on a drained soil with a high organic matter content that the overall N losses through the drains contributed to only 3% of the total N export, since the plant uptake was very efficient. Yet, as high mineralisation rates were found to be a relevant process for delivering mobile N, they still suggest measures to take the process into account during the calculation of N fertilisation rates. Increased NO_3^- losses following the lowering of the water table only occur if there are adequate temperatures, adequate soil pH and the nutritional status of the soil allows microbial activities, which explains why enhanced NO_3^- losses have not always been found. On organic soils with low pHs, the export of NH_4^+ may be more relevant than the NO_3^- losses (Holden et al., 2004).

5.2.3. Gaseous N losses

Nitrous gas emissions from agricultural soils are known to strongly depend on the amounts of the applied fertilisers, and they have recently been found to respond exponentially to increasing amounts of fertiliser application (Shcherbak et al., 2014). Furthermore, other site factors, including land drainage, may also influence the final emissions. The effects of field drainage on N_2O losses are complex and not yet completely understood (Jungkunst et al., 2006; Maljanen et al., 2010; Snyder et al., 2009). In particular, little is known about the indirect N_2O emissions from surface waters and groundwater bodies caused by leaching or runoff from agricultural fields (Hama-Aziz et al., 2016). Under aerobic conditions with a water-filled pore space of between 35 and 60%, N_2O emissions seem to occur during autotrophic nitrification processes, while with a water-filled pore space of above 70%, N_2O emissions occurring through denitrification processes are dominant. In general, N_2O emissions are expected to increase with an increasing water-filled pore space and the associated increasing denitrification potential (Bateman and Baggs, 2005; Smith et al., 2003). Whether denitrification in a specific case will be complete and NO_3^- reduced to N_2 or whether N_2O is emitted to the atmosphere also directly depends on the soil structure. An incomplete reduction can be expected if the produced

N_2O can rapidly diffuse to aerated pores. In practice, this means that completely saturated soils do not necessarily have higher emissions than drained soils with a large enough proportion of water-filled pore space (Smith et al., 2003). These characteristics may explain why in some studies higher emissions have been observed on well-drained mineral soils and in others the opposite. Jungkunst et al. (2006) for example observed higher emissions on well-aerated than on redoximorph soils. In a study investigating the effects of drainage on N_2O emissions under cereal production in France, lower emissions were measured on drained than on undrained mineral soils (Grossel et al., 2016). In another study, no effect was observed (Nash et al., 2015). Further, seasonal shifts in the soil pore water content can also significantly affect N_2O emissions. It has, for example, been found that in spring N_2O emissions are higher in well-drained sandy soils, while in autumn they are higher in not well-drained clay soils (Skiba and Ball, 2002). A further study investigating the effect of tile drainage systems on N_2O emissions under corn production found that decreased emissions occurred under wet conditions, although there were no effects seen during drier periods (Fernández et al., 2016).

The emissions of N_2O from intact peatlands are generally considered to be low due to both low nitrification rates limiting N_2O production and complete denitrification processes (Nykänen et al., 1995; Regina et al., 1999; Smith et al., 2003). The N_2O losses can, however, be relevant on drained peat soils with limited oxygen availability, which was discussed above in relation to mineral soils (Leppelt et al., 2014; Smith et al., 2003). A further literature review (including data from Finland, the Netherlands and Sweden) comparing the N_2O emissions from drained organic soils under cereal production or grassland with undrained conditions also found nearly no emissions under undrained conditions, while the highest losses were found under drained conditions with cereal production (Kasimir-Klemedtsson et al., 1997). In a study using data from Finland, Norway and Sweden, the N_2O emissions from organic soils drained for agricultural use (perennial grass, barley, potatoes and carrots) were found to be on average more than four times higher than the emissions from mineral soils (Maljanen et al., 2010).

Ammonia losses are mainly relevant on calcareous soils with high pH values. Neutral or acidic soils generally only directly lose ammonia following the application of fertiliser in the form of urea or animal urine (Cameron et al., 2013).

5.3. Plant protection products

In all the studies known to the authors, the highest losses of plant protection products from subsurface drained agricultural fields were observed in the first few flushes following the application. These peak concentrations are most relevant for the ecotoxicological evaluation, since such short-term elevated concentrations may pose a risk to several animal species (Wettstein et al., 2016), although more chronic exposure may also be critical (Moschet et al., 2014). The mass fraction of the applied products finally lost from the fields as well as the height of the peak concentrations in the outflow, however, depended greatly on the site characteristics, such as the connectivity to surface waters (Frey et al., 2009), and the properties of the applied substances, such as the sorption capacity, degradation, metabolite formation and volatility (e.g. (Brown and van Beinum, 2009; Gomides Freitas et al., 2008; Kladivko et al., 2001; Leu et al., 2004a, b; Wettstein et al., 2016)).

5.3.1. Surface runoff, erosion and drainflow

Apart from plant uptake and volatilisation, the main pathways for PPP losses are through surface water runoff, soil erosion or subsurface flow (Reichenberger et al., 2007). The PPP concentrations measured in surface runoff waters are generally higher than those in subsurface drainage waters, since hardly any sorption processes occur at the soil surface (Evans et al., 1995; Flury, 1996; Kladivko et al., 2001).

Schwab et al. (1985), for example, found reduced losses of atrazine, dicamba, aldrin and dieldrin in the subsurface drains when compared to surface runoff in a three-year study conducted on a clay soil in Sandusky, Ohio, USA. Lower concentrations of atrazine, trifluralin and metolachlor were measured under subsurface drained compared to only surface drained conditions in two studies conducted on the Mississippi River alluvial flood plain in the USA (Bengtson et al., 1990; Southwick et al., 1997). Similar results were obtained in a study using isoproturon, mecoprop, fonofos and trifluralin on a clay-loam soil in Cockle Park, Northumberland, England (Brown et al., 1995). There are, however, also circumstances in which similar concentrations are measured in surface and drain flows. Riise et al. (2004), for example, compared two PPPs with different mobility characteristics (bentazone and propiconazole), which were applied on three fields with varying site conditions in Norway. For the more mobile compound, namely bentazone, nearly as high peak concentrations were measured in the drainage water as in the surface runoff at one of the study sites.

In relation to the losses occurring on the soil surface, water runoff is considered much more important than erosion losses, since the volume of eroded soil is much smaller than the water volume lost via surface runoff. The only exception concerns compounds that strongly adsorb into soil surfaces on sites prone to surface erosion (Reichenberger et al., 2007; Riise et al., 2004).

Similar to P, the subsurface export of strongly adsorbing PPPs is mainly relevant in cases where preferential flow into the drainage system occurs or if shortcuts via manholes or storm drains exist (Doppler et al., 2012; Gomides Freitas et al., 2008; Reichenberger et al., 2007; Riise et al., 2004; Sandin et al., 2018; Ulén et al., 2014). Preferential flow effects have been found to be most relevant during large rain events (Stone and Wilson, 2006). In this context, it has been observed that strongly adsorbing compounds reached the outflows at the same time as weakly adsorbing compounds, which indicates that preferential flow must have been a relevant pathway under the studied conditions (Flury, 1996). In another study carried out in Switzerland, similar losses of neutral and acidic compounds were observed in two different catchments (Gomides Freitas et al., 2008). The importance of preferential flow with respect to PPP losses is also emphasised in the work of Wettstein et al. (2016), who studied the losses of five different PPPs (plus two metabolites) from seed dressings and spray applications on a tile drained field. They found the highest concentrations of all the applied substances in the outflow during the first flush shortly after application. The mass recoveries following the first flush of the different products, however, decreased with increasing degradation and increasing sorption strength of the compounds. Only the peak concentration of one metabolite (clothianidin) was, as expected, slightly retarded. Additionally, the manholes of drainage systems have been shown to be an important pathway for PPPs. They also serve to reduce the effect of compounds' characteristics on their outflows on a corn field on the Swiss Plateau. In the same study, however, the compounds' characteristics were important for the macropore flow into the drainage systems, with higher concentrations being observed for the weakly adsorbing compounds (Doppler et al., 2012). In a study from Indiana, USA, higher losses of substances with lower sorption coefficients were found, although all the products reached the drainage outlet at the same time (Kladivko et al., 1991). Differences in the preferential flow pathways probably explain why not always lower losses of weakly adsorbing compounds were observed.

5.3.2. Influence of site characteristics and management

The relative importance of surface and subsurface flow losses again depends on additional site-specific characteristics, which will be described in further detail below using a few case studies. One very important factor, which was mentioned above, is the timing of the PPP application, since the most important losses of PPP have predominantly been found during the first rainfall event directly after application, while the longer the interval between the application and the first rainfall event, the lower the PPP losses (Brown and van Beinum, 2009; Kladivko et al., 2001; Leu et al., 2004a; Riise et al., 2004). Generally, the annual amount of rainfall and the pre-saturation of soils seem to be important, since high losses of PPPs have been observed on wet sites with a direct hydrologic connection to surface waters, which is caused by surface runoff or preferential flow into drainage pipes (Leu et al., 2004b; Stamm and Singer, 2004). A study carried out in France, for example, found that the water status of hydromorphic silty clay soils at the time of application of PPPs was a relevant factor in determining the amount of PPPs being discharged via drainage waters (Marks-Perreau et al., 2013).

A second factor of high relevance here is the topography. In a case study investigating the losses of three simultaneously applied neutral herbicides (atrazine, dimethenamid and metolachlor) from 13 cornfields on poorly drained Gleysols and well-drained Cambisols in Switzerland, the authors found only rather small differences in the herbicide losses between the different products from one specific field. The differences between different fields, however, were large, up to a factor of 56. Therefore, the authors conclude that the key factors influencing herbicide losses from agricultural fields are the topography, the permeability of the soils and the location of subsurface draining systems, with the relevance of topography being ranked highest (Leu et al., 2004a, b).

As also discussed by Leu et al. (2004b), the soil characteristics represent an additional relevant factor for PPP movement in soils. Among other aspects, the amount of organic matter plays a role. A high organic matter content in soils generally increases the sorption capacities and, hence, one can expect lower losses of well-adsorbing compounds through drainage water (Vereecken, 2005). In fact, in a study from Norway, reduced losses were observed from a soil with a high organic matter content when compared to soils with low contents. However, the soils also differed in terms of other characteristics, since they had a higher aggregate stability and porosity (Riise et al., 2004). From the product side, compounds with high sorption coefficients for organic matter are less prone to losses from organic soils (Jones et al., 2000).

However, as found in batch experiments with glyphosate on sandy soils, dissolved organic matter may also compete with the PPPs for sorption sites, depending on the product properties or organic matter characteristics (Gerritse et al., 1996). On clay soils, crack formation has also been found to be a relevant process for PPP transport. The losses of metolachlor, for example, have been found to be higher on a drained clay soil than on a silt loam under comparable management and climate conditions in a study from France (Novak et al., 2001). In a Swedish case study conducted on marine clay soils, the clay content of soils has been found to be more relevant for the leaching patterns than the product characteristics or the soil management (Ulén et al., 2014). The results of another recent case study from three small sub-catchments in Sweden confirm these findings, with significantly higher PPP concentrations being seen in the streams from the catchment with clay soils when compared to the one where coarse sandy soils prevail (Sandin et al., 2018).

Additionally, the site management influences the effect of drainage systems on PPP losses. In several studies, for example, it has been found that ploughing reduces losses by interrupting macropore channels (Isensee et al., 1990; Kladivko et al., 2001; Larsbo et al., 2009; Schwab et al., 1985).

In a similar way as for water flows, the drainage spacing also has an influence on PPP losses. Indeed, with higher drainage intensity (e.g. 5 m distance compared to 20 m distance between tiles), higher amounts of PPPs were found to be lost in a study from Indiana, USA (Kladivko et al., 1991).

Brown and van Beinum (2009) compared the PPP losses from 23 field studies with subsurface drainage, including 39 different compounds, carried out in Europe. They found the average seasonal losses to range from not detectable to 10.6% (97 records overall, while 55 (57%) of the records showed losses <0.1%, in 14 (14%) records the losses were >1%). They state that the reported values found for Europe are comparable to the seasonal losses reported in the review by Kladivko et al. (2001), wherein 30 studies from North America were reviewed (41% of the records showed losses <0.1%, while 13% showed losses >1). Brown and van Beinum (2009) also used a multiple regression analysis to model the maximum concentrations in the drain flow, and they found a strong correlation between the interval between product application and the first drain flow, the strength of PPP sorption, the soil clay content and the half-life of the PPPs in the soil. In agreement with the factors discussed above, the model for the total seasonal losses included the sorption characteristics of the compound, the percentage of the PPPs remaining in the soil at the time of the first subsequent drainage, the clay content and the drain spacing.

While the percentages of the applied products finally lost through drainage systems to surface waters were below 1% in more than 80% of the observations considered by Brown and van Beinum (2009), the concentrations of several PPPs in river waters close to areas intensively used for agriculture have been found to exceed the chronic ecotoxicological quality criteria in several cases (Langer and Junghans, 2017; Ochsenbein, 2007; Spycher et al., 2018; Wittmer et al., 2014).

5.4. Synthesis of drainage effects on nutrient and plant protection product flows

From the reviewed studies, it can be concluded that the installation of drainage systems on agricultural soils generally causes similar effects on the organic N, ammonium N and P fluxes, while the NO_3^- fluxes are differently affected. The effects on the plant protection products cannot be easily generalised, since they differ greatly in terms of their solubility, degradability and sorption characteristics. However, it can be said that the products with high sorption capacities tend to show similar runoff characteristics to organic N, ammonium N and P, while the weakly adsorbing products must be considered separately (Table 3).

Due to their sorption characteristics, one may expect a significant reduction in the P, NH_4^+ and organic N flows following the installation of drainage systems on hillslopes with slopes >2%, since surface runoff with generally higher concentrations can be reduced. Similar effects are expected for the plant protection products, with a more pronounced effect being seen for the strongly adsorbing compounds than for the weakly adsorbing compounds. For the NO_3^- fluxes, the drainage effect on slopes is less pronounced, since its concentrations in the outflows depend more on both the groundwater quality (NO_3^- concentrations) and water table height. Drainage installation leads to increased NO_3^- losses as the discharge volumes increase and the groundwater often contains higher concentrations. It must, however, be noted that for all the elements, studies comparing drained and undrained conditions with each other are rare.

On flat plains and basins with no connection to surface waters, the installation of drainage systems enhances the losses of all substances overall, with the losses of weakly adsorbing compounds being enhanced to a greater extent. The clay and organic matter contents are good sorbents for many compounds in the soil. Therefore, if drainage systems cause a shift towards more subsurface flow when compared to surface runoff, the retention effect is higher on soils with increased clay or organic matter content than on loamy or sandy soils, with the effect being more relevant for strongly adsorbing compounds. However, it should be noted that heavy clay soils are very prone to crack formation and substance losses through preferential flow. In fact, this effect was found to be more important, at least for PPP outflows, in the review by Brown and van Beinum (2009). The depth of the drainage installation also plays a role, since the lower the drainage system is installed, the lower the expected concentrations of strongly adsorbing nutrients and PPPs. However, as increased water flow volumes are expected if drainage systems are installed at lower depths, for the total losses, the opposite effect may result. Until now, it has been difficult to predict quantitatively enhanced substance fluxes through preferential flow paths under different soil conditions into the drainage pipes. Several studies, however, suggest that this process is not only relevant on heavy clay soils as traditionally assumed, but also on loamy and sandy soils. Additionally, the contribution of drainage systems' manholes and the storm drains of roads or farmyard runoff as transport short-cuts is sometimes mentioned in the literature (Doppler et al., 2012). Yet, the extent to which this pathway contributes to the substance concentrations ultimately found in surface waters remains unclear. The discussed effects are summarised in Table 3.

Even though significant differences exist between the characteristics of the relevant substances, the concept of so-called critical source areas (CSA) may prove useful in terms of achieving a combined estimation of the risk of surface flow and diffuse pollution at specific sites (Betson and Marius, 1969;

Gburek and Sharpley, 1998), since it includes the effects of the “pollutant source”, “mobilization risk” and “transport risk including hydrological connectivity” factors (Doppler et al., 2012; Thomas et al., 2016). The resolution of the digital elevation is, however, crucial for such estimations, since in praxis it strongly influences the quality of the estimations.

Table 3. Expected influence of various site factors on the N, P and PPP fluxes under drained and undrained conditions. Slopes are defined as areas with an elevation of >2%.

	Topography **Slopes – plains**	**Soil characteristics** **Clay -- loamy -- sandy**	**Organic matter**	**Drainage type**	**Rainfall**
PO_4^{3-} /NH_4^+/org. N	Reduction of effluxes on slopes/irrelevant for plains and basins not connected to surface waters (only effects of preferential flows)	In general, decreasing losses on heavy clay soils, exception: crack formation; Less strong effect on loamy and sandy soils; preferential flow	High sorption capacities of OM decrease losses; High N storage in organic soils might cause the opposite effect via mineralisation.	Deeper drainage systems cause lower concentrations in the outflow, but in most cases higher losses due to higher water flow volumes than shallow drains. Higher drainage intensity increases losses.	Time between application and the first relevant precipitation event highly relevant for all substances. Rainfall intensities and volumes are also critical. Exception: NO_3^- export reduced directly after precipitation events due to generally higher concentrations in the groundwater.
NO_3^-	Groundwater level and concentrations more relevant than hillslopes	Little effect of high clay contents	High N storage in organic soil; oxidation may produce higher NO_3^- losses.	Increasing drainage depth and intensity increases losses due to higher water volumes. Higher losses due to higher mineralisation rates with deeper water tables.	
Plant protection products (strongly adsorbing)	On slopes: lower losses likely. On plains (not connected to surface waters): only effects of preferential flow	In general, decreasing losses on clay soils through sorption, exception: increased losses caused by crack formation. Less strong effect on loamy and sandy soils; preferential flow	High OM contents reduce losses (however, no evidence in the review of Brown and van Beinum)	Deeper drainage systems have lower concentrations, but probably higher losses due to higher water flows than shallow drains.	
Plant protection products (weakly adsorbing)	On slopes: effect small. On plains and basins (not connected to surface waters): enhanced losses	No strong effect of texture; exception: crack formation, preferential flow	No strong effect of OM	Deeper drainage systems have lower concentrations, but probably higher losses due to higher water flows than shallow drains.	

6. Synthesis and conclusion

The influences of drainage systems on the different substance fluxes are diverse (Figure 2). While the total annual water losses and N losses generally increase following subsurface drainage installation, the P losses and erosion are in most cases reduced. The effects on the peak water flows, however, are highly variable, depending strongly on the site characteristics. One factor of particular importance to water flows in general and, hence, to most substance flows is the site topography. For example, sites containing depression without natural connectivity to surface waters can exhibit significant effects as water reservoirs or in relation to the on-site retention of nutrients and PPPs, and they could form a category of sites with enhanced risks if they are drained. In light of these variable effects, it is in theory necessary to perform site-specific risk assessments prioritising locally relevant compounds and processes in order to decide on the future use of a site affected by waterlogging. Furthermore, the effects of all relevant site factors need to be included, while depending on the land use locally more relevant factors should be focused on. As such, a detailed analysis is often not feasible in practice. For a more widely applicable decision-making process, it might be necessary to first define categories of relevant compounds and combinations of soil and site characteristics that cause high cumulative risks for the environment under intensive agricultural use.

Many studies dealing with the effects of drainage systems on water and substance flows are already available in the literature; however, studies conducted at larger scales (multiple watersheds) and over longer time periods remain rare. Longer-term studies in particular (i.e. more than 3–4 years) concerning drained organic soils with respect to the water balance and N losses would assist in addressing questions such as the effects of losses of organic soil layers on the water retention capacity or long-term N losses from the stock in the organic matter. Preferential flow is a process of relevance to all substances and the water balance. Even though large number of studies have considered its importance, the specific relevance to loamy and sandy soils is still not entirely clear and, hence, more studies are needed. There is also a need for further case studies concerning N, P and, especially, PPPs that directly compare drained and undrained conditions with each other, since the majority of studies only evaluate the losses through drainage systems, while comparisons to undrained conditions are rare.

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Figure captions

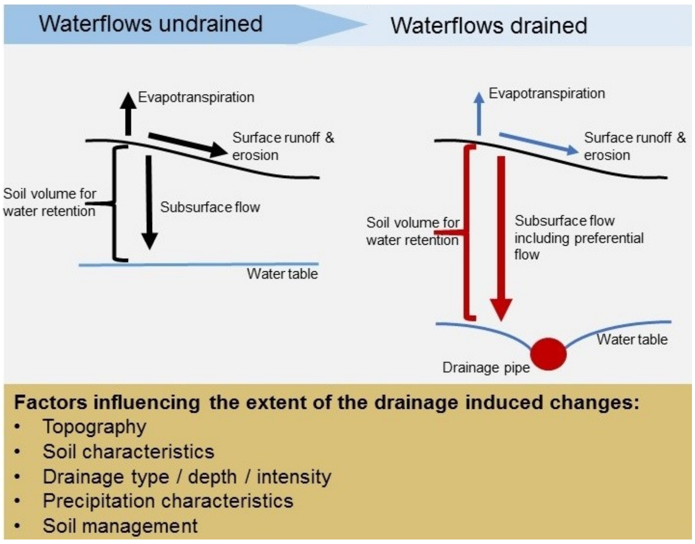

Fig. 1. Effects of drainage on surface runoff, subsurface flow and evapotranspiration, as well as the main factors influencing the extent of drainage-induced changes. Blue arrows indicate reduced fluxes, while red colours indicate increased flows or retention capacity under drained compared to undrained conditions.

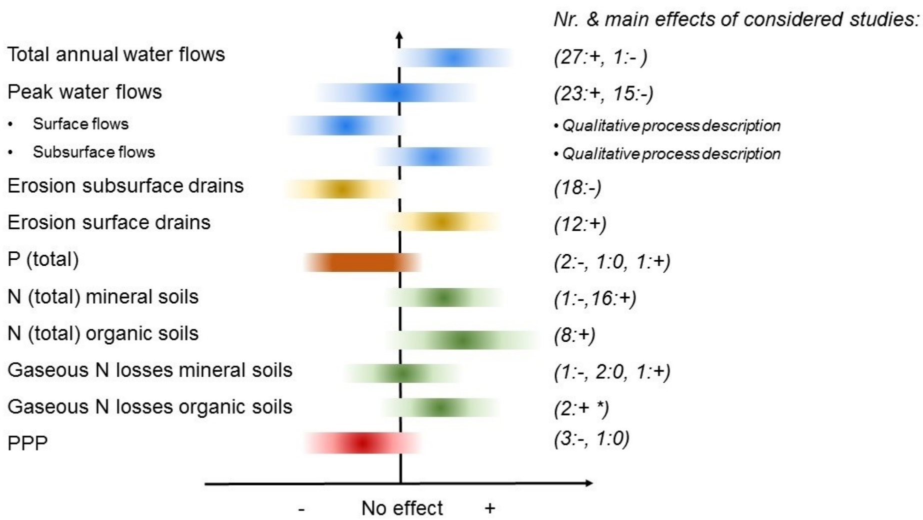

Fig. 2. Rough characterisation of the effects of drainage on water flows (total annual and peak flows), erosion and substance flow. The "+" symbols indicate an increase in fluxes following drainage installation/intensification, while the "-" symbols indicate reduced fluxes. The numbers on the right-hand side indicate the number of considered studies reporting reducing (-), unclear (0) and enhancing (+) effects on the fluxes. All the studies considered for this graph are listed in Table S.3. *The two review articles concerning gaseous N losses on organic soils include a large number of emission measurements from soils under drained and undrained conditions from several countries.

Supplementary information

Table S.1. Keywords (including combinations) used for the literature search.

Water flows	Erosion	Phosphorus	Nitrogen	Plant protection products
agriculture,	agriculture,	agriculture,	agriculture,	agriculture,
drainage,	drainage,	drainage,	drainage,	drainage,
subsurface,	subsurface,	subsurface,	subsurface,	subsurface,
mole,	mole,	mole,	mole,	mole,
tile,	tile,	tile,	tile,	tile,
open ditch,	open ditch,	open ditch,	open ditch,	open ditch,
drain flow,	drain flow,	drain flow,	drain flow,	drain flow,
peak flow,	preferential flow,	preferential flow,	preferential flow,	preferential flow,
preferential flow,	runoff,	runoff,	runoff,	runoff,
hydrology,	leaching,	leaching,	leaching,	leaching,
runoff,	mineral,	mineral,	mineral,	mineral,
subsurface flow,	organic,	organic,	organic,	organic,
flood,	soil,	soil,	soil,	soil,
management,	season,	season,	season,	season,
mineral,	crop,	crop,	crop,	crop,
organic,	tilling,	tilling,	tilling,	tilling,
soil,	topography,	topography,	topography,	topography,
season,	erosion,	phosphorus,	nitrogen,	plant protection,
crop,	wind,	PO_4^3	NO_3^-,	products,
tilling,	water,		NH_4^+,	sorption,
topography,	USLE		N_2O,	short cut
TWI			mineralisation,	
			water table,	
			greenhouse gas,	
			climate,	
			emission,	
			indirect	

Table S.2. Number of articles considered in the review, separated into places of origin (four categories: “USA/Canada”, “Continental Europe”, “UK/Ireland” and “Other countries”).

	Water flows	Erosion	Phosphorus	Nitrogen	Plant protection products
Total	60	16	56	45	33
USA/Canada	18	8	35	17	8
Continental Europe	25	4	15	20	22
UK/Ireland	15	4	6	6	3
Other countries	2	0	0	2	0

Table S.3. Studies considered for Figure 2.

Total annual flows
Bengtson et al. (1988)
Seuna and Kauppi (1981)
Schilling and Helmers (2008)
Blann et al. (2009) - citing four studies
Skaggs et al. (1994) - citing six studies
Holden et al. (2006a) - citing ten studies (1:0, 9:+)
Evans et al. (1995)
Hennig and Hilger (2007)
Zollner and Cronauer (2003)
Tuohy et al. (2016)
Muma et al. (2016)
Peak flows
Information was taken from Table 1
Erosion subsurface drains
Blann et al. (2009) - citing 17 studies
Turtola and Paajanen (1995)
Erosion surface drains
Newson (1980)
Holden et al. (2004) - citing 11 studies
Phosphorus (total)
Bengtson et al. (1988)
Bengtson et al. (1995)
Menberu et al. (2017)
Haygarth et al. (1998)
Koskinen et al. (2017)
Nitrogen (total) mineral soils
Seuna and Kauppi (1981)
Blann et al. (2009) - citing five studies
Skaggs et al. (1994) - citing five studies
Williams et al. (2015)
Evans et al. (1995)
Grigg et al. (2003)
Kladivko et al. (2004)
Lennartz et al. (2011)
Bengtson et al. (1988)
Nitrogen (total) organic soils
Holden et al. (2004) - citing seven studies
Menberu et al. (2017)
Gaseous N losses mineral soils
Jungkunst et al. (2006) - redoximorphic soils compared to well-aerated soils
Fernández et al. (2016)
Grossel et al. (2016)
Nash et al. (2015)
Gaseous N losses organic soils *(The two review articles concerning N_2O emissions from organic soils include large numbers of emission measurements under drained and undrained conditions from several countries, although there have been no direct comparison studies.)*
Kasimir-Klemedtsson et al. (1997)
Leppelt et al. (2014)
PPP
Bengtson et al. (1990) (atrazine and metolachlor)
Southwick et al. (1997) (metolachlor and trifluralin)

Brown et al. (1995) (isoproturon, mecoprop, fonofos and trifluralin)
Riise et al. (2004) (bentazone [w] and propiconazole [s])