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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.

1. Introduction

It is estimated that approximately 34% of the farmland in north-western 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,

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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; Holden et al., 2004, 2006a,b; 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 (Fig. 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 (Fig. 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