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Classifying hydrological events to quantify their impact on nitrate leaching across three spatial scales

Andreas Bauwe [a,*], Bärbel Tiemeyer [b], Petra Kahle [a], Bernd Lennartz [a]

[a] Faculty of Agricultural and Environmental Sciences, Rostock University, Justus-von-Liebig-Weg 6, 18059 Rostock, Germany
[b] Thünen-Institute for Climate-Smart Agriculture, Bundesallee 50, 38116 Braunschweig, Germany

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SUMMARY

Nitrate is one of the most important sources of pollution for surface waters in tile-drained agricultural areas. In order to develop appropriate management strategies to reduce nitrate losses, it is crucial to first understand the underlying hydrological processes. In this study, we used Principle Component Analysis (PCA) and Linear Discriminant Analysis (LDA) to analyze 212 discharge events between 2004 and 2011 across three spatial scales (68 events at the collector drain, 72 at the ditch, and 72 at the brook) to identify the controlling factors for hydrograph response characteristics and their influence on nitrate concentration patterns. Our results showed that the 212 hydrological events can be classified into six different types: summer events (28%), snow-dominated events (10%), events controlled by rainfall duration (16%), rainfall totals (8%), dry antecedent conditions (10%), and events controlled by wet antecedent conditions (14%). The relatively large number of unclassified events (15%) demonstrated the difficulty in separating event types due to mutually influencing variables. NO_3-N concentrations showed a remarkably consistent pattern during the discharge events regardless of event type, with minima at the beginning, increasing concentrations at the rising limb, and maxima around peak discharge. However, the level of NO_3-N concentrations varied notably among the event types. The highest average NO_3-N concentrations were found for events controlled by rainfall totals ($NO_3\text{-N} = 17.1$ mg/l), events controlled by wet antecedent conditions ($NO_3\text{-N} = 17.1$ mg/l), and snowmelt ($NO_3\text{-N} = 15.2$ mg/l). Average maximum NO_3-N concentrations were significantly lower during summer events ($NO_3\text{-N} = 10.2$ mg/l) and events controlled by dry antecedent conditions ($NO_3\text{-N} = 11.7$ mg/l). The results have furthermore shown that similar hydrological and biogeochemical processes determine the hydrograph and NO_3-N response on storm events at various spatial scales. The management of tile-drained agricultural land to reduce NO_3-N losses should focus explicitly on flow events and, more specifically, active management should preferably be conducted in the winter season for discharge events after snowmelt, after heavy rain storms and when the soil moisture conditions are wet.

1. Introduction

Hydromorphic soils are frequently tile-drained to lower the groundwater table and improve moisture conditions, aeration, root growth, and trafficability of the soil (Skaggs et al., 1994). But as artificial tiles and ditches accelerate drainage and hence chemical leaching, nitrate concentrations in surface waters of artificially drained catchments often exceed the thresholds required for a 'good ecological status' according to the European Water Framework Directive (European Parliament and European Council, 2000; LUNG-MV, 2012). In extensively tile-drained areas such as the US Midwest, the Netherlands, or North-Eastern Germany, diffuse nitrate pollution mainly originates from tile-drained agricultural land (Behrendt and Bachor, 1998; Kladivko et al., 1999; Rozemeijer et al., 2010a; Tiemeyer et al., 2008). To develop appropriate management strategies for the reduction of nitrate losses, it is crucial to understand the underlying hydrological and biogeochemical processes.

Hydromorphic soils are often made of fine textures and the hydraulic active pathways within such soils have a wide spectrum of pore sizes ranging from small fine pores of the soil matrix to large macropores (Kung et al., 2000a,b). Using tile drainage as a monitoring system could reveal how a combination of physical factors (chemical properties, hydrometeorological conditions, antecedent soil water content, agricultural activities) dictates the

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* Corresponding author. Tel.: +49 (0) 381 498 3189; fax: +49 (0) 381 498 3122.
E-mail addresses: andreas.bauwe@uni-rostock.de (A. Bauwe), baerbel.tiemeyer@ti.bund.de (B. Tiemeyer), petra.kahle@uni-rostock.de (P. Kahle), bernd.lennartz@uni-rostock.de (B. Lennartz).

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transport of agrochemicals (e.g., nitrate or pesticides) through these pathways (Richard and Steenhuis, 1988; Kladivko et al., 1999; Kung et al., 2000a,b; Tomer et al., 2003). For example, most sorbing substances such as agrochemicals or phosphorus tend to be transported via macropore flow (Jarvis, 2007; Kladivko et al., 1999; Stone and Wilson, 2006), while soluble substances like nitrate frequently move with matrix flow (Inamdar et al., 2004; Magesan et al., 1995; Wagner et al., 2008).

Rainfall characteristics such as intensity, duration, and total amount dictate the initiation of different transport pathways and hence determine both the flow hydrograph and mass flux of chemicals to drains and to deeper aquifers (Gish et al., 2004; Kung et al., 2005). Vidon and Cuadra (2010) observed in a tile-drained field that maximum precipitation intensity regulated the hydrograph response time, while bulk precipitation controlled the maximum tile drain discharge, time to peak, and runoff ratio. Heppell et al. (2002) found that both bulk precipitation and precipitation intensity trigger the initiation of chemical transport through macropore flow. Higher rainfall intensities are often found to increase the proportion of macropore flow (Jarvis, 2007; Kumar et al., 1997; Vidon and Cuadra, 2010). The effects of rainfall characteristics on nitrate concentrations frequently depend on whether matrix or macropore flow is triggered. Wagner et al. (2008), for example, showed that bulk precipitation was highly positively correlated with maximum nitrate concentrations during spring storms in agricultural catchments in Indiana, United States.

Given similar rainfall characteristics, catchment response is mainly determined by the antecedent moisture conditions. Under wet antecedent conditions, Macrae et al. (2010) found a more pronounced hydrological response with higher runoff ratios in an agricultural and tile-drained catchment in Southern Ontario, Canada. Vidon and Cuadra (2010) observed a close relationship between the antecedent water table depth and both peak flow and hydrograph response time in a tile-drained field in the US Midwest. They concluded that even a small difference in the groundwater table can significantly impact tile drain discharge response to precipitation. The effect of antecedent conditions on macropore flow is complex (Jarvis, 2007; Hrachowitz et al., 2013). In some studies, macropore flow increased under wetter antecedent conditions (Kung et al., 2000a,b). Under dry antecedent conditions, soil characteristics become important. While flow response tends to be slow in well-drained soils, cracks and water repellency may develop especially in heavy soils (Jarvis, 2007). Under these conditions, macropore flow occurs under dry antecedent conditions, mainly triggered by heavy rainfall (Shipitalo and Edwards, 1996). Antecedent conditions are thought to cause differences in nitrate mobilization, since a high water table in combination with high soil moisture may lead to higher nitrate export rates through increased matrix flow (Macrae et al., 2010). Similarly, Christopher et al. (2008) measured the maximum nitrate concentrations shortly before peak discharge under wetter antecedent conditions, while nitrate was diluted under dry antecedent conditions. In contrast, a prolonged high groundwater table or soil moisture close to saturation changes the redox conditions, which become more favorable for denitrification and may therefore cause lower nitrate concentrations. Furthermore, under wet antecedent conditions and after several consecutive discharge events, nitrate available for leaching might be depleted (Magesan et al., 1995).

In summary, there is a very complex underlying relationship between hydrological processes and nitrate leaching patterns. Consequently, it is necessary to analyze a large number of hydrological events in order to improve the understanding of these multifactorial patterns and, eventually, to develop appropriate management strategies to reduce nitrate losses. Multivariate statistics are ideal to unravel complex causal relationship (Butturini et al., 2006; Fučík et al., 2012; Heppell et al., 2002; Orchard et al., 2013; Rozemeijer et al., 2010b). While much work has been done to capture the response of tile-drained fields and small catchments to ‘rainfall characteristics’ and ‘antecedent conditions’ (e.g., Reid and Parkinson, 1984; Heppell et al., 2002; Macrae et al., 2010; Rozemeijer et al., 2010b; Vidon and Cuadra, 2010), much less is known about the transfer of these response characteristics to larger spatial scales, although the usual monitoring and management scale for water quality problems (e.g. within the frame of the European Water Framework directive) is the catchment scale. In a rare synthesis study on tile-drained catchments, Boland-Brien et al. (2014) found that the presence of tile drains homogenizes the hydrologic response up to catchment sizes of 2200 km^2. Bridging the gap between these spatial scales is necessary to improve the interpretation of the results of monitoring programs. Furthermore, moving from single collector drain outlets to larger scales allows us to judge the representativeness of results gained at the collector drain scale, especially in settings which are heterogeneous both in the soil properties and in agricultural management. While there has some work been done to on the translation of water quality parameters to larger scales (van der Velde et al., 2010a), there has been to our knowledge no attempt been made to follow both statistical hydrological and nitrate event characteristics of tile-drained catchments across spatial scales.

By analyzing a large number of storm events across three spatial scales (tile drain, ditch, brook) using multivariate statistics we addressed the following hypotheses: (i) Both the antecedent conditions and the precipitation characteristics control the hydrograph response and can be used to identify “event types”, (ii) the event type controls the nitrate concentrations, and (iii) the same controlling factors underlie the event types and nitrate concentration patterns at the three spatial scales.

2. Materials and methods

2.1. Study area

The study area ‘Dummerstorf’ is located about 10 km southeast of the city of Rostock in the Pleistocene lowlands of Northeastern Germany. The small rural catchment of the Zarnow brook is a tributary of the river Warnow, which discharges into the Baltic Sea. Elevations range from 30 to 50 m above sea level, and the catchment is characterized by gentle slopes. Long-term mean temperature, annual precipitation, and reference crop evapotranspiration are 8.2 °C, 665 mm, and 490 mm. The tile drain discharge occurs mainly during the winter period from December to April, because of a precipitation surplus caused by lower temperatures and low evapotranspiration rates. Details on the study area and the sampling setup can be found in Tiemeyer et al. (2006, 2010).

2.2. Field and laboratory methods

To investigate the effects of tile drainage on catchment hydrology and hydrochemistry, we chose a nested sampling setup with monitoring stations at a collector drain outlet, a ditch, and a brook. Data on air temperature, wind speed, humidity (UGT GmbH, Müncheberg, Germany) and precipitation (Seba Hydrometrie GmbH, Kaufbeuren, Germany) were directly recorded at the field site. All meteorological and hydrological data were logged in 15-min intervals and aggregated to hourly values. Daily values of the reference crop evapotranspiration ET_0 were calculated from the meteorological data recorded at the site according to Allen et al. (1998). Global radiation data was taken from the meteorological station Rostock–Warnemünde, which is 20 km away from the