Science of the Total Environment 542 (2016) 935–945

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

The seasonal dynamics of the stream sources and input flow paths of water and nitrogen of an Austrian headwater agricultural catchment

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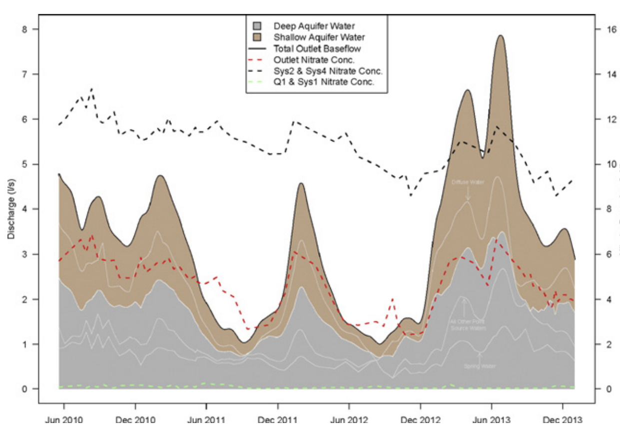
HIGHLIGHTS

- There is nitrogen seasonality in streams in headwater agricultural catchments.
- We measured the major nitrogen point inputs contributing to the stream.
- We applied an endmember mixing model for the source water seasonal dynamics.
- Tile drainage and the diffuse groundwater inputs had significant seasonal variability.
- Seasonality of the nitrate was due to the alternating aquifer source contributions.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 7 August 2015
Received in revised form 29 October 2015
Accepted 29 October 2015
Available online 9 November 2015

Editor: D. Barcelo

Keywords:
Source separation
Flow pathways
Nitrate
Seasonality
Diffuse agricultural pollution
Catchment hydrology

ABSTRACT

Our study examines the source aquifers and stream inputs of the seasonal water and nitrogen dynamics of a headwater agricultural catchment to determine the dominant driving forces for the seasonal dynamics in the surface water nitrogen loads and concentrations. We found that the alternating aquifer contributions throughout the year of the deep and shallow aquifers were the main cause for the seasonality of the nitrate concentration. The deep aquifer water typically contributed 75% of the total outlet discharge in the summer and 50% in the winter when the shallow aquifer recharges due to low crop evapotranspiration. The shallow aquifer supplied the vast majority of the nitrogen load to the stream due to the significantly higher total nitrogen concentration (11 mg-N/l) compared to the deep aquifer (0.50 mg-N/l). The main stream input pathway for the shallow aquifer nitrogen load was from the perennial tile drainages providing 60% of the total load to the stream outlet, while only providing 26% of the total flow volume. The diffuse groundwater input to the stream was the largest input to the stream (39%), but only supplied 27% to the total nitrogen load as the diffuse water was mostly composed of deep aquifer water.

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http://dx.doi.org/10.1016/j.scitotenv.2015.10.151
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1. Introduction

Excessive discharges of nutrients to the aquatic environment have been found to adversely affect human health and aquatic ecosystems (Romstad et al., 1997; Walling et al., 2002). Mass algal blooms in rivers and lakes from an abundance of nitrogen and phosphorous can produce harmful toxins and encourage bacteria that subsequently reduce oxygen levels for fish stocks. This eutrophication of lakes, rivers, and coastal zones is currently one of the primary issues facing surface water environmental policy (Clercq, 2001). In response to public concern and the scientific evidence of the hazards of water pollution, many developed countries, including the European countries and the European Union (EU) as a whole, have enacted environmental legislation to combat the growing problem of water pollution.

Agricultural management and catchment conditions regulate the nutrient conversions and release into the groundwater and surface water. These include fertilizer application rates and timing, crop type and growth periods, soil type and composition, precipitation rates and seasonality, the size of the riparian area, and many others. Improved knowledge on these important conditions and processes will improve the accuracy of nutrient transport models and ultimately better target those processes that can best reduce excessive nutrients to the water bodies. Natural systems are inherently difficult to isolate and test specific processes to determine the effect and sensitivity of those specific processes to the response of the entire system. Consequently, identifying and determining the causes of recurring changes in the nutrient concentrations and loads over several years in a single catchment where many of the catchment conditions are kept the same (e.g. soils, land management, etc.) may be more appropriate than comparing multiple different catchments with varying catchment conditions over the same period.

One of these recurring nutrient changes over several years that many researchers have observed is the seasonal pattern of nitrogen concentration in streams that increase in winter and decrease in summer. This phenomenon has been observed on all sizes of streams and rivers from headwater streams to major rivers. There are several explanations in the scientific literature for the apparent seasonality of nitrate loads and concentrations. One explanation is attributed to higher in-stream nitrogen uptake and denitrification rates during the summer as compared to the winter (Mulholland et al., 2008; Peterson et al., 2001; Alexander et al., 2009). The second explanation is attributed to increased leaching from seasonal biochemical changes in the vegetation and soil microorganisms associated with certain source waters (Holloway and Dahlgren, 2001; Ocampo et al., 2006; Molenat et al., 2008; Arheimer et al., 1996; Burns et al., 2009). Many of these studies have attributed the riparian zone as the primary source of the seasonal biochemical changes and uptakes. Others have found that the seasonality is caused by changes in the relative source water contributions throughout the year without a clear impact from seasonal biochemical reactions (Martin et al., 2004; Grimaldi et al., 2004; Pionke et al., 1999). A final possible candidate is the seasonal agricultural land management associated with fertilizer application timing and crop growth when direct surface runoff is significant.

There are wide varieties of catchments. Some have unique characteristics that only exist in a few isolated locations, while others have typical catchment characteristics representative of broader regional catchments. We have chosen to investigate a headwater agricultural catchment that has typical characteristics of soils, land use, and precipitation for the region. These seasonal nitrate and total nitrogen concentrations have also been observed at our small headwater agricultural catchment called the Hydrologic Open Air Laboratory (HOAL) in Petzenkirchen, Austria (Fig. 1).

The goal of our study is to determine the primary mechanisms that cause the seasonal dynamics of the nitrogen loads and concentrations at the surface water outlet of a headwater agricultural catchment. We accomplished this goal through analyses of monthly input and output totals of water and nitrogen loads entering and exiting the catchment, point and diffuse input contributions of water and nitrogen to the surface waters, and finally the source water contributions to the catchment outlet.

2. Field site

The study was performed at the Hydrologic Open Air Laboratory (HOAL) catchment located in Petzenkirchen in Lower Austria, approximately 100 km west of Vienna (Fig. 2) (Blöschl et al., 2015). The catchment is about 66 ha in area with about 82% of arable land, 3% riparian forest, 5% planted trees with grass undergrowth, 8% grassland, and 2% impermeable surfaces (e.g. paved roads, buildings, etc.). It also has a first order stream that runs about 620 m through the catchment (Fig. 2).

The catchment area of 66 ha is defined as the topographic region where rainfall would flow over the surface and converge to the stream outlet gauge. The stream outlet gauge is named MW. 631 mm and 742 mm of precipitation fell during 2011 and 2012 respectively, while 133 mm and 124 mm left the catchment from surface waters for 2011 and 2012 respectively. The average discharge during these two years was 2.8 l/s and 2.6 l/s. There are six tile drainage systems along the stream named Sys1, Sys2, Sys3, Sys4, Frau1, and Frau2. Additionally, there are four known springs with two measured directly at the source (Q1 and K1) and two springs measured at a location 40 m down gradient of the actual springs before they enter the main stream (A1 and A2). There are also two locations on the edge of the riparian area that drain much of the overland flow during heavy rainfall events from the adjacent fields called erosion gullies (E1 and E2). Although the term spring may also refer to tile drainages that have perennial flow, springs in this study are defined as locations along the riparian area of the stream where water is visibly flowing out of the soil.

During normal baseflow conditions, water entering the stream at Sys4 will take approximately 3 to 4 h to reach the catchment outlet. During this time, the riparian area provides almost continuous shading for the stream. The depth of the water in the stream ranges from 5 cm in the upper end to 20 cm at the outlet. The HOAL exhibits general properties which are typical throughout the range of catchments of the prealpine area alongside the eastern Alps with intensive agriculture associated with the seasonality of rainfall, runoff, and drainage density (Merz and Blöschl, 2007).

Based on a detailed soil survey conducted in 2010, the soils throughout the catchment are generally classified as silt loam or more specifically as Cambisols that have 7.2% sands (0.51 coefficient of variation (CV)), 68.7% silts (0.11 CV), and 24.1% clays (0.30 CV) (Deckers et al., 2002). The Cambisols also have hydromorphic characteristics such as Stagnosols and Gleysols, and these types of soils cover almost 50% of the land of the federal province of Lower Austria. The soil survey found that the silt loam extends vertically at least 0.7 m below the surface throughout the catchment. A detailed geologic survey has not been performed in this catchment, but based on core samples from piezometers placed in and around the riparian area and production wells installed by the local farmers the silt loam extends down approximately 5 to 7 m below the surface where it meets a fractured siltstone unit. There is neither information about the thickness of the fractured siltstone unit nor what geologic units are below it. Due to the high clay and silt content of the soil, cracking of the soil occurs frequently during the dry summer months.

The deep aquifer is defined as the water contained within the fractured siltstone unit, while the shallow aquifer is associated with the water draining the shallow subsurface soil (i.e. the silt loam) (Fig. 3). The origin of the Q1 spring can be seen visually as this fractured siltstone, and subsequently the water from Q1 is used to define the water from the fractured siltstone unit. The chemical and hydrologic dynamics of the deep aquifer are distinctly different from water draining the shallow aquifer. The shallow aquifer water is primarily identified by the baseflow water from the perennial tile drainages (i.e. Sys2 and Sys4) as most of the tile drainages were installed between 1 to 1.5 m below

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