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Groundwater flow and transport of nutrients through a riparian meadow — Field data and modelling

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Summary Groundwater flow and nutrient transport were studied in a riparian meadow during a three-year period. The meadow is situated along a first order stream in the River Gjern catchment area, Jutland, Denmark. Field data included measurements of hydraulic head, hydraulic conductivity and soil characteristics. Groundwater sampled from piezometers was analysed for nitrate, ammonium and phosphate. Nitrogen and phosphorus contents in above-ground plant biomass were also measured. For the interpretation of our data we developed a one-dimensional hydraulic-transport model for the lateral groundwater flow, transport of nitrate, and nitrate removal in the meadow. The model is based on Darcy's equation, and input data are horizontal and vertical distances, hydraulic heads, hydraulic conductivities, and nitrate concentrations. We also developed a scheme for evaluating uncertainties of the modeling results.

Annual removal of nitrate in the saturated zone of the riparian meadow was 326, 340, and 119 kg NO_3^--N ha^{-1} y^{-1} (59–68% of groundwater input) through the three-year period. The largest nitrate removal took place outside the growing seasons. Net loss of ammonium from the saturated zone was 0.4, 6.7, and 10.3 kg NH_4^+-N ha^{-1} y^{-1}. In two of the years this was counter-balanced by atmospheric nitrogen deposition. Phosphate was not retained during the first two years but lost at rates of 0.88 and 0.36 kg P ha^{-1} y^{-1}. In year 3 phosphate retention was 0.47 kg P ha^{-1} y^{-1}.

These data show how a riparian ecotone along a first order stream can reduces nitrogen pollution from agricultural areas. Also, the pronounced year to year variations in our nutrient budgets show that shorter studies, for example based on one year of observations, should be interpreted cautiously as representing a general picture of nutrient pathways.

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Introduction

Riparian wetlands or so-called buffer strips have received much attention due to their ability to remove and retain nutrients. Especially nitrate removal has been in focus (Peterjohn and Correl, 1984; Cooper, 1990; Haycock and Pinay, 1993). In riparian wetlands characterized by shallow lateral groundwater flow originating from upland areas discharging groundwater to a nearby stream, denitrification is believed to be the main process responsible for nitrate removal (Cooper, 1990; Schipper et al., 1993; Hoffmann et al., 2000; Vidon and Hill, 2004a). Denitrification has been determined using different approaches based on stable isotopes (Mariotti et al., 1988; Ostrom et al., 2002), soil sampling and immediate incubation with C_2H_2 (Cooper, 1990; Schipper et al., 1993), conservative tracer experiments with chloride and bromide (Jacobs and Gilliam, 1985; Smith et al., 1996), laboratory microcosmos experiments (Groffman et al., 1996; Hoffmann et al., 2000), and mass balance calculations (Haycock and Pinay, 1993).

Intensive field studies using multiple piezometer nests are time consuming to deploy and use, but they give detailed information about hydraulic heads, groundwater flow patterns, concentration of substances such as nitrate, biogeochemical interaction between waterborne substances, zones of enhanced denitrification, and finally, water and nutrient flows. Such quantifications are important, because they demonstrate linkages between inputs, responses and outputs of the riparian ecosystem. In other words, they throw light on the environmental benefits of natural riparian wetlands acting as buffer zones or ecotones between terrestrial and aquatic environments. This role of riparian wetlands is the focus in this paper.

Catchment area and study site Anbæk, Voldby Brook

The study was conducted in a riparian meadow at Voldby Brook (Fig. 1), a first order stream in the River Gjern catchment area, Jutland, Denmark (UTM Zone 32 ED 50 N 623689 E 552210). The catchment area of River Gjern is 114 km^2. The land use is mainly agriculture, 77.4%, while forests occupy 13.9%, towns and paved areas 4.6%, and meadows and wetlands 4.4%. Soil types are sandy loams, 61.2%, loam, 34.8% and loamy sand 4.0% (Svendsen et al., 1995 , Svendsen, personal communication).

The meadow bufferstrip is only 20—25 m wide, and is recharged by shallow lateral groundwater flow originating from an agricultural field, which was set aside in 1994. The groundwater level changes during the year between 0.2 and 1 m below the soil surface. The meadow was flooded once (approximately one month in February—March 1994) during the study period.

The meadow geology consists in the upper 30—50 cm of sandy sapric and hemic peat. Below this layer is 1—2 m of medium-grained sand with gravel and pebbles. The organic content is very sparse. Closer to Voldby Brook medium-grained sand alternates with fine-grained sand. The sandy layers are underlain by a low-permeable till, which consists of silty clayey sand (Figs. 2 and 3).

The dominant plant species in the meadow are *Dáctylis glomerata* L., *Phleum praténse* L., *Agrótis ténuis Sibth.*, *Urtica dioéca* and *Epilobium montánum* L., and with presence of *Achilléa millifólium*, *Myosótis palústris* L., *Stellaria graminea* L. and *Caltha palústris*.

Field design

A first picture of the groundwater flow through the meadow was obtained in a pilot study conducted in the period September 5, 1991 to October 24, 1991. Four piezometer nests with two piezometer levels at each station (6—9) were installed (Fig. 1). The measuring depths were 0.95—125 cm and 175—200 cm below soil surface of the meadow, respectively. The upper level was placed in a hydraulically active layer of mainly sandy deposits. The lower level was placed in a hydraulically inactive low-permeable clayey till. Hydraulic head hydrographs from the first month showed only minor gradient changes between measuring points. A horizontal equipotential map for the upper active level was then drawn. Based on this a permanent transect of four piezometer nests, which is not perpendicular to the brook, were then established along a groundwater flow path (Fig. 1). Measuring depths at these four stations (1—4) are described below. A continuous water level gauge was placed in Voldby Brook at the end of the transect (station 5). Hydraulic heads in all piezometers were then measured for half a month more and hydrographs analyzed. Head gradients were still quite stable in this period. A horizontal equipotential map for the active upper layer from the latest measuring date shows that the transect followed a groundwater flow line (Fig. 1). From the same date a vertical equipotential map (Fig. 2), was drawn along the transect from station 1 at the small hillslope to station 5 in Voldby Brook. The map shows a minor downward head gradient at the hillslope, horizontal gradients throughout the main part of the meadow, and small upward gradients close the brook.

The permanent transect established as a result of the pilot study, is 21 m long and follows the groundwater flow direction from the hillslope to the brook most of the year (i.e. there is no groundwater discharge a few days in summer). Each piezometer nest (station) was equipped with 3 or 4 polyethylene piezometers (PEH tubes) with 10 cm slotted well points (screens), placed at known depths above the low-permeable till (20—30 cm, 60—70 cm, 100—110 cm and 160—170 cm). Piezometer nest 1 was located at the top of a small slopehill (1 m high) and nest 2 only 3 m away from station 1 at the foot of the hillslope. Piezometer nest 3 was located in the middle of the riparian meadow 12 m from nest 1, while nest 4 was located next to the brook and 21 m from nest 1 (Fig. 3).

The water levels in the piezometers were measured with a Plexiglas tube with a tape measure attached. The Plexiglas tube was further connected to a piece of flexible rubber tube. By blowing air gently into the rubber tube and at the same time lowering the Plexiglas tube into the piezometer until it reaches the water table, it is possible to make accurate measurements of the water level (±2 mm), simply by placing a fingernail at the lip of the piezometer tube and press it against the tape measure, exactly when the tongue senses the air bubbles. The water level was measured in