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Modelling of nitrogen leaching from watersheds with large drained peat areas

Anatoli Vassiljev*, Katrin Kaur, Ivar Annus

Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia

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ABSTRACT

The SOIL and MACRO models with different versions of SOILN initially developed for small field-scales were used to simulate the water flow and nitrate N concentrations in two watersheds in Estonia that contain large areas of peat soils. Monitoring data show that nitrogen concentrations tend to increase in some rivers even where the human activity is very low. This may be connected to soil self-degradation processes taking place in drained peat soils where it is difficult to use most of the hydrological models. Results show that SOIL, MACRO and SOILN may be successfully applied at the watershed scale to model the water quantity and quality on watersheds with high content of peat soils. The analysis revealed that the nitrate nitrogen level trends depend considerably on the meteorological conditions.

1. Introduction

A serious environmental issue faced is to reduce the nutrients discharging into the Baltic Sea via rivers. Monitoring data show that in spite of a significant decrease in fertilization in Estonia, nitrogen concentrations have shown an increasing trend in some rivers. Such trends may be found even in watersheds with very low human activity [2]. In our earlier publications [1,3,4], those high concentrations were found to be connected to soil self-degradation processes taking place in drained peat soils (mineralization of organic matters and leaching of nutrients). Our recent study [5] shows that the export coefficients for drained peatlands in Estonia can be much higher than those for arable lands. Therefore, this source of nitrogen cannot be ignored.

Typically, models developed for water quality analysis from arable lands neglect peat areas. Peat areas are considered on areas with extensive agriculture [6] or as source of the greenhouse gas [7]. But peat soil itself may also contribute to the discharge of nutrients [8]. The models SOIL [9] and MACRO [10,11] with different versions of SOILN [12] are able to model water quantity and quality from peat areas but the models are developed for the field-scale. On the other hand, the national River Basin Management plans and national monitoring programmes are based at the watershed scale.

In this paper, water quantity and quality of two watersheds in Estonia with large percentage of peat soils were modelled. The aim of the paper was to use two models developed to model nitrogen transport for small field-scales at the watershed scale. The approach was tested by the modelling of nitrate nitrogen concentrations in the river water of two watersheds (with areas of 79 and 481 km^2). Modelled nitrogen concentrations were compared with concentrations obtained by national monitoring data.

Based on Vassiljev's study [1], this paper includes results from both the MACRO and the SOIL model. Also, the efficiency of modelling is estimated using the Nash-Sutcliffe efficiency (NSE) [13,14].

2. Models and study area

2.1. Field-scale models used for simulation

Usually, the modelling of nitrogen leaching includes two main tasks. The first is to model water fluxes because water is a carrier of nitrogen. The second task is to model the chemical behaviour of nitrogen. Most conceptual hydrological models cannot provide the data needed to calculate nitrogen transformations in soils, and it is difficult to couple them with the nitrogen-leaching models. The models SOIL [9] and MACRO [10] were developed to simulate data needed for nitrogen-leaching models but they can be used only for small field-scales. These models are one-dimensional, developed for use in small homogeneous areas at the field or plot scale. In the SOIL model water flow to the drainage system is calculated using a simple empirical approach where the horizontal flow rate is assumed to be proportional to the hydraulic gradient and to the thickness and saturated hydraulic conductivity of each soil layer. In the MACRO model groundwater seepage to a drainage system (i.e. streams, canals, or perimeter field ditches) is calculated in the model as a means of regulating water table heights when

* Corresponding author.
E-mail address: anatoli.vassiljev@ttu.ee (A. Vassiljev).

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the bottom boundary condition option accounting for a water table located in the profile is used. Details about the calculation methods are given in [9,11].

The SOIL model simulates water and heat processes in soil taking into account the plant cover. The basic structure of the model is the depth profile of the soil. Two coupled differential equations for the water and heat flow represent the central part of the model. These equations are solved with an explicit numerical method [9]. Stability criteria for water, solute and temperature fluxes (depending on which switches are in use) are used to automatically choose a value for the time step in the program which gives the maximum speed of execution, whilst ensuring numerical stability of the explicit solutions. Meteorological data, most importantly, precipitation, air temperature, air humidity, wind speed, and cloudiness, are the driving variables to the model.

The MACRO model considers the division of the soil profile into the micro- and macropore. Soil macropores (e.g. root and worm holes, structural shrinkage cracks) allow rapid non-equilibrium fluxes of water in soil [15], and consequently influence the leaching of nitrogen. Larsson and Jarvis [10] showed that such influence might be quite significant. Hydrological models developed for watersheds usually ignore the exchange of water and nutrients between micro- and macropores. In this study, in addition to the SOIL, the MACRO model was used because some authors [16,17] have indicated the presence of macropores in peat soils.

The SOILN model simulates major C and N-flows and corresponding processes in soils and plants. The model has a daily time step and simulates flow and state variables at a field level. Input variables like daily data on the air temperature, solar radiation, evaporation, soil heat and water conditions etc. are gained from the SOIL or MACRO model. The soil vertical profile is divided into layers. In each layer, mineral N is represented by one pool for ammonium N and one for nitrate N. Ammonium N is usually regarded as immobile whereas nitrate form is transported with the water fluxes (a special option can also make ammonium mobile). The ammonium pool might be increased by the nitrogen supplied from manure application, mineralization of organic material and by atmospheric deposition, and it is decreased by immobilization to an organic material, nitrification to the nitrate pool and plant uptake. The nitrate store increases through the nitrification of the ammonium pool, fertilization and atmospheric deposition. The leaching, denitrification and plant uptake reduce the amount of nitrate N in the soils. Water flows that transport nitrate N between the layers are responsible for nitrogen leaching. The rate of the decomposition of organic matter depends on soil moisture and temperature conditions. Nitrogen dynamics of the organic matter is governed by C flows and mineralization or immobilization depends on the C/N ratio of the decomposed material and availability of mineral N [11]. SOILN for MACRO takes into account the nitrate exchange between the macro- and micropores [10,18].

2.2. Adaptation of models for simulation at the watershed scale

To use the models at the watershed scale, as compared to the field-scale, additional information on the watershed scale is required, e.g. soil types and plant cover distribution over the watershed, relief, typical ground water depths, etc. Usually the data about the watershed are scattered–e.g. maps of soils and land use are often available but information on the thickness of the zone of aeration in different parts of the watershed is not easily obtained from available data bases. The models were adapted according to the scheme described in [19]. The scheme includes calculations for the different soil profiles and simulation of water movement in the river system.

2.2.1. Calculations for different soil profiles

Differences between small homogeneous fields and heterogeneous watersheds are quite significant. Various types of land cover and soils can be included by dividing the watershed into subareas with similar characteristics. The zone of vertical aeration extends from the surface to the water table and is usually thin in ground water discharge areas, e.g. stream beds, and quite thick in areas located far from streams, e.g. on the hills. The soil profile with a thin zone of aeration will be saturated very quickly, forming surface runoff. The soil profile with a thick zone of aeration needs much more water for saturation and very rarely forms surface runoff. The contribution of the aeration zones with different thicknesses in the formation of a water flow and nitrogen transport depends on their areal fractions of the watershed. The quantity and quality of water fluxes from the fractions were calculated with the SOIL/MACRO and SOILN models and the results were aggregated to represent the entire catchment. Daily inflow to the river system from a watershed represented by N profiles was calculated as:

$$I_t = \sum_{i=1}^{N} I_{i,t} * k_i \tag{1}$$

where t is time, $I_{i,t}$ represents water discharge from the area represented by each field (profile) i at the time t, and k_i is the fraction of the watershed area occupied by the ith soil profile. The watersheds are represented by a set of five different profiles with a depth of 60, 90, 120, 170, 340 cm. The distribution of the profiles in the watershed is unknown. The areas occupied by each profile are found by the optimization procedure. This approach is similar to hydrologic response units (HRU) used in SWAT [20] and usually gives good results.

In this study, the measured water flow was used to calibrate k_i. It was mentioned above that different soil profiles produce different waves of water flow. For instance, soil profiles with a thin zone of aeration produce a water flow after any storm, including summer periods. On the contrary, soil profiles with a thick zone of aeration produce a water flow only during wet periods (autumn, winter and spring). Every year there are usually dozens of waves formed under different conditions. Different impact of different soil profiles gives an opportunity to use the shape of the hydrographs to find the fraction of the whole watershed represented by the soil profile i.

2.2.2. Calculations for the river system

Inflow at any point on the watershed travels a certain distance to reach the outlet of the watershed. During that travel, it undergoes changes caused by channel storage. The transformation undergone by the inflow is due to (a) the translation effect and (b) the storage effect, consisting of a time lag and shape modification [21]. Also some biogeochemical processes occur in the river systems that may retain nitrogen. Comparison of the results from a linear model with those from the St Venant equations applied for Estonian rivers [19] showed that in common simple cases (without backwater effect or other complex phenomena), both of the approaches showed the same precision. Therefore, the linear river routing model was used in this investigation. The linear model for water movement is:

$$Q_t = \sum_{\tau=1}^{\max} [I_{t-\tau+1}\, h_\tau] + Q_{gr,t} \tag{2}$$

where Q_t is the water discharge at the outlet of the watershed at time t, I represents the inflow to the river system, h_τ is the ordinate of the response function (takes into account the characteristics of watershed), where τ represents the consecutive numbers of these ordinates (from 1 to max).

The response function may be approximated by a flexible function with a low number of parameters. Some standard optimization procedures may be used to find the parameters of the response function. In this study, the representation of the response function suggested by Kalinin and Miljukov [22] was used. This can be described as:

$$h_\tau = \frac{1}{k\Gamma(n)}\left(\frac{\tau}{k}\right)^{n-1} \exp\left(-\frac{\tau}{k}\right) \tag{3}$$