Nitrogen Retention Modeling using Biologically Mediated Redox Reactions

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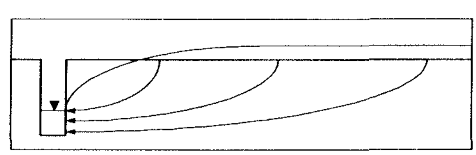
Introduction: This paper describes the two-dimensional simulation of the transport of oxygen and nitrate, and the redox reactions in a land infiltration project. The model is used to analyze the hydrological and chemical conditions in a nitrogen retention project carried out in Sweden.

Background: In Sweden an old farming practice known as "water meadows" has been tested out as a method for removing excess nutrients from rivers and streams. The technique was originally devised to increase fodder production. It was widely used in Scandinavia and northern Europe but the practice was discontinued during the 1950:s due to the ready availability of artificial fertilizers. In "meadow watering", stream water is diverted and distributed over large meadow areas. A water level 5-20 cm above ground surface is maintained with a slow overland flow. Almost all water is infiltrated and is transported as groundwater to drainage ditches surrounding the meadow. The increased fodder production was achieved both by introducing nutrients carried by the water into the root zone and from the irrigation effect.

Field study: In the field study an old "water meadow" system was used. The water distribution system consists of a dam in the nearby river forcing the current onto the meadow where it is distributed through a system of shallow canals. The experiment area is 11 ha. Massbalance was measured for water and nitrate during one full year. The hydraulic loading during the field study was 1000 mm/week during the flooding phase. The average nitrate content in inflowing water was 2.0 mg NO_3-N/l and in the outflow 1.4. This yields a nitrate retention of only 30%.

Laboratory study: The field results were later tested against a column experiment using undisturbed soil columns taken from the field test site. In the column study various hydraulic loadings and nitrate concentrations were tested. The experiment showed a strong dependance in retention depending on infiltration rate with a retention of 99% for 100 mm/week, 80% for 1000 mm/week and 17% for 7000 mm/week.

Problem formulation: In land infiltration it is important to achieve a uniform infiltration to optimize the retention time in the soil. If the retention time is too short the anaerobic conditions required to start denitrification might not occur and if too long, the field will be poorly utilized. The meadow used during the field experiment was 400 m wide. The soil layering counting from the top was 30-50 cm of organic soil followed by 10 m of sand followed by clay. With an aquifere that is vertically thin but wide the ground water flow rate will be higher close to the borders. To study the effect on nitrate retention of this uneven infiltration a two-dimensional transport and redox reaction model was written and run to simulate the conditions during the field study.



Flow pattern near the edge of the meadow.

Transport model: In the model, for each timestep, the velocity field is first calculated using the IADI method (Iterative Alternating Direction Implicit procedure). After that, transport of chemicals dissolved in the pore water is calculated using Method Of Characteristics. Last in each timestep changes due to chemical reactions and diffusion to or from the biophase are calculated.

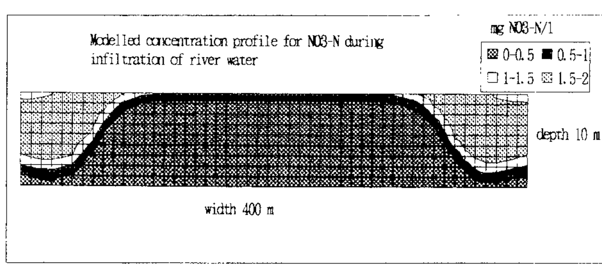
The inflow to the model contains nitrate and dissolved oxygen. Nitrate values are taken from the field study. Oxygen concentration was not measured in the field experiment but as the inflowing river water contained little or no organic carbon and had free access to air, oxygen saturation was assumed. The organic carbon available for reaction is supplied by release from the soil matrix.

$$S_{aer}=v_{rate}[1-F(O)]\frac{C_{carbon}}{C_{min.carbon}+C_{carbon}}\frac{C_{oxygen}}{C_{min.oxygen}+C_{oxygen}}X1 \quad (1)$$

$$S_{den}=v_{rate}[F(O)]\frac{C_{carbon}}{C_{min.carbon}+C_{carbon}}\frac{C_{nitrate}}{C_{min.nitrate}+C_{nitrate}}X1 \quad (2)$$

$$\frac{\delta X1}{\delta t}=yield_{aer}S_{aer}+yield_{den}S_{den}-Decay \quad (3)$$

Chemical model: In the chemical model three phases are considered, pore water, biophase, and soil matrix. All chemical reactions are considered to occur in a biophase growing on the soil particles and no reactions occur in the free pore water phase. The pore water phase is used only as a transport medium. All chemicals are transported from pore water phase to bio phase by diffusion using the same first order transport function for all chemicals. Organic carbon is released from the soil matrix directly into the biophase. A separate subroutine calculates redox reactions using the method described by Kinzelbach and Schäfer, (1991)[1]. In this method microorganism consumption of oxygen and nitrate is calculated using Eq 1&2 using concentration in the bio phase of nitrate, oxygen and organic carbon. X1 is microorganism colony size and is calculated using Eq 3. F(O) is a switch function from oxygen to nitrate respiration at low O_2 concentration. The parameters for the chemical model were calibrated using data from the laboratory column study and one dimensional flow. These parameters were then entered into the two-dimensional model.



Results: The two-dimensional model gave an outflow concentration of 1.31mg NO_3-N/l. This fits the field experiment result of 1.4 mg NO_3-N/l remarkably well. The two-dimensional model shows that in the areas closest to the edge of the meadow the infiltration rate is far higher and that the retention time here is too short. In the central part of the field the nitrate retention is more or less total but as the infiltration rate is very low this means very little in the mass balance. The nitrate retention can be improved by refining the flooding technique so as to flood only the central areas. The two-dimensional model also shows that parameters obtained by laboratory column studies can sometimes be successfully applied to field scale calculations.

1.Kinzelbach and Schäfer , (1991), "Numerical Modelling of Natural and Enhanced Denitrification Processes in Aquifers", Water Resources Research, vol 27, No 6, pp.1123-1135.