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Attempt to use the SWATREZ and UNDYS models for the simulation of ground water pollution in agrosystems irrigated by municipal sewage

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Abstract. For the simulation of water movement and pollutant transport in the hydromorphic soil profile two numerical models SWATREZ and UNDYS were used. These models are based on water movement in porous materials and hydrodynamic dispersion equations. The results obtained by numerical simulation were verified by field research data from the 'Hajdów' experimental station situated near Lublin (Poland). The 'Hajdów' experiment combines the municipal waste treatment process with industrial plant production. Empirical verification obeyed the groundwater table level, Nitrogen ion concentration in the soil water at various depths and in water outlets from the drainage system. The simulation results presented show the important role of plant roots in the use of Nitrogen at 'Hajdów' type stations. It indicates that the best design and management of such objects must take into account not only ground filter, but also plant growth theory. The SWATREZ model gives a quite good approximation of empirical data. It can be used for the water management process in 'Hajdów' type stations. Simulation based on the UNDYS model shows that the continuation of numerical research is very necessary.

Keywords: modelling, waste water, ground water, Nitrogen, hydromorphic soil

INTRODUCTION

The purification of municipal waste water supplying ground water needs on-going control of the level of their pollution [1–3,5]. To predict ground water pollution with waste waters mathematical modelling may be a good solution.

The traditional model of waste water disposal consists of a combined or separate sewage system and treatment station. Purified waste water can be sent into a sewage receiver – usually a river. Most existing treatment stations in Poland are not equipped to dispose of Nitrogen, Potassium and Phosphorous. The exclusive use of water in this system is not economical.

To solve the N, P, K, ions problem, the traditional system has often been extended in recent times by the agrosystem. That solution is also interesting from an economical point of view.

Operating the agrosystem is very simple. Sewage which is spread on the agricultural zone is utilised by the ground filter and growing plants. The designing and exploitation processes are not so easy. The traditional designing method can lead to pollution of ground water and poor plant growth.

Numerical models can be used to process designing for newly constructed objects as well as to manage existing ones [1–3,5]. The total dynamics of the meteorological, soil and plant changes can be included in this calculation method. The sewage irrigation rate calculated in this way can be optimised for ground water pollution protection and maximisation of plant yield aspects.

The aim of this paper is the presentation of water and pollution movement in hydromorphic soils using two mathematical models SWATREZ and UNDYS in ground water pollution aspect.

SIMULATION MODEL

Two one dimensional numerical models (SWATREZ and UNDYS) were used for the simulation research [1,2,7]. The SWATREZ program describes water movement in the soil profile in the system: soil-plant-atmosphere. The second program, UNDYS, describes pollutant transport in soil profile, based on previously calculated water movement, soil and plant parameters.

Water flow in the soil-plant-atmosphere system is described by Richard's equation with source factor:

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$$\nabla\left[k_r k_s \Delta(h+z)\right] + S = \left(C+\beta S_s\right)\frac{\partial h}{\partial z} \qquad (1)$$

where: ∇ – operator, $k_r = k(h)/k_s$ – relative water conductivity, k_s – filtration coefficient, h – water head pressure, z – vertical altitude co-ordination, S – resource factor for water uptake by plant roots, $C = d\theta/dh$ – differential water capacity, S_s – retention properties, β – coefficient (1 for full saturation).

Description of water movement in porous material (soil) needs the determining of many parameters: physical soil parameters, including the retention curve, hydraulic conductivity at saturated and unsaturated conditions in selected soil profiles, type and height of plants, roots distribution in profile, geometry of profile, boundary and initial conditions. The top boundary conditions are determined by meteorological data (precipitation, temperature, humidity, soil cover, radiation and wind velocity), especially for source factor calculation – soil evaporation and plant transpiration. Bottom boundary conditions are determined by ground water supply mode, drainage and irrigation system. A full description of the model is given by Feddes, Kowalik and Zaradny [2].

As a result of the simulation work by the SWATREZ model, it is possible to describe the dynamic of ground water level and moisture distribution changes in all selected soil profiles. The results obtained from that model – the distribution of water content and water flow velocity field in the soil profile, make it possible to calculate Nitrogen pollution transfer.

Transport of the soil water pollutants, in saturated and unsaturated porous media was described by the hydrodynamic dispersion equation. Such a mathematical description in the UNDYS model allows the adsorption process of a dissolved substance on the soil particle surface to be taken into consideration. In the case of Nitrogen flow, the nitrification and denitrification process is also included. The model, for consideration below, assumed a great adsorption of Nitrogen ions making their flow practically negligible. The hydrodynamic dispersion equation which takes into account the above presented processes is described as follows:

$$\frac{\partial\left(C\theta + K_d\rho^g C\right)}{\partial t} = \frac{\partial}{\partial z}\left[D\theta\frac{\partial C}{\partial z} - vC\theta\right] + k_1\rho^g C_1 - k_2\theta C - \lambda\left(\theta C + K_d\rho^g C\right) - SC \qquad (2)$$

where: θ – soil moisture; C, C_1 – concentration of pollutant (Nitrogen) dissolving in ground water; D – coefficient of hydrodynamic dispersion; v – velocity of ground water flow; K_d – adsorption process constant; k_1, k_2 – nitrification and denitrification parameters; λ – constant describing the first-rate reaction; S – resource factor for water uptake by plant roots; z –co-ordinate.

A full description of the equation presented is given by Maciejewski [7] and the use of the UNDYS program model of transformation of Nitrogen compounds is given by Richter [8].

The UNDYS model gives the numerical solution of hydrodynamics dispersion equation for the top boundary condition as an assumed concentration or mass supplied on the ground surface. The bottom boundary is described by the assumed concentration or ideal inter-mixed condition. The results obtained include the dynamic distribution of Nitrogen concentration in the soil profile.

EXPERIMENTAL OBJECT

The 'Hajdów' experimental station is situated near the City of Lublin (Poland). The station connects the municipal sewage treatment process with industrial plant production [3]. The total area of the station extends to some 8 ha with a preponderance of hydrogenic, peat soils. The experimental station is divided into three main zones – intensively, moderately and non irrigated zones, each zone consisting of 7 blocks with different plants (Fig. 1).

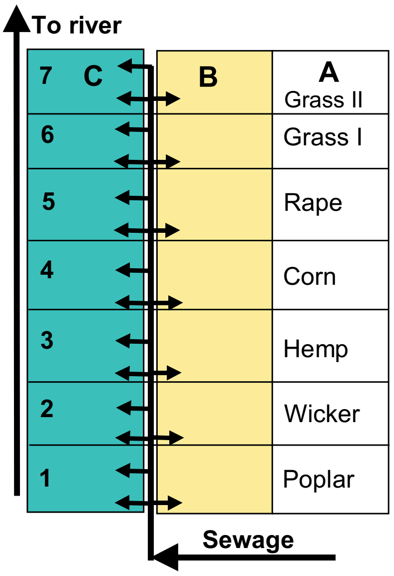

Fig. 1. Scheme of experimental object 'Hajdów': 1,2, ..., 7 – plant blocks, A,B,C – zones without, moderate and intensive irrigated.

The basin irrigation and drainage system accomplished make possible even intensive sewage irrigation for industrial – grass, willow etc. plants. Typical municipal sewage after the first, mechanical, purification step was used for the irrigation. The individual irrigation dose is 75 and 150 mm, as allowed during the vegetation period (April – October 1997) dose 900 and 1800 mm.

Field research provided at the experimental station conforms to the quality composition of input sewage, concentration of various chemical compounds (include Nitrogen ion) on various soil levels and to the drainage outlet, physical and chemical soil parameters, ground water level and plant productivity. All experiments were provided in range of research program PBZ-31-03 [3].

The simulation and verification presented in this article was based on 1 of 21 blocks, with hemp cultivation. Figure 2 presents the measured retention curve and water conductivity of soil layers from this block (3B). The field research was performed using the piezometer installed and observation wells for ground water level tests. Soil water samples for chemical analyses were taken using ceramic filters installed in soil profiles.

SIMULATION RESULTS

The example of simulation results is presented on Fig. 3. During simulation the authors of the article did not have the experiment results at their disposal, so it was necessary to make each simulation assuming ideal pollution levels with the relative maximum input concentration of 1.0. Later that relative concentration was compared with the total Nitrogen average concentration in sewage used for irrigation – 30–65 g m^{-3}.

All simulations were made for the period from the 139 to the 268th day of 1997. During that time, irrigation was assumed to be on days 152, 165, 185, 213, 225 and 245.

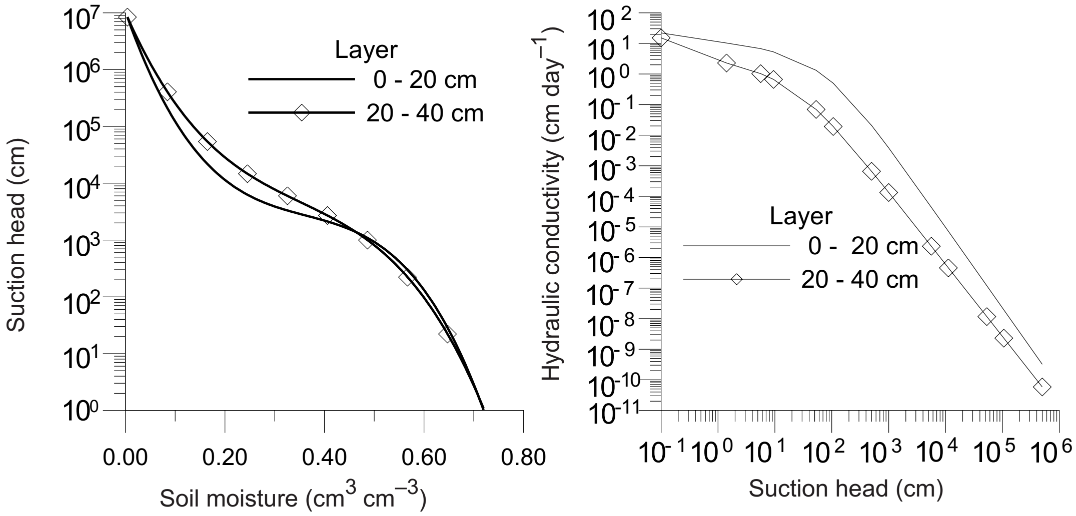

Fig. 2. Example of retention curve (left) and water conductivity (right) of 3B block.

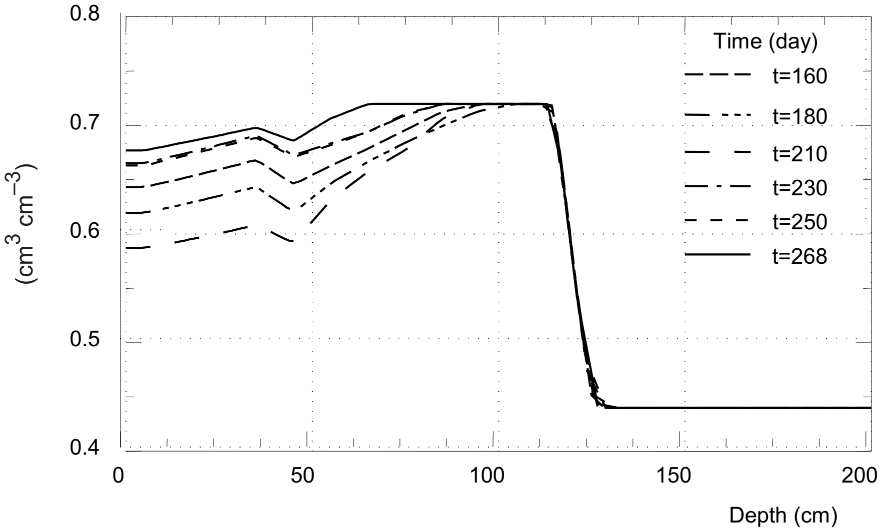

Fig. 3. Soil moisture distribution in profile – SWATREZ simulation results.

The individual irrigation dose was 75 mm of sewage.

At the beginning, the distribution of water content and water flow velocity in the soil profile was calculated based on soil parameterisation using the SWATREZ program. Those results were used as input data for pollutant transport modelling by the UNDYS model. Those calculations were provided for passive contamination which means that the pollutant can be taken by the plant roots or expelled by the drainage or the bottom boundary of the soil profile with soil water.

The results of the SWATREZ calculation of the distribution of water contents in the soil profile are presented in Fig. 3. The distribution of the relative concentration (compared with average total Nitrogen concentration – 30.65 g m^{-3}) of pollutants calculated by UNDYS is presented on Fig. 4.

It can be seen from the calculations that Nitrogen supplied with sewage to soil profile goes only to the top zone. Nitrogen dissolved in soil water, taken up by the roots, cannot migrate to deeper layers. This means, that the role of the roots is very important for Nitrogen transport in soil profile. Nitrogen uptake by the plant roots in function nitrification and denitrification parameters is presented on Fig. 5.

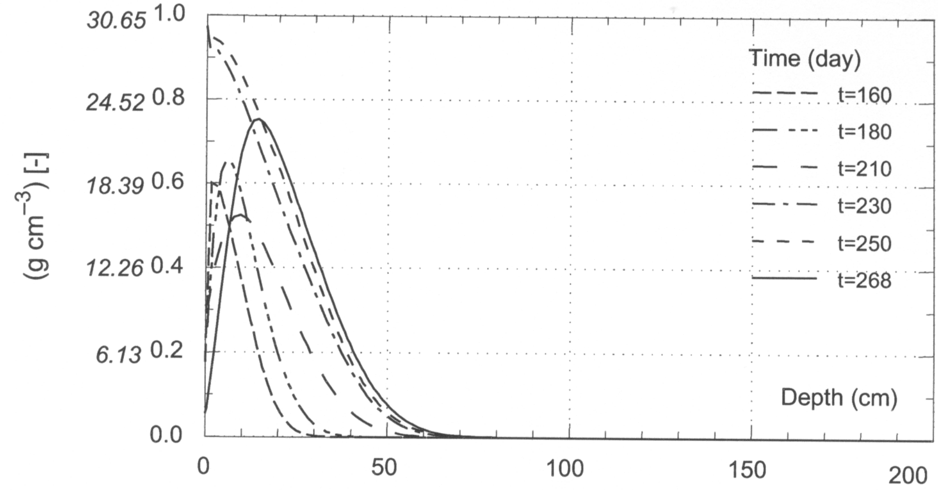

Fig. 4. Distribution of relative [-] and normal (g cm^{-3}) concentration of total Nitrogen in ground water (for nitrification $k_1 = 0.1\ d^{-1}$ and denitrification $k_2 = 0.1\ d^{-1}$ coefficients) at various soil profile depth - UNDYS simulation results.

EMPIRICAL VERIFICATION

Empirical verification has been provided in two ways: 1) ground water level, as the SWATREZ results verification, 2) Nitrogen concentration in soil water, for UNDYS estimation. The example of simulation and experimental results comparison for ground water level is presented on Fig. 6.

We can see a correlation between the calculated and measured data in Fig. 6. The calculated values of the ground water level lie higher than those measured, although the changes in trend of both the compared data is very similar. This can be the result of soil parametrization, made by laboratory tests only to 40 cm of depth. The description of soil profile, made to 125 cm of depth [3] indicates the same soil type from 40 to 125 cm, but no laboratory test was done. The statistical estimations of differences between both type of data, calculated by formulas of standard error S and average deviation α of estimation:

$$S = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(y^i_{meas} - y^i_{calc}\right)^2} \tag{3}$$

$$\alpha = \frac{1}{n}\sum_{i=1}^{n}\left|y^i_{meas} - y^i_{calc}\right| \tag{4}$$

where: y^i_{meas} – measured, y^i_{calc} – calculated groundwater level are: S = 11.1 cm, α = 10.38 cm, indicate the necessity of better soil parametrization.

The empirical data of the total Nitrogen concentration in the soil profile is presented in Fig. 7. It is difficult to compare simulation results (Fig. 4) with the field measurements. The lack of time available for the field experiment does not allow the complete verification for the whole vegetation period. Comparing both figures one can clearly see some similarities: the highest Nitrogen concentration occurs in the upper layers; the concentration in the drainage outlet, after 10 days of simulation is very low, sewage irrigation slightly influences the lower layers of soil profiles. Unfortunately there are also some essential differences between measured and calculated data. The time to reach the maximum value of nitrogen concentration is essentially shorter for field results. Concentrations changing the dynamic in the top layer are very high. After a strong decrease, considerable growth is observed. So, verification must be continued for the SWATREZ - UNDYS combined model presented.

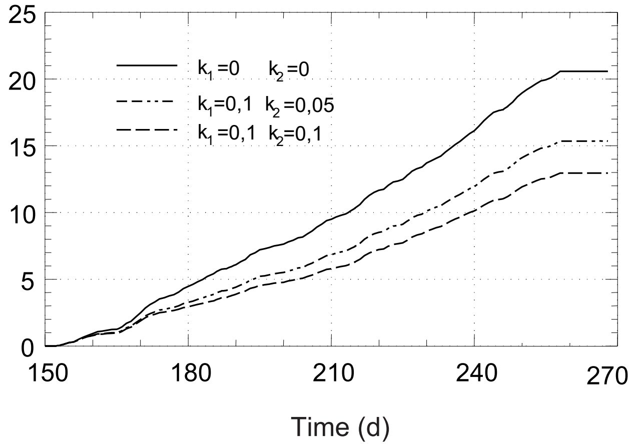

Fig. 5. Relative [-] root uptake of Nitrogen in dependence of nitrification k_1 and denitrification k_2 parameters.

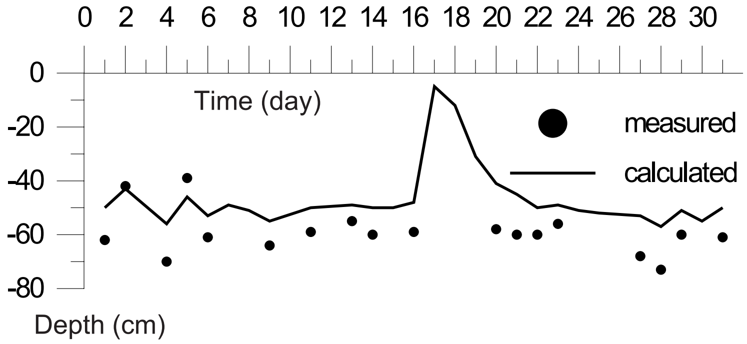

Fig. 6. Calculated (SWATREZ) and measured ground water level (Block 3B, May 1997).

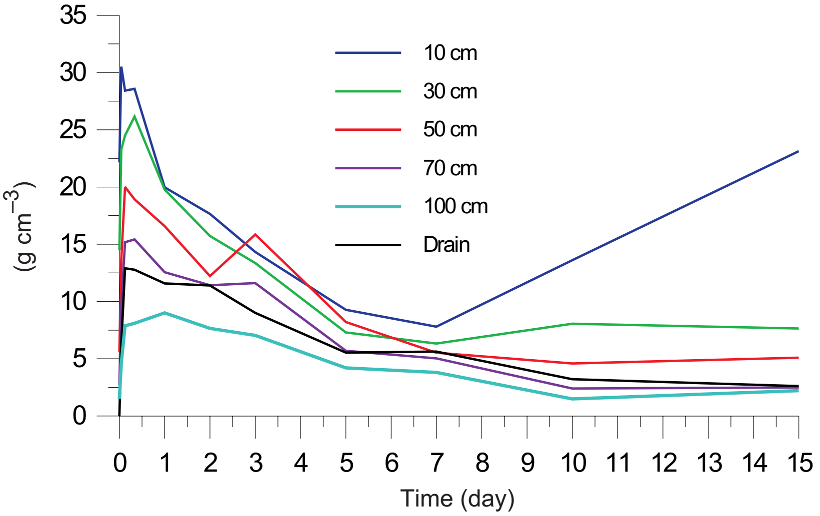

Fig. 7. The results of experimental tests for general Nitrogen concentration in ground water in soil profile. Drain signifies the drainage outlet.

CONCLUSIONS

1. The comparison of the two numerical models SWATREZ and UNDYS for the simulation of ground water pollution with sewage water after purification in the agrosystem, with the empirical data obtained shows quite good results, but still did not satisfy calculation accuracy. The SWATREZ model gives a quite good approximation of empirical data. It can be used for the water management process of the 'Hajdów' Research Station type. Results obtained by the UNDYS model indicate that the continuation of numerical research is very necessary.

2. The results obtained show the great role of roots in using Nitrogen at a 'Hajdów' type research stations. So the best design and management of such stations require both the ground filter and plant growth theory to be taken into consideration.

3. The calculation and verification work presented indicate that the numerical modelling method can be used for the prediction of ground water flow and pollution translocation in the soil profile. The application of the models examined requires labour-intensive work connected with soil parametrization and the calibration of the models, but after that procedure, simulation work will be more satisfactory.

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