Model for Nitrate Migration Studies

G. KIENITZ

Research Centre for Water Resources Development /VITUKI/, Budapest

Introduction

The pollution of natural surface and subsurface waters by nitrogen compounds /especially by nitrate/ today occupies a prominent place among problems involved in the protection of the environment. Among the various sources of this type of pollution, those related to agricultural cultivation practices are of great importance, they can only be identified with difficulty, because they are of a non-point source type, and because of the character of the processes involved, which are partly natural and partly induced by human activities. The problems centre on the content of nitrogen compounds in the root zone, which is enriched naturally as well as through fertilization, and which is the source of both the nitrogen supply to the vegetation and of the pollution of natural waters. The nitrogen balance in the root zone is therefore of a very delicate nature, the balance actually is between the agriculturally useful and the environmentally harmful. Observations on and research into the processes involved are carried out worldwide and many attempts have been made to model the latter, e.g. by CREAMS /1979/. However, possibly because of the complex and intricate nature of these processes, the elaborated models have a tendency to become overcomplicated and to rely on a number of parameters whose determination encounters difficulties.

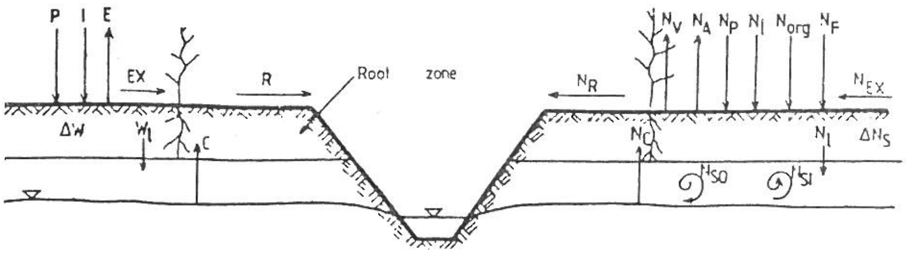
These circumstances have induced the author and his collaborators, while solving a specific task, to elaborate a practical input-output model to simulate the water and nitrogen management in the root zone by making use of simple experimental relationships well-known from practice. /Note: The task referred to was the elaboration of the chapter "Alternative measures to prevent non-point source pollution" of the FAO Project HUN/82 004 Prevention of Non-Point Source Pollution./ Emphasis was laid on the ability of the model to work without sophisticated parameters /difficult to procure/, while still being useful in judging the ameliorating and exacerbating effects of various agricultural practices from the aspect of the pollution of the surface/subsurface waters. Being orientated towards these aspects, only forms of nitrogen which could be displaced by water were of concern, hence the name of the model: DISNIT /DISplaceable NITrogen/.

Characteristics of water/nitrogen regime of the soil

Nitrogen, an element of basic necessity for life, occupies an important position in the biological cycle /FURRER, 1984/, the principal stations of which are as follows: The plant utilizes inorganic N compounds to produce organic N compounds which are indispensable for animal life; these, in turn, are re-converted to mineral N compounds, partly by the animals and completely by the microorganisms of the soil. One phase of this cycle takes place in the root zone of the soil, where the N forms characteristic of most of the phases of the cycle can be found. But beyond the cycle meant in a biological sense - which is manifested in chemical processes, the interconversion of various forms of N - a cycle of N manifested in physical movement also takes place in the root zone of the soil. This is due to the fact that various forms of N are continuously being introduced into the soil, after which they migrate within the soil, meanwhile undergoing various conversions before finally leaving the soil. The vehicle of this physical movement, and at the same time also an important requisite of the conversions, is water, which itself forms a cycle in nature, one part of which also takes place in the soil. The cycles of N and water are therefore closely linked to each other in the soil and should always be investigated together.

Although the cycles of both N and water also concern deeper layers of the soil, it is sufficient to limit attention to the root zone when investigating non-point source pollutions of agricultural origin.

The sketch in Fig. 1 shows the elements participating in the two kinds of cycles. There are input and output elements in relation to the root zone



The Water Cycle

Input: P = precipitation; EX = external water; I = irrigation water; C = capillary rise.

Output: ET = evapotranspiration; R = surface runoff; W_t = seepage to deeper soil layers; ΔW = change in soil moisture storage.

The Nitrogen Cycle

Input: N_P = from precipitation; N_{EX} = from external water; N_I = from irrigation water; N_C = from capillary rise; N_{org} = of organic origin; N_{SO} = released from soil; N_F = from fertilization.

Output: N_V = vegetal consumption; N_A = departure into the air; N_R = departure with surface runoff; N_1 = departure with seepage; N_{SI} = integrated into the soil; ΔN_S = change in the N of the root zone.

Fig. 1

Scheme of the water and nitrogen cycle of the root zone of the soil for both N and water. For water, the inputs are precipitation (P), external water originating from neighbouring areas (EX), irrigation water (I), and capillary rise from the groundwater (C), while the outputs are evapotranspiration (ET), surface runoff (R), infiltration from the root zone towards the groundwater (W_1), and a change in the W soil moisture content, which also has to be considered (ΔW).

For nitrogen, the inputs are N_p arriving with precipitation, N_{EX} arriving with external waters, N_I arriving with irrigation waters, N_C arriving with capillary rise, N_{org} of organic origin, N_{SO} released from the soil particles and N_F introduced into the soil from fertilizers; while the outputs are: N_V consumed by the vegetation, N_A departing into the atmosphere in the form of gas, N_R departing with surface runoff, N_1 leached towards the groundwater, and N_{SI} integrating into the soil particles; a change in the N_S nitrogen content displaceable with water also has to be considered (ΔN_S). Using these symbols, the water/N balance of the root zone can be described with the following equations:

$$P+EX+I+C = ET+R+W_1+\Delta W \quad (mm/ha) \qquad /1/$$

$$N_p+N_{EX}+N_I+N_C+N_{org}+N_{SO}+N_F = N_V+N_A+N_R+N_1+N_{SI}+\Delta N_S \quad (kg/ha) \qquad /2/$$

Simulation of the water/nitrogen regime of the root zone with DISNIT Model

Considerations and basic relationships used

When setting up the type of simplified model referred to in the Introduction, equations /1/ and /2/ have been used as a starting point, but some members thereof have been neglected, and others have been contracted.

In equation /1/ the following have been neglected: EX /i.e. an elementary surface is investigated, without interaction with the adjacent areas/; I /i.e. cases with no irrigation are considered/ and C /i.e. areas are considered where the capillary fringe does not cut into the root zone/.

In equation /2/ the corresponding members N_{EX}, N_I and N_C have been neglected as well as N_R which is related to precipitation waters which have not yet infiltrated into the soil and are thus not yet polluted through a leaching effect.

Contraction concerns only equation /2/: Members N_p, N_{org} and N_{SO} are contracted /i.e. those which represent N introduced into the soil in a natural way or with compost, livestock and liquid manure/ with members N_A and N_{SI} /i.e. those which represent N leaving the soil without being transported by water/. The amalgamated members are represented as L, the "natural N-production" of the soil.

The model thus uses the following simplified equations:

$$P = ET+R+W_1+ \Delta W \quad (mm) \qquad /1a/$$

$$N_F+L = N_V+N_1+ \Delta N_S \quad (kg/ha) \qquad /2a/$$

Emperical relationships have been made use of when constructing the model.

ΔW: *Infiltration into the soil*

The ΔW mm/day water intake of any soil depends on its momentary W moisture content. Experimental curves depicting this relationship have been used, referring to various S soil types characterized by 10% field capacity: ΔW_S^{10} (W). In the case of a soil with an FC field capacity outside this range, readings from the curves are duly adjusted. Finally, the ΔW_S determined in this way is multiplied by an e cultivation factor, reflecting the influence of agricultural cultivation on infiltration: e = 1 in level areas, and may be smaller or greater depending on the slope and the method of cultivation. Table 1 gives an estimated range for these values, where the relative magnitude of the latter is of importance. The infiltration capacity on a day when there is W moisture content in the root zone:

$$\Delta W_S^{FC} = e \cdot \Delta W_S^{10} \frac{10}{FC} W \quad (mm/d) \qquad /3/$$

Table 1

Dependence of the e "factor of cultivation" from slope and cultivation conditions

Characteristics of cultivation	Slope categories /percentages/			
	0-5	5-12	12-17	> 17
Ploughing in the direction of the slope	1.0	0.6	0.3	0.1
Ploughing in the direction of the slope and deep ploughing, or ploughing along the contour lines	1.4	0.75	0.4	0.2
Ploughing along the contour lines and deep ploughing, or cultivation in strips	1.8	1.0	0.6	0.4
Ploughing along contour lines, farm management with stubble-remainders, and deep ploughing	2.0	1.3	0.8	0.6

W_1: *Infiltration from the root zone into the lower soil layers*

A root zone with a depth of DR can store only

$$W_{max} = DR \frac{FC}{100} \quad (mm) \qquad /4/$$

amount of water, the rest of the ΔW_S^{FC} infiltration from the surface becoming W_1 infiltration below the root zone:

$$W_1 = \Delta W_S^{FC} - W_{max} \quad (mm/d) \qquad /5/$$

ET: *Evapotranspiration of the vegetation*

Under different climatic conditions, although the daily amounts of ET for a given crop depend on a number of factors, the curves describing these values show a certain similarity for the same crop if different years and crops grown on different soils are compared. This gave rise to the idea of introducing dimensionless ET curves for the various plants, with the abscissae starting at 0 /sowing/ and ending at 1.0 /harvesting/ and the area below the curve being 1.0. This curve should then be stretched between the actual sowing and harvesting dates, the area below it still remaining 1.0, and the potential value of ET_{pot} at date t_i calculated as

$$ET_{pot}(t_i) = ET_{Pl}^{tot} \cdot et_{pl}(t_i) \quad (mm/d) \qquad /6/$$

where ET_{Pl}^{tot} is the total amount of ET necessary to produce an optimum amount of yield of plant Pl, if the water and nutrient supplies are not limited. This ET_{pot} may, however, be limited by the amount of water available in the root zone $/W(t_i)/$. The effective ET value will be:

$$ET(t_i) = \left(\frac{W(t_i)}{W_{max}} \right)^{c} ET_{pot}(t_i) \quad (mm/d) \qquad /7/$$

where W_{max} is that calculated by equation /4/ and c is the lumped "ET-limiting parameter" reflecting all effects of the relationship between the given plant and the hydraulic characteristics of the given soil /it should therefore be constant for given plant/soil combinations/.

N_V: *Vegetal N consumption*

Vegetal N consumption is approximately proportional to the plant ET. Therefore, if the total consumption of the Pl plant during the growing season is noted as $N_{V\,tot}^{Pl}$, then the consumption on date t_i will be:

$$N_V(t_i) = \frac{N_{V\,tot}^{Pl}}{E_{Pl}^{tot}} \cdot ET(t_i) \quad (kg/ha/d) \qquad /8/$$

N_l: *N leached from the root zone into deeper layers*

This N is linked to the W_l calculated with equation /5/, as

$$N_l = b \cdot N_S \cdot \frac{W_l}{W} \quad (kg/ha/d) \qquad /9/$$

where N_S is the momentary N content of the root zone, W is its moisture content and b is an experimental constant /approximated as 0.7/.

L: *The "natural N production" of the soil*

L is characterized by the l(t) experimental dimensionless curve /running through the whole year, the area below it being 1.0/, whose ordinates should be multiplied by L_{tot} /the total amount of estimated annual natural N production/ to obtain $L(t_i)$, the production at date t_i:

$$L(t_i) = L_{tot} \cdot l(t_i) \quad (kg/ha/d) \qquad /10/$$

The auxiliary relationships of the calculations are $ET_{Pl}^{tot}(Yd)$ and $N_{V\ tot}^{Pl}(Yd)$, the relationships between crop yield on the one hand, and total amount of ET and total N consumption during the growing season on the other hand. These are experimental relationships. Another important thing is the Yd_{opt} value, the genetically possible optimum yield of the given crop, if there is no limitation either to its water or to its nutrient requirements.

Development of the model

The above considerations and basic relationships /DEBRECZENI, 1983/ have been used in constructing a model which represents an input/output system both in respect of water and of N displaceable with water. In space the system refers to the root zone, whose depth depends on the given plants, while in time it is delimited by the growing season of the plant, i.e. the period between sowing and harvesting /as an approximation, the sowing date of winter cereals has been replaced by the date of final snow melting at the advent of spring/. The model uses one-day time steps; the calculation procedure is outlined in the Flow Chart /Fig. 2/.

The input includes time series of P(t) precipitation, of $F_1(t)$ base fertilizers and of $F_2(t)$ top-dressing; empirical functions as listed above, together with their pertaining parameters; finally the initial conditions: the t_o starting and t_n final days of the investigations , the soil type (S) and its field capacity (FC) , the plant grown (Pl) and its genetically potential yield (Yd_{opt}), the initial $W(t_o)$ moisture content and $N_s(t_o)$ N content of the root zone, and finally the DR depth of the former.

The calculations start at date t_o by calculating the water balance. First, the momentary water intake capacity of the soil per day is determined and compared tc the precipitation that day, if the latter is greater, the difference becomes runoff. Then the case of possible top-dressing is dealt with: if there is runoff, and there had been top-dressing in the course of the last 10 days, and this has not yet been washed away on the previous days, nor leached into the soil by infiltration attaining a value a /estimated at 3 mm/, then that part thereof which corresponds to the runoff/precipitation proportion will be washed away. The new water content of the soil is then calculated: if the latter exceeds W_{max}, the difference is considered as infiltration to deeper layers, carrying away part of the N reserves of the root zone. Now follows the calculation of ET: the value required to produce an optimum crop yield is curtailed by the water available in the root zone, the regulating parameter being c. With this the water content of the root zone can finally be reduced and the water balance is ready.

There are also two elements at hand concerning the N balance /the N leached to deeper layers and that washed away from top-dressing/, the calculation of which proceeds by determining the "natural N production" of the

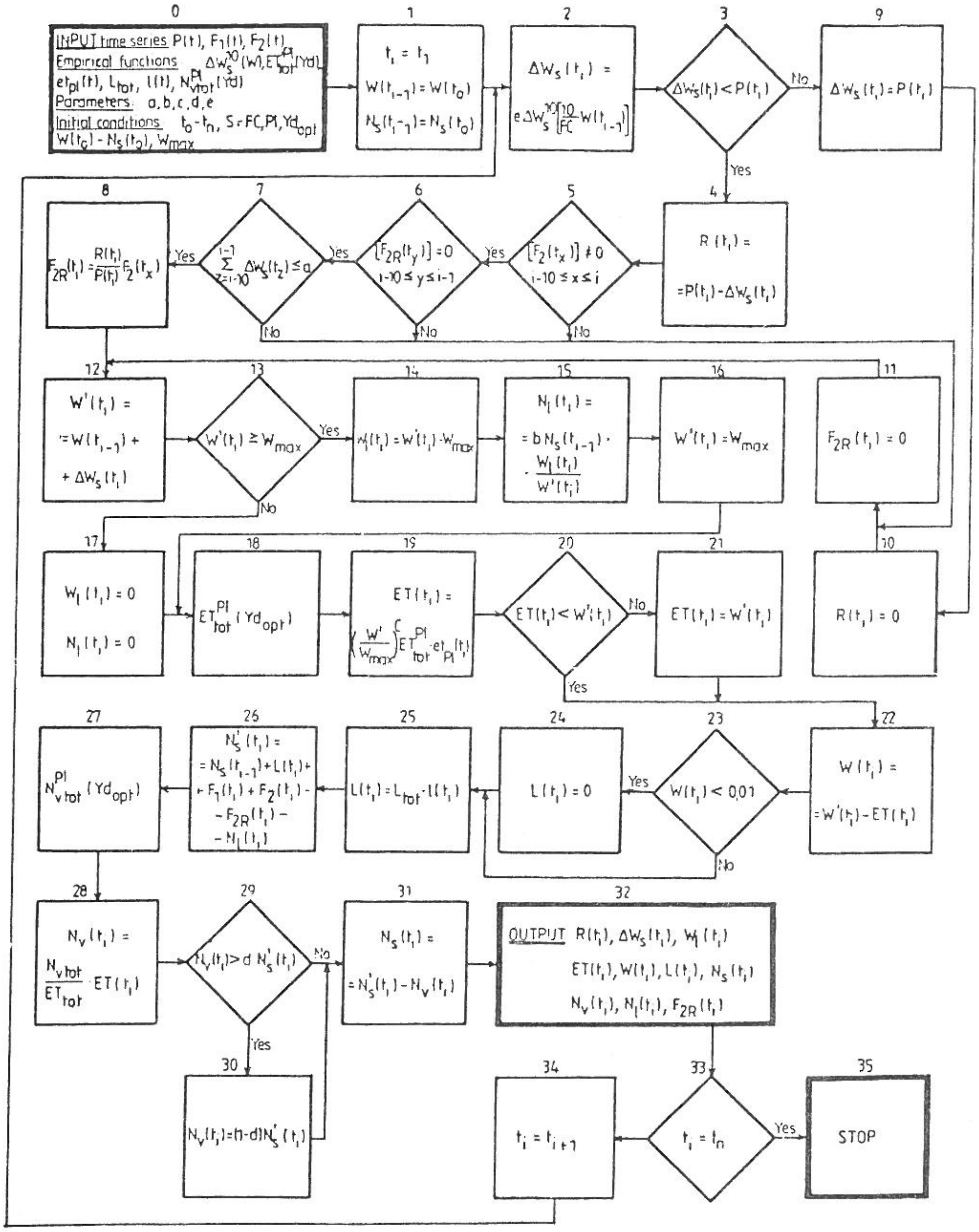


Fig. 2
Flow chart of the DISNIT model

Table 2

Investigation of Plot No. 1 of the Pamlény Basin

Input data

Starting date	Final date	Crop	Soil	FC %	DR cm	L_{tot} kg/ha	$W(t_o)$ mm	$N_S(t_o)$ kg/ha	Yd_{opt} t/ha	o	Top-dressing date	Top-dressing kg/ha
1	2	3	4	5	6	7	8	9	10	11	12	13
02.23 1983	07.06 1983	wheat	clayey loam	9	80	27.2	65	64	8	1.3	–	–

Results for the alternatives investigated:

Description of the alternative	e	Water balance, mm ΔW +	ΣP =	ΣR +	ET_{tot} +	ΣW_1	Runoff coef-ficient	$\Sigma\Delta W$
1	2	3	4	5	6	7	8	9
A. Base situation: slope ploughing	0.6	30.4	222.6	116.3	137.2	0	0.52	106.8
B. Contour ploughing	0.75	28.0	222.6	104.8	146.2	0	0.47	118.3
C. Deep ploughing strip cultivation	1.0	24.7	222.6	89.7	158.1	0	0.40	133.4
D. Contour ploughing, deep cultivation, stubble management	1.3	22.0	222.6	75.3	169.8	0	0.34	147.8

Alter-native	e	Nitrogen balance, kg/ha ΔN_S+	ΣF_2+	ΣL =	N_{vtot}+	ΣN_1+	ΣF_{2R}	ΣRN_s	I_{RN}	Crop yield according to ET_{tot}	N_{vtot}	eff.
1	2	10	11	12	13	14	15	16	17	18	19	20
A.	0.6	54.2	0	13.6	67.7	0	0	4229	1.00	2.3	2.7	2.3
B.	0.75	58.6	0	13.6	72.2	0	0	3814	0.90	2.6	2.8	
C.	1.0	62.7	0	13.6	76.3	0	0	3805	0.90	2.8	3.0	
D.	1.3	62.8	0	13.6	76.3	0	0	2820	0.67	3.1	3.0	

soil and then adjusting the value of the N content in the root zone on the previous day. Vegetal N consumption is then determined /taking care that at least a d portion /estimated at 0.5/ of the soil's reserves should be left behind/ and with that the final N balance is drawn. The output for the day can now be printed and the round of calculations for the next day started; this is continued until the final t_n date is reached.

The output includes the daily values of runoff, surface infiltration, deep infiltration, ET and the water content of the root zone; further, the "natural N production", vegetal N consumption, leached down N, washed away N and the N content of the root zone.

The computer programme has been written in FORTRAN for a PROPER 8 computer.

Practical application of the model

The model has been applied to plots chosen in the North-Eastern and South-Western parts of Hungary /in the Rakaca basin and the Tetves basin, respectively/, using data from the years 1983 and 1984 as input. The soils were clayey loam /Rakaca/ and sandy loam /Tetves/ and the crops were wheat and maize.

The procedure was to fix the e "cultivation factor" for the present level of cultivation /Table 1/, then determine the value of the c "ET limiting parameter" characterizing the plant/soil relationship in such a way that the crop yields corresponding to the calculated total ET and N consumption should match the yield actually attained. New levels of agricultural cultivation have now been tried by choosing e values from Table 1, while the value of c has been kept constant. The successive computer runs have resulted in a spectrum of results enabling the comparison of the effects of different levels of agricultural cultivation on the water/N balance of the soil, which ultimately influences the pollution of natural waters. Fig. 3 gives a graphical representation of some of the results calculated in one of the investigations, while Table 2 contains the input and output figures for the same investigation, the latter figures grouped so as to represent balances for the whole growing season at various levels of agricultural cultivation.

The evaluation of the experimental results was based on an inter-comparison of the same, rather than on absolute numbers. In the water balance, with higher levels of cultivation, surface infiltration increases significantly and surface runoff becomes correspondingly less on heavier soils, while on more open soils these effects are of less importance. For evapotranspiration, the increased water storage of the soil enables greater ET, and consequently, a higher crop yield, a phenomenon again experienced even more on heavier soils. Turning now to the N balance, it is a general observation that with higher levels of cultivation the vegetal N consumption increases parallel to improvements in the water regime characteristics of the soil; increased ET implies an increase in N consumption, if there is enough N available in the soil for that purpose. This underlines the necessity of always adjusting the amount of N fertilizers applied to the water conditions: under-dosage means the loss of the opportunity represented by greater amounts of water stored in the soil, while over-dosage means an increase in the N pollution hazard of natural waters, the remainder of N in the root zone at the end of the growing season being the probable source.

As for the actual N pollution of natural waters, the investigations have shown no occurrence of top-dressing being washed away from the soil surface, as the date and quantity of application was always successfully chosen

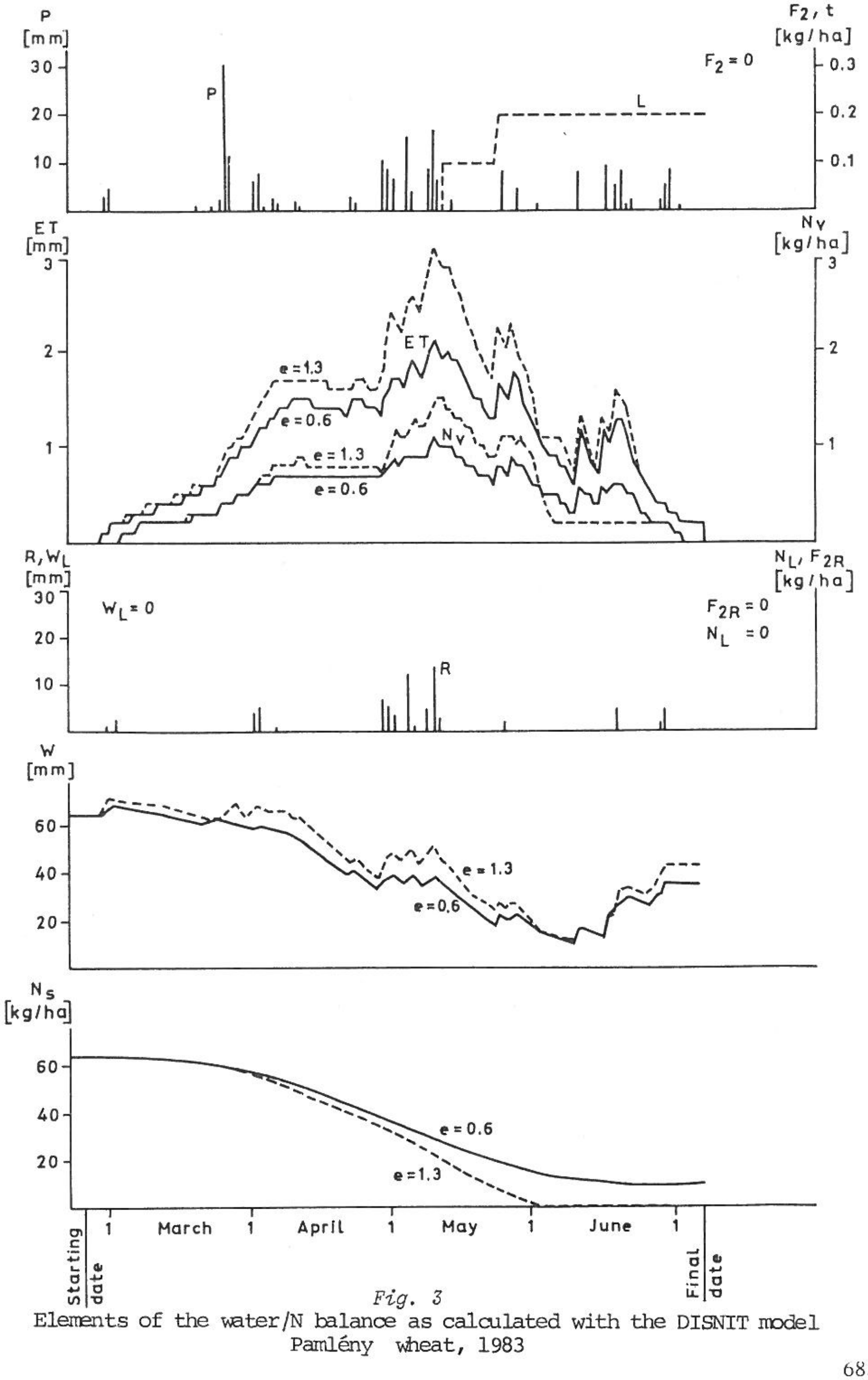


Fig. 3
Elements of the water/N balance as calculated with the DISNIT model
Pamlény wheat, 1983

in respect to precipitation events in the cases investigated. This, however, does not mean that the hazard does not exist; indiscriminate application of top-dressing during wet periods /not to mention applying it on frozen soils on top of the snow-pack/ involves extreme hazards of pollution. As far as N leached from the root zone into the deeper soil layers is concerned, the investigations have definitely shown that this can be neglected during the growing season: vegetal N consumption renders this danger insignificant. In the dormant season, however, when the N left over at the end of the growing season is available for downward leaching, this hazard /to be investigated with further applications of the model in round-the-year runs/ is a reality, and again draws attention to the necessity for the correct application of N fertilizers.

Finally, the problem of N pollution of surface waters, in which respect the model was not expected to give direct results, was approached in an indirect way. Starting from the idea that the R surface runoff, the N_R original N content of which was neglected when constructing the model, can be N polluted through contact with the soil surface while on its way towards the recipient, an index was sought to mark the degree of that pollution. In each case when the calculations resulted in R runoff values, these were multiplied by the N content of the root zone on the day in question (N_S), and the series of products gained for an investigation period were added up (ΣRN_S). Repeating this procedure for the investigation of the same case at different levels of cultivation, and dividing the sum of products in each case by the sum of products pertaining to the present situation, various cultivation levels could be characterized by I_{RN} indices /See Table 1/, expressing the expected lowering of the N pollution hazards of the surface waters at higher levels of cultivation.

Summary

An unsophisticated model has been constructed to simulate with easily available input data the water and N balances of the root zone, with special regard to detecting the pollution caused to natural waters by nitrogen displaceable by water. Results gained in practical applications have revealed the changes in this pollution expected to be brought about by different levels of agricultural cultivation. The model could thus also become the basis of further investigations concerning the economic side of improving agricultural practices, i.e. a base model in a series of models serving efficiency investigations.

The DISNIT model is also expected to become a practical tool in agricultural water engineering planning and management. Improvements to parts of the model - based on the experience gained and supported by field experiments already underway in an experimental basin - are envisaged to render the model more efficient.

References

CREAMS, J., 1979. A field model for chemicals runoff and erosion from agricultural management systems. USDA Manuscript.

DEBRECZENI, B., 1967. (Some relationships between soil moisture and the supply of nutrients in the case of field crops.) [In Hungarian] Mezőgazd. Kiadó. Budapest.

FURRER, Otto G., 1984. Nitratbelastung des Grundwassers durch die Landwirtschaft. Grundwasserschutz, Tagung für Siedlungs- und Industriewasserwirtschaft. Baden.