MODEL ANALYSIS FOR NITROGEN EFFLUENT FROM UPLAND FIELD CONSTRUCTED WITH UNDER-DRAIN

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ABSTRACT
A mathematical model to estimate nitrogen (N) effluent from the upland field cultivated with barley, where under-drain pipes were installed 60 cm below the field surface, was developed and N effluents for several rainfall patterns during the cultivation period were analysed. The model is composed of the water drainage model and N cycle model. The water drainage model is made up of Sugawara's tank model in which the field is divided into two soil types, permeable soil and watertight soil, and macro pore. The N cycle model can calculate the N reactions including nitrification, denitrification, mineralization, immobilization, urea hydrolysis and N transportation in the field. By using this model, N effluents caused by rainfall were analysed and characteristics of N effluent were clarified. The under drainages caused by heavy rains which occur around 60 days after fertilization contribute greatly to the amount of N effluent load during a cultivation period. Also, split application of fertilizer is not effective for the reduction of N effluents under any cultivation conditions, especially in winter crops. A large quantity of N effuses out of the field because the major portion of rainfall in a cultivation period occurs in the latter half of the period.

KEYWORDS : Paddy field; Upland field; Drainage; Nitrogen leaching; Model analysis

INTRODUCTION
In Japan, over 25 % of paddy fields have been converted into upland fields because of over production of rice, where under-drain systems are constructed to accelerate drying of the fields. With this, nitrogen (N) effluents from the fields have increased and caused serious problems of water pollution in rural areas. Shiratani et al. (1986) reported that 30 % - 60 % of applied N were effused out of barley field constructed with under-drain and this was one of the major N source for the eutrophication of agricultural canal water in winter crop season.

To build suitable measures of the water quality conservation, it is necessary to quantify inflowing N loads and to estimate the effectiveness of the measures. As N effluent from cultivated fields depends on complicated N reactions and water movement in field soils, mathematical models are useful to solve these problems.

The model which calculates the N effluent should be composed of two sub-models. One is for water movement in the field (drainage model) which calculated the surface drainage, under drainage, evapo-transpiration from the field, and the other is for the N reactions in the field (N cycle model). Since the N cycle model was formerly developed by Shiratani et al. (1997), the purpose of this paper is to develop a drainage model and analyze N effluents from some conditions of an upland field cultivated with barley combining the N cycle model and the drainage model.

DETAILS OF TEST FIELD
The study field shown in **Fig. 1** is located on lowland with alluvial soil on the shore of Ariake Bay, Japan. In the field shown in **Fig. 2**, the farmland consolidation project was implemented in 1970 and the main under-drain system was constructed at the depth of 0.5-0.7 m. Supplementary drains were burrowed at right angles to the main under-drain before cultivation at about 0.3 m depth. Field drainage reaches the creek from the outlet of the under-drainage and surface drainage. Cultivation history is summarized in **Table 1**. Formerly, paddy rice had been cultivated in summer and barley in winter. However, the rice summer crop was replaced by soybean after 1982, and returned to paddy rice in 1984.

Major clay mineral is montmorillonite and soil texture of the field is LiC in the top 20 cm layers and HC in deeper layers. Specific gravity of the soil particles is 2.56 in the top layers, 2.63 in the plowsole and 2.62 in the subsoil, respectively. Annaka and Shiratani (1987) suggested that cracks grew in the subsoil due to drying and contraction of the soil through the conversion of paddy fields to upland fields.

Table 1 Cultivation history of the test field

	Summer crop (Jun.-Nov.)	Winter crop (Dec.-May)
1980-'81	Paddy rice	Barley
1981-'82	Paddy rice	Barley
1982-'83	Soybean	Barley
1983-'84	Soybean	Barley
1984-'85	Paddy rice	Barley

We observed the water quality and quantity of the test field drainage for two periods of barley cultivation, December 1983 - May 1984 (referred to as 1984 barley) and December 1984 - May 1985 (referred to as 1985 barley). As shown in **Fig. 2**, surface drainage was automatically measured using a 3 inch Parshall measuring flume connected to the outlet of the surface drain, while the under-drainage discharge was measured with a flow meter (40 mm in diameter) connected to the outlet of the pipe drain. Here, it is assumed that percolation through the levee is negligible and that the outlet of the under-drain operates within the center lines between the pipe drain and neighbor drain with a width of 13.75 m and length of 113.0 m.

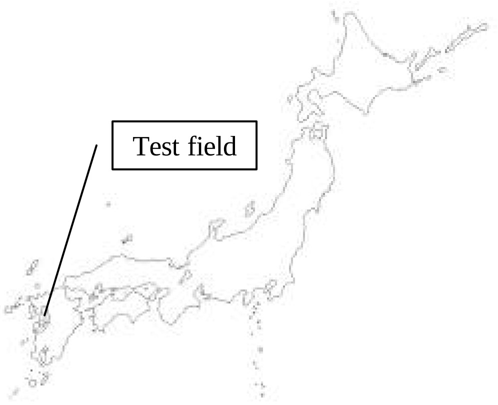

Fig. 1 Location of the test field

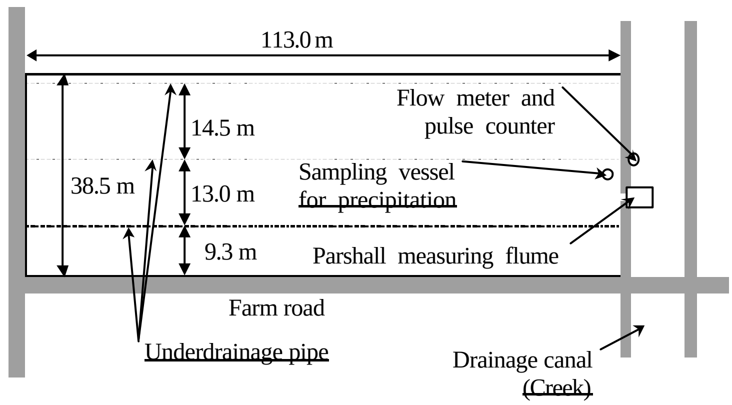

Fig. 2 Outline of the test field and measuring stations

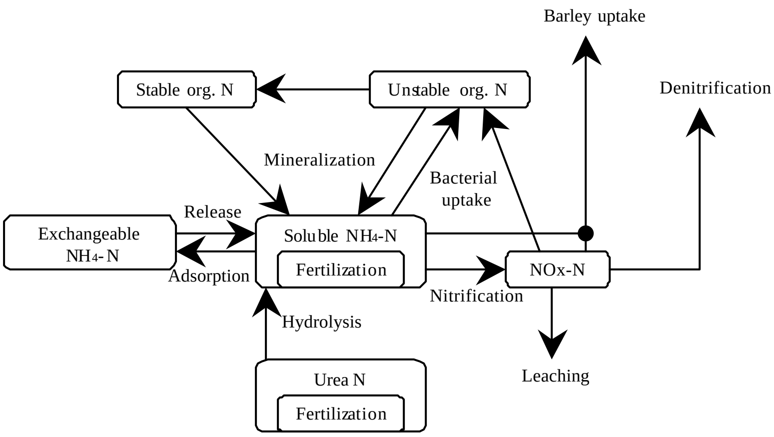

Fig. 3 Nitrogen cycle in barley field

NITROGEN CYCLE MODEL (SHIRATANI ET AL., 1997)

To analyse the N effluent from the field, we used the N cycle model formerly developed for the barley field by Shiratani et al. (1997). The model expressed the N cycle in soils as depicted in **Fig. 3**.

Box model was applied at this model. In which the state variables are represented as the quantities of each N forms in the whole field soil (113×13.75 m^2 and 0.6 m in depth).

N reaction Rates

First order kinetics was applied for several N reaction rates, and for temperature dependence, the Arrhenius law was applied referring to Sugihara et al. (1986). Soil moisture dependence was neglected as several layers, top layer, plowsole layer and sub soil, were considered to correspond to the usual water content in a narrow range (50–55 %). So, the N reaction rates were represented by Eq. [1].

$$V = k'\exp\left[\frac{Ea\cdot(T-T')}{RTT'}\right]N\,, \qquad [1]$$

where N: nitrogen content in soil (kg), k': reaction rate constant at the standard temperature (day^{-1}), Ea: apparent activation energy (J/mol), R: gas constant ($J\,K^{-1}mol^{-1}$), T: soil temperature (K) and T': standard temperature (K).

Barley Uptake Rate

The logistic equation was applied to barley growth, and the growth rate was converted into nutrient uptake rate from the field as in Eq. [2]. It was also assumed that barley takes up NH_4-N or NO_X-N depending on the proportion of N contents for both N forms in the field.

$$P = \frac{dp}{dt} = lp\left(1 - \frac{p}{p_e}\right), \qquad [2]$$

where P: barley uptake rate (kg/d), l: growth constant (d^{-1}), p: N content in barley (kg), p_e: N content in barley at harvesting.

N leaching rate

Nitrogen concentration of the drainage water was considered to be in proportion to the amount of NO_X-N in the field. Thus, N effluent rate was expressed in Eq. [3].

$$L = eN_N Q, \qquad [3]$$

where L: N leaching rate (kg/d), e: constant (m^{-3}), N_N: NOx-N content in the field (kg) and Q: drainage rate (m^3/d).

Several values of parameter were given as mean values in references (Mehran and Tanji, 1974, Xie et al., 1993). Shift rate coefficient of unstable org.-N to stable org.-N, nitrification rate, denitrification rate and temperature dependences of the bio-chemical reactions were estimated as optimum values within a considerable range using a genetic algorithm (Shiratani et al., 1997).

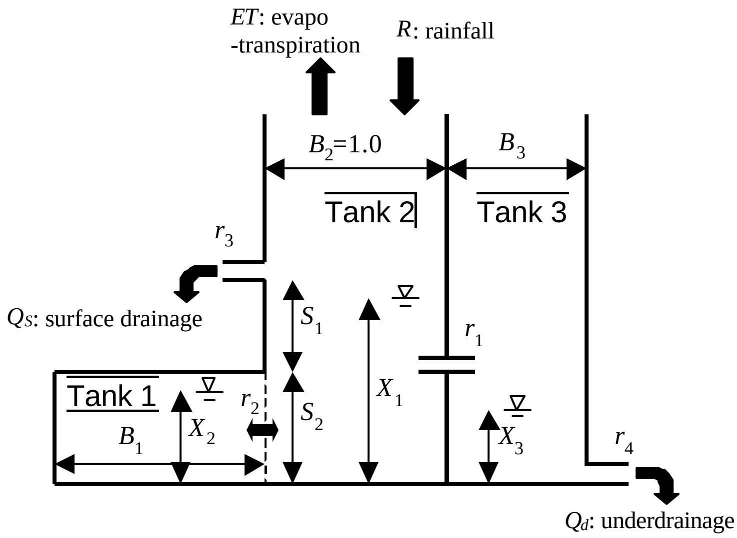

Fig. 4 Tank model for water drainage of the barley field

DRAINAGE MODEL

Model Construction

It is known that water movement in soil matrix could be expressed by Fick's law in which water content gradient in soil is its driving force. However, the soil structure in an upland field constructed with under-drainage system locating on alluvial lowland is complex, thus there could be watertight soils, permeable soils and cracks. For the modeling, we modify the Sugawara's tank model in which the field soils are expressed as watertight soil (Tank 1), permeable soil (Tank 2) and macro pore (Tank 3), and apply to the test field to calculate percolation flows in the soil matrixes, bypass flow in the macro pore and drainages (**Fig. 4**).

Changes of water depth for each tank can be described as follow equations;

$$\frac{dX_1}{dt} = \frac{W_2}{B_1}, \qquad [4a]$$

$$\frac{dX_2}{dt} = R - W_1 - W_2 - Q_S - ET, \qquad [4b]$$

$$\frac{dX_3}{dt} = \frac{W_1 - Q_d}{B_2}, \qquad [4c]$$

where X_i: water depth of Tank i (mm), R: rainfall (mm/d), ET: evapo-transpiration (mm/d), Q_S: surface drainage (mm/d), Q_d: under-drainage (mm/d), W_1: water movement rate from permeable soil to macro pore (mm/d), and W_2: water movement rate from watertight soil to permeable soil (mm/d), B_i: relative width of Tank i to B_2 (=1.0), r_j: coefficient of water movement at section j described in **Fig. 4**.

Water movements and drainage occurs as followings.

$$W_1 = r_1 \boldsymbol{I}\,[X_1\text{-max.}(S_1, X_3)], \quad [5]$$

where $\boldsymbol{I}\,[x] = x$ when $x > 0$, $\boldsymbol{I}\,[x] = 0$ when $x = 0$ or $x < 0$.

$$W_2 = r_2(X_1\text{-}X_2) \text{ when } X_2 = S_1 \text{ or } X_2 < S_1, \quad [6a]$$

$$W_2 = 0 \text{ when } X_2 > S_1. \quad [6b]$$

$$Q_S = r_3 \boldsymbol{I}\,[X_1 - (S_1 + S_2)]. \quad [7]$$

$$Q_d = r_4 B_2 X_3. \quad [8]$$

Evapo-transpiration can be simply calculated by Makkink method by using air temperature and solar radiation conditions.

Table 2 Parameter values of the tank model

Parameters	1984 barley	1985 barley
S_1	28.0	39.0
S_2	27.0	25.0
B_1	8.0	7.0
B_3	0.5	0.5
r_1	0.7	0.9
r_2	0.3	0.1
r_3	0.93	0.93
r_4	0.97	0.97
Initial conditions		
X_1	27.0	28.0
X_2	27.0	28.0
X_3	0.0	0.0

Model Validation

Parameter values of the drainage model were derived by curve fitting with drainage data observed for two periods of barley cultivation field (1984 and 1985). The constant values used here are listed in **Table 2**. There are slight differences in parameter values between 1984 barley and 1985 barley. It may be considered that these differences are caused by the difference of the previous crops, soybean for 1984 barley and paddy rice for 1985 barley. Soils in paddy fields swell and decrease cracks, to decrease the water movement trough Tank 1 and Tank 2 and to increase the water retainment in Tank 2. With these parameter values, the model could be traced by the observed data of field drainage and N concentration as shown **Figs. 5** and **6**.

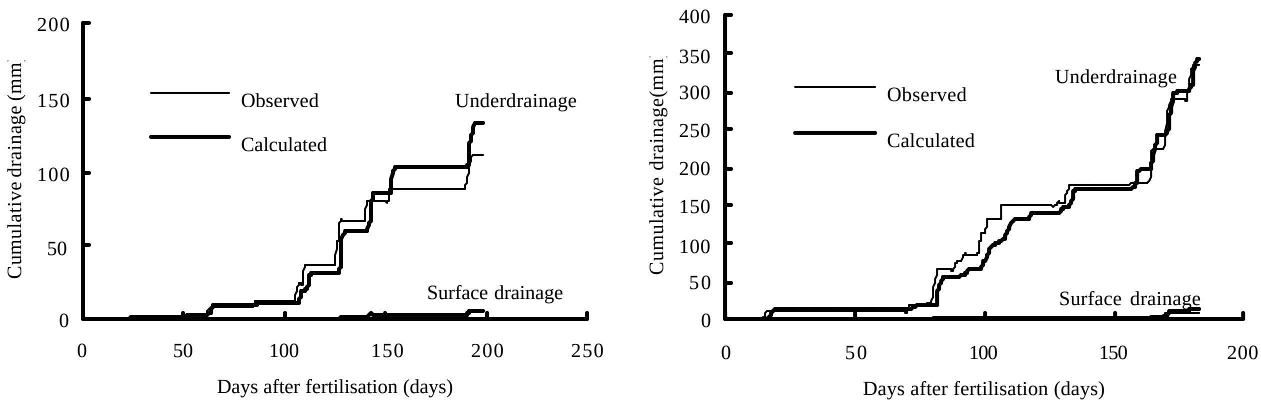

Fig. 5 Cumulated curve of observed and calculated field drainage

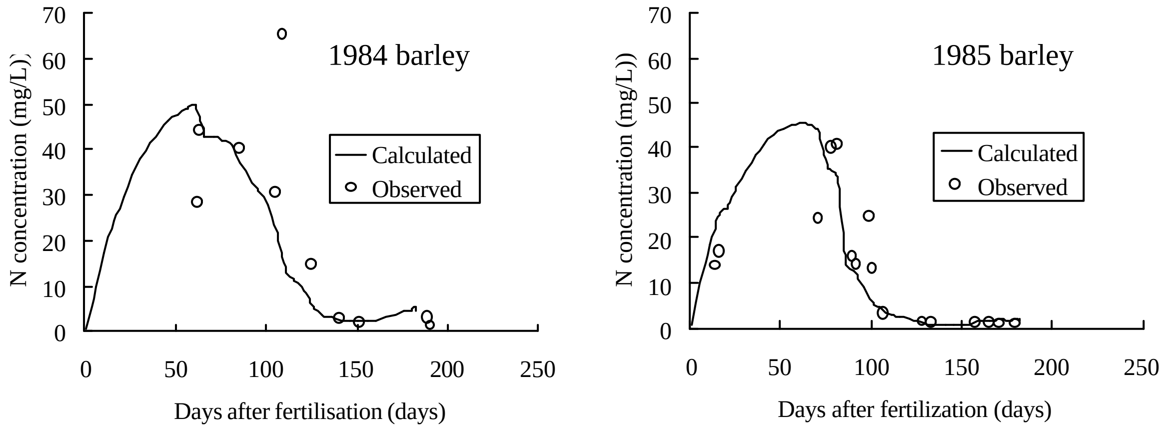

Fig. 6. Observed and simulated N concentration of under-drainage water

From this, we can conclude that the N effluent model composed with the N cycle model and the drainage model enable to simulate well N concentrations of the field drainage water from the field.

Table 3 Cases for analysis

	Rainfall distribution	Fertilization method
Case 1	Standard	64.0 kg/ha at seeding
Case 2		32.0 kg/ha at seeding, and 32.0 kg/ha at 50 days after
Case 3	Large amount in the first half of the cultivation period	64.0 kg/ha at seeding

MODEL ANALYSIS

Cases for Analysis

By using the developed model with constant values derived for 1985 barley, N effluents were simulated for three cases of rainfall distribution and fertilization method to analyze characteristics of N effluent in relation to rainfall and distribution in time and fertilisation timing as listed in Table 3. In general, Rainfalls in a barley cultivation period (December – May) inclined heavily toward the first half of cultivation period. The rainfall distribution was the most standard in these twenty years in Case 1 and Case 2, and the rainfalls in the first half of the cultivation period fell more heavily in Case 3 than other Cases. Fertilizer in Case 1 and Case 3 was applied 64.0 kg/ha as the basal application at seeding barley, and in Case2, a half amount of fertilizer (32.0 kg/ha) was applied at seeding and at 50 days after.

Field Drainage

Figure 7 shows rainfalls and calculated water drainages for the Cases of standard rainfall distribution. The total amount of rainfalls in the cultivation period was 646.5 mm and more than 85 % of the total rainfall was in the latter half of cultivation period (March – May). Consequently, a large amount of water drainages occur in this duration of the cultivation period, and surface drainages occupied approximately 97 % of total drainages. On the other hand, the rainfalls and water drainages in Case 3 are calculated as shown in Fig. 8. Total amount of rainfalls in the cultivation period was 735.5 mm and 45 % of it fell in the first half of cultivation period. More than 97 % of the total field drainages had occured via surface drainage.

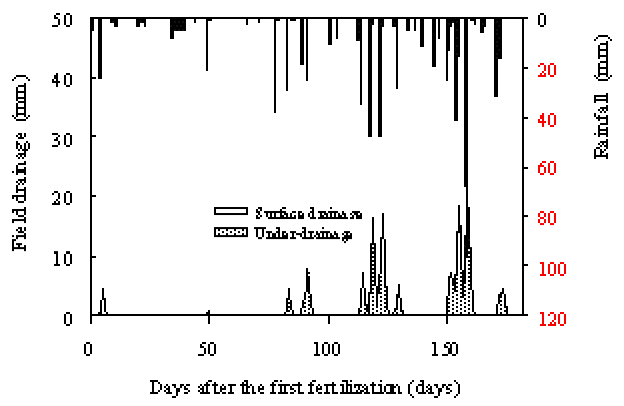

Fig. 7 Rainfalls and field drainages in Case 1 and Case 2

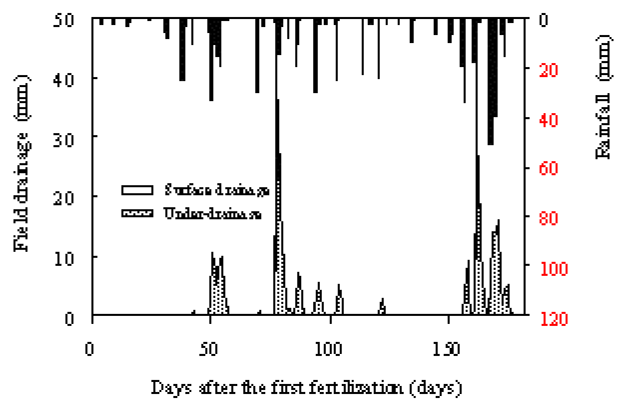

Fig. 8 Rainfalls and field drainages in Case 3

Nitrogen Effluent

Figure 9 shows the changes of N concentration in time and cumulative N effluent loads for Case 1 and Case 2. N concentrations of field drainage increased just after the first fertilization, to reach their peak around 60 – 75 days after, and then decreased rapidly. For the first 90 days when the first fertilization affects N concentrations, the N concentration in Case 1 was higher than that in Case 2 because the amount of N fertilization at seeding in Case 1 was twice as much as that in Case2. For the latter 70 days, the N concentration in Case 1 was conversely lower than that in Case 2 because 32.0 kg/ha of N fertilizer was added at 50 days after the first N fertilization in Case 2. Consequently, the cumulative N effluent in Case 2 (27.5 kg/ha) was 13 % larger than that in Case 1 (24.4 kg/ha). From this, the split application of fertilizer may bring about the increase of N effluent as a greater part of rainfalls fall in the latter half of the cultivation period in a winter crop season.

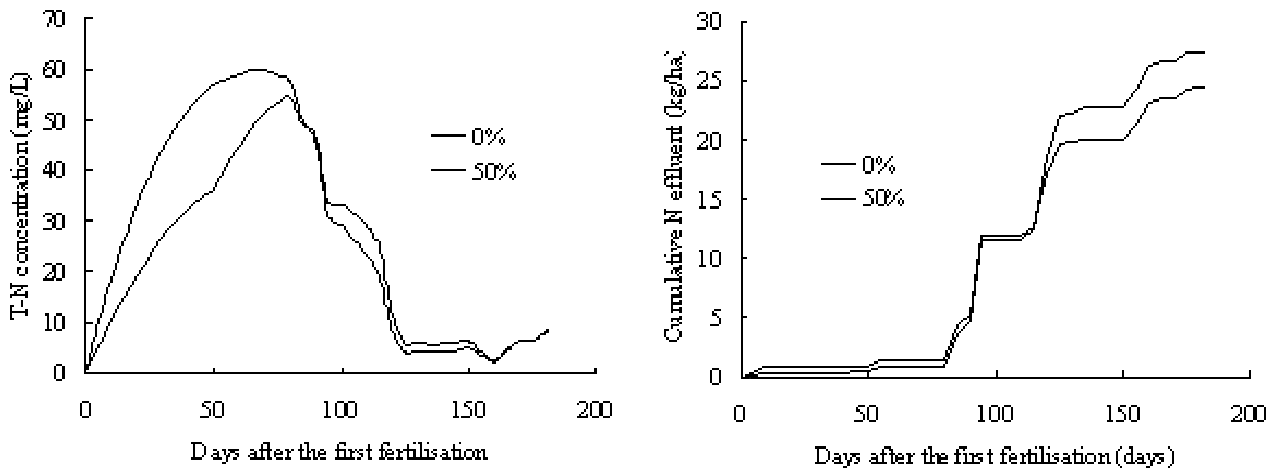

Fig. 9 Changes of N concentration in time and cumulative N effluent loads for Case 1 and Case 2

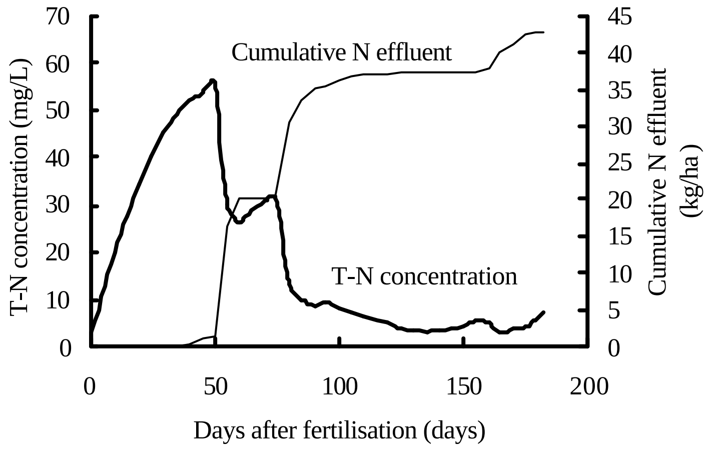

Fig. 10 Change of N concentration and cumulative N effluent load for Case 3

Figure 10 shows the changes of N concentration in time and cumulative N effluent loads for Case 3. There are two meaningful peaks of N concentration during the cultivation period. The N concentration rose to 58 mg/L in the first 50 days, and falls right down to 25 mg/L with considerable field drainage during the period 50 to 60 days. After that, there was a rise of 5 mg/L during the period 60 to 75 days and a rapid drop again. This means that the nitrification was proceeding steadily in the first 75 days while NOx-N in the field was reduced by field drainages. Consequently, the total of the effluent N amounts to 42.7 kg/ha. N effluents during the period 50 to 80 contribute much to the total N effluent.

CONCLUSION

A mathematical model was developed to estimate field drainages from the upland field cultivated with barley crop. The model was verified for two cultivation periods, which could be traced by the observed data of field drainage and N effluent from the field.

Combining the drainage model and the N cycle model, N effluents caused by rainfall were analyzed and characteristics of N effluent were clarified in relation to rainfall patterns and fertilization timing. The under-drainages caused by heavy rains which occured around 60 days after fertilization contributed more to the amount of N effluent load during a cultivation period. Thus the split application of fertilizer may increase the N effluents in winter crops since the major portion of rainfall in a cultivation period occurs in the latter half of the crop period.

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