# Combining GIS and a Quasi-Two Dimensional Mechanistic Model to Assess the Nitrate Balance at Regional Scale

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## Abstract

Fertilised cropland is a potential non-point source of nitrogen contributing to the nutrient enrichment of surface water ecosystems. Nitrogen is present in drainage outflow primarily because of the addition of fertilisers. The purpose of this study is to model the nitrate leaching to surface waters using a quasi two-dimensional mechanistic flow model (DRAINMOD) in combination with a GIS. The GIS is used to describe for the catchment the spatial distribution of soil type and land use, and to present the simulated nitrate leaching over the catchment. This paper summarises the method used to model the nitrate leaching at field scale and how the GIS was applied to present the spatial distribution of nitrogen loss by natural and artificial drainage. The method was applied to the Witte Nete catchment in Belgium having a total catchment area of 40.7 km$^2$. The study shows great advantages of the association between a GIS and a nitrate simulating model where spatial data management, taken care of by the GIS, is combined with temporal variable simulation, taken care of by the mechanistic model. Furthermore, the study illustrates that a GIS in combination with a mechanistic field scale model is a powerful and suitable tool for modelling and analysing nitrate leaching at regional scale. The resulting vulnerability map depicts the nitrogen leaching as a function of soil type and land use and gives the decision maker the opportunity to diversify the nitrogen leaching standards.

## 1 Introduction

Most nitrogen found in surface waters is emerging from land drainage (Viessman and Hammer, 1998). The use of agrochemicals endangers the quality of land and water resources and necessitates measures. In Flanders for example the nitrate drinking water standard of 50 mg l$^{-1}$ is exceeded in many groundwater systems (Christiaens et al., 1996). This is mainly a result of the

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nitrate-nitrogen leaching from excessive fertilised agricultural land (Geypens and Rutten, 1994). Legislation measures for controlling the fertiliser application and reducing the nitrate pollution are currently considered (VLM, 1993).

The case study described in this study was carried out with the aim to quantify in a predominantly rural catchment, the Witte Nete basin with an area of 40.7 $km^2$, the contribution from fertilisers and organic matter to the nitrate load found in the surface water. To model the transfer of nitrogen from the soil-crop system to the river use is made of a quasi two-dimensional mechanistic flow model DRAINMOD in combination with a Geographic Information System (GIS).

The DRAINMOD model calculates the daily nitrate leaching for a given soil, crop, climate, geo-hydrological and farming scenario. The GIS pre-processes the regional data in a format suitable for the simulation model and summarises the main simulation results in tables and maps. The nitrate model covers the entire land phase of the hydrological cycle from the source on the soil surface, through the soil profile and the shallow drainage system to the river. The modelling results were used to produce the nitrate leaching map for the Witte Nete catchment.

# 2 Field data

## 2.1 General description of the catchment

The Witte Nete catchment, 40.7 $km^2$ in size, is situated in the upstream part of the larger Nete basin in Belgium. It is drained by one main river the Witte Nete fed by three branches: Vleminckloop, Achterste Nete and Voorste Nete. In the catchment there are two main villages, Dessel and Mol, both of them have urbanised and rural areas. Although the three classical pollution sources as agriculture, urbanisation and industry are present, the major source of pollution is coming from agriculture.

## 2.2 Data requirements and processing

### 2.2.1 Soil type

Based on the soil series observed in the region statistical profiles were selected from the soil information system AARDEWERK-BIS (Van Orshoven and Vandenbroucke, 1993). For the statistical profiles the geometry of the soil profile (boundaries of the pedogenetic horizons), the soil hydraulic parameters and the soil organic carbon content are available in the database. The soil distribution in the Witte Nete basin can be characterised by eight different soil types. The soil types in the catchment are sandy soils (Zap0, Zbm, Zbf and Zdg), loamy sand soil (Sdm), light sandy loam soil (Pdc0) and heavy clay soil (Uep). The names between brackets are according to the Belgian soil classification system. The sandy soils have different drainage conditions ranging from dry to medium wet, and profile development ranging from poorly to strongly differentiated horizons.

### 2.2.2 Land use

Land use information was derived using the TELSAT land use map (1995) of Flanders (OC GIS, Vlaanderen) providing information on land use for grid cells 30 x 30 m. It provides information on the spatial distribution of thirty land use types. Making distraction of the smaller agricultural land units the main four crops in the catchment are grassland, maize, fodder beet and potato (Vanongeval et al., 1996).

### 2.2.3 Nitrogen application

The Flemish Government recently introduced regulations aiming at controlling the use of nitrogen fertilisers to prevent further contamination of the environment. The fertiliser standards in the Manure Action Plan (MAP) are listed in Table 1.

## 3 Method

The DRAINMOD (Skaggs, 1997) model is used to simulate the performance of drainage and related water table management systems. DRAINMOD-N (Brevé et al., 1997) is an add module to DRAINMOD for simulating the nitrogen dynamics in artificially drained soils. Nitrate-nitrogen ($NO_3$-N) is the main N pool considered. The model is a quasi two-dimensional model because the nitrogen movement component considers only vertical transport in the unsaturated zone and both vertical and lateral transport in the saturated zone. The controlling processes considered by the model (Brevé et al., 1992) are rainfall N-deposition, fertiliser dissolution, net mineralisation of organic nitrogen, denitrification, plant uptake, and surface runoff and subsurface drainage losses. Assuming one-dimensional (vertical) flow processes in the unsaturated zone the nitrogen transport can be presented by the advective-dispersive-reactive (ADR) equation (Brevé et al., 1998):

$$\frac{\partial(\theta C)}{\partial t} = \frac{\partial}{\partial z}\left(\theta D \frac{\partial C}{\partial z}\right) - \frac{\partial(qC)}{\partial z} + \Gamma \tag{1}$$

where: C is the $NO_3$-N concentration [M $L^{-3}$], θ is the volumetric water content [$L^3$ $L^{-3}$], q is the vertical water flux [L $T^{-1}$], D is the coefficient of hydrodynamic dispersion [$L^2$ $T^{-1}$], Γ is a source/sink term [M $L^{-3}$ $T^{-1}$] used to represent additional processes (plant uptake, transformations, etc.), z is the co-ordinate direction along the flow path [L], and t is the time [T].

In DRAINMOD-N, functional relationships are used to quantify processes other than $NO_3$-N transport (the source/sink term in Eq. 1), as indicated by Brevé et al. (1998):

$$\Gamma = \Gamma_{dep} + \Gamma_{fer} + \Gamma_{mnl} - \Gamma_{rnf} - \Gamma_{upt} - \Gamma_{den} \tag{2}$$

where: $\Gamma_{dep}$ stands for rainfall deposition [M $L^{-3}$ $T^{-1}$], $\Gamma_{fer}$ for fertiliser dissolution [M $L^{-3}$ $T^{-1}$], $\Gamma_{mnl}$ for net mineralisation [M $L^{-3}$ $T^{-1}$], $\Gamma_{rnf}$ for loss [M $L^{-3}$ $T^{-1}$] in surface runoff, $\Gamma_{upt}$ for plant uptake [M $L^{-3}$ $T^{-1}$], and $\Gamma_{den}$ for denitrification [M $L^{-3}$ $T^{-1}$]. A detailed description of each functional relationship is given by Brevé et al. (1997).

**Table 1: Nitrogen standards**

| **Crops** | **Nitrogen (kg ha$^{-1}$)** | | |
|---|---|---|---|
| | Animal or organic | Chemical or mineral | Total amount |
| Grassland | 150 | 200 | 350 |
| Crops with low nitrogen need | 55 | 70 | 125 |
| Other crops, e.g.: potato, sugar beet, winter wheat and maize | 125 | 150 | 275 |

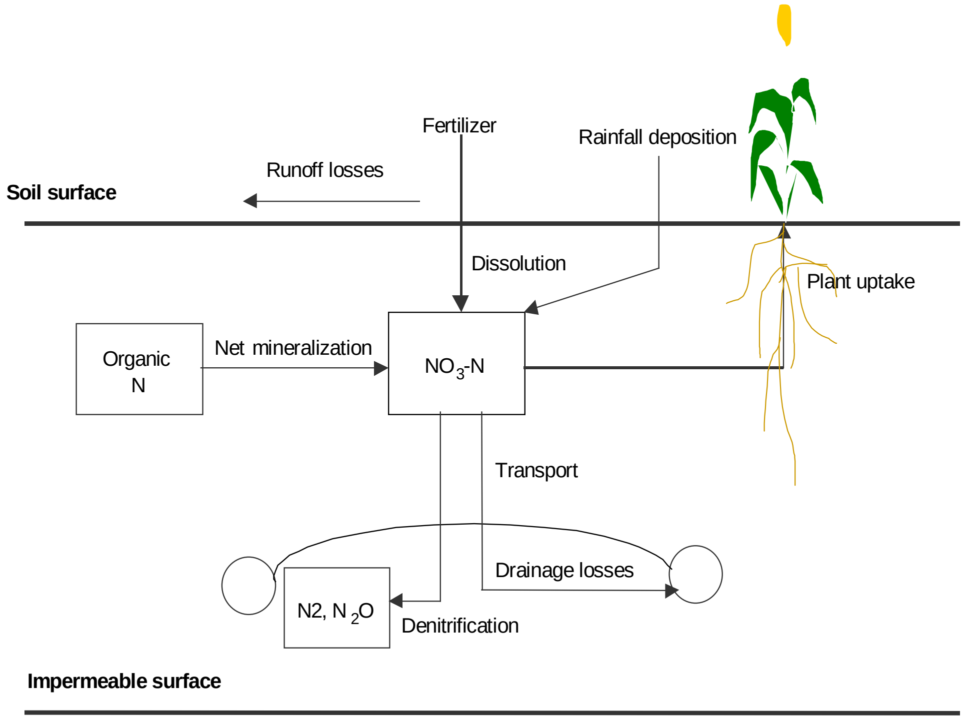


Figure 1: Nitrogen cycle considered in DRAINMOD-N

# 4 Materials

The climate, soil, crop and crop management data, required as input for the water and nitrate transport modelling, were collected. The distribution over the catchment of the model input and simulation results were presented graphically using GIS. The concepts in the coupling of the quasi two-dimensional leaching model (DRAINMOD) and GIS is illustrated in Fig. 2.

Combination between soil type and the main agricultural land units resulted in 32 scenarios, being the result of eight soil types and four main field crops. The soil-land use map was overlaid by the parcel map and for each parcel the climate, soil, crop conditions and nitrogen application depth were determined and used as input for DRAINMOD model. The leaching period from 1 January 1993 to 31 December 1997 ($0 < t < 1826$ day) was simulated using the measured $NO_3$-N concentrations on 16 December 1992 as initial condition. Water flow and nitrate leaching are modelled in the flow domain of 12.5 m width, representing half the drain spacing, and a depth of the soil profile of 2 m. The drain was located at 120 cm depth and described as a half circular hole with real physical dimensions (inner diameter = 5 cm). The inner wall of the drain was described as a seepage face, implying that the drain is always practically empty. In the simulations no pounding at the soil surface was allowed. As atmospheric conditions daily precipitation and evaporation data were used. The average groundwater level midway between the drains was taken as representative for the depth of the initial water table.

In a first step the water flow and nitrate leaching out of the soil profile was simulated for each scenario (individual field) as a function of soil type, land use and fertiliser application. In a second step the results at field scale were aggregated to derive the nitrate leaching at catchment scale.

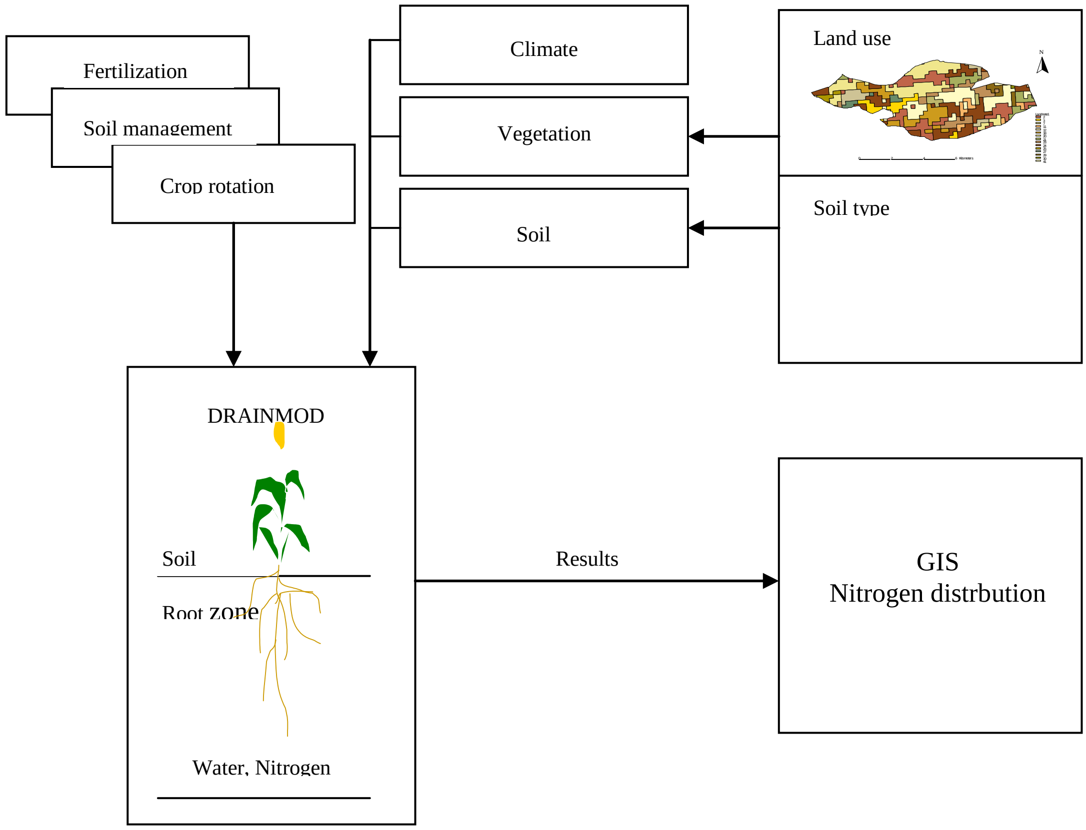


Figure 2: Coupling of the quasi two-dimensional leaching model (DRAINMOD) and GIS

## 5 Results and discussion

The daily rainfall and comparison between the simulated discharge with DRAINMOD after aggregation from field to regional scale and the discharge measurements at the catchment outlet are shown in Fig. 3. The comparison indicates that the modelling system simulates the hydrological regime with acceptable accuracy and strengthens the assumption that it is possible to predict at catchment scale the nitrate load coming from the rural area considering the nitrate load at the scale of the catchment as the sum of the nitrate leached out of the individual fields.

To take the possible nitrate transformation from the drain outlet to the river into account the simulation results should be adjusted by a correction factor. This factor may be derived as:

$$X = C_g / C_s \quad (3)$$

where: X is the adjustment factor, $C_g$ is the average regional simulated $NO_3$-N concentration in drain water (M $L^{-3}$) over the simulation period of 1826 days and $C_s$ is the observed $NO_3$-N concentrations in the surface water (M $L^{-3}$) averaged over the same period. The adjustment factor will be catchment dependent and function of the nitrate concentrations in both the surface water and groundwater, which on their turn are controlled by the spatial distribution in soils, land use, fertiliser management, weather and geo-hydrologic condition.

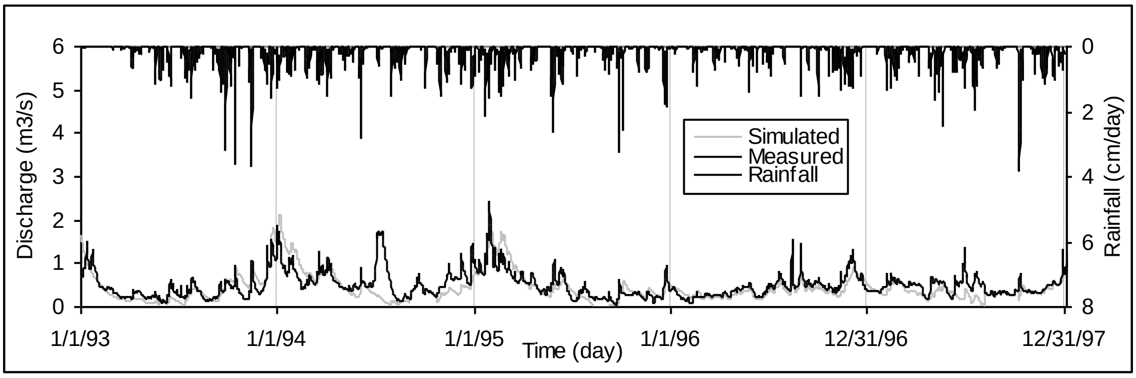


Figure 3: Daily rainfall and comparison of the simulated cumulative and measured discharge at the catchment outlet

Comparison of the average daily simulated $NO_3$-N concentration in the drain water, aggregated over all agricultural fields in the catchment applying a weighted approach based on the field area, with the daily observed $NO_3$-N concentration in the river water in the catchment outlet revealed that the $NO_3$-N concentration in the drain water, averaged over the entire catchment, on average need to be divided by a factor 2.4 to obtain the nitrate concentration in the river water at the basin outlet. Figure 4 shows the simulated nitrate concentrations leaving the soil profile and nitrate concentrations measured in the Witte Nete river after having divided the average simulation results by the factor 2.4. The GIS package ARC-INFO was finally used to present the simulation results in a cartographic way. The $NO_3$-N leaching risk vulnerability map for the Witte Nete catchment is shown in Fig.5.

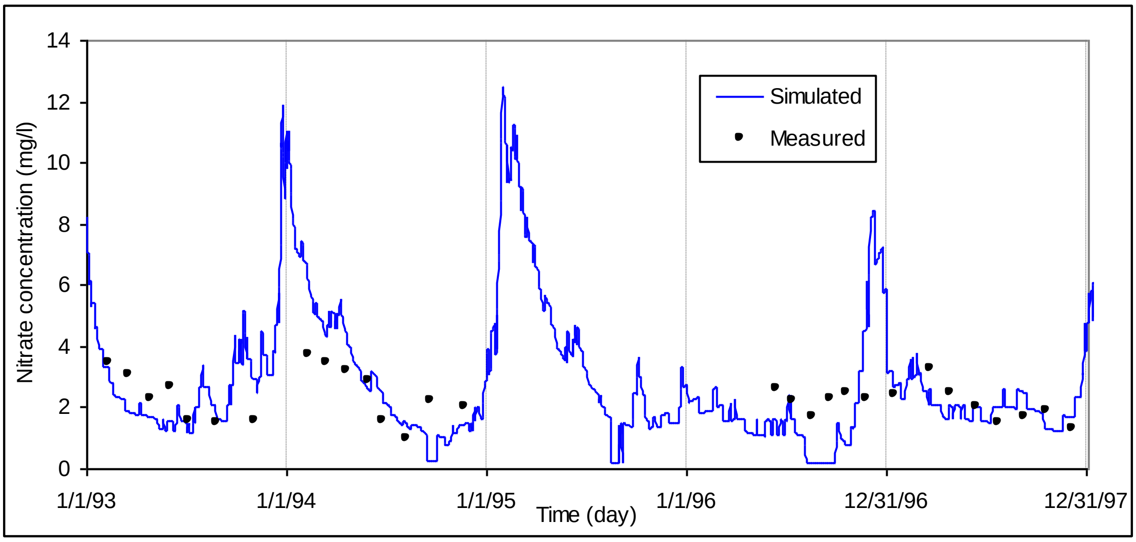


Figure 4: The simulated $NO_3$-N leaving the soil profile and the measured $NO_3$-N in the Witte Nete river

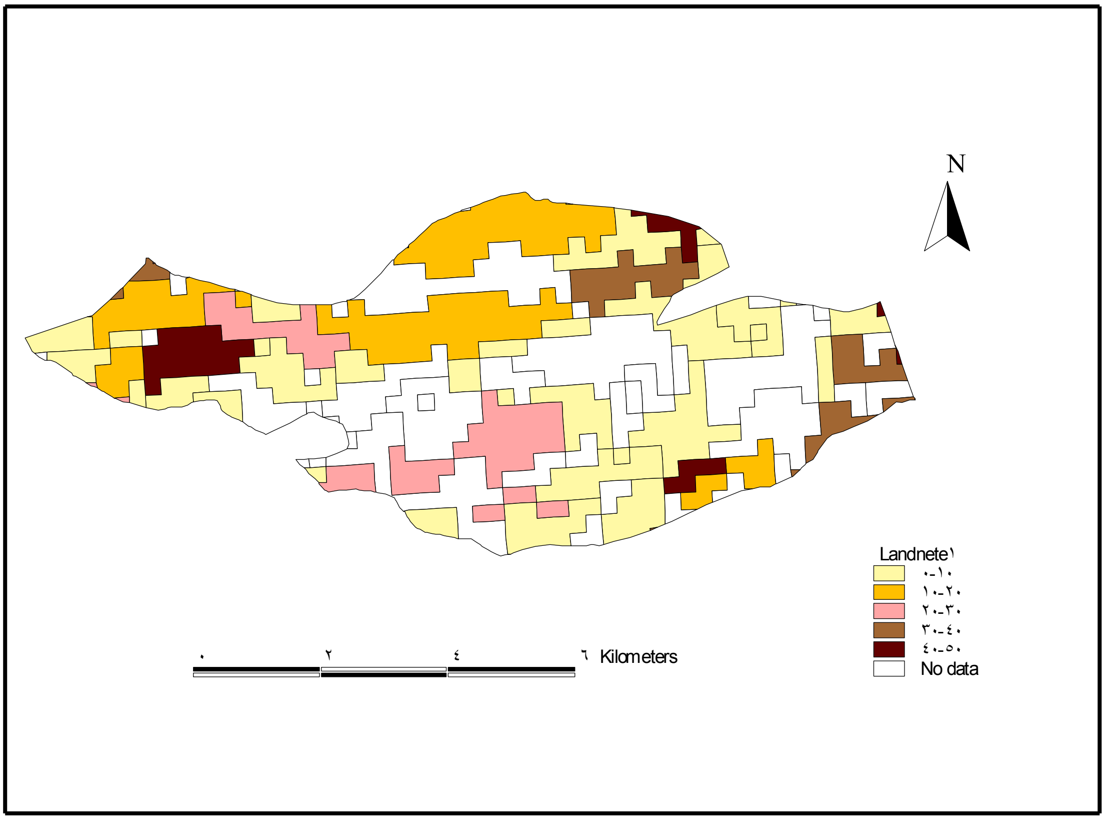


Figure 5: $NO_3$-N (mg/l) leaching risk vulnerability map for the Witte Nete catchment

# 6 Conclusions

The study illustrates the capacity of DRAINMOD in combination with a GIS to predict the regional nitrate load of agricultural fields to the surface water system. The approach enables to account for the different soil types reacting physically, chemically and biologically in a different way, and having a different geo-hydrological setting and applied fertiliser package, resulting in a different leaching pattern. Since the exact fertiliser package per field for the period of analysis could not be reconstructed the threshold values for N-fertilisers, as specified in the fertilisation standards of the Flemish Government were applied. This could have led to an underestimation, respectively to an overestimation of the nitrate leaching from the individual fields. Notwithstanding a fairly constant ratio was found between the cumulative nitrate load from the individual fields and the nitrate load measured in the river outlet. The ratio is the result of the combined impact of the unknown nitrate-nitrogen load from the urbanised area and the few industries present in the catchment, and the reduction of nitrate during the transport process in the saturated zone and the river from the point of entrance in the river to the river outlet. By lack of sufficient measurements it is yet impossible to define the exact rate of reduction of the nitrate when it leaves the drainage system. Therefore more data need to be collected on the nitrate entering the aquifer system and the contribution of the aquifer to the nitrate load in the river, as well as the contribution of the nitrate load from the domestic and industrial sector.

Notwithstanding the lack of data the study shows the potential of a GIS-nitrate model association where spatial data is combined with temporal variable simulation. The study illustrates that a GIS in combination with a mechanistic field scale model is a powerful and suitable tool to model and analyse the nitrate leaching at regional scale. The approach appears valid to estimate water flow and nitrate concentrations at regional scale based on field scale predictions. The cumulative simulated nitrate leaching from the individual fields have to be adjusted by a factor 2.4 which accounts for non-detectable and difficult to measure nitrogen pollution sources and the possible nitrate transformations from the drain outlet to the river. It may be concluded that the methodology can relatively easily be applied to larger mainly rural areas and used as decision support tool for evaluation of legislative and management measures aiming at reducing nitrate contamination risks.

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