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Comparison of water quality in drainage basins under agricultural and forest land use

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ABSTRACT In the area to the north of the Edersee Reservoir investigations have been carried out since 1975 into the quality of streamwater in drainage basins with different land use. The main subject of interest is a comparison of the loss of plant nutrients from drainage basins under agricultural and forest land use. The total phosphorus loss from drainage basins under agriculture is higher than that from wooded areas, because storm events with overland flow are more frequent in agricultural areas than in forested areas. In comparison, ortho-phosphate concentrations in runoff depend more on the absorption capacity of soils and geological substrates than on land use. Nitrate concentrations in runoff from agricultural areas are markedly higher than those found in wooded drainage basins. The seasonal trends of nitrate concentrations and the concentration patterns during storm events are explained with reference to several models.

Comparaison de la qualité de l'eau des ruisseaux dont les bassins versants sont utilisés par l'agriculture ou les forêts

RESUME Depuis 1975, des recherches sur la qualité de l'eau de petits ruisseaux sont effectuées dans une région au nord du barrage de Eder. Les bassins versants de ces ruisseaux sont utilisés de différentes façons. Le point capital de ces recherches est la comparaison des pertes de substances nutrives pour les végétaux entre les exploitations agricoles et forestières. La perte totale de phosphore est plus élevée dans les bassins versants utilisés pour l'agriculture que dans les régions forestières. Ceci est dû au fait que les crues avec écoulement de surface sont plus fréquentes dans les régions d'exploitations agricoles. Par contre, les concentrations d'ortho-phosphate dépendent plutôt de la capacité d'absorption du sol et du substratum géologique que de l'utilisation des terres. Les eaux des bassins versants d'exploitations agricoles ont incontestablement une plus haute concentration en nitrates que les eaux des régions forestières. On explique à l'aide de différents modèles les changements saisonniers de la concentration de nitrates ainsi que la répartition des concentrations lors des crues.

INTRODUCTION

In recent decades, the quality of waters in central Europe has deteriorated considerably causing enormous problems for drinking and industrial water supplies. At first, the main problem was that of eutrophication by phosphorus, but today the magnitude of nitrate concentration in water is becoming much more important. High nitrate levels can represent a health risk, and an increase of nitrate content has been detected in many water treatment plants.

Phosphorus and nitrate are the main plant nutrients and are applied in high quantity in agricultural areas through different types of mineral fertilizer and organic manure. The extent to which agricultural land use is responsible for water pollution therefore represents a longstanding question, and in order to resolve it, investigations have been undertaken in drainage basins with both agricultural and forest land use.

STUDY AREA

Since 1975, water quality investigations have been undertaken at several measuring stations located in sub-basins of the Reiherbach basin, which drains into the Eder Reservoir (Fig.1). In order to compare the quality of waters from agricultural and wooded areas, five of the streams were selected for investigation in this study. Three of these basins drain only agricultural land (A-streams), one drains a mainly wooded area (F-creek), and in the remaining basin (AF) the land use is equally divided between forest and agriculture. In addition, a spring in a wooded area was chosen for study. The area of the drainage basins ranges from 0.75 to 1.25 km^2 (Table 1).

Geologically, the area of investigation is underlain by strata of Unterer Buntsandstein (su), which is the lower unit of the Lower Triassic and is partly covered with loess. In this unit, the Korbach sequence contains more siltstone and claystone than the overlying Waldeck sequence which has a higher content of coarse-grained sandstone. Soils in the study area consist predominantly of various sub-types of Brown Earth. In addition to Pseudogley-Brown Earth soils, Pseudogley soils have also developed locally (mostly on gentle slopes). Gley soils are found in the lower broader valleys and originate from colluvial and fluvial sediments and high groundwater levels.

METHODS

In the study area three weather stations were set up and were equipped with a raingauge (Hellmann), a rain recording gauge and a hygrothermograph. The discharge of the five streams is measured with triangular weirs (Thompson) in conjunction with water-stage recorders. Runoff from the F-creek and the forest spring is measured using pails, and water samples are collected at the same time. Stream water samples are taken weekly to determine the following parameters: ortho-phosphate, total phosphorus, suspended

TABLE 1 Morphometric characteristics of the study basins

Stream	Abbreviation	Area (ha)	Land use %			Abbreviation for land use character	Mean slope (%)	Range of slopes (%)	Average slope of the main channel (%)
			Arable land	Grassland	Forest				
Vogelgraben	Vo	125	60	38	2	A	8	1-30	2.8
Sachsengraben	Sg	95	42	58	-	A	8	1-25	3.4
Saubach	Sb	75	60	25	15	A	9	1-30	3.2
Erleborn	Er	76	22	30	48	AF	16	3-45	3.6
Hünenburggraben	Hb	109	9	11	80	F	18	3-45	4.1

TABLE 2 Chemical characteristics (mean values) of the study streamwaters

Stream water	Chloride ($mg\ l^{-1}$)	Sulphate ($mg\ l^{-1}$)	Water hardness caused by carbonates ($°dH \hat{=} 0.357\ mval\ l^{-1}$)	Water hardness (°dH)	Sodium ($mg\ l^{-1}$)	Potassium ($mg\ l^{-1}$)	EC ($\mu S\ cm^{-1}$.20°C)
Vogelgraben	19.9	37	6.8	10.2	7.9	2.0	357
Sachsengraben	25.9	41	11.5	15.1	8.3	1.8	501
Saubach	20.5	37	9.1	12.6	7.5	1.9	412
Erleborn	16.0	35	3.9	6.8	8.5	2.5	256
Hünenburggraben	14.8	42	2.5	5.1	8.0	2.0	208
Quelle Selbach	16.0	38	16.1	18.7	7.5	1.8	574

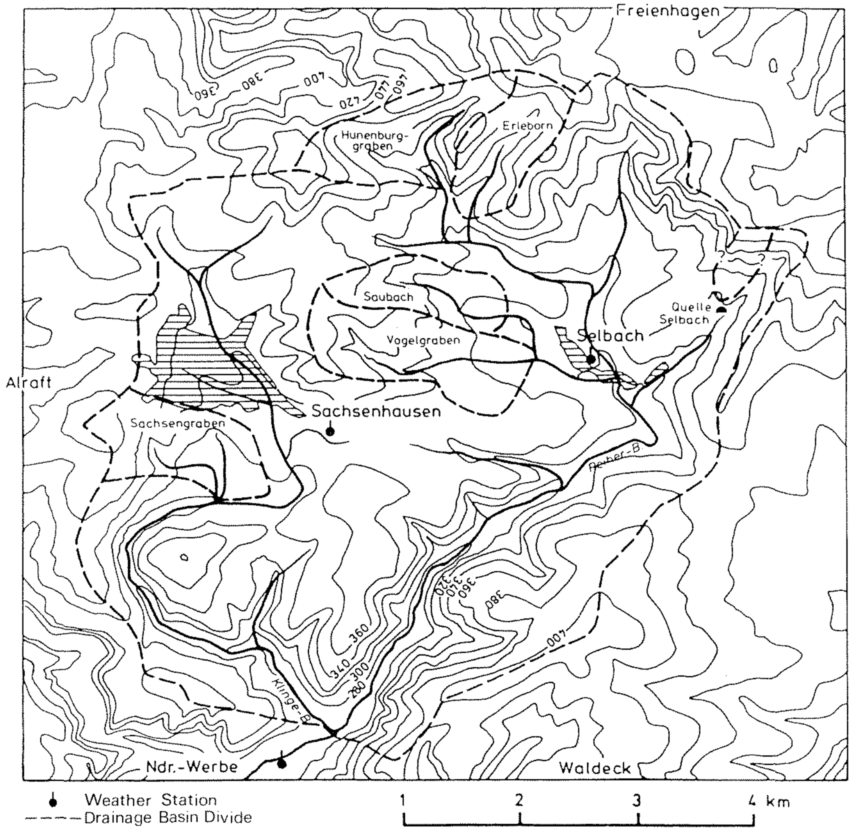

FIG.1 The study area.

material, $KMnO_4$-demand, nitrate, ammonia, chloride, sulphate, sodium, potassium, calcium, magnesium, water hardness, water hardness caused by carbonates, EC and pH. An automatic water sampler in use at the Saubach gauging station since the spring of 1981 collects samples at 15, 30, 60, 120 or 180 min intervals when the stream stage exceeds a preset threshold level during storm events.

RESULTS AND INTERPRETATION

Weathering and runoff during the study period

During the seven years of investigation there have been both very dry and wet years. The water year of 1976 (November 1975-October 1976) was very dry and warm, whereas in the water years 1977-1980 the annual precipitation was in general close to the average annual value but the summers of these years were colder than average. In the water year 1981, the annual precipitation was higher than average and rainfall was especially frequent in the summer months. In the water year 1982 the annual precipitation remained lower than average, but temperatures in the summer and early autumn months were exceptionally high (Fig.2). High discharge levels have characterized water years since 1979. During the snowmelt following the winters 1978/1979 and 1979/1980 when the snow cover was very thick, extraordinarily high peaks of discharge occurred. Both precipitation and annual runoff during the water year 1981 were the highest of the investigation period, but in the dry and warm conditions of the water year 1982 runoff decreased (Fig.2).

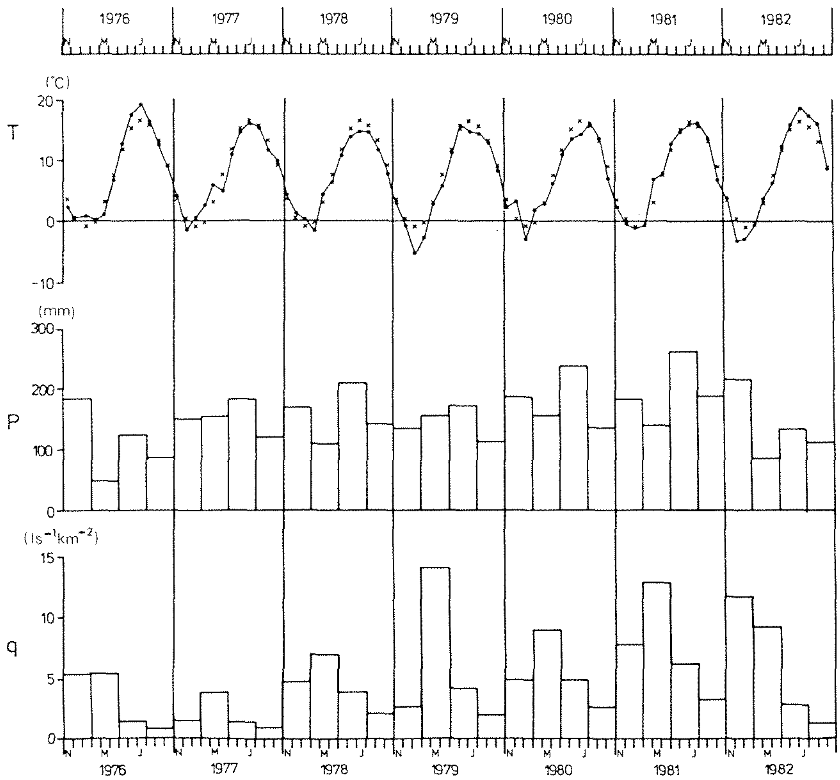

FIG.2 Monthly temperatures (long period averages denoted by crosses), quarterly precipitation and quarterly discharge of the Vogelgraben stream during the study period.

Hydrochemical characteristics

With regard to the hydrochemical content, the six streamwaters can be divided into two groups. The three A-streams and the forest spring belong to the first group and have drainage basins underlain by the Korbach sequence (suK), which has a higher content of Ca and Mg than the layers of the Waldeck sequence. EC values of the suK-waters therefore range from 350 to 580 $\mu S\ cm^{-1}$ and are higher than those of the two streams (200-260 $\mu S\ cm^{-1}$) in drainage basins underlain by the Waldeck sequence (suW) (Table 2). The Na and K concentrations of the six stream waters do not differ a great deal, but the Ca and Mg concentrations do vary, and the alkaline earth metals account for a greater proportion of the cation content in suK-waters than in suW-waters (Fig.3). Bicarbonate is the dominant anion, but accounts for a smaller proportion of the anion content in suW-waters than in suK-waters. Sulphate concentrations exhibit only a small difference between the six stream waters (35-42 mg l^{-1}), whereas chloride concentrations of the three A-waters are higher (20-25 mg l^{-1}) than those of the two F-waters and the AF-water (*c.* 15 mg l^{-1}). Klett (1965) regards chloride concentration as a measure of the intensity of fertilizer application in a drainage basin, and this view is supported by the present investigation.

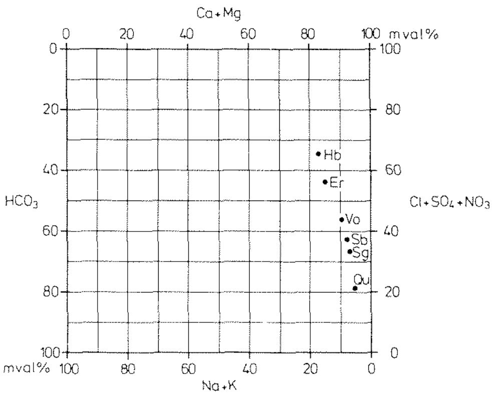

FIG.3 Anion-cation-diagram for the six study stream-waters.

Phosphorus behaviour

Since total phosphorus concentrations are largely determined by the content of suspended material, high total phosphorus levels occur in flood events. During dry weather flow suspended load mainly originates from eroded bed material. During flood events additional eroded material enters the stream in overland flow and by the erosion of bank slopes. Part of the phosphorus associated with the soil material dissolves causing an increase in ortho-phosphate concentrations. An example of these relationships is evident in Fig.4 which illustrates the variation of runoff, suspended material content and total phosphorus and ortho-phosphate concentrations during a storm event in June 1981 in the Saubach stream (Göttlicher, personal communication). The more soil transported as suspended material, the higher the total phosphorus and even the ortho-phosphate concentrations, and land use which favours soil erosion, therefore increases the loss of phosphorus. Streams with a high percentage of agriculture in their drainage basins and a relatively high channel slope in the lower course have the highest total phosphorus and the highest particulate and organic phosphorus concentrations (Table 3). These include the A-streams, Vo and Sg, which have average total phosphorus concentrations of about 170 µg P l^{-1} and average particulate and organic phosphorus concentrations of approximately 110 µg P l^{-1}. Particulate and organic phosphorus concentrations were calculated as the difference between total phosphorus and ortho-phosphate P. The

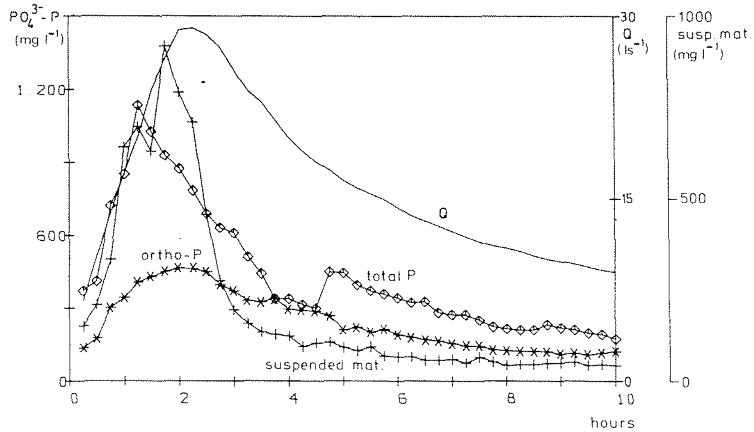

FIG.4 Hydrograph and concentration responses of orthophosphate, total phosphorus and suspended material during a storm event in the Saubach stream.

AF-stream, Er, also has a mean total phosphorus concentration of 170 μg P l^{-1}, of which about 80 μg P l^{-1} consists of particulate and organic phosphorus. The low channel slope in the lower reaches of the A-stream, Sb, is the main reason for the relatively low average level of particulate and organic phosphorous at 50 μg P l^{-1}. The lowest particulate and organic phosphorus concentrations are found in the F-stream, Hb, (mean *c.* 20 μg P l^{-1}) and the forest spring, Qu, (mean 11 μg P l^{-1}).

The ortho-phosphate content of low flows, which is not affected by the phosphorus associated with eroded soil material, has been determined and varies markedly between the three groups of streamwaters. The three A-streams (Vo, Sg, Sb) have higher ortho-phosphate concentrations (*c.* 15-40 μg P l^{-1}) than the forest spring (Qu) (6 μg P l^{-1}), but lower concentrations than the AF- and F-streams (Er and Hb) (*c.* 60-80 μg P l^{-1}). Less P-fertilizer is used in the latter two drainage basins than in the A-streams so that agricultural

TABLE 3 Phosphorus concentrations (μg P l^{-1}) in the study streamwaters

Streamwater	*Mean total phosphorus*	*Mean ortho-phosphate*	*Ortho-phosphate level during dry weather flow*
Vogelgraben	*157*	*57*	*20-40*
Sachsengraben	*177*	*56*	*15-30*
Saubach	*106*	*57*	*20-40*
Erleborn	*170*	*90*	*60-80*
Hünenburg-graben	*95*	*75*	*60-80*
Quelle Selbach	*17*	*6*	*-*

applications of P-fertilizers seem to have no definite influence on the ortho-phosphate level during low water flow. It appears that the potential for phosphate precipitation and solution and the absorption and desorption potential of the soils and the parent rocks in a specific drainage basin determine the ortho-phosphate concentration of the water. Most important for the P-balance in most soils of central Europe, according to Scheffer & Schachtschabel (1976), is the absorption of phosphate by Fe and Al oxides and hydroxides, which largely cover the surface layer of clay minerals. The absorption capacity of these oxides and hydroxides increases with falling pH values. Furthermore, phosphate can be made less available through combination with Ca to form Ca-phosphates which have a different bond strength. The higher the pH, the lower the solubility of the different types of Ca-phosphate. Moreover, an increase in Ca content in the soil leads to an increase in pH value. The Ca content is low in the coarse grained, clay deficient soils of the adjacent Er and Hb drainage basins. In consequence, a considerable amount of phosphorus may not be bonded. The soil content of Fe and Al oxides and hydroxides is relatively small because of the clay deficiency, so that no large amount of phosphate can be absorbed. These conditions are responsible for relatively high ortho-phosphate levels in low water flows of both AF- and F-streams (Er and Hb). The Ca as well as the clay content, and therefore the content of Fe and Al oxides and hydroxides, is higher in the soils of the A-stream drainage basins. As a result, lower ortho-phosphate concentrations occur in baseflows, despite greater application of P-fertilizers. The reasons for lower ortho-phosphate concentrations in the forest spring (Qu) may lie in the relatively high Ca and clay content in the soil of the drainage basin, and in the long flow paths and the long contact time of groundwater which appears in the spring.

Nitrate behaviour

Nitrate is the most important nitrogen compound in the unpolluted waters of central Europe. In comparison, ammonia occurs only in very low concentrations, and in the six waters investigated average values range from 0.02 to 0.08 mg N l^{-1}. Ammonia concentrations usually increase during storm events, and peak concentrations can reach as high as 0.7 mg N l^{-1}. The mean nitrate concentrations for the three A-waters (Vo, Sg, Sb) and the AF-water (Er) can be calculated at approximately 5 mg N l^{-1}, whereas those of the F-water (Hb) and the forest spring (Qu) reach only *c.* 2 mg N l^{-1}. (Table 4). The annual trend of nitrate concentration at the spring (Qu) exhibits little fluctuation, but the lowest concentrations at the five streams occur generally during minimum flow conditions, when discharge consists almost solely of groundwater. Maxima for nitrate concentrations are observed during storm events, which are more frequent in winter months. In general, nitrate levels are higher in the winter half of the year than in the summer months.

These results and investigations at springs and drains in the study basins definitely show that nitrate concentrations are higher in drainage from agricultural areas than from forest areas which are not treated with fertilizer. However, large differences in nitrate levels are also apparent between springs and drains within agricultural

TABLE 4 Nitrate concentrations (mg N l^{-1}) in the study streamwaters

Streamwater	*Mean*	*Maximum value during a storm event*	*Minimum level*
Vogelgraben	*5.6*	*10.9*	*3.5-5.0*
Sachsengraben	*4.8*	*10.8*	*2.5-4.0*
Saubach	*5.2*	*11.8*	*2.0-2.5*
Erleborn	*5.5*	*10.2*	*3.0-4.5*
Hünenburggraben	*2.4*	*5.8*	*1.3-1.8*
Quelle Selbach	*2.1*	-	-

areas. The nitrate concentrations of springs and drains in grassland areas range from 3 to 5 mg N l^{-1}, whereas those in arable land vary from 6 to 14 mg N l^{-1}, and topographic and associated pedological conditions are responsible for these differences. Arable land is generally characteristic of low slopes and plateaus on the margins of the drainage basins, and the conditions for nitrification and nitrate displacement in the soils are better in these areas because of favourable air and water regimes. Grassland is mainly found on flat areas near to river channels, where groundwater influences the soil. The air and water regimes of these Gley soils on the valley floors, which generally have a high clay content, leads to conditions where denitrification occurs more frequently, and this accounts for low nitrate concentrations in runoff. The land use distribution is also an important influence on the occurrence of high nitrate levels in winter. The runoff from the arable land, which tends to drain more quickly, has a higher nitrate content than that of the grassland on the valley floor, which drains more slowly and evenly. In consequence, a greater proportion of the discharge comes from arable land in winter than in summer, and this promotes higher nitrate levels in the winter period.

It is of particular interest to investigate the trend of nitrate concentrations during storm events, since it is in these conditions that the most notable variations in concentrations take place. Figure 5 illustrates for a storm in the Saubach basin that nitrate concentrations increase from a low level, reach a maximum after the peak discharge and then slowly decline. The same trend in nitrate concentrations during storm events has been observed both by Walther (1979) in the plains at the foot of the Harz Mountains and by Grünwald & Wernecke (1982) in the drainage basin of the Saidenbach Reservoir near Dresden. This nitrate behaviour may be explained by assuming different nitrate loadings for the three runoff components of overland flow (Q_O), interflow (Q_I) and groundwater flow (Q_G) which occur in sloping areas. It is known through water quality investigations of overland flow, that the nitrate concentration in this runoff component may increase at the beginning of a storm event, but then falls rapidly to reach levels typical of precipitation (Preuss, 1977; Sokollek & Süssmann, 1979). Since nitrogen and nitrate are generally found in greatest quantities in the upper layers of a soil profile, it

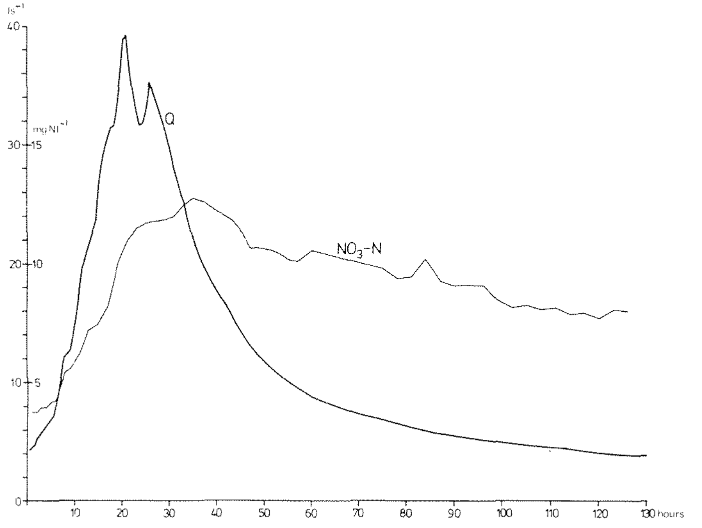

FIG.5 Hydrograph and response of nitrate concentration during a storm event in the Saubach stream.

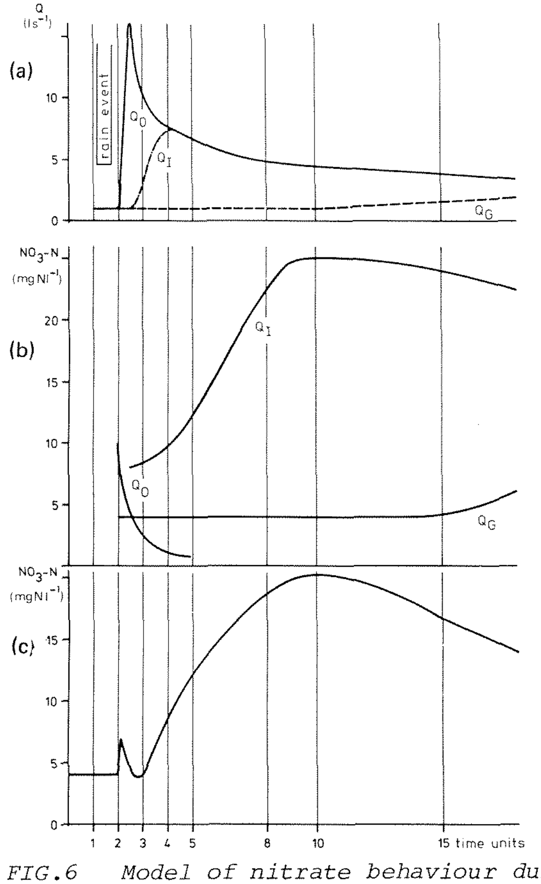

FIG.6 Model of nitrate behaviour during a storm event, (a) runoff components, (b) response of nitrate concentration in individual flow components, (c) response of nitrate concentration in total runoff.

can be assumed that there are higher nitrate concentrations in interflow (Q_I) compared with groundwater flow (Q_G). Because subsurface runoff in hilly regions flows both laterally and vertically, the nitrate which is accumulated through fertilizer application and/or mineralization in the upper soil layers is not only transported quickly to the river channel in interflow, but also is removed by infiltration and after a certain time lag it appears in the main channel by groundwater flow at lower concentrations. The nitrate concentrations of the interflow (Q_I) are therefore generally higher than those of the groundwater flow (Q_G) and even those of the overland flow (Q_O). Consequently, the peak in nitrate concentration occurs when the heaviest nitrate loaded interflow (Q_I) dominates the hydrograph. Based upon these considerations a nitrate model, illustrated in Fig.6, has been developed (Süssmann, 1980).

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