

Impact of nitrogen fertilizers on the natural weathering-erosion processes and fluvial transport in the Garonne basin

Khadija Semhi, Philippe Amiotte Suchet¹, Norbert Clauer, Jean-Luc Probst

Centre de Géochimie de la Surface, CNRS/Université Louis Pasteur, Ecole et Observatoire des Sciences de la Terre, 1 rue Blessig, 67084 Strasbourg, France

Abstract

Knowledge of the impact of N-fertilizers on the weathering-erosion processes of soils in intensively cultivated regions is of prime importance. Nitrification of NH_4^- fertilizers produces HNO_3 in the basin of the Garonne river, enhancing soil degradation. Their influence on the weathering rates was determined by calculating the consumption rate of atmospheric/soil CO_2 by soil weathering and erosion, and its contribution to the total dissolved riverine HCO_3^- . This contribution was found to be less than 50% which corresponds normally to a complete carbonate dissolution by carbonic acid, suggesting that part of the alkalinity in the river waters is due to carbonate dissolution by an acid other than carbonic acid, probably HNO_3 .

1. Introduction

In recent years, pollution by NO_3 leaching from agricultural land has become an important concern (Gray et al., 1978; Etchanchu and Probst, 1988; Postma and Boesen, 1991; Goolsby and Battaglin, 1993), because of potential pollutions of surface and ground waters (Korom, 1992; Lacroix, 1993; Battaglin et al., 1994). This pollution includes spreading of N-fertilizers, mismanagement of irrigated crops, disposal of livestock waste (Hallberg, 1989) and cultivation of virgin land (Ronen et al., 1988). Many studies examined specifically the relationships between land use in

drainage basins and N export by river waters and the origin of N (Behnke, 1975; Mariotti et al., 1975; Mariotti and Létolle 1977; Caussade et al., 1984; Collin et al., 1984; Probst, 1985; Blaison et al., 1985; Mariotti, 1986). Positive correlations were reported between (1) N loadings in river waters and demographic indices of various countries (Meybeck, 1982; Peierls et al., 1991), (2) N loss from agricultural land areas and N increase in surface waters (Omernik, 1976; Vagstad et al., 1997) and (3) application of fertilizers and N levels in stream waters (Smith, 1977). Hoyas et al. (1997) showed that approximately 85% of the total supply of N to a catchment area relates to agricultural activities, of which application of mineral fertilizers alone contributes 65–70%.

Nitrate can be produced from NH_4 in the presence of O_2 (is nitrification by autotrophic bacteria), or can be reduced to N_2O or N_2 in the absence of O_2 (is deni-

¹ Present address: Laboratoire Géosol, Centre des Sciences de la Terre, Université de Bourgogne, 6 Boulevard Gabriel, 21000 Dijon, France.

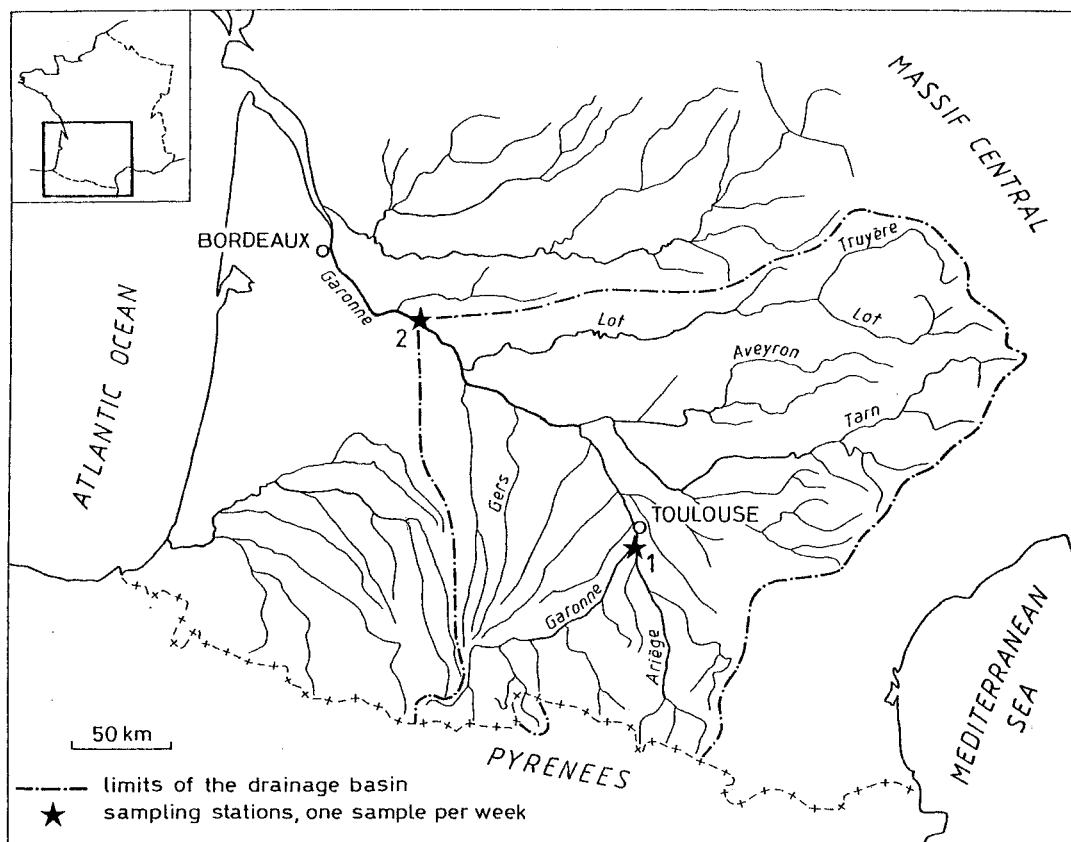


Fig. 1. Geographical sketch of the Garonne drainage basin with location of the two sampling stations.

trification). These two processes can take place simultaneously within a soil profile depending on the local O_2 fugacity (Reddy et al., 1976), nitrification releasing protons which may contribute to carbonate dissolution. Khdyer and Cho (1983) noted that the production rate of NO_3^- decreases with soil depth, as the microbial activity, organic matter content and partial pressure of O_2 decrease.

The study of the chemical composition of the Garonne river water from 1971 to 1984 by Etchanchu and Probst (1988) showed that the evolution of Ca^{2+} , Mg^{2+} and HCO_3^- cannot be related to a readjustment of the calcite equilibrium since the coefficient of calcite saturation for the water fluctuates around equilibrium. This can be explained by protons released during carbonate dissolution (Faurie, 1977; Durand and Dutil, 1972; Yanagita, 1990) from nitrification of N-fertilizers. The main objective of this study is to determine the effect of N-fertilizers on weathering-erosion processes, more specifically on the carbonate dissolution in the Garonne basin. The new aspects addressed here are (1) a regular measurement of the dissolved NO_3^- concentrations in the Garonne waters over a 3-a

period (one sample a week), and (2) a study of the relationship between the NO_3^- concentrations and the proportion of weathering-related CO_2 consumption as reflected in the dissolved HCO_3^- concentration.

2. Physical and hydrological setting of the Garonne basin

The city of La Réole located about 100 km to the south of Bordeaux in southwestern France, marks the outlet of the Garonne-river drainage basin. The drained area of 52,000 km^2 includes most of the Aquitaine basin which is bounded by the highlands of the Massif Central to the north-east, the Pyrénées mountains to the south and the Atlantic ocean to the west (Fig. 1). The Massif Central consists mainly of carbonate-rich marine sediments mostly of Jurassic age, as well as of Tertiary and Quaternary volcanics. The pre-Jurassic schists, gneisses and granites of the Pyrénées mountains were thrust under Mesozoic marine limestone about 40 Ma ago during the Alpine orogeny. The crystalline core of the Pyrénées mountains also

includes Precambrian granites. The floor of the Aquitaine basin was flooded several times during the Oligo-Miocene by the westerly ocean. Each retreat of the marine waters was followed by lacustrine–fluvial deposits of limestones and of molasses above carbonates in transitional continental environments (Bourgeat et al., 1984).

During the study period (1989–1992), the yearly discharge of the Garonne river ranged between 52 and 4790 m³ s⁻¹, averaging 403 m³ s⁻¹ at La Réole (station 2 on Fig. 1). The upstream Garonne river and the Ariège tributary together supply about 32% of the total Garonne discharge at the basin outlet, whereas tributaries draining the Massif Central contribute 62%, and small rivers draining the Molasse in the center of the basin contribute the remaining 5–6%. The study period is recognized to be a drought period: when compared to the interannual discharge from 1910 to 1992, the average discharge of the study period shows a deficit of 25% in the upper drainage basin, and of 34% in the whole Garonne basin. The most important hydrological deficit was observed in 1989.

3. Methodology

3.1. Sampling and analytical methods

The Garonne river was sampled weekly at two stations during the 1989–1992 period, one of which is located upstream (at Portet, station 1 on Fig. 1) that is influenced by drainage from the Pyrénées mountains and the other is located downstream (at La Réole, station 2 on Fig. 1) being influenced by the whole basin (Fig. 1). The measured discharges were made available by the ‘Service Hydrologique Centralisateur’ (Toulouse) by the speed exploration method and by jaugeage. The speed exploration method consists in measurements of runoff volumes at a given section in the basin along a vertical and by integrating the volumes along the section between the bottom and surface of the stream, allowing determination of an average discharge in m³ s⁻¹. The jaugeage method is based on the tarage curve. The samplings were made in order to follow the interannual variations of the major dissolved elements (Semhi, 1996), and to quantify the amounts of atmospheric/soil CO₂ consumed by rock weathering. The water samples collected in polyethylene bottles, were pressure filtered through a Millipore HAWP 047-00 filter of 0.45 μm pore size, consisting in an ester of cellulose (nitrate + acetate) filter. The major cations (Ca²⁺, Mg²⁺, Na⁺ and K⁺) were analyzed by atomic absorption on a Z 8200 spectrometer with an air–C₂H₂ gaseous mixture. La was added (0.5%) to the sample for Ca²⁺ and Mg²⁺ analyses. These

Table 1

Ratios (in eq eq⁻¹) between dissolved elements and Cl⁻ in atmospheric precipitation (Meybeck, 1986)

C _i	Na ⁺	K ⁺	Mg ²⁺	Ca ²⁺	HCO ₃ ⁻	SO ₄ ²⁻
C _i /Cl ⁻	0.850	0.018	0.190	0.037	0.004	0.100

measurements were made with an accuracy of 1 μmol L⁻¹. The major anion (NO₃⁻, Cl⁻ and SO₄²⁻) concentrations were determined by liquid-ion chromatography on a Dionex chromatograph 4000I equipped with columns AG11 and AS11 and NaOH as eluant. The detection limit was 1 μmol L⁻¹. The HCO₃⁻ concentrations were measured by alkalimetric titration with H₂SO₄. The total analytical precision varies between 1 and 2%.

3.2. Calculations of the Garonne river fluxes

The fluxes were calculated on the basis of following equation:

$$Fa = \sum_{i=1}^n C_{im} \times Q_{im},$$

where Fa is the annual flux (in kmol), *n* the number of measurement periods (in weeks), *Q_{im}* the weekly discharge (in m³ s⁻¹), and *C_{im}* the weekly discharge-weighted mean of the concentration (in mmol L⁻¹) calculated as follows:

$$C_{im} = \frac{C_1 Q_1 + C_2 Q_2}{Q_1 + Q_2}$$

where *C₁* and *C₂* are the instantaneous concentrations (in mmol L⁻¹) of the first and last sample, respectively, during each measurement period, and *Q₁* and *Q₂* are the corresponding discharges (in m³ s⁻¹).

3.3. Corrections for atmospheric inputs

The contribution of the atmospheric input to the amounts of the major dissolved elements was estimated on the basis of the ratio between the concentrations of the dissolved elements *C_i(p)* and the chlorides *Cl(p)* in precipitation (Meybeck 1986; Table 1). The mean Cl⁻ concentration in the atmospheric precipitation over the Garonne basin was estimated by using the decrease of Cl⁻ concentrations measured in precipitation at several stations in France (Ulrich et al., 1994), relative to the distance of the sampling location (*d*) to the ocean (Fig. 2). The corrected concentrations from atmospheric input *C_{i(f)cor}* can be estimated as follows:

$$QC_{i(f)cor} = QC_{i(f)} - PC_{i(p)}$$

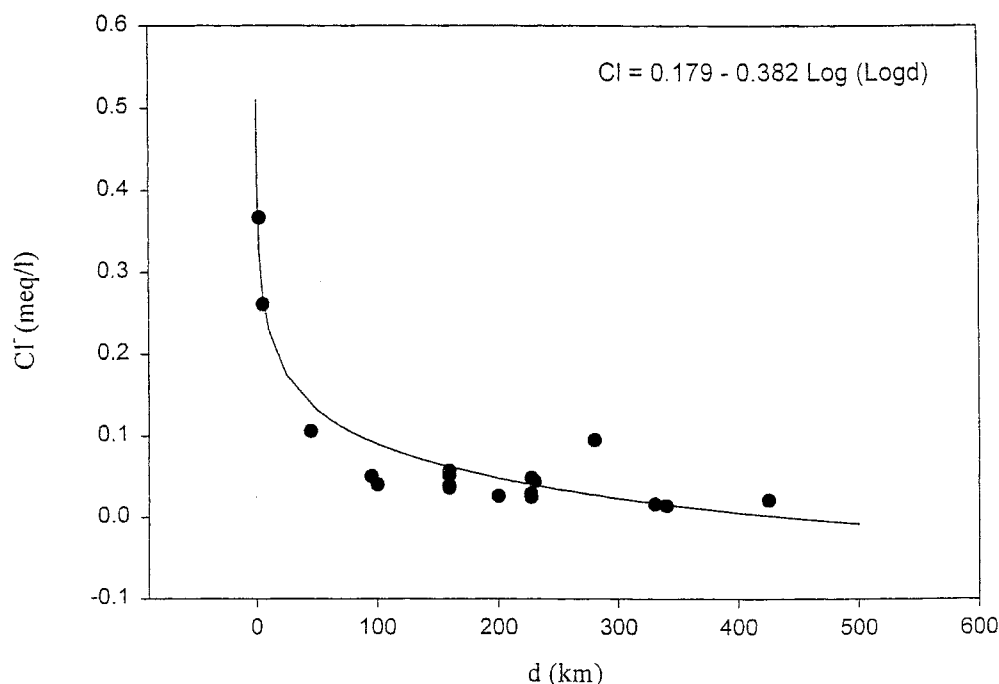


Fig. 2. Relationship between Cl^- concentrations (in meq L^{-1}) in precipitation and distance (in km) to the Atlantic coast.

$$C_{i(f)\text{cor}} = C_{i(f)} - \frac{P}{Q} C_{i(p)},$$

where $C_{i(f)}$ is the observed concentration of the dissolved elements, $C_{i(p)}$ the concentration of the same elements dissolved in precipitation P calculated on the basis of the above mentioned ($C_{i(p)}/C_{i(p)}$) ratio, Q (in $\text{L km}^{-2} \text{s}^{-1}$) the annual mean discharge and P (in $\text{L km}^{-2} \text{s}^{-1}$) the annual mean precipitation. The precipitation P were estimated by using the regression between the mean annual discharge Q_s (in $\text{L km}^{-2} \text{s}^{-1}$) and the annual precipitation P (in cm) in the Garonne basin, on the basis of following regression:

$$Q_s = 0.034 P - 19.5.$$

3.4. CO_2 flux consumed by chemical weathering: the code MEGA

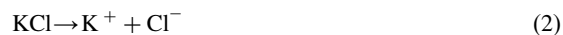
The amount of atmospheric/soil CO_2 consumed by chemical weathering was estimated from HCO_3^- ion fluxes measured in the waters and from major dissolved elements, by using the geochemical code MEGA (Amiotte Suchet, 1995; Amiotte Suchet and Probst, 1996) to calculate the contribution of the atmospheric CO_2 to the total exported HCO_3^- flux. The modeling procedure decomposes the major-element fluxes and it uses the stoichiometric dissolution or hydrolysis of the different minerals susceptible to react. It

allows, after correction of the atmospheric input of cations and anions, determination of the mineralogical origin of the major elements dissolved in the river waters. In the code, Na is supposed to be released by dissolution of halite (Eq. (1)) and Na-silicates (for example Eqs. (7) and (8)), Cl by dissolution of halite and sylvite (Eqs. (1) and (2)), K by dissolution of sylvite and orthose (Eqs. (2) and (6)), SO_4 by dissolution of gypsum (Eq. (3)), Ca by dissolution of gypsum (Eq. (3)), calcite (Eq. (4)) and Ca-silicates (Eq. (9)), Mg by dissolution of dolomite (Eq. (5)) and Mg-silicates (for example Eq. (10)). An illustration of the concept is given in Fig. 3. The different reactions involved are:

- halite dissolution



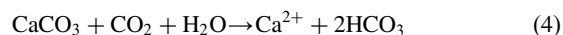
- sylvite dissolution



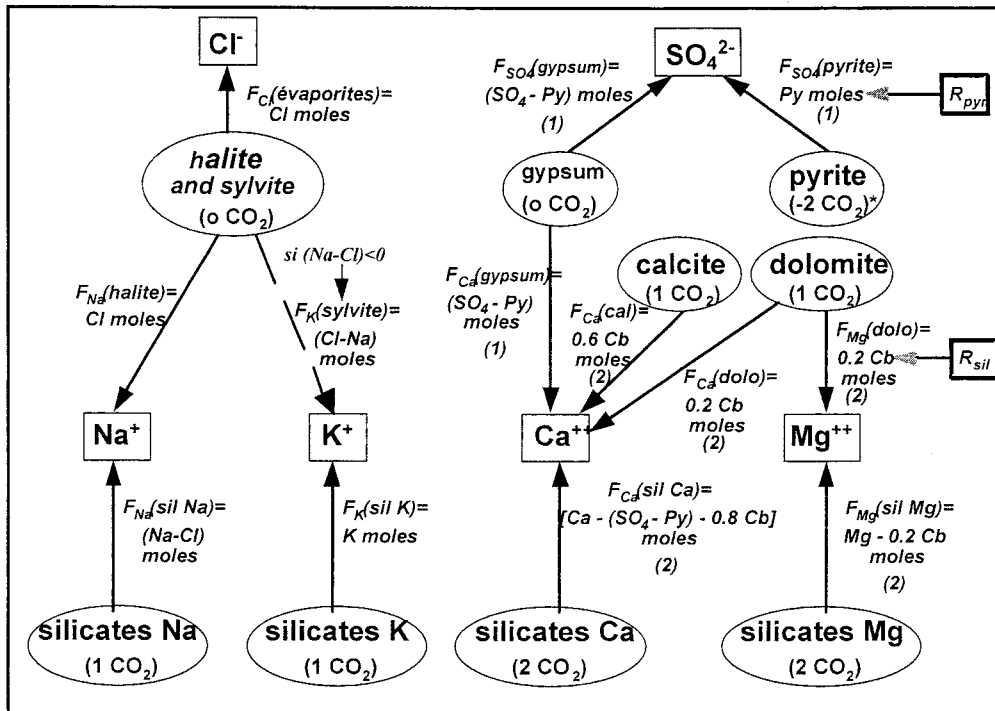
- gypsum dissolution



- calcite dissolution

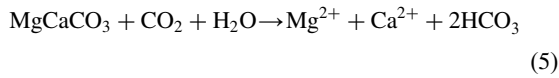


- dolomite dissolution

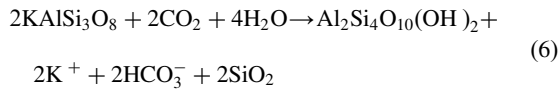


(1) $Py =$ molar flux of SO_4 produced by pyrite oxidation, $Py = R_{pyr}(Na+K+Cl)/(1/R_{sil}+1)$
 $R_{pyr} = SO_4/(Na+K+Ca+Mg)$ and $R_{sil} = (Na+K)/(Ca+Mg)$ is measured in waters draining silicate rocks
 (2) $Cb =$ molar flux of Ca and Mg derived from carbonate weathering;
 $Cb = Ca+Mg-(SO_4-Py)-1/R_{sil}(Na+K+Cl)$, $R_{sil} = (Na+K)/(Ca+Mg)$ is measured in waters draining silicate rocks

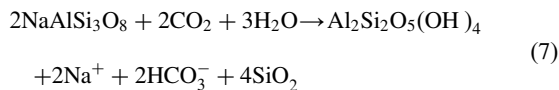
Fig. 3. Schematic concept of the MEGA code for the origins of the major dissolved elements relative to weathering of silicate, evaporitic and carbonate rocks (Amiotte Suchet and Probst, 1996).



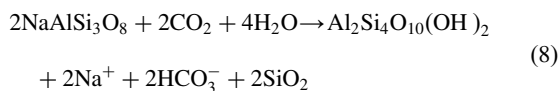
- hydrolysis of orthoclase to montmorillonite



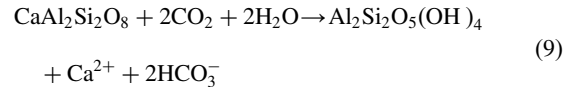
- hydrolysis of albite to kaolinite



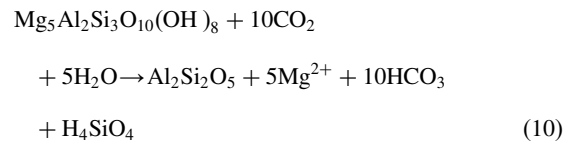
- hydrolysis of albite to montmorillonite



- hydrolysis of anorthite to kaolinite



- hydrolysis of chlorite to kaolinite



The flux of HCO_3^- contributed by carbonate dissolution ($F_{carb}HCO_3$) was calculated as follows:

$$F_{carb}HCO_3 = F_{Ca\ carb} + F_{Mg\ carb}$$

where $F_{Ca\ carb}$ is the amount of Ca released by dissolution of calcite, and $F_{Mg\ carb}$ the amount of Mg released by dissolution of dolomite. The flux of CO_2 (F_{CO_2}) is the difference between the total HCO_3^- ($F_T HCO_3^-$) measured in the waters of the Garonne river and $F_{carb}HCO_3$, as follows:

Table 2

Mean chemical compositions of the Garonne waters during the 1989–1992 period (in mmol L⁻¹)^a

Elements	Upstream (Portet)		Downstream (La Réole)	
	This study	P&B ^a	This study	E&P ^a
Na ⁺	0.192	0.174	0.348	0.304
K ⁺	0.032	0.026	0.051	0.051
Mg ²⁺	0.134	0.206	0.247	0.247
Ca ²⁺	0.982	0.848	1.047	1.197
NO ₃ ⁻	0.082	0.048	0.161	0.097
SO ₄ ⁻	0.164	0.125	0.187	0.198
SiO ₂	0.071	0.083	0.075	0.116
HCO ₃ ⁻	1.826	1.738	2.131	2.344
Cl ⁻	0.179	0.141	0.366	0.310

^a P&B stands for data by Probst and Bazerbachi (1986) during the 1980–1981 period, E&P for data by Etchanchu and Probst (1988) during the 1971–1983 period.

$$FCO_2 = F_t HCO_3 - F_{carb} HCO_3$$

4. Fluvial transport of nitrates

Under normal physico-chemical conditions encountered near the earth's surface, N compounds generally occur as NH₄⁺, NO₂⁻, NO₃⁻, dissolved organic N or particulate organic N in natural waters. Natural levels of dissolved N in rivers are very low, equivalent to 8.6 μmol L⁻¹ on average, of which only 15% are present as NH₃ and 1% as NO₂⁻ (Meybeck, 1982). Inorganic N dissolved in natural waters (N-NO₃+N-NO₂+N-NH₄) is estimated to be equivalent to 12.9 μmol L⁻¹ in the temperate zone, 6.5 μmol L⁻¹ in the tropical zone, 10 μmol L⁻¹ in the taiga and 2.2 μmol L⁻¹ in the tundra (Meybeck, 1982). The percentage of N-NH₄ ranges from a few percent to as much as 80%. Nitrite-N is never abundant in rivers, accounting for no more than 7% of the total dissolved inorganic N (Meybeck, 1982). The most important N species of surface waters are nitrates and organic N (Hutchinson, 1957). In the waters of the Seine river (central France), NO₃⁻ concentrations could be as high as 483 μmol L⁻¹ during winter and 241 μmol L⁻¹ during summer time (Greiner, 1997). Williams et al. (1995) noted NO₃⁻ concentrations of about 20 μmol L⁻¹ for the Emerald lake waters (southern Sierra Nevada, CA). Nitrates are soluble in water, but not significantly adsorbed by clay-rich soils. They may be picked up by plants or reduced into nitrites within the root zones in soils.

One of the most detailed study of the N budget in river waters was that of Bennekomp and Salomons (1981) who noted that man's activity has increased the N load by a factor of three to four. Probst (1985) com-

Table 3

Annual fluxes of dissolved elements exported by the Garonne river during the 1989–1992 period (kmol km⁻² a⁻¹)^a

Elements	Upstream (Portet)		Downstream (La Réole)	
	This study	P&B ^a	This study	E&P ^a
Na ⁺	80.43	126.52	83.91	121.74
K ⁺	12.53	16.11	14.32	15.35
Mg ²⁺	56.79	135.80	62.14	107.00
Ca ²⁺	401.25	587.03	267.33	496.26
NO ₃ ⁻	31.29	27.42	36.61	41.94
SO ₄ ⁻	68.47	82.31	46.10	83.25
SiO ₂	29.45	53.08	18.14	46.59
HCO ₃ ⁻	752.95	1189.34	537.05	967.21
Cl ⁻	86.48	93.80	90.99	132.39
TDS	1519.65	2311.42	1156.59	2011.72
Q (m ³ /s)	134	217	403	684

^a P&B stands for data by Probst and Bazerbachi (1986) during the 1980–1981 period, E&P for data by Etchanchu and Probst (1988) during the 1971–1983 period.

pared the amounts of nitrates exported by the Garonne river to the total amount of N-fertilizers and concluded that river exportations depend on both fertilizer inputs, and intensity of soil leaching which relates to the river discharge. In this study, the authors examined the global seasonal variations of NO₃⁻ fluxes without distinction between natural and anthropogenic origin.

4.1. Mean concentrations and annual fluxes of major dissolved elements

The mean annual concentrations and fluxes of the Garonne waters were estimated by Semhi (1996). During the 1989–1992 period, the concentrations of the major elements in the waters are within the range of concentrations of the elements in most surface waters. Like waters in many rivers, those in the Garonne river have Ca²⁺ as the major cation and HCO₃⁻ as the major anion (Table 2). The average NO₃⁻ concentrations were 82 and 161 μmol L⁻¹ NO₃⁻ at Portet and La Réole, respectively. Compared to results obtained during more humid cycles (+15 and +33% relative to the mean interannual discharge, for the upstream and downstream stations, respectively), the river transport of the soluble elements is less important for all elements during the study period than during the humid ones, except for the nitrates at Portet (Table 3).

4.2. Seasonal variations of NO₃⁻ concentrations

The seasonal variations of the NO₃⁻ concentrations

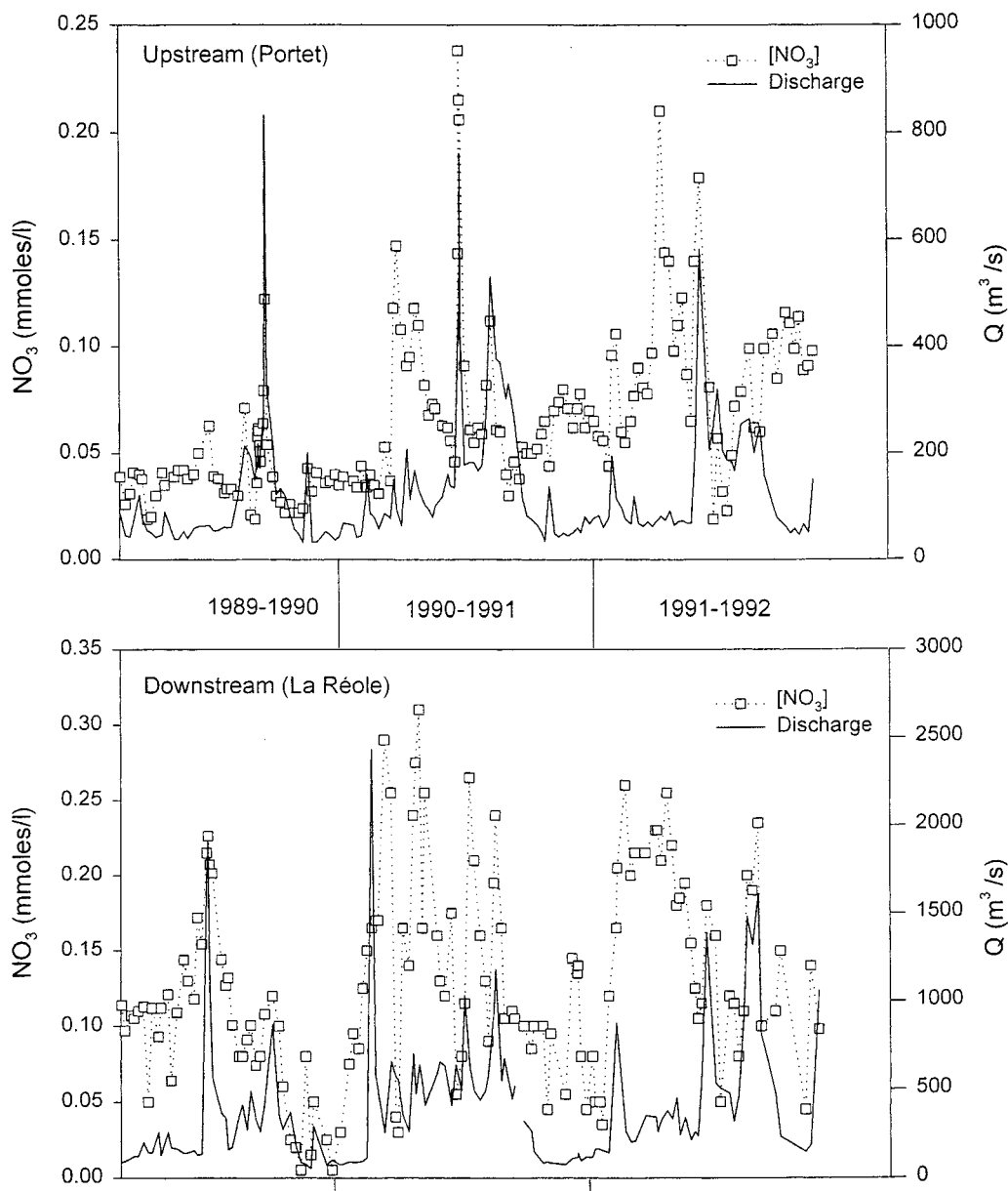


Fig. 4. Seasonal variations of daily discharge (dotted lines) and NO_3 concentrations (crosses and straight lines) in the waters of the Garonne river during the 1989–1992 period.

is marked by high concentrations during high-water periods (Fig. 4). This suggests that NO_3^- concentrations in the waters relate to removal of NO_3^- from soils, since fertilizers represent the main source of NO_3^- in this extensively farmed region. Seasonal distinctions emerge in the winter and spring periods during which NO_3^- concentrations increase most with increased discharge (Fig. 5). The NO_3^- concentrations vary widely during the summer for small discharge variations, suggesting that (1) the discharge does not significantly

influence the NO_3^- contents during this period of the year and (2) other factors, such as biological processes, affect them more significantly. Among these biological inputs, one may suggest that raising different types of crops around the year induces different N-uptakes and consequently different types of N-residuals in the soils. In addition, large variations in NO_3^- concentrations during summer could be induced by mineralization and nitrification processes increasing the NO_3^- contents in soils and subsequently enhancing NO_3^- removal by

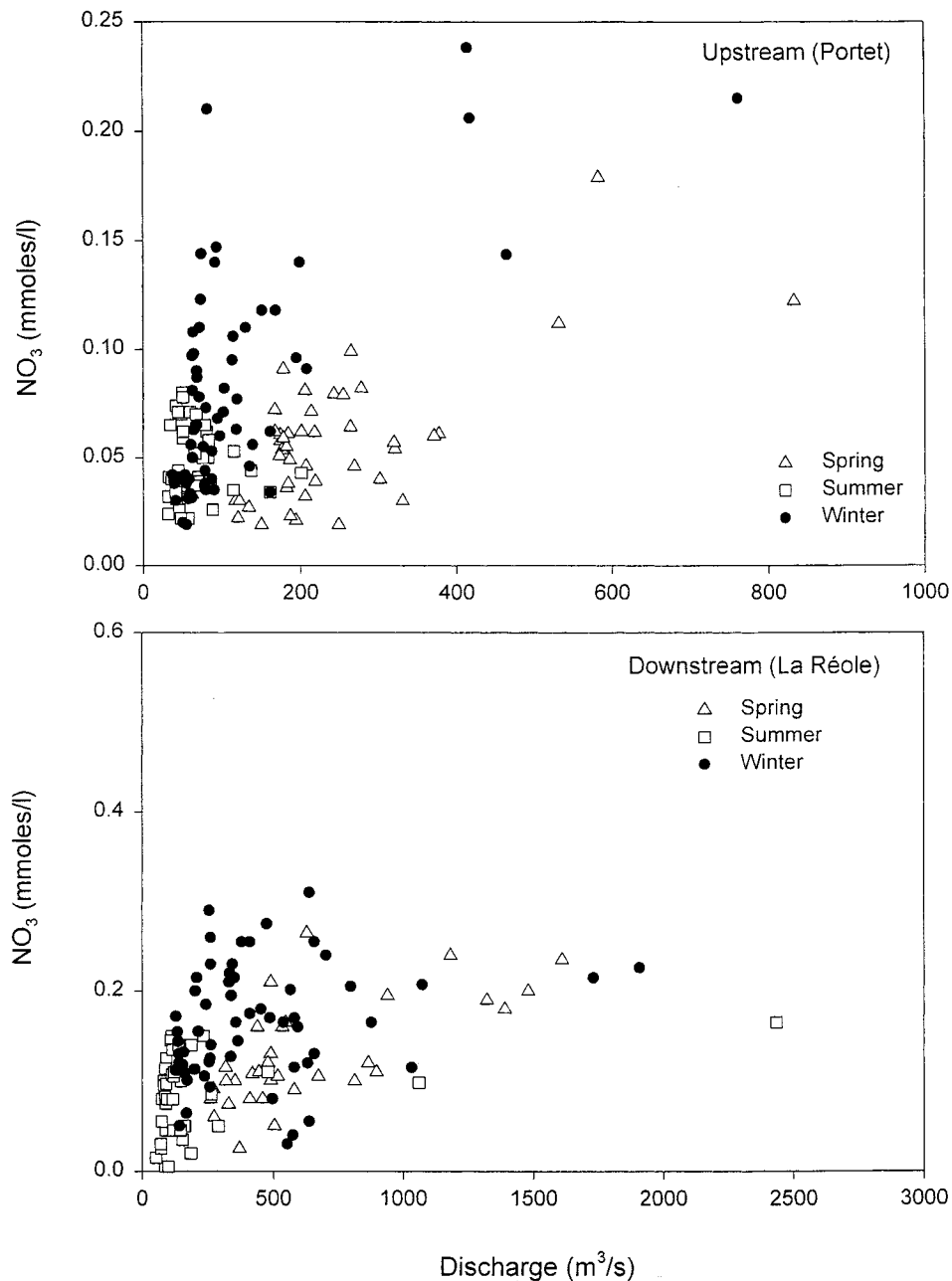


Fig. 5. Relationship between NO₃ concentrations (in mmol L⁻¹) in waters and discharge (m³ s⁻¹) measured during the 1989–1992 period.

running waters after rainfalls. Similar seasonal variabilities reported by Elder (1985) in the Apalachicola river (in northwestern Florida), were explained by variable rates of uptake and N-metabolism by microbiota activity during summer. Determine and Lamberts (1987) considered that nitrification of NH₄⁻ is a major source of NO₃ flux in the Belgian part of the Meuse

river during low discharge periods, especially in the waters having important NH₄ loads.

When the discharge is very high, the NO₃⁻ removed from soils is diluted by surface runoff waters that are less concentrated in nitrates. This observation reported by Foster (1981) can explain the small variations of the NO₃⁻ concentrations for large discharge variations

during winter and spring. During summer, however, ground waters become dominant suppliers to rivers. Ground waters transport dissolved nitrates, that are derived in varying amounts from decaying plants and agricultural fertilizers, and delivered to the river waters during summer.

4.3. Nitrate fluxes, concentrations and export rates

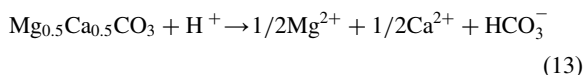
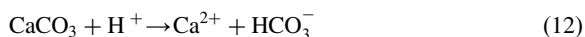
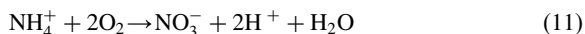
The NO₃ budget in the Garonne waters during the 1989–1992 period was estimated to be 31.3 kmol km⁻² a⁻¹ upstream and 36.6 kmol km⁻² a⁻¹ downstream. As already mentioned, the NO₃ load increases, while most other elemental loads decrease during the dry period. Calculation of the NO₃ fluxes from the Pyrénées mountains and Massif Central+Molasse region indicates that 4–59% of the measured nitrate flux at La Réole originates in the Pyrénées mountains. The highest contributions of the Pyrénées region occurred during spring and summer, which are also the periods of high discharge (Semhi, 1996). Best correlations between these two variables were also obtained during winter time.

Cooke and Williams (1970) reported that most agricultural soils contain from 107 to 429 kmol ha⁻¹ of organically bound N in their upper 150 mm. During this study, the NO₃ concentrations measured in the Garonne waters at Portet and La Réole, increased relatively to those measured by Probst (1985). The NO₃ concentrations increased by 78% at La Réole during the 1971–1984 period (Etchanchu and Probst, 1988), which was attributed to increased use of N-fertilizers, spreading having nearly doubled during the last 20 a in the Aquitaine basin (Probst, 1985).

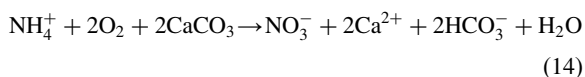
5. Weathering and consumed atmospheric/soil CO₂

The amount of atmospheric/soil CO₂ consumed by chemical weathering in a drainage basin can be estimated from HCO₃⁻-ion flux measured at the outlet of the basin. The contribution of atmospheric/soil CO₂ to the total river alkalinity reaches 100% in the case of silicate hydrolysis, according to the hydrolysis reaction of albite (Eqs. (7) and (8)). On the other hand, the contribution of atmospheric/soil CO₂ to the total river alkalinity may not exceed 50% in a drainage basin such as that of the Garonne river where carbonate outcrops are abundant, according to the stoichiometric coefficients of the calcite-dissolution reaction (Eq. (4)).

The transformation of inorganic or organic N to a more oxidized state releases protons (Eq. (11)) which may contribute to carbonate dissolution (Eqs. (12) and (13); Faurie, 1977; Yanagita, 1990). The equations of these two reactions are the following:



and the global equation becomes:



or

Table 4

Annual fluxes of dissolved HCO₃⁻, Ca + Mg and atmospheric CO₂ consumed by weathering^a

		Upstream (Portet)		Downstream (La Réole)	
		this study (1989–1992)	this study (1989–1992)	AS ^a (1971–1991)	E&P ^a (1971–1984)
HCO ₃ ⁻ (kmol km ⁻² a ⁻¹)	silicate	19	52	47	–
	carbonate	775	504	798	–
	total	794	556	845	802
Ca + Mg (kmol km ⁻² a ⁻¹)	silicate	136	57	30	–
	carbonate	369	258	434	–
	total	505	315	505	600
atmospheric CO ₂ (kmol km ⁻² a ⁻¹)	silicate	19	41	47	–
	carbonate	356	355	364	–
	total	375	269	411	441
Q	(m ³ s ⁻¹)	217	403	620	684

^a AS stands for data by Amiotte Suchet (1995) and E&P for data by Etchanchu and Probst (1988).

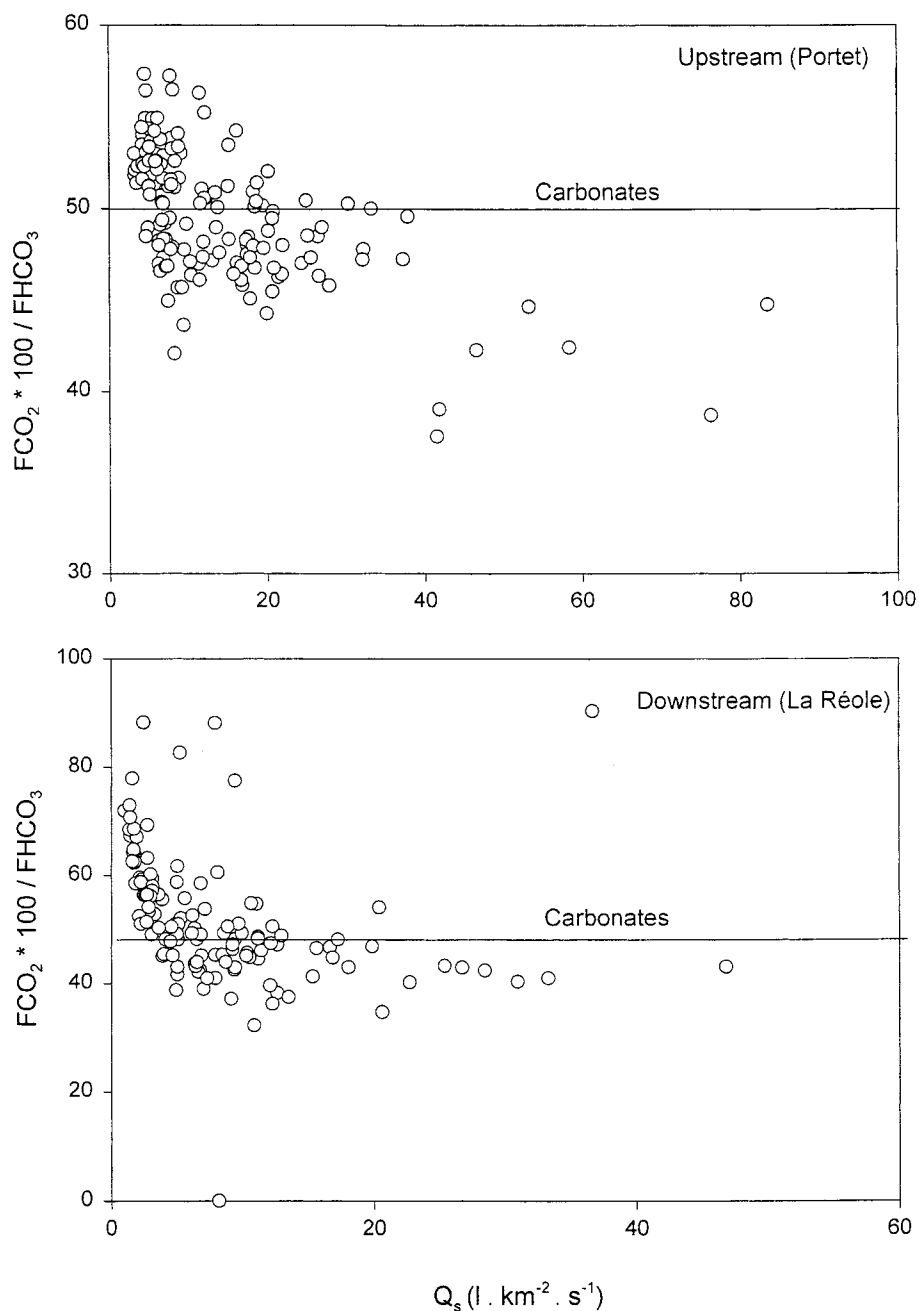
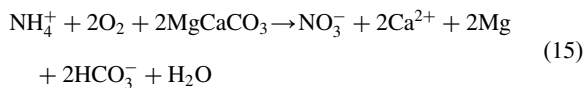


Fig. 6. Relationship between the contribution of atmospheric/soil CO_2 to the total river alkalinity and the Garonne river discharge (in $\text{L km}^{-2} \text{s}^{-1}$).



The observed flux in $\text{Ca} + \text{Mg}$ during the 1989–1992 period was estimated to be $505 \text{ kmol km}^{-2} \text{ a}^{-1}$ upstream and $315 \text{ kmol km}^{-2} \text{ a}^{-1}$ downstream (Table

4). About 73% of this flux comes from weathering of the carbonate rocks upstream and 82% from weathering of the same rocks downstream, leaving silicate rocks contributing only 27% of the total flux upstream and 18% downstream. On the other hand, the HCO_3^- flux comes mainly from weathering of the carbonate rocks: about $775 \text{ kmol km}^{-2} \text{ a}^{-1}$ were observed

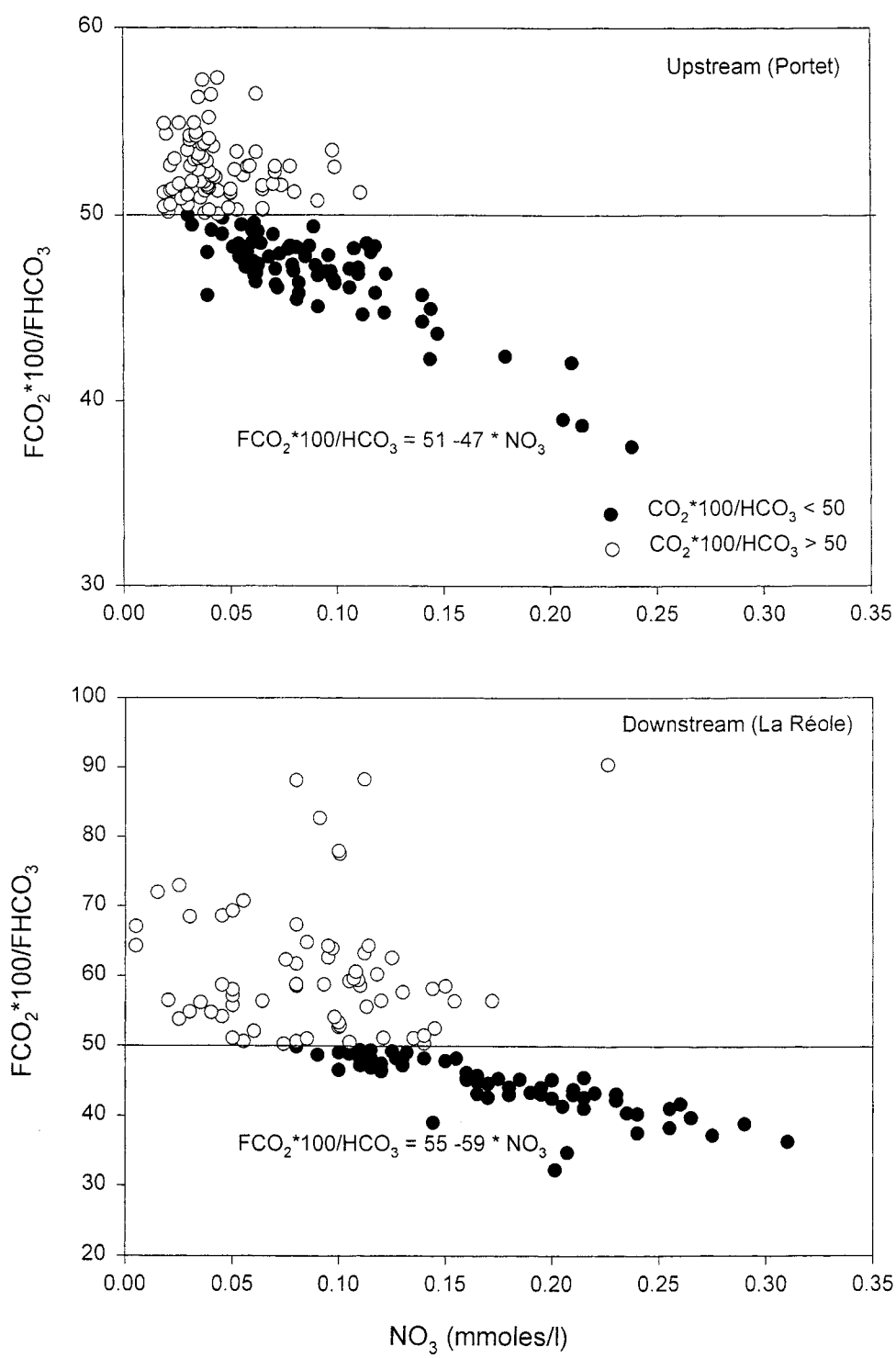


Fig. 7. Variations of the CO_2/HCO_3 ratio relative to NO_3 concentrations ($mmol L^{-1}$) in the Garonne waters during the 1989–1992 period.

upstream the Garonne river, and $504 \text{ kmol km}^{-2} \text{ a}^{-1}$ downstream (Table 4). The contribution of weathering of the silicate rocks to the total HCO_3^- flux is only $19 \text{ kmol km}^{-2} \text{ a}^{-1}$, or about 2.4%, upstream and $52 \text{ kmol km}^{-2} \text{ a}^{-1}$ or about 9.4%, downstream.

The relationship between the discharge and the ratio involving the consumed CO_2 flux for rock weathering and observed alkalinity in waters indicates that atmospheric CO_2 is not the unique weathering agent in the Garonne basin. Contribution of the atmospheric/soil CO_2 to the total river alkalinity decreases when the river discharge increases at the two stations Portet and La Réole, and it tends to an average contribution of 44% (Fig. 6). In unpolluted areas, this contribution varies between 100% for crystalline rocks corresponding to the hydrolysis of silicate minerals (Eqs. (7) and (8)), and 50% for carbonate rocks corresponding to carbonate dissolution (Eq. (9)).

The difference observed for the contribution of the atmospheric/soil CO_2 to the total river alkalinity in the Garonne basin (44% instead of 50%) may be attributed to carbonate dissolution by HNO_3 released by nitrifying N-fertilizers (Eq. (14)), as already suggested by Amiotte Suchet and Probst (1996); a good relationship being observed between the theoretical $\text{CO}_2/\text{HCO}_3^-$ ratio and the NO_3^- concentrations in the waters (Fig. 7). The increase of the HCO_3^- flux corresponding to a $\text{CO}_2/\text{HCO}_3^-$ ratio below 50%, is correlated with an increase of the NO_3^- content in the waters (correlation coefficient of 0.77 upstream and of 0.62 downstream). For the same NO_3^- concentration, the $\text{CO}_2/\text{HCO}_3^-$ ratio decreases more rapidly downstream than upstream, confirming that weathering in the Garonne basin is most probably not only due to the action of CO_2 , but also to HNO_3 produced by the fertilizers in the basin.

As can be seen in Eq. (12), calcite dissolution releases only 1 mol of HCO_3^- . This reaction produces alkalinity without consumption of atmospheric/soil CO_2 , which may explain the long term changes of Ca, Mg and HCO_3^- concentrations in the river waters. The changes cannot be directly related to discharge variations and/or to readjustments of calcite equilibrium, as the calcite-saturation coefficient remains always at about unity (Etchanchu and Probst, 1988). For some sub-basins, such as that of the Gers river (a tributary of the Garonne river originating in the Pyrénées mountains), this contribution drops to 37% (Semhi, 1996). By taking into account the equation of the carbonate dissolution by fertilizers (Eqs. (14) and (15)) and the $\text{CO}_2/\text{HCO}_3^-$ ratio (44% as average and 37% for the Gers river), it can be seen that 12–26% of carbonate dissolution could be due to HNO_3 induced by N-fertilizer spreading, rather than to natural weathering processes by carbonic acid. It supports previous estimations of Probst (1985) and Etchanchu and Probst (1988) that 30% of the total carbonate dissol-

ution in the Garonne basin may be attributed to N-fertilizers. In terms of the exported flux of Ca + Mg to the oceans, 6–13% seem to have been produced by weathering induced by fertilizers used for agricultural purposes.

6. Conclusion

Nitrification of NH_4^+ from the fertilizers used in the Garonne basin produces nitrates. Increased use of these N-fertilizers is correlated with increased NO_3^- concentrations in the riverine fluxes, mainly leached from soils to the surface waters during heavy rains. The chemical composition of the Garonne waters during the 1989–1992 period, was controlled by basement rocks in the drainage basin consisting of silicate and carbonate rocks, and was used to make estimations of the atmospheric CO_2 flux consumed by weathering of these rocks.

In the Garonne drainage basin dominated by carbonate rocks, the $\text{CO}_2/\text{HCO}_3^-$ ratio of the river waters reaches a mean value of 44%. Part of the dissolved HCO_3^- seems then not to be due to the action of atmospheric CO_2 . On the other hand, a significant positive correlation was found between increase of the HCO_3^- flux corresponding to a $\text{CO}_2/\text{HCO}_3^-$ ratio below 50%, and NO_3^- concentrations in the waters. However, nitrification of NH_4^+ -fertilizers releases protons which may produce nitric reagents that induce carbonate dissolution supplying HCO_3^- ions in Garonne waters. Such a reaction explains the differences between the estimated contribution of atmospheric CO_2 to the total river alkalinity ($\text{CO}_2/\text{HCO}_3^-$ ratio of 44%) and the theoretical contribution ($\text{CO}_2/\text{HCO}_3^-$ ratio of 50%) corresponding to carbonate dissolution.

Acknowledgements

The authors are grateful to Dr. M. Meybeck (Laboratoire de Géologie Appliquée, Paris) for constructive comments of a previous draft, to Dr. Y. Van Herpe (University of Ghent, Belgium) and an anonymous reviewer for their thorough review, and to Dr. S. Chaudhuri (Kansas State University, USA) for improving the English presentation of the final script. We would like also to thank Y. Hartmeier, G. Krempp and D. Million for technical assistance during this study funded by the Program DBT (INSU-CNRS)/Project ONT Garonne, the Agence de Bassin Adour-Garonne for collection of the river waters, and the colleagues of the program RENECOFOR (REseau National de suivi à long term des ECOSystèmes FOREstiers) for providing precipitation data.

References

- Amiotte Suchet, P., 1995. Cycle du carbone, érosion chimique des continents et transferts vers les océans. In: Sciences Géologiques Mémoires, Strasbourg, 97 (156 pp.).
- Amiotte Suchet, P., Probst, J.L., 1996. Origine du carbone inorganique dissous dans les eaux de la Garonne: variations saisonnières et interannuelles. Sciences Géologiques Bulletin Strasbourg 49, 101–126.
- Battaglin, W.A., Goolsby, D.A., Mueller, D.K., 1994. Relations between use, concentration and transport of agricultural chemicals in the Mississippi river basin. In: Marston, R.A., Hasfurther, V.R. (Eds.), Effects of human-induced changes on hydrologic systems. Proceedings Annual Summer Symposium of the American Water Resources Association, Jackson Hole, Wyoming, 1994, June 26–29.
- Behnke, J., 1975. A summary of the biogeochemistry of nitrogen compounds in ground water. *Journal of Hydrology* 27, 155–167.
- Bennekou, A.J.V., Salomons, W., 1981. Pathways of organic nutrients and organic matter from land to ocean through rivers. In: Martin, J.M., Burton, J.D., Eisma, D. (Eds.), River Input to the Ocean System. UNESCO-UNEP, SCOR Workshop, Rome, pp. 33–51.
- Blaison, N., Létolle, R., Dassonville, G., 1985. Les nitrates dans le champ captant d'Aubergenville: recherche de leur origine et de leur évolution. *Water Supply* 3, 187–197.
- Bourgeat, F., Revel, J.C., Begon, J.C., 1984. Morphogenèse et pédogenèse récentes dans le secteur central des Pyrénées et l'avant pays molassique. *Revue Géographique des Pyrénées et du Sud-Ouest* 1, 333–347.
- Caussade, B., Pierre, D., Prat, M., 1984. Modèle d'étude et de gestion de la teneur en azote des eaux de surface dans un bassin-versant sous culture. *Journal of Hydrology* 73, 105–128.
- Collin, J.J., Landreau, A., Martin, G., Talbo, H., 1984. Dénitrification provoquée des eaux souterraines. Site expérimental de Messac (Ille-et-Vilaine). Principaux résultats scientifiques du B.R.G.M., pp. 195–197.
- Cooke, G.W., Williams, R.J.B., 1970. Losses of nitrogen and phosphorus from agricultural land. *Water Treatment and Examination* 19, 253–276.
- Determine, B., Lamberts, L., 1987. Nitrate nitrogen in the Belgian course of the Meuse river: fate of the concentrations and origin of the inputs. *Journal of Hydrology* 93, 91–99.
- Durand, R., Dutil, P., 1972. Contribution à l'étude de l'évolution des sols en milieu calcimagnésique. *Science du Sol* 1, 25–36.
- Elder, J.F., 1985. Nitrogen and phosphorus speciation and flux in a large Florida river wetland system. *Water Resources Research* 21, 724–732.
- Etchanchu, D., Probst, J.L., 1988. Evolution of the chemical composition of the Garonne river during the period 1971–1984. *Hydrological Sciences Journal* 33, 243–256.
- Faurie, G., 1977. Etude in vitro du rôle de la nitrification sur la lixiviation du calcium dans les sols calcaires. *Science du Sol* 4, 204–218.
- Foster, I.D.L., 1981. Modeling nitrate behaviour in a small catchment, East Devon, UK. *Agro-Ecosystems* 6, 325–341.
- Goolsby, D., Battaglin, W.A., 1993. Occurrence, distribution and transport of agricultural chemicals in surface waters of the Midwestern United States. Open file report, US Geological Survey, 93-0418, 1-25.
- Gray, E.M.B., Holland, J., Breach, J., Rowland, C., 1978. Nitrate in groundwater, procedures in the collection and preparation of rock and water samples. In: Wilkinson, W.B. (Ed.), *Groundwater Quality, Measurements, Prediction and Protection*. Water Research Centre, Medmenham, UK, pp. 373–384.
- Greiner, I., 1997. Analyse de la variabilité fonctionnelle de la plaine alluviale de la Seine et modélisation des transferts de nitrates. Ph.D. thesis, Univ. Paris VI (241 pp.).
- Hallberg, G.R., 1989. Nitrate in ground water in the United States. In: Follett, R.F. (Ed.), *Nitrogen Management and Groundwater Protection: Developments in Agricultural and Managed-Forest Ecology*, vol. 21. Elsevier, New York, pp. 35–74.
- Hoyas, T.R., Vagstad, N., Bechmann, M., Eggestad, H.O., 1997. Nitrogen budget in the river Auli catchment: a catchment dominated by agriculture, in southeastern Norway. *Ambio* 26, 289–295.
- Hutchinson, G.E., 1957. *A treatise on limnology*. Wiley, New York (1015 pp.).
- Khdyer, I., Cho, C.M., 1983. Nitrification and denitrification of nitrogen fertilizers in a soil column. *Soil Science Society of America Journal* 47, 1134–1139.
- Korom, S.F., 1992. Natural denitrification in the saturated zone: a review. *Water Resources Research* 28, 1657–1668.
- Lacroix, m., 1993. Influence des irrigations sur la régulation des teneurs en nitrates dans les nappes sous-jacentes. In: *La Basse Durance (Vaucluse, France)*, Comptes Rendus de l'Académie des Sciences, Paris, vol. 316, Série II, pp. 991–996.
- Mariotti, A., 1986. La dénitrification dans les eaux souterraines, principes et méthodes de son identification: une revue. *Journal of Hydrology* 88, 1–23.
- Mariotti, A., Létolle, R., 1977. Application de l'étude isotopique de l'azote en hydrologie et en hydrogéologie. Analyse des résultats obtenus sur un exemple précis: le bassin de Mélarchez (Seine-et-Marne, France). *Journal of Hydrology* 33, 157–172.
- Mariotti, A., Létolle, R., Blavoux, B., Chassaing, B., 1975. Détermination par les teneurs naturelles en ^{15}N , de l'origine des nitrates: résultats préliminaires sur le bassin de Mélarchez (Seine-et-Marne). In: *Comptes Rendus de l'Académie des Sciences, Paris*, vol. 280, Série D, pp. 423–426.
- Meybeck, M., 1982. Carbon, Nitrogen, and phosphorus transport by world rivers. *American Journal of Science* 282, 401–450.
- Meybeck, M., 1986. Composition chimique des ruisseaux non pollués de France. *Sciences Géologiques Bulletin, Strasbourg* 39, 3–78.
- Omernik, J.M., 1976. The influence of land use on stream nutrient levels. US Environmental Protection Agency, Washington (EPA-600/3-76-014).
- Peierls, B.L., Carraco, N.E., Pace, M.L., Cole, J.J., 1991. Human influence on river nitrogen. *Nature* 350, 386–387.
- Postma, D., Boesen, C., 1991. Nitrate reduction in an unconfined sandy aquifer: water chemistry, reduction processes,

- and geochemical modeling. *Water Resources Research* 27, 2027–2045.
- Probst, J.L., 1985. Nitrogen and phosphorus exportation in the Garonne basin (France). *Journal of Hydrology* 76, 281–305.
- Probst, J.L., Bazerbachi, A., 1986. Transports en solution et en suspension par la Garonne supérieure. *Sciences Géologiques Bulletin, Strasbourg* 39, 79–98.
- Reddy, K.R., Patrick, W.H., Philips, R.E., 1976. Ammonium diffusion as a factor in nitrogen loss from flooded soils. *Soil Science Society of America Journal* 40, 528–533.
- Ronen, D., Magaritz, M., Almon, E., 1988. Contaminated aquifers are a forgotten component of the global N₂O budget. *Nature* 335, 57–59.
- Semhi, K., 1996. Erosion et transferts de matières sur le bassin versant de la Garonne: influence de la sécheresse. Ph.D. thesis, Univ. Strasbourg (202 pp.).
- Smith, R.V., 1977. Domestic and agricultural contribution to the inputs of phosphorus and nitrogen to lough Neagh. *Water Research* 11, 453–459.
- Ulrich, E., Lanier, M., Schneider, A., 1994. Dépôts atmosphériques et concentrations des solutions du sol (sous réseau CATAENAT). Rapport scientifique 1993–1994. Office National des Forêts, Département des Recherches Techniques (165 pp.).
- Vagstad, N., Eggestad, H.O., Hoyas, T.R., 1997. Mineral nitrogen in agricultural soils and nitrogen losses: relation to soil properties, weather conditions, and farm practices. *Ambio* 26, 266–272.
- Williams, M.W., Bales, R.C., Brown, A.D., Melack, J.M., 1995. Fluxes and transformations of nitrogen in a high-elevation catchment, Sierra Nevada. *Biogeochemistry* 28, 1–31.
- Yanagita, T., 1990. *National Microbial Communities: Ecological and Physiological Features*, vol. XXI. Japan Scientific Societies Press/Springer, Tokyo (485 pp.).