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# Aquatic macrophyte communities as bioindicators of eutrophication in calcareous oligosaprobe stream waters (Upper Rhine plain, Alsace)

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## Abstract

The results cover a statistical analysis of the correlations between aquatic macrophyte communities and chemical parameters ($N\text{-}NH_4$, $N\text{-}NO_3$, $P\text{-}PO_4$, COD, Temperature, dissolved $O_2$, Cl) in unpolluted hard waters (upper Rhine rift valley).

This study was based on a table of phytosociological relevés for six plant communities, named A, B, C, CD, D and E. The ecological determinism of the communities were defined from:
The study of the seven foregoing physico-chemical parameters for 29 groundwater streams on periodical samples of water.
The study of the change with time in the aquatic vegetation after change of the trophic status, confirmed by analysis.
The comparative study of the vegetation of the streams and parts of the streams with different trophic statuses but fed by the same groundwater table of the Wurmian Rhine gravels.

Analysis of the main components showed the good correlation between the macrophyte communities and the trophy ($N\text{-}NH_4$, $P\text{-}PO_4$). These six communities were classified according to the trophic scale. Discriminant analysis was used to compare the classification of the phytosociological sequence with that based on the statistical analysis. The authors give a very precise bioindication scale (based on the macrophyte community) for the eutrophication degree in unpolluted hard waters.

## Introduction

The use of aquatic macrophytes to reveal water quality parameters is relatively recent (Carbiener 1969; Kohler 1971, 1975, 1982; Glänzer *et al.* 1977; Carbiener & Kapp 1981; Pott 1981, 1983; Haslam 1982; Haslam & Woseley 1981; Meriaux 1983; Wiegleb 1978, 1980, 1981, 1984). Earlier studies, in the field or in the laboratory, dealt with bioindicators for a few species (review for example in Westlake 1975), or with the classical differenciation between the vegetation of poorly mineralized water (soft water-courses flowing from siliceous watersheds) and that of hard water-courses (flowing from calcareous watersheds or watersheds rich in basic rocks).

The starting point for this study was the comparative field observations on both 'soft' stream waters (Engel & Kapp 1964) where the presence of *Potamogeton polygonifolius*, which is very sensitive to eutrophication is strongly restricted by human pollution, and streams with hard water (Carbiener 1969: homologous sensitivity of *Potamogeton coloratus* Horn.). These two species are generally good examples of river plants with a high bioindication value (oligotrophy); many other species can play a similar role, as we shall show in this paper, for example with *Zannichellia palustris*, *Potamogeton densus* as indicators of eutrophication in hard water. But aquatic macrophyte communities have a more precise bioindicator value than the isolated species according our observations. Wiegleb (1984) and Haslam (1978) have the opposite opinion, partly based on the research of Kohler, saying that the bioindication in aquatic milieu is better based on the species than on the communities. This astonishing opinion (many species have a wide ecological amplitude and give little information) is explained by the difficulties that the syntaxonomy of aquatic vegetation continues to face even now. As species with wide trophic amplitude, we would mention *Sium erectum*, *Callitriche obtusangula*, *Elodea canadensis*, *Nuphar lutea*, *Sparganium emersum*, and, from a moderate eutrophication, *Ranunculus circinatus*, *Lemna trisulca*, *Fontinalis antipyretica* (Casper & Krausch 1980, 1981).

Our study site is a very homogeneous experimental hydrological sector, enabling the effect of trophy on the vegetation of running oligosaprobe stream waters to be tested with a great security.

In this case (hard water, about 100 ppm $Ca^{++}$), the gradation of the trophy is based on the biogen nutrients near the minimum, i.e., phosphorus and nitrogen which are the key nutrients of the biocenoses evolution in these hard waters. As we shall emphasize, ammonia toxicity, which is increased in hard waters, plays an important role, previously emphasized by Glänzer *et al.* (1977).

## Aims of the study

The aims of this study are to define the ecological determinism of a phytosociological sequence (eutrophication catena of plant communities previously described by Carbiener & Ortscheit, 1987) by:

- the analysis of the physico-chemical parameters based on periodical water sampling
- the study of the diachronic evolution of the aquatic vegetation after modifications of the trophic status, confirmed by the analysis of a few streams during the period 1970–1988.
- the comparative synchronic study of the vegetation of different streams and parts of streams with different trophic status but fed by the same groundwater-table (very homogeneous hydrochemical features with a few exceptions, due to human influences: fringe of chloride pollution along the Rhine, nitrate pollution from agriculture in the Central Ried area, at half way between the Ill and the Rhine – see study site).

We have already provided clear evidence that the trophy is the major ecological determinant of the floristical composition (Carbiener & Ortscheit 1987), which completely tallies with the results of Kohler (1971, 1982).

The physical parameters, such as current velocity, morphometry, temperature, intervene only at quantitative levels (facies) or by subordinate qualitative modifications (level of the subcommunity for example).

This paper seeks to establish, by statistical treatment of available data, the correlations between the ecologically relevant physico-chemical parameters of water and the plant communities, in oligosaprobe hard water. To this end, we used principal component analysis, which is actually the classical way to describe tables of phytosociological relevés with n lines (relevés) and p columns (parameters) (Carrel *et al.* 1986; ter Braak 1987).

The bioindication of plant communities can also reveal:

- the transfer mechanisms either from surface waters to groundwater (infiltration of overflows, seepages through river beds) or vice versa (the main process in the case of draining groundwater streams). In the two major ecological systems of the plain of Alsace, the transfer from the channelled Rhine, differs greatly from that of the Ill with a functional flood plain (Carbiener *et al.* 1988)

– a hydrological flow path to localize these transfers. Thus, macrophyte communities in running waters also play a role as 'ecological describers' of the hydrological exchanges, elicited by complex hydrosystems formed by large alluvial rivers connected to an extensive groundwater-table. To this end, the precise correlation is intended to improve the precision of this ecological describer function of the hydrological functioning.

– monitoring of the hydrological modifications (e.g., the effects of the recent canalisation of the Rhine).

## Study site

The upper Rhine rift valley (Alsace, France) is filled with a thick layer of sandy and gravelly alluvium deposit, rich in carbonate coming from the alpine catchment basin of the Rhine (Sittler 1985). This alluvium deposit supports one of the largest groundwater-table in Europe (Simler *et al.* 1979), which is in exchange relation with the main rivers of middle Alsace, upstream of Strasbourg, i.e., the Rhine in the east and its main and only tributary the Ill in the west. Because of particular geomorphological and tectonic conditions in middle Alsace, the Ill runs parallel to the Rhine along the Vosges foothills, gathering all the streams flowing from the Vosges.

Between the Ill and the Rhine and from Colmar to Strasbourg (Long. east 7° 40, Lat. north 48° 20), the geomorphological conditions peculiar to the 'Grand Ried Central d'Alsace' (Carbiener 1983a) allow a hydrographical network to drain the groundwater-table: the groundwater-streams. These streams, the so-called 'rivières phreatiques' ('Brunnenwasser' in the local dialect), are rare on the right bank of the Rhine (Baden side) where the terraces and alluvial cones of the Black Forest streams lie closer to the river. The groundwater stream network forms a noticeable hydroecological pattern, characterized, where it surfaces, by the constancy of the main physico-chemical parameters: low temperatures (stenothermal cold streams, 11° ± 0.5° where it surfaces), undersaturation in dissolved $O_2$ (40%–70% of saturation), permanent absence of suspended matter (very clear), highly mineralized hard water: rich in calcium bicarbonate ($>100$ ppm $Ca^{++}$) but oligotrophic, with low phosphate and ammonia nitrogen levels (Carbiener 1983b; Carbiener & Ortscheit 1987; Carbiener *et al.* 1988) in the undisturbed sites. The groundwater streams are optimal biotopes for Salmonides (*Salmo trutta fario*, *Thymallus thymallus*). In these fast-flowing waters (main slope of the plain $>0.5‰$ in this sector) the beds dug out in the Wurmian gravel, forming the basement of Holocene alluvium deposits and providing the spawning grounds. Moving downstream, there is a progressive decrease in the stenothermy, and a progressive eutrophication due to the external contribution of the riparian vegetation, or the anthropic influences. The aquatic macrophyte communities which colonize these streams precisely reflect this evolution.

The groundwater streams studied (Fig. 1) were:

1) the streams of the broad floodplain (10000 ha) of the Ill or its tributaries on the west of the study area. The river-groundwater exchanges of the Ill are highly individual and have recently been clarified (Klein & Carbiener 1988; Carbiener *et al.* 1988).

2) a network of 'Brunnenwasser', with a flow influenced by the Rhine in the eastern part of the area, particulary in the sectors of Schoenau, Rhinau-Daubensand, Erstein-Plobsheim, between Marckolsheim and Strasbourg. The exchanges between the polluted and eutrophicated channelled Rhine and the groundwater-table are quite different from those in the Ill. In the study site, the Rhine seeps into its groundwater-table via its minor bed, its overflow bed being suppressed by the canalisation; thus, the groundwaters are eutrophicated along the Rhine. On the

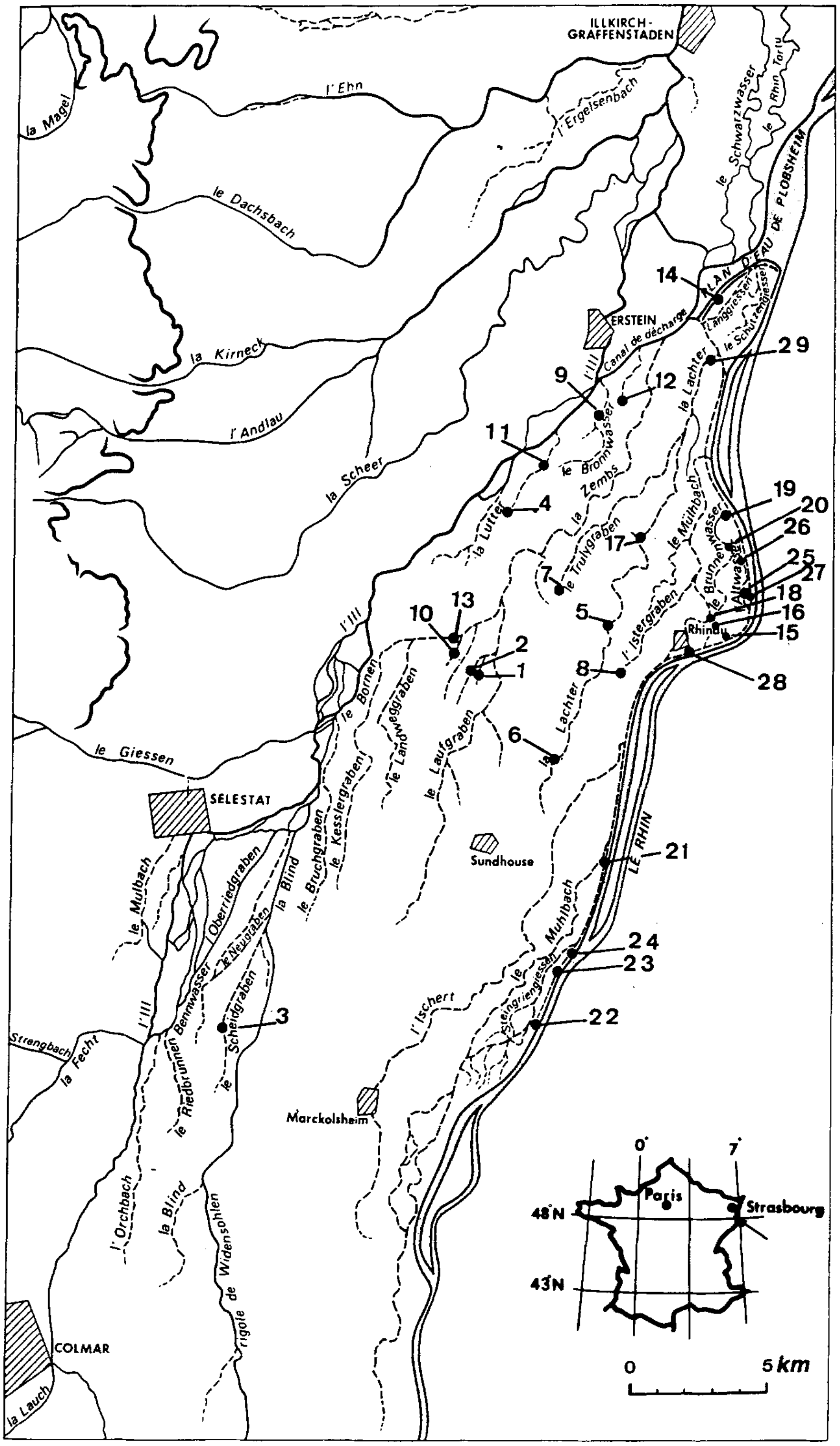

*Fig. 1.* Map of sites.

contrary, the Ill feeds the groundwater-table by flood water seepage through the self-purifying system of alluvial forest and meadow-hydromorphous soils, and thus provides very pure oligotrophic groundwater despite its high load of organic pollution.

## Definition of macrophyte communities

Carbiener & Ortscheit (1987) described a phytosociological sequence of eutrophication, determined by the trophic factor and more specifically by the amounts of P-$PO_4$ and N-$NH_4$ in solution. This sequence was tested here in relation to hydrological parameters. Let us briefly describe this sequence, symbolized by the letters A, B, C, CD, D, E (Table 1):

Community A, highly oligotrophic with *Potamogeton coloratus*, *Chara hispida* and *Juncus subnodulosus fo. submersa*, as characteristic species;

Community B, oligo-mesotrophic, mainly negatively characterized by *Sium erectum fo. submersa* (a eurytopic species) dominant and *Mentha aquatica fo. submersa*;

Community C, meso-eutrophic with dominant *Callitriche obtusangula* but characterized by the absence of eutrophic species

Community D, eutrophic rheophilic with *Zannichellia palustris*, *Potamogeton densus*, *Ranunculus trichophyllus* (rare in the area but typical), and *Callitriche obtusangula*. The occurrence of a riparian fringe with *Nasturtium officinale* and *Lemnion*-community (with *Lemna minor*, *Lemna minuscula*, *Spirodela polyrhiza*, *Azolla filiculoides*) is very typical for the D community;

Community E, the most eutrophicated with *Ranunculus fluitans* and *Oenanthe fluviatilis* (rheophilic facies with *Ranunculus fluitans*, lenitic facies with *Potamogeton pectinatus*) where the *Nasturtietum* decrease when the *Lemnion* communities are maintained or increase.

The B community is mainly determined by the absence of *Potamogeton coloratus* (characteristic of A) and the absence or very limited presence of *Callitriche obtusangula*, dominant in C. *Sium erectum*, dominant, and even almost monospecific, in B is not a characteristic species since it is found in the whole sequence (A to E). In the same way, the C community is defined negatively by the absence of the plants of D, and is dominated by *Callitriche*, found from C to E, and which, like *Sium erectum* in B, is not characteristic of C by itself. But it can be held that *Sium erectum* (and, to a lesser measure, *Callitriche obtusangula*) are 'ecological describers' of groundwater inflow, as are *Nasturtium officinale* or *Chara globularis* in the case of eutrophicated groundwater. They are typical of all the streams draining the alluvial water-table. A community intermediate between C and D, named CD was defined by the abundance of *Callitriche* and *Sium*, the appearance of *Lemna trisulca* (often very abundant), *Fontinalis antipyretica*, *Veronica anagallis fo. submersa*, and the presence, in low quantity, of species characteristic of D, such as *Zanichellia palustris*, *Potamogeton densus*, *P. crispus* and *Nasturtium officinae* on the banks.

## Methods

The water, the aquatic vegetation and the riparian zonation with pleustophytes, helophytes (influenced by the trophic status of waters) have been sampled since 1971, mostly 5–6 times a year, but not regularly, for each of the sites studied. Temperature, pH, ammonia nitrogen, nitrate nitrogen, phosphate, chloride, COD and dissolved oxygen were measured. The hardness, the current velocity and the conductivity were also measured. But these parameters were not included in the analysis because the results of both diachronic and synchronic observations indicated that these parameters were not discriminant at the level of the communities (Carbiener & Ortscheit 1987), and indeed could lead to considerable distortions of the visual habitus of the vegetation through the formation of eurytopic species facies. Diachronic analysis of various streams showed a change in the vegetation with a trophic change but without any changes in the physical characteristic. The number of species of the communities increase from A to E and sta-

*Table 1*. Synoptic table of communities A to E. Code of presence degree according to Braun-Blanquet (1964).

| Communities symbol | A | B | C | D | E |
|---|---|---|---|---|---|
| Potamogeton coloratus Vahl | V | | | | |
| Juncus subnodulosus fo. subm. Schrank | V | | | | |
| Chara hispida L. | III | | | | |
| Chara vulgaris L. em Wallr | (I) | | | | |
| Mentha aquatica L. fo. subm. | IV | V | I | | |
| Agrostis stonolonifera L. fo. subm. | III | IV | II | | |
| Sium erectum fo. subm. Huds. | V | V | V | V | IV |
| Phalaris arundinacea L. fo. subm. | I | V | II | I | I |
| Veronica anagallis aq. L. fo. subm. | r | II | III | IV | II |
| Myosotis palustris L. fo. subm. | I | II | II | | I |
| Callitriche obtusangula Le Gall | | II | V | V | V |
| Sparganium emersum fo. fluitans God. Gren. | | II | III | II | IV |
| Lemna trisulca L. | | I | II | II | II |
| Elodea canadensis Michaux Fil. | | II | II | II | III |
| Fontinalis antipyretica Hedw. | | I | I | III | III |
| Scirpus lacustris (L.) Palia fo. subm. | | I | II | I | |
| Nasturtium officinale R. Brown fo. subm. | | I | I | II | I |
| Nuphar lutea L. | | II | II | I | II |
| Myriophyllum verticillatum L. | | | (I) | I | |
| Potamogeton densus L. | | | II | IV | III |
| Potamogeton friesii Rupr. | | | III | II | II |
| Elodea nuttallii St. John | | | II | I | IV |
| Ranunculus circinatus Sibthorp | | (I) | I | I | |
| Zannichellia palustris fo. repens W. Koch | | | | V | II |
| Potamogeton crispus L. | | | | IV | III |
| Potamogeton pectinatus L. | | | | II | V |
| Hippuris vulgaris L. | | | | I | I |
| Ranunculus trichophyllus Chaix | | | | I | |
| Ranunculus fluitans L. | | | | | IV |
| Oenanthe fluviatilis Coleman | | | | | IV |
| Chara globularis Thuil. | | | | I | (I) |
| Myriophyllum spicatum L. | | | | | III |
| Ceratophyllum demersum L. | | | | | II |
| Potamogeton pusillus L. | | | | | |
| Elodea ernstae St. John | | | | | I |
| Potamogeton perfoliatus L. | | | | I | I |
| | | | | (I) | I |
| Sparganium erectum L. fo. subm. | I | I | | I | II |
| Pellia fabroniana Raddi | I | (I) | (I) | | |
| Chiloscyphus pallescens Dum. | | I | (I) | I | I |
| Leptodictyum riparium Warnst. | | | | I | II |
| Drepanocladus aduncus Mönkem | | | I | | |
| Species or contiguous communities (algae, Lemnetea...)<br>+ = optimal, (+) = frequent, / present, (/) = rare | | | | | |
| Batrachospermum monoliforme Roth | + | + | / | | |
| Hildenbrandia rivularis Ag. | | + | (+) | / | (/) |
| Cladophora crispata | | | | + | (+) |
| Enteromorpha intestinalis (L.) Grev. | | | | + | / |
| Lemna minor L. + Lemna minuscula Hert. | | | | (+) | (+) |
| Spirodela polyrhiza (L.) Schleid. | | | | / | (+) |
| Azolla filiculoides Lam. | | | | (/) | / |
| Nasturtium officinale – community (riparian fringe) | | | | + | / |

(Nomenclature references: for flowering plants, E. Oberdorfer, Pflanzensoziologische Exkursions Flora 1983, Casper S.J. & Krausch H.D. Süsswasserflora von Mitteleuropa T.23,24 1980, 81, for bryophytes, J. Augier, Flore des bryophytes, Paris 1966, for alga P. Bourelly, Les algues d'eau douce, Paris 1966, 68).

bilize, then perhaps decrease by hypertrophy. On the contrary, in the case of organic pollution, Haslam (1982) based the bioindication on the impoverishment of the phytocenoses.

### *Hydrological parameters*

All the parameters were analyzed according to the methods described in AFNOR (1986) and modified as follows: ammonia nitrogen was determined by the indophenol blue method, phosphate, by formation of a phosphomolybdic complex whose blue color is concentrated with isobutanol (measured concentration around 3 $\mu$g/l), COD, by the quantity of oxidant ($KMnO_4$) required for the total oxidation of the organic matter dissolved in water.

### *Data analysis*

The data used (relevés and water samples) were not intended for statistical treatment, which is why we did not use too sophisticated methods of analysis. We worked only on mean data. 400 samples were collected from 29 sites (Fig. 1) over 17 years. The pH (relatively constant between 7 and 7.5) was not included in the analysis.

We used principal component analysis (PCA) and factorial discriminant analysis, the latter to classify sites with problems such as additional data. This series of treatments enabled data selection and homogenisation for the sake of clarity.

We deliberately left aside temporal seasonal variations in data since the analyses were not sufficiently frequent to take into account the seasonal rhythms (linked, for example with the biomass evolution); but in the case of the highly homeostased groundwater streams, these rhythms were weak. On the other hand when a stream undergoes trophic modifications, this is revealed by a phytosociological change, so obviously this stream falls into a new category for data processing. Table 2 gives the site definition, the means of the physicochemical parameters and the aquatic macrophyte communities previously defined (A, B, C, CD, D, E) and numbered 1 to 6 (communities were checked regularly for each site, the phytosociological status of some sites changing drastically during the study as a result of changes in this trophic status). For the sake of comparison, we also give the parameters measured in both the Ill and the Rhine. The correlation circle and the factorial map of the sites are shown in Figure 2 for the PCA.

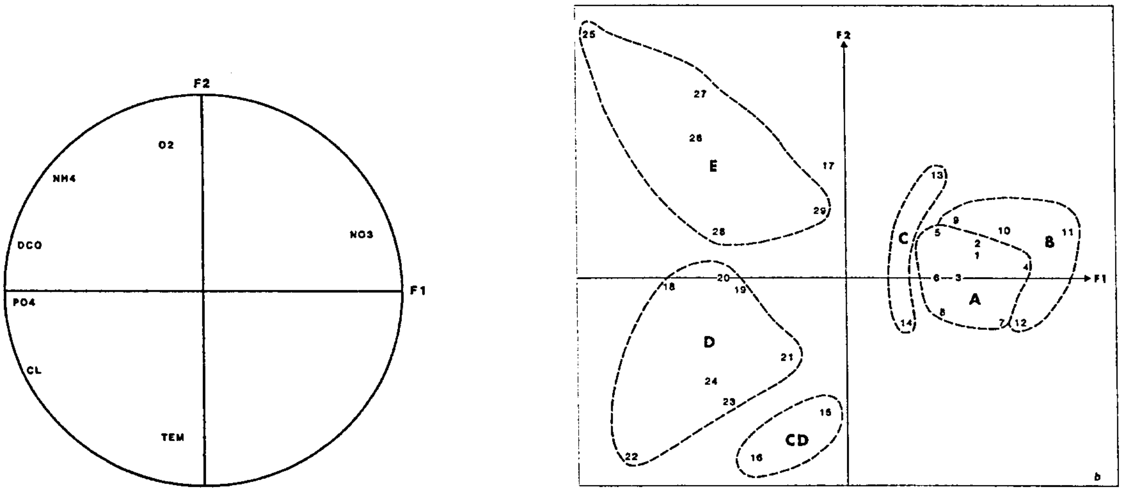

*Fig. 2.* Principal component analysis for 29 sites, based on 7 physico-chemical parameters (T°, $N\text{-}NH_4$, $N\text{-}NO_3$, $P\text{-}PO_4$, COD, dissolved $O_2$, $Cl^-$). (a) Factorial representation of parameters; (b) Factorial representation of sites.

*Table 2.* Definition of sites and means for physico-chemical parameters. (n = number of samples).

| Code | | Stations | n | °C 1 Temp. | µg/l 2 N-NH$_4$ | mg/l 3 N-NO$_3$ | µg/l 4 P-PO$_4$ | mg/l 5 DCO | mg/l 6 O$_2$ | mg/l 7 Cl |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | A | Fossés de Drainage Witternheim | 10 | 11.0 | 8.7 | 5.2 | 9.4 | 0.6 | 6.5 | 65.2 |
| 2 | | | 10 | 11.2 | 6 | 5.4 | 7.4 | 0.7 | 7.0 | 64.8 |
| 3 | | Scheidgraben | 18 | 11.5 | 2.1 | 4.4 | 9.6 | 0.5 | 8.1 | 90.4 |
| 4 | | Hanfgraben Source 'Ste Materne' | 10 | 11.4 | 9.4 | 5.2 | 6.6 | 0.4 | 5.6 | 42.2 |
| 5 | | Lachter Friesenheim | 8 | 11.0 | 5 | 1.8 | 4.0 | 0.7 | 9.0 | 53.7 |
| 6 | | Lachter Bindernheim | 22 | 11.4 | 4.7 | 2.3 | 12.9 | 0.4 | 8.0 | 68.5 |
| 7 | | Trulygraben Belle source | 26 | 11.1 | 5.8 | 3.9 | 6.4 | 0.4 | 4.3 | 63.3 |
| 8 | | Istergraben Source | 12 | 12.5 | 8.7 | 3.0 | 8.7 | 0.5 | 7.2 | 76.6 |
| 9 | B | Bronnwasser Oberwald | 11 | 11.3 | 16.8 | 4.5 | 7.6 | 0.8 | 7.0 | 46.4 |
| 10 | | Donnerloch Riedhof | 27 | 11.7 | 9.9 | 5.5 | 6.9 | 0.6 | 7.5 | 42.4 |
| 11 | | Hanfgraben | 12 | 11.5 | 8.1 | 7.4 | 7.1 | 0.4 | 6.9 | 40.4 |
| 12 | | Sauerbrunnen | 12 | 12.3 | 12.6 | 4.9 | 6.4 | 0.4 | 4.3 | 44.6 |
| 13 | C | Zembs | 30 | 11.5 | 17.6 | 5.9 | 13.4 | 0.8 | 8.7 | 47.4 |
| 14 | | Contre Canal de Drainage Plobsheim | 14 | 13.6 | 7.1 | 2.4 | 9.4 | 0.6 | 8.8 | 77.5 |
| 15 | CD | Brunnenwasser Sources | 23 | 13.0 | 6.4 | 0.8 | 9.4 | 0.7 | 5.7 | 144.2 |
| 16 | | Brunnenwasser résurgences | 4 | 13.9 | 11.4 | 0.7 | 30.0 | 0.9 | 2.7 | 126.0 |
| 17 | D | Lachter Boofzheim | 13 | 12.7 | 56.0 | 4.7 | 20.8 | 0.8 | 9.5 | 72.3 |
| 18 | | Brunnenwasser Schantzbrücke | 21 | 13.3 | 51.0 | 0.8 | 40.8 | 0.8 | 8.1 | 133.2 |
| 19 | | Brunnenwasser D 20 | 7 | 12.9 | 25.0 | 0.8 | 26.3 | 0.8 | 8.9 | 121.7 |
| 20 | | Brunnenwasser Daubensand | 16 | 13.1 | 36.2 | 0.9 | 24.9 | 0.9 | 8.7 | 118.9 |
| 21 | | C. Canal de Drainage pk249 | 11 | 14.1 | 11.2 | 1.0 | 17.7 | 0.8 | 8.3 | 117.5 |
| 22 | | C. Canal de Drainage pk246 (source) | 14 | 14.3 | 17.8 | 1.0 | 56.4 | 1.2 | 2.4 | 132.7 |
| 23 | | C. Canal de Drainage pk247.5 | 5 | 12.7 | 20.2 | 0.9 | 33.3 | 0.9 | 3.8 | 133.7 |
| 24 | | C. Canal de Drainage pk248 | 7 | 12.4 | 13.2 | 0.9 | 35.6 | 0.9 | 5.4 | 152.0 |
| 25 | E | Altwasser Amont 1 | 4 | 8.9 | 76.8 | 1.5 | 41.2 | 1.5 | 9.3 | 108.1 |
| 26 | | Altwasser Amont 2 | 7 | 9.6 | 31.0 | 1.2 | 33.1 | 1.1 | 10.5 | 119.2 |
| 27 | | Canal de Drainage pk264 | 4 | 9.5 | 51.5 | 1.9 | 35.5 | 1.0 | 10.8 | 105.3 |
| 28 | | Canal de Drainage pk261.7 | 4 | 12.3 | 41.3 | 1.3 | 27.2 | 0.9 | 9.7 | 120.5 |
| 29 | | Lachter confluence avec canal de drainage | 4 | 14.4 | 43 | 4.1 | 31.0 | 0.7 | 10.8 | 54.1 |
| | | Rhin | 20 | 12.8 | 232.2 | 1.4 | 74.9 | 2.0 | 10.3 | 121.4 |
| | | Ill | 33 | 12.7 | 775.3 | 2.5 | 201.8 | 2.3 | 8.3 | 116.2 |

## Results

### *Principal component analysis*

The correlation circle (Fig. 2) shows the existence of two gradients:

Factor 1 is correlated to the trophy (nutrient factor): it takes into account the content in N-NH$_4$, N-NO$_3$ and P-PO$_4$ with respective correlation values of $-0.68$, $+0.81$ and $-0.92$. The second principal component reflects the temperature and the dissolved O$_2$ content (correlated parameters) with significant correlation, respectively $-0.71$ and 0.78. The factorial map of site distribution shows that the sites fall into three groups according to the first principal component: the group A B, whose differenciation is difficult to establish, the intermediate communities C, CD, and finally the group of the D and E communities. The first group is characterized by low phosphate and ammonia contents ($<15$ ppb N-$NH_4$, P-$PO_4$), but with the highest nitrate contents of all the sites studied ($>4$ ppm), which may be considered paradoxical. On the contrary, the D and E communities are defined mainly by a high ammonia content ($>20$ ppb for the D community, $>30$ ppb for the E one), and also by a high phosphate content ($>20$ ppb P-$PO_4$) but a low nitrate content ($<2$ ppm N-$NO_3$), with a few exceptions. This nitrate problem will be discussed later. C and CD represent an intermediate sequence (N-$NH_4$ content between 10 and 20 ppb and P-$PO_4$ between 10 and 30 ppb). An ecological gradient of the nutrient factor of the streams characterized by the phytosociological sequence A, B, C, CD, D and E, clearly emerges.

### *Factorial discriminant analysis*

This analysis enables sites to be reclassified according to hydrochemical parameters.

The correlation circle and the community distribution map are given in Figure 3. For 80% of the communities, the site classified according to the nature of the community corresponds to that of the analysis.

A few sites are badly classified, for example sites numbered 1, 2, 4, 21, 28 and 29 (Table 2).

– Site 4 mapped as A according to the vegetation relevés becomes B with this analysis. This regrouping could be explained by the N-$NH_4$ and N-$NO_3$ contents being superior to the mean for the A sequence, the other parameters remaining comparable. We shall see the disturbing role of the nitrate, which is of very low content in the waters under the influence of the Rhine, often the most P-eutrophicated.

– The regrouping of the sites 1 and 2 (drains) in B could be explained in the same way as previously. Let us therefore note that the A and B communities are very near from an ecological point of view. The B community seems to be characterized by disturbing peaks more particularly of the N-$NH_4$ content, which, in spite of the very good water quality outside these disturbing episods, prevents the settling of oligotrophic species such as *Potamogeton coloratus*, *Chara hispida*, extremely sensitive to ammonia toxicity (Glänzer *et al.* 1977).

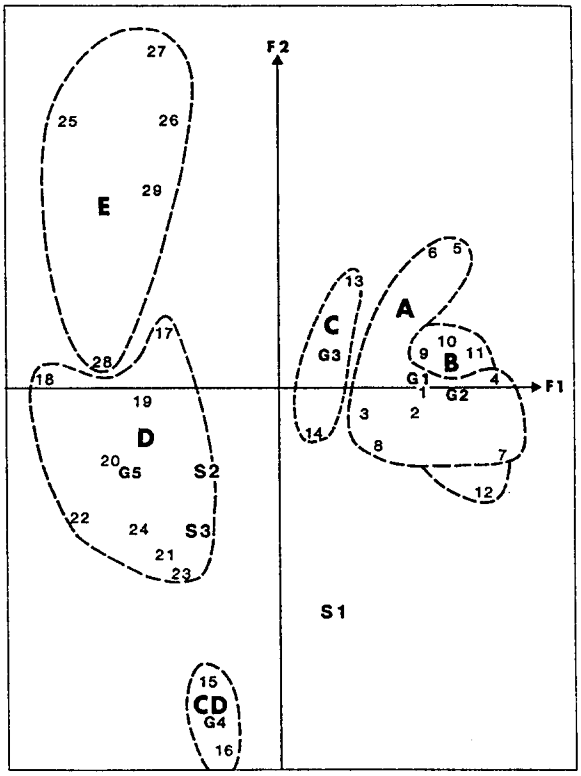

*Fig. 3.* Factorial discriminant analysis for 29 sites, based on the chemical parameters, with 3 additional sample sites.

– Site 28 (drainage canal parallel to the canalised Rhine, sampled near Rhinau), mapped as E according to the vegetation, is classified in the D sequence while Site 27 of the same stream, sampled 3 km downstream, remains classified as E. This fact seems surprising since upstream of Site 28, the drainage channel receives eutrophic waters via a junction with the ‘Rhine-Rhone Canal’. This may imply that the number of samples was not sufficient to integrate all the variations in the chemical parameters during the year; nevertheless these variations are integrated by the vegetation (the sampling perhaps favoured the flood groundwater period with purer waters).

The head of the same stream (Sites 22, 23 and 24, sampled upstream of the confluence of a phreatic stream draining the whole neighbouring forest area) is one of the most representative sites of 'Rhine filtrate' feeding the groundwater-table we studied, the so-called 'Schoenau spring'. It is classified and mapped as D, as is the middle of a stretch, upstream of Site 28 before the confluence with the 'Canal du Rhone au Rhin'.

- Site 21, sampled downstream of the confluence with the groundwater stream draining the forest area, is classified as C when it is mapped as D. But this modification could be explained by the fact that the hydrographical network draining a large Rhine alluvial forest area previously quoted, brings western groundwaters (further from the Rhine), thus purer and perhaps self-purified by the forest root system which is in contact with the superficial fringe of this groundwater-table. Later studies could clarify these aspects.
- Site 29, mapped as E, is classified as C, which could again be explained, by a high nitrate content (> 5 mg/l) close to that of the C community, the other parameters corresponding to E ones.

### *Analysis of additional data with the discriminant analysis*

Three sample sites of a same stream were used to compare the results of the statistical analysis and the field observations and thus to test the validity of the previous correlations established by analysis.

The stream studied was a former fast-running arm of the Rhine, called the 'Giessen' (Carbiener 1983b), cut off from the river by the building (1970) of the Canal d'Alsace. The stream, at present fed solely by the groundwater-table, now has a moderate current velocity, but remains under the eutrophicated 'Rhine filtrate' influence. It lies in the large Rhine forest area of Erstein, south of the Plobsheim pond (Fig. 4).

Water and vegetation analyses have been done

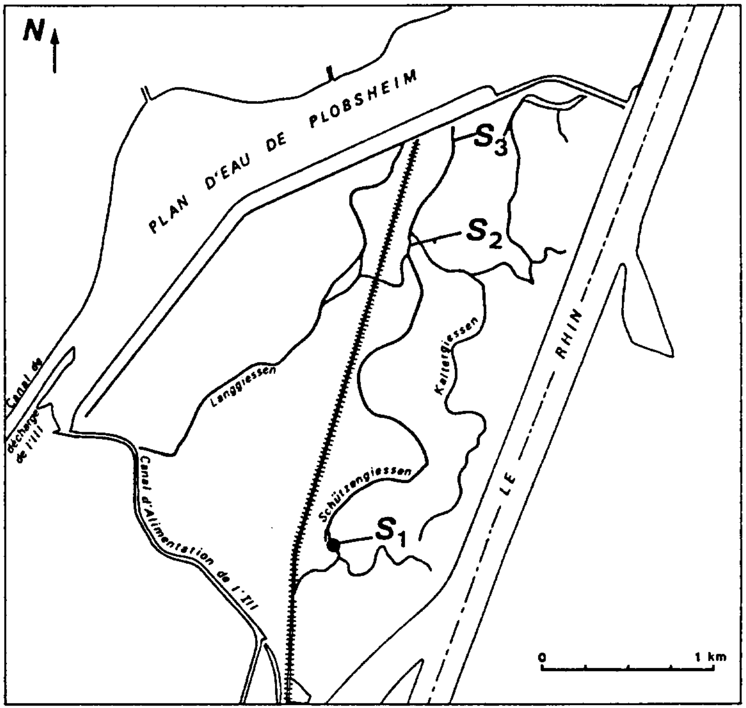

*Fig. 4.* Map of 'Schützengiessen'.

on his stream since 1982 in three sectors, the spring, or upstream, sector (S1), the half-way sector (S2) downstream of the confluence with the Langengiessen, coming from the very eutrophicated drainage channel (plant community E) and the downstream sector (S3) near the confluence with the Plobsheim drainage channel which this stream flows into.

The analytical data (Table 3) show clear eutrophication from upstream to downstream (S1 to S2). The Langengiessen brings waters rich in ammonia, nitrate and phosphate, which are diluted in the cleaner waters of the stream under observation. However, sector 3 is less eutrophicated than sector 2, probably due to a dilution by groundwater entering the bed of the stream directly (the discharge effectively increases). We still have to note variations of around 100% for the ammonia content, 50 to 70% for the phosphate content during the year. Discriminant analysis classifies sector S1 of this stream in the sequence CD. The other two sectors are classified as D. The vegetation relevés from the three sectors confirm this classification. In this case, field observation and statistical analysis tally. The study of this special case confirms the existence of close correlations between trophic parameters and vegetation.

### *Bioindicator values of aquatic macrophyte communities*

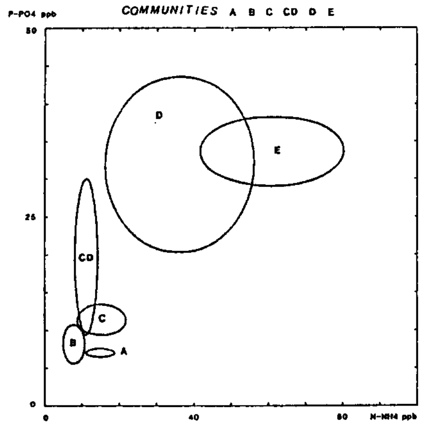

*Fig. 5.* Graphic representation of correlations between communities and trophic factors (N-$NH_4$, P-$PO_4$), calculated on the basis of the mean for each site ± $\sigma$.

Figure 5 shows the plant community distribution according to the N-$NH_4$ and P-$PO_4$ content: mean and standard deviation were calculated according to the mean got for each site (these means were used in the statistical analysis). The A and B communities are differenciated by the N-$NH_4$ content, the phosphate content being very close. On the contrary C and CD are distinguished from B and from each other by the phosphate content. At the end of the sequence, we again find D and E communities differentiated by the N-$NH_4$ content.

Table 4 gives the intervals in the values for the 3 parameters expressing Factor 1 and characterizing the communities; the means and the standard deviations were calculated on the base of all the data, time by time. We clearly distinguish 3 groups (A, B), (C, CD) and (D, E) classified according to the N-$NH_4$ and P-$PO_4$ content. The nitrate seem to differenciate the A, B, C communities (with a surprisingly high nitrate content of the water) from the group CD, D and E (with a relatively low nitrate content), but we shall see that it is a sampling artefact. The aquatic vegetation mapped in six clearly separate communities integrate with a high degree of precision the

*Table 3.* Physico-chemical parameters for 'Schützgiessen' stream.

| | Temp. | N-$NH_4$ µg/l | N-$NO_3$ mg/l | P-$PO_4$ µg/l | DCO mg/l | $O_2$ mg/l | Cl mg/l |
|---|---|---|---|---|---|---|---|
| S1 upstream | 13.20 | 8.1 | 1.1 | 8.5 | 0.6 | 5.6 | 97.6 |
| S2 middle | 13.70 | 19.8 | 2.4 | 15.1 | 0.7 | 9.1 | 97.2 |
| S3 downstream | 13.40 | 11.0 | 1.4 | 8.9 | 1.1 | 9.5 | 99.3 |

*Table 4.* Distribution of aquatic macrophyte communities in relation to trophic parameters (mean calculated on the base of each sample, at each time, showing standard deviation).

| | | A | B | C | CD | D | E |
|---|---|---|---|---|---|---|---|
| $N\text{-}NH_4$ | Mean | 6.5 | 11.2 | 13.6 | 11 | 33.8 | 45.6 |
| µg/l | STD-deviation | 8.8 | 17.5 | 14.7 | 17.5 | 46.8 | 43.5 |
| | Tolerance | 0–15 | 0–29 | 0–29 | 0–29 | 0–80 | 2–90 |
| $P\text{-}PO_4$ | Mean | 8.5 | 6.9 | 12.4 | 12.5 | 32.6 | 33 |
| µg/l | STD-deviation | 7.9 | 3.2 | 10 | 9.3 | 21.5 | 9 |
| | Tolerance | 1–17 | 4–10 | 2–23 | 3–22 | 11–54 | 24–42 |
| $N\text{-}NO_3$ | Mean | 3.9 | 5.7 | 5 | 0.9 | 1.4 | 2 |
| mg/l | STD-deviation | 1.8 | 2.5 | 2.5 | 0.7 | 1.7 | 1.2 |
| | Tolerance | 2–6 | 3–9 | 2.5–7.5 | 0.2–1.6 | 0–3 | 0.8–3.2 |

progressive increase in eutrophication factors. To have the same discrimination of the hydrochemical parameter, the number of samples should be much greater.

## Discussion

### *Hydrochemical parameters*

The correlation between nitrate and the community distribution is accidental. Thus, the observations show that most of the communities A, B and C are observed in the streams of the Ill plain whose nitrate content (due to agriculture: Bernhard 1985; Bernhard *et al.* unpublished findings; Carbiener *et al.* 1988; Klein & Carbiener 1988) is higher (4–8 ppm $N\text{-}NO_3$) than that measured in the Rhine sector (1–2 ppm), and can reach the highest values in the area. The nitrate content measured in the Rhine is always low compared to that measured in the Ill and is comparable with that in the groundwater streams near the Rhine and thus under its influence: the nitrate transfer is direct from the Rhine, which seeps through its bed ('Rhine filtrate') into the groundwater-table and the groundwater streams through the Rhine gravel. Thus, streams classified as A, located near the Rhine, such as the Istergraben spring and the Lachter, upstream (Sites 8 and 6 respectively) are low in nitrate. On the contrary, the Ill does not seep through its bed and the groundwater is only fed during the overflow, as shown by Carbiener & Krause (1975) using chloride pollution as a hydrological tracer and by Klein & Carbiener (1988) in a study of the functioning of two groundwater streams of the Ill flood plain (these studies show that the flood waters – highly self-purified by the passage through the forest and meadows soils – feed the groundwater-table in the Ill flood plain).

Kohler (1971), Kohler & Zeltner (1981) found no correlation between nitrate and distribution of the communities in a very comparable hydrological sector. The nitrate content they measured was, on average, as much as 10 times higher than that in our sites: they measured nitrate content up to 140 ppm (31.6 ppm $N\text{-}NO_3$) in the stations with *Potamogeton coloratus*, but this figure remains exceptional. It is not surprising when we know the ecophysiological minima and the low toxicity of nitrate for the aquatic macrophytes. Melzer (1980) showed that *Potamogeton coloratus*, very sensitive to ammonia pollution, develops a high nitrate reductase activity and thus uses nitrate as a nitrogen source.

This correlation between the A, B and C communities and the relatively high nitrate content is only due to a sampling artefact, favouring the Ill sites which are much richer in oligotrophic streams (A-B-C quality) than the Rhine ones, where the groundwater-table has been spoiled since the river was channelled and has become uniformly eutrophicated (D-E quality). The nitrate has no influence on the aquatic vegetation composition below 12 ppm N-$NO_3$ (drinkable limit and the upper limit measured in the sector). They are easily leached through the soils because not bound to the soil colloids and so are very good hydrological tracer: for example, a spring with a high nitrate level though located near the Rhine (Site 8, the Istergraben spring, with an A community) indicates a phreatic current from the agricultural nitrated area of the 'Ried'. In contrast the 'Schoenau spring' (situated on the bank of the channelled Rhine) whose nitrate content is low and phosphate content high, close to those of the Rhine, is directly influenced by the 'Rhine filtrates'.

In the same way, the chloride parameter is also a good hydrological tracer (Carbiener & Krause 1975) but has little influence on the vegetation at the concentrations measured (50–150 mg/l). The waters of the Ill flood plain are poorer in chloride than those of the Rhine sector, more highly contaminated by discharges from the 'Mines de potasse d'Alsace'. This parameter clearly distinguishes these two sectors.

The correlation between plant communities and temperature or dissolved $O_2$ (parameters correlated to the second principal component) shows that A, B and C seem to be restricted to streams low-temperature and, C and CD, to high temperature ones. E is an exception: the mean temperature is about that measured in the A community, but, in this case, most of the measurements were made in the winter.

The cold stenothermy decreases from upstream to downstream in phreatic streams, which corresponds to the normal evolution of the community distribution from A to E along a stream when there is no outside perturbation. The correlation between low-temperature and oligotrophic communities is also an artefact: the most oligotrophic A and B communities are often, but not exclusively, recorded near springs fed by groundwater, hence, at the head of the stream, where the water is cold (9–11 °C) in all seasons. On the contrary, the most eutrophicated sectors, with D and E communities, often lie in the eurythermized downstream sector. In the sites of cold springs, where the A and B communities are found, dissolved $O_2$ is relatively low (30–40% of saturation, which corresponds to the $O_2$ content in the superficial fringe of the groundwater-table); more downstream, where the balance with the atmosphere is reached, $O_2$ saturation of the waters is observed. It should be noted that the springs of the Rhine sector (Sites 22 and 23), classified as D, have a particulary low $O_2$ content (less than 1–2 ppm). Because of the pollution of the river by organic matter, the 'Rhine filtrates' have active ammonization and are less oxygenated than the pure groundwater of the Ried (where we find 4 ppm dissolved $O_2$ at 10–11 °C). Thus, the apparent link between the dissolved oxygen and the phytosociological sequence is a sampling artefact, as was the correlation with the temperature.

### *Bioindicator value of the communities*

The comparison of our data with those of the Centr-Europa litterature (specially the works of Kohler and some data of Wiegleb) in the range of calcic bicarbonate waters of rhitral or rhitral-potamal type, confirms and improves the precision of the bioindicator value of plant communities defined by Carbiener & Ortscheit (1987).

– The A community is characterized by the oligotrophic ecological group of *Potamogetonetum coloratus* with *Potamogeton coloratus*, *Chara hispida* and *Juncus subnodulosus*.

The maximal threshold of P-$PO_4$ and N-$NH_4$ is 15 ppb in the Rhine valley.

Kohler (1971), Kohler & Zeltner (1981) give a threshold of 30 ppb of P-$PO_4$ and N-$NH_4$ for the same community. These values, higher than ours, could be explained by the presence of peat-bogs in their study site (the humic acid decreasing the ammonia toxicity) or even by temporary human disturbances, or even by the lower hydrological range, (the prealpine groundwater-tables studied by Kohler are less powerful than that of Alsace). If the trophic organisation of the phytosociological sequence described by Kohler is very similar to ours, their values are always more dispersed. They reach values which, in our study site, correspond to the most eutrophicated streams. In the same way, the catena of plant communities published by Kohler in correlation with increasing eutrophication contain fewer communities (A, B, C and D).

– The B community with *Sium erectum-Mentha aquatica fo. submersa* is only characterized negatively by the absence of A and C communities species. *Sium* generally predominates but does not characterize the community.

The interval is 3–10 ppb of P-$PO_4$, traces-29 ppb of N-$NH_4$ (Table 4). There too, the values given by Kohler are higher and more dipersed: 0–20 ppb P-$PO_4$, 0–70 ppb N-$NH_4$.

– The C community of the *Callitrichetum obtusangulae* (defined by Carbiener & Ortscheit 1987) is also negatively characterized by the absence of the D species. We confer on it a more restrictive sense than other authors (Kohler 1971; Wiegleb 1978 and Meriaux 1983). It does not include a specially discriminant ecological group although *Callitriche* generally predominates but not enough to characterize this community (*Sium erectum* is often abundant in rheophilic facies).

The interval of values is traces-23 ppb P-$PO_4$, traces-30 ppb N-$NH_4$.

– The eutrophic D community of the *Zannichellio-Callitrichetum* (cf group 4b of Wiegleb 1978) is characterized by the ecological group: *Zannichellia palustris*, *Nasturtium officinale* (as a riparian community of *Nasturtietum*, the submersed form can be found, either in short supply or abounding, as a disturbance indicator in B or C communities), *Potamogeton densus* (which is slightly less eutrophic than the previous ones), *Ranunculus trichophyllus* (rare in the dition). This community is generally dominated by *Callitriche obtusangula*, and also *Sium erectum* if the current is fast. This community corresponds to the *Callitrichetum obtusangulae* of the previous authors. In the karst springs and streams which are always more eutrophicated than the prealpine alluvial groundwater, it is replaced by the vicariant rheophilic community *Ranunculo trichophylli-Sietum erecti* (Th. Müller 62).

The interval of values is 10–60 ppb P-$PO_4$, traces-80 ppb N-$NH_4$. Kohler gives the following values: traces-130 ppb N-$NH_4$, traces-50 ppb P-$PO_4$ for the community he called C and which corresponds to our communities C and D.

An intermediate community that we called CD is defined by the interval of values traces-29 ppb N-$NH_4$, 3–22 ppb P-$PO_4$, which cannot distinguish it from the C community. But the ecological group with *Lemna trisulca* (optimum?), *Fontinalis antipyretica* (absent or rare in C) and with abundant *Veronica anagalis aquatica fo. submersa* is typical of the CD community.

– The E community is characterized by the ammoniophilic plants, *Ranunculus fluitans*, *Oenanthe fluviatilis* (subatlantic limit area), *Potamogeton perfoliatus*, *P. pectinatus*, *Ceratophyllum demersum*, but the nitrate must be above the minimum (0.2–1 ppm N-$NO_3$).

The interval: 24–42 ppb P-$PO_4$, traces-90 ppb N-$NH_4$ characterizes the E community that Kohler called D, with the following values traces-700 ppb P-$PO_4$, traces-475 ppb N-$NH_4$.

– Groups covering two or more levels of the scale:

*Hottonia palustris*, *Myriophyllum verticillatum*, *Veronica anagallis aquatica fo. submersa*, *Potamogeton friesii*, *Hippuris vulgaris* which cover the C and D communities.

*Ranunculus circinatus* (lenitic facies), *Elodea canadensis*, *Nuphar lutea* cover C, D and E; *Ranunculus trichophyllus* (lotic facies), *Potamogeton crispus*, *Lemna trisulca* are present in (C), D and E.

*Myriophyllum spicatum*, *Elodea nuttalii*, *Chara globularis* (*fragilis*) are found in D and E; *Elodea ernstae* in (D) and E, *Chara contraria* in D and (E).

For the Lemnides contact-communities we observe:

*Lemna minor* in (C), D, E

*Spirodeletum polyrhizae*, sub-community with *Azolla* corresponds to the group with *Spirodela polyrhiza*, *Lemna minor*, *Lemna minuscula*, *Azolla filiculoides*, *Enteromorpha sp.* *Cladophora crispata* in D and E.

### *The role of morphometry and current velocity*

We did not integrate these factors into the analysis, but they have frequently been put forward by some authors (Wiegleb 1984). Current velocity interferes with the bioavailability of ions and especially the competition of benthic and epiphytic algae (both decrease when current velocity increases). Our opinion is based purely on field experiments; we bring out that while current velocity may favour a few species (e.g., *Hottonia palustris*, *Ranunculus circinatus*, *Nuphar lutea*, *Sparganium emersum*... for the lenitic facies, *R. trichophyllus*, *R. fluitans*, *Sium erectum* for the lotic facies) it is not a discriminant factor in syntaxonomic differenciation: thus, the vegetation of a stream with natural morphometry giving succession of lenitic and lotic reaches shows a succession of facies which appear very different because of the dominance of lotic or lenitic eurytopic species. But if the trophic status is homogeneous, vegetation analysis with the Braun-Blanquet method – requiring relevés of long stream sections (100–200 m) – only reveals a connection of these facies in one community. Another argument is that examples of each of the communities described can be found in streams or rivers of very variable morphometry.

On the second hand our assessment is based on a series of diachronic vegetation analyses of streams affected by recent man-induced changes in their trophic status. Let us quote two oligotrophic streams affected at their head by the creation of trout hatcheries. Downstream of the hatchery, the vegetation formerly of type A was transformed into the D type in both cases after a spell of devastation due to saprobic conditions (their catenas changed from AB to ADC). For example, riparian *Lemnaceae* (considered as typically lenitic), appeared 'de novo' even on streams with a fast current after the eutrophication. The drainage channel of the Canal d'Alsace (D community) where the current velocity in the channel fluctuates between 0.5 and 1 $\mathrm{m \cdot s^{-1}}$ (general eutrophication of the Rhine riparian groundwater-table by the seepage of the channeled river through its bed) gives an example.

### *Disturbance indicators: ecological describers of hydrological processes*

The aquatic macrophytes integrate the seasonal or disturbance factors which hydrochemical analyses do not reveal, because sampling is usually too infrequent; thus, phytosociological analysis is more sensitive than the statistical one to hydrochemical data. More particularly, plant communities can integrate short-term variations in the water chemistry, which can be localized through variations in the species composition of the community. These variations act as ecological describers (in the sense of Bournaud & Amoros 1984) of these disturbances. Thus the species involved can be considered as disturbance indicators. They also offer an opportunity to reveal under favourable conditions, the functioning of hydrological exchanges.

For example, in the Rhine valley, the relations between the surface waters (rivers and their floodplain) and the groundwater-table were clarified with this method (Klein & Carbiener 1988; Carbiener *et al.* 1988). Many species, such as *Sium erectum*, *Potamogeton densus*, *Nasturtium officinale*, *Lemna trisulca*, *Chara globularis*,..., by their xenosaprobe behaviour are 'ecological describers' revealing the location of groundwater springs characteristic of the complex network of the saprobe braided arms of the Rhine, upstream of Strasbourg (polluted through the connection with the same river, Robach *et al.* unpublished findings).

In the same way, in the case of the Ill floodplain, the groundwater streams show abnormal cohabitations of meso-eutrophic (but oligosaprobe) species such as *Callitriche obtusangula*, *Lemna trisulca*, *Hottonia palustris*, *Veronica anagalis aquatica fo. submersa*, *Nasturtium officinale* with plants of the A community, which localise the temporary discharge of eutrophic (but diluted) Ill water during overflows. On the contrary, the reappareance of the A group, downstream of eutrophicated stretches, localize oligotrophication through limnocrene springs.

It is thus possible to describe the hydrological events occurring along a groundwater stream in the form of an alphabet translating the possible different patterns of the vegetation catena. For example, and schematically, normal upstream – downstream catena ABCDE can be replaced by

– catena inversion (D) CBA if eutrophication takes place at the head of the stream and oligotrophication downstream.

– simplified catena AD or AC, BD (streams running through a village)

– complex catena ABCA as a result of the above-mentioned complex hydrological functioning.

The homology observed in the comparable geomorphological hydrosystems of the Haut-Rhône upstream of Lyon are noteworthy in this respect (Castella & Amoros 1984, 1986). The bioindication scale formulated can be used to characterize of the hydrological exchange between the compartment stream and river-vegetation and soil-groundwater table (Carbiener *et al.* 1988).

## Résumé

Les résultats présentés ont été obtenus sur la base d'une analyse statistique d'un tableau de relevés phytosociologiques à 6 groupements (associations végétales aquatiques d'eaux bicarbonatées calciques) et 7 variables hydrologiques (température, $O_2$ dissous, DCO, $N$-$NH_4$, $N$-$NO_3$, $P$-$PO_4$, Cl). Le déterminisme écologique de la séquence a pu être précisé par:

– l'étude des paramètres physico-chimiques du milieu aquatique sur des prélèvements d'eau périodiques

– l'étude de l'évolution diachronique (modifications au cours des ans) de la végétation aquatique à la suite de modifications du statut trophique, confirmées par l'analyse chimique

– l'étude synchronique comparative de la végétation de différentes rivières et portions de rivières de statut trophique différent mais alimentées par la même vaste nappe des graviers rhénans würmiens d'Alsace.

L'analyse en composantes principales normée a permis d'établir la très bonne corrélation existant entre les six associations de macrophytes aquatiques et le facteur trophie ($N$-$NH_4$, $P$-$PO_4$). L'analyse factorielle discriminante a été utilisée afin de vérifier le classement d'après les relevés de végétation avec celui obtenu par l'analyse. Les auteurs donnent ainsi une échelle très précise de bioindication (basée sur les associations végétales) du degré d'eutrophisation de cours d'eau en milieu bicarbonaté calcique oligosaprobe.

## Zusammenfassung

Die Studie beruht auf der statistischen Auswertung der Beziehungen zwischen aquatischen Makrophytengesellschaften und wasserchemischen Parametern ($N$-$NH_4$, $N$-$NO_3$, $P$-$PO_4$, COD, Temperatur, gelöster Sauerstoff, $Cl^-$) von Fliessgewässern der Oberrheinischen Tiefebene.

Die untersuchten Gewässer sind Grundwasserbäche mit oligosaprobem (ausser Ausnahmen) hartem Wasser aus dem Würmzeitlichen Schotterreservoir.

Langfristige Pflanzensoziologische Untersuchen ergaben für diese Gewässer eine klare Gliederung in sechs Vegetationseinheiten die eine Catena steigender Eutrophierung darstellen und durch die Symbole A, B, C, CD, D und E bezeichnet werden (Carbiener & Ortscheit 1987).

Zur Errechnung der Korrelationen wurden 29 Grundwasserbäche erfasst, und durch ebenfalls jahrelange periodische Wasserproben (insgesamt mehrere tausend Messungen) der 7 Parameter auf die pflanzensoziologische Catena geeicht.

Die Diskussion der Resultate stützt sich daher sowohl auf synchronische als auch diachronische Veränderungen sowohl der Pflanzengesellschaften als auch der Wasserchemie. Wir betrachten daher die Resultate als sehr gesichert und auf andere Untersuchungsgebiete übertragbar.

Die Analyse der Hauptkomponenten zeigt die gute Beziehung zwischen den Pflanzengesellschaften und der Trophie ($N$-$NH_4$, $P$-$PO_4$), unter Ausschluss von $N$-$NO_3$. Die sechs Pflanzengesellschaften wurden entsprechend der Trophieniveaus geordnet. Anhand einer diskriminierden Faktorenanalyse wurden die Trophie-

bewertungen der jeweiligen Gewässerabschnitte überprüft.

Die Autoren schlagen damit eine sehr präzise Bioindikationsskala (auf der Basis von Makrophytengesellschaften) für den Grad der Eutrophierung in unverschmutzten Gewässern mit hoher Wasserhärte vor.

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