

LONGITUDINAL CHANGES IN MACROINVERTEBRATE ASSEMBLAGES IN THE MEUSE RIVER: ANTHROPOGENIC EFFECTS VERSUS NATURAL CHANGE¹

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ABSTRACT

A collaborative study among three nations (France, Belgium, Netherlands) along the Meuse River developed a consistent approach for collecting and interpreting macroinvertebrate data. Specific mesohabitats were sampled in 16 locations along an 800-km stretch of this lowland regulated river. The objective was to assess the 'river health' using macroinvertebrate communities as indicators of biological and ecological variation in space. The main changes in assemblages were investigated using multimetric and multivariate approaches. The authors examined relationships between faunal variations and both physico-chemical gradients and man-made disturbances. We related species traits to faunal changes and habitat characteristics.

Both a gradual shift from a macroinvertebrate assemblage dominated by insects to a community dominated by crustaceans and molluscs and a drastic decrease in biotic index values were observed along the longitudinal gradient. Taxa were distributed according to oxygen, nitrate and ammonium concentrations, pH, conductivity and summer hydraulic conditions. But major faunal differences among sites could not be explained simply by physico-chemical variables. The trait analysis underlined the role of temporary habitats in structuring the summer macroinvertebrate community of sites of the uppermost French sector, which supported the most diverse community in terms of trait combination. Downstream the macroinvertebrate community exhibited a more simple and less stable functional organization.

We concluded that the Meuse River exhibited both a high biodiversity and a 'reasonably good' water quality in the upper reaches. Two transition zones highlighted the influence of a high degree of human impact on stream integrity. Regulation for navigation, ship traffic and heavily polluted effluent discharges influenced instream conditions via multiple processes determining a decline of both habitat stability and diversity. However, the rare occurrence of habitat-sensitive species in the lower reaches indicated that a partial recovery of communities may be predicted if restoration and protection of disturbed (especially riparian) habitats are fulfilled. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS: anthropogenic impact; biological traits; macroinvertebrates; Meuse River; physical habitat; regulated river; river continuum; water quality

INTRODUCTION

The increasing need for methods to evaluate 'river health' and to assess the impact of alternative management schemes has stimulated research on the use of aquatic communities as indicator systems or as criteria to identify conservation or restoration tools (Cairns and Pratt, 1993; Armitage *et al.*, 1995; Barbour *et al.*, 1996; Palmer *et al.*, 1996; Pardo and Armitage, 1997; Reynoldson *et al.*, 1997; Bailey *et al.*, 1998; Dolédec *et al.*, 1999; Karr, 1999; Smith *et al.*, 1999; Usseglio-Polatera *et al.*, 2000a). Owing to their diversity of forms, habits and responses to environmental stresses, benthic macroinvertebrate assemblages are good candidates for the bioassessment of stream quality and/or integrity (Rosenberg and

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¹ This paper arose from the Eighth International Symposium on Regulated Streams (EISORS).

Received 1 August 2000
Revised 18 January 2001
Accepted 5 March 2001

Resh, 1993). Aquatic conservation, to be effective, must be based on a clear understanding of the structure and function of 'natural' river ecosystems (Ward, 1998; Townsend and Riley, 1999).

As a result, a first international survey of benthic invertebrate fauna was carried out by the International Commission for the Protection of the Meuse (C.I.P.M.) in 16 sites along an 800-km stretch of the Meuse, a large lowland regulated river. The explicit goal was a first assessment of the 'river health' using macroinvertebrate communities as indicators of biological and ecological variation in space. But analysis of this data set has provided an opportunity to assess effects of natural river changes, as well as man-induced disturbances on native macrobenthic assemblages. The main changes and transition zones in assemblages along the longitudinal gradient were investigated using multimetric and multivariate approaches. Possible relationships between faunal variations and both environmental parameters (physico-chemical variables and hydrology) and specific man-made disturbances (engineering works, passage of commercial navigation vessels, sewage effluent inputs) were examined. A functional approach relating species traits to faunal changes and habitat characteristics, which has been successfully used to compare environments at different spatial/temporal scales and supplement studies of biodiversity (Resh *et al.*, 1994; Richards *et al.*, 1997; Townsend *et al.*, 1997; Usseglio-Polatera *et al.*, 2000b), was used to discriminate among organizational structure of communities. This scientific programme was the first international collaborative study allowing a coordinated assessment of the biological integrity of the whole Meuse River.

STUDY AREA AND METHODS

Sampling locations and field procedures

The River Meuse has its source near the Plateau of Langres (altitude 409 m) in France. Then, it flows through France (492 km), Belgium (194 km) and the Netherlands (239 km), where it enters the North Sea by forming with the Rhine and Schelt a complex system of channels, nowadays entirely dammed for flood control (Figure 1). The river has alkaline nutrient-rich waters (Meurisse-Genin *et al.*, 1987; Gosselain *et al.*, 1994), is relatively clean in the French upper part, but becomes heavily polluted in the Belgian part, although chemical discharges have been reduced during the past few years (Meurisse-Genin *et al.*, 1987; Descy *et al.*, 1988; Admiraal *et al.*, 1993; Van Genderen *et al.*, 1994; Stuijzand *et al.*, 1996). The upper reaches, from the headwaters to the Chiers confluence (near Sedan), correspond to a subnatural meandering sector. Upstream of Troussey, the Meuse is unnavigable. From Troussey to Sedan, the Meuse River and the navigable 'East Canal' flow in parallel, with frequent connections. Nevertheless, the main channel still exhibits some near natural characteristics. The middle reaches, from the Chiers confluence to Eijsden (average gradient: 0.23‰), have been heavily regulated (with weirs and locks) in order to enable a high level of ship traffic with high loading gauge (1350 T upstream from Namur; 9000 T downstream—Evrard and Micha, 1995). From Eijsden to Stevensweert, the Meuse separates into the main channel, a non-canalized river section with a rather strong average gradient (0.40‰), and a parallel canal ('Juliana Canal') for navigation. Downstream from Stevensweert, the Meuse River becomes a typical lowland embanked and regulated river (0.08‰).

Sixteen sampling locations (each defined as an area covered by the width of the main channel with a total length of about 1 km) were selected (Figure 1). Within the framework of this international monitoring programme, either those 'biotopes' (= mesohabitats, *sensu* Armitage and Pardo, 1995) that occurred along the whole river were sampled, or being characteristic in river locations distinguished as 'stones in the near-shore zone', 'littoral bottom', 'aquatic vegetation', 'profundal bottom' and 'artificial substrate'. Within a sampling location, different sampling sites could be distinguished depending on the place where the 'biotopes' to be sampled could be found.

Stones in the littoral zone were sampled with the help of a surber sampler (net 500 µm mesh). Littoral bottom and aquatic vegetation were sampled with a standard macroinvertebrate hand net (opening 25–30 cm width, net 500 µm mesh). A triangular dredge, a grab or a box-correr, depending on size of the bottom



Figure 1. Map of the basin of the River Meuse, with the location of the study sites (solid circles)

particles, were used for the profundal bottom. Artificial substrates consisted of pieces of brick ($\pm 4-8$ cm in size) in a polyethylene netting (potato bag of 38×48 cm). Each netting was filled with 4 L of the substrate and firmly packed in order to prevent rolling of the material. The colonization period was 28 ± 1 days.

In August 1998, faunal samples were simultaneously collected (eight surber or hand net samples, except for Lanaken) or retrieved (two to three artificial substrates) from banks and the channel (one to three dredge samples) at each sampling location (Table I). In Belgium and the Netherlands, surber or hand-net samples corresponding to the same mesohabitat type (i.e. a combination of a substrate type and a range of current speed) were pooled. The same strategy was used for dredge or grab samples of profundal bottom. As a result, the number of 'sample units' varied from five to fourteen in the stations according to the substrate mosaic heterogeneity (but the sampling effort was quite similar).

Invertebrates were identified at the species or genus level (except for Diptera, for which sub-family and family levels were used, and for Nematoda, Oligochaeta and Hydracarina, which were recorded as such).

Table I. Design of the sampling programme (description of the biotopes/mesohabitats sampled at each station. Number of sample units per mesohabitat/biotope type)

Stations	Goncourt ^a	Brixy ^a	Saint-Mihiel ^a	Inor ^a	Donchery ^a	Ham-sur-Meuse ^a	Heer	Lustin	Namèche	Chokier	Hermalle	Eijsden	Lanaken	Kinrooi	Belfeld	Keizersveer
Sampling methods Surber or net sampler	Mesohabitats/ Biotopes															
	Stones in the near-shore zone	2	3	3	1	2	2	1	1	1	1	1	0 ^c	1	1	1
	Littoral bottom	2	1	1	2	1	2	1	1	1	1	1	0 ^c	1	1	1
	Aquatic vegetation	4	4	4	5	5	4	0 ^b	1	0 ^b	1	1	0 ^b	0 ^b	1	0 ^b
Dredge or grab	Profundal bottom	3	3	3	3	3	3	1	1	1	1	1	1	1	1	1
Artificial substrate	3	3	3	2	3	0 ^d	2	2	2	2	2	2	0 ^d	3	2	2

^a Sampling strategy according to the French I.B.G.A. protocol.

^b No aquatic vegetation in the station.

^c The water level did not allow the sampling of the littoral and near-shore zones.

^d All the artificial substrates were not recovered.

Weekly physical and chemical characteristics (17 variables) of sampling locations were provided by the C.I.P.M.

Statistical procedures

Changes and transition zones in longitudinal assemblages were investigated using four basic approaches:

1. A Correspondence Analysis (CA) was carried out to compare the faunal structure (=ln(x + 1)-transformed abundance distribution of taxa) of sampling sites (Figures 2 and 3).
2. A combination of indices (taxonomic richness, 'Indice Biologique Global Adapté aux grandes rivières' (I.B.G.A.) and 'Biological Monitoring Working Party' index (B.M.W.P.)) was used to evaluate the biotic integrity of communities (Figure 4).
3. We used co-inertia analysis to check for a relationship between faunal changes and physico-chemical variables (Figures 5 and 6) and
4. to demonstrate the importance of 11 biological traits (i.e. attributes describing the 'life history' of organisms) and 11 ecological traits (i.e. characteristics describing organism/habitat relationships) of 159 benthic macroinvertebrate taxa to discriminate among functional structure of faunal assemblages (Figures 7 and 8).

Mean values of physico-chemical variables during the 3-month period before the faunal sampling date were considered as representative of the mean water quality of each sampling station during the major growing period of macrobenthic organisms. The resulting data were processed by standardized principal component analysis (PCA; results of this analysis were not developed in this paper). Then, co-inertia analysis—an appropriate method for relating any kind of data sets (sharing the same statistical units: sampling locations in this case) using any kind of standard analysis (Dolédec and Chessel, 1994)—was used to demonstrate a common structure between faunal and physico-chemical characteristics of stations.

To structure biological and ecological information, we documented features concerning the life cycle, the resistance or resilience potential of organisms, general physiological traits, and behavioural aspects of

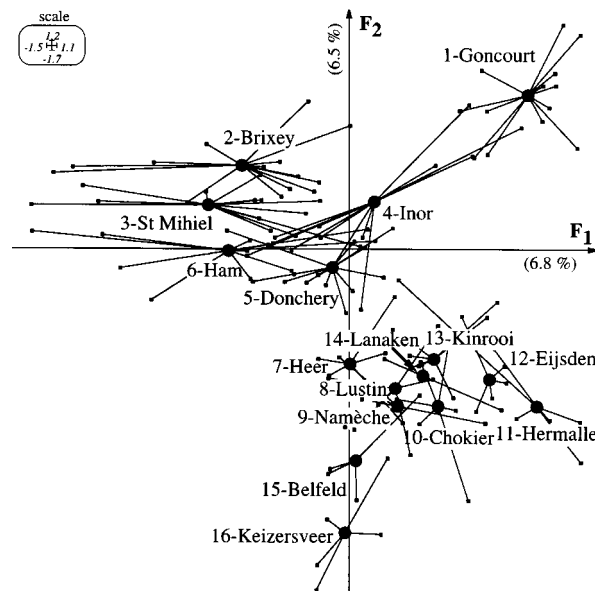


Figure 2. Ordination of sampling locations by correspondence analysis. Distribution of 16 stations (solid circles) on the first factorial plane. Stations are positioned at the weighted average of their samples (small squares). Lines link samples to their stations. An illustration of the within-station variability of the faunal structure is obtained. Stations are numbered from 1 to 16, along the longitudinal gradient. Explained variance (%) is indicated for each axis

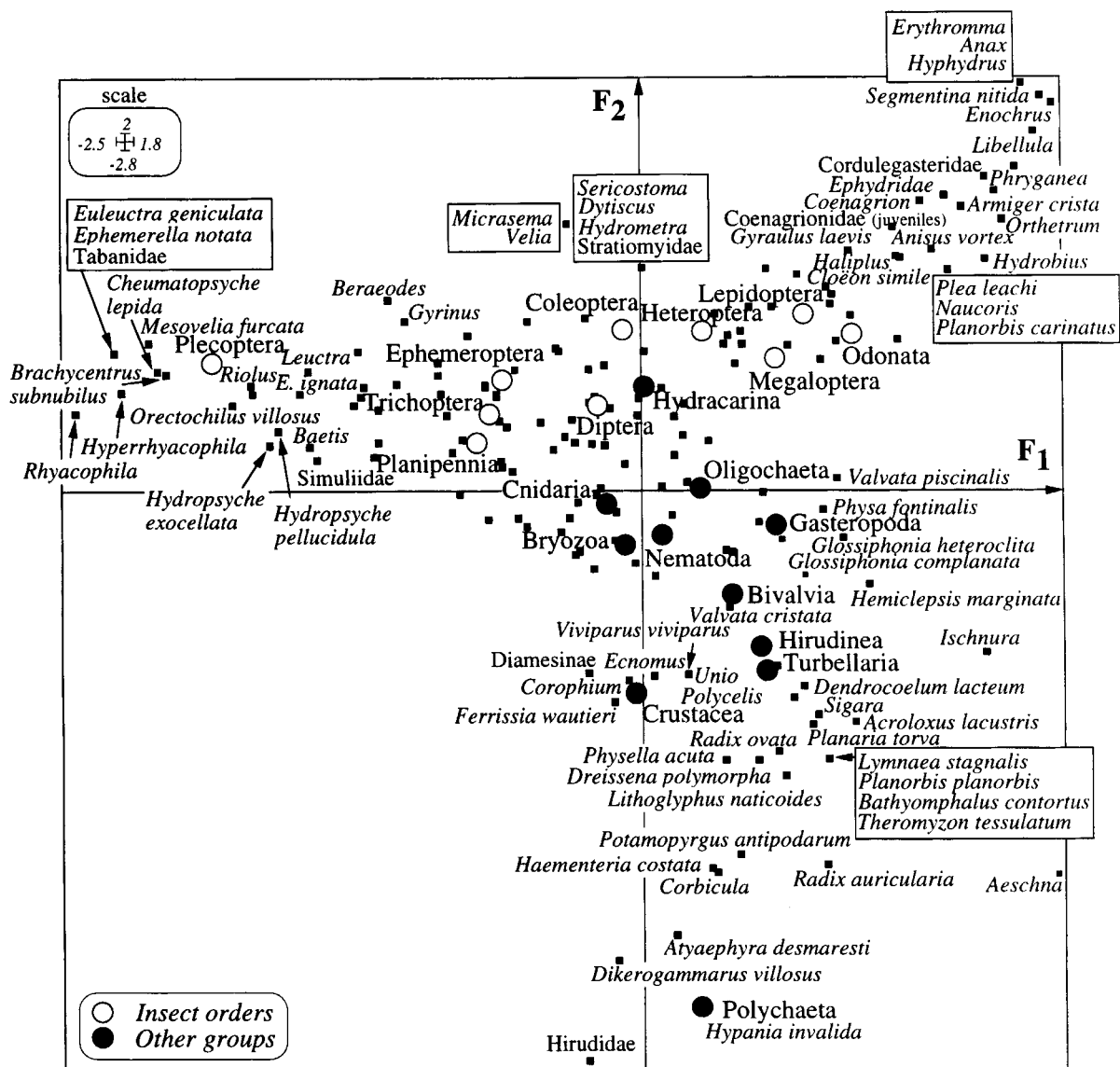


Figure 3. Ordination of taxa by correspondence analysis. Distribution of 21 faunal groups (circles) on the first factorial plane. Groups are positioned at the weighted average of their taxa (i.e. species, genera, sub-families and/or families = small squares) locations. For readability, only labels of taxa displaying a characteristic location on the plane are indicated. Framed labels correspond to taxa having the same location

reproduction or nutrition of taxa. For ecological information, we focused on variables that we expected to serve as large-, intermediate- or micro-scale descriptions of spatial characteristics of the ‘habitat’ used by the taxa (for further information, see Tachet *et al.*, 2000). We resolved variables describing traits into a number of categories (for further information about variables and categories, see Usseglio-Polatera *et al.*, 2000a,b). To ‘translate’ the available knowledge about traits of organisms into numerical values, we assigned a score to each taxon describing its affinity to each trait category, from ‘0’ indicating ‘no affinity’ to ‘5’ indicating ‘high affinity’ (Usseglio-Polatera, 1991; Chevenet *et al.*, 1994; Tachet *et al.*, 2000). Thereby, the relevant features of a taxon were described by the relative distribution of the information among the categories of each trait. First, the trait data matrices (each composed of 159 taxa and 11 traits)

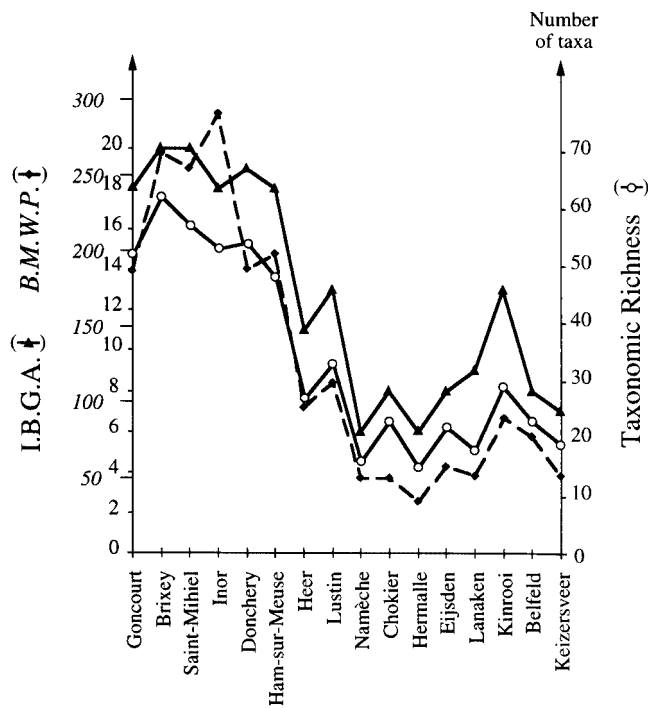


Figure 4. Assessment of the biological quality of the Meuse River. Longitudinal variations in taxonomic richness, I.B.G.A. and B.M.W.P.

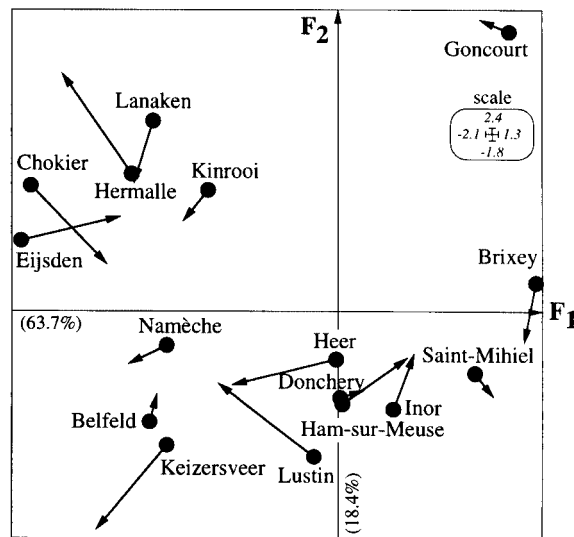
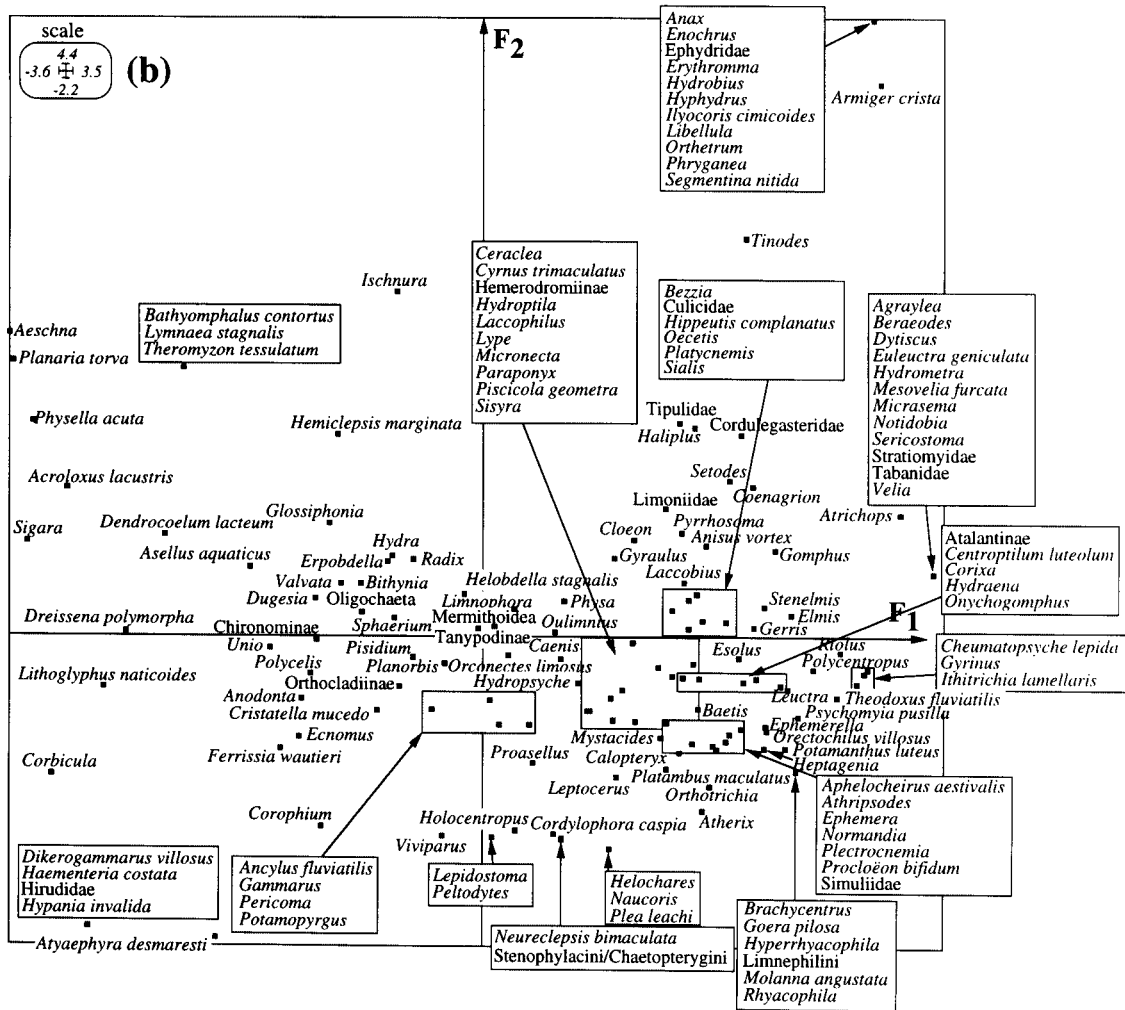
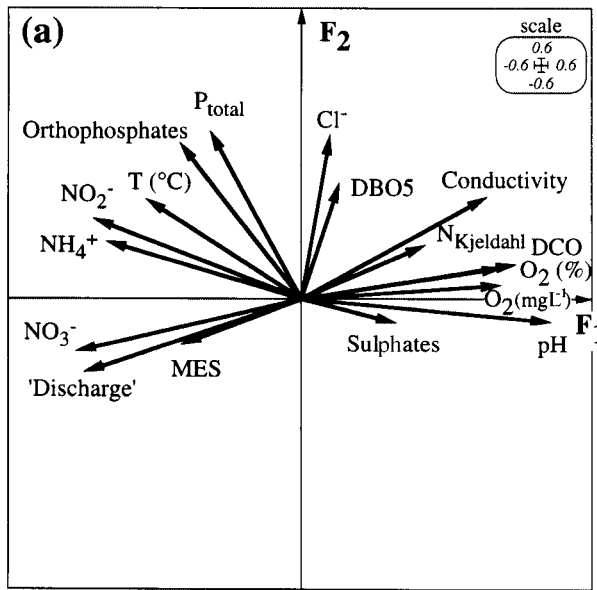


Figure 5. Co-structure between physico-chemical variables and abundances of taxa by co-inertia analysis. Comparison of station positions on the two F_1 - F_2 planes by co-inertia analysis. Each station is defined by an arrow. The beginning of the arrow (solid circle) marks the station position according to its physico-chemical characteristics and the end of the arrow marks its position according to its faunal assemblage. Explained variance (%) is indicated for each axis



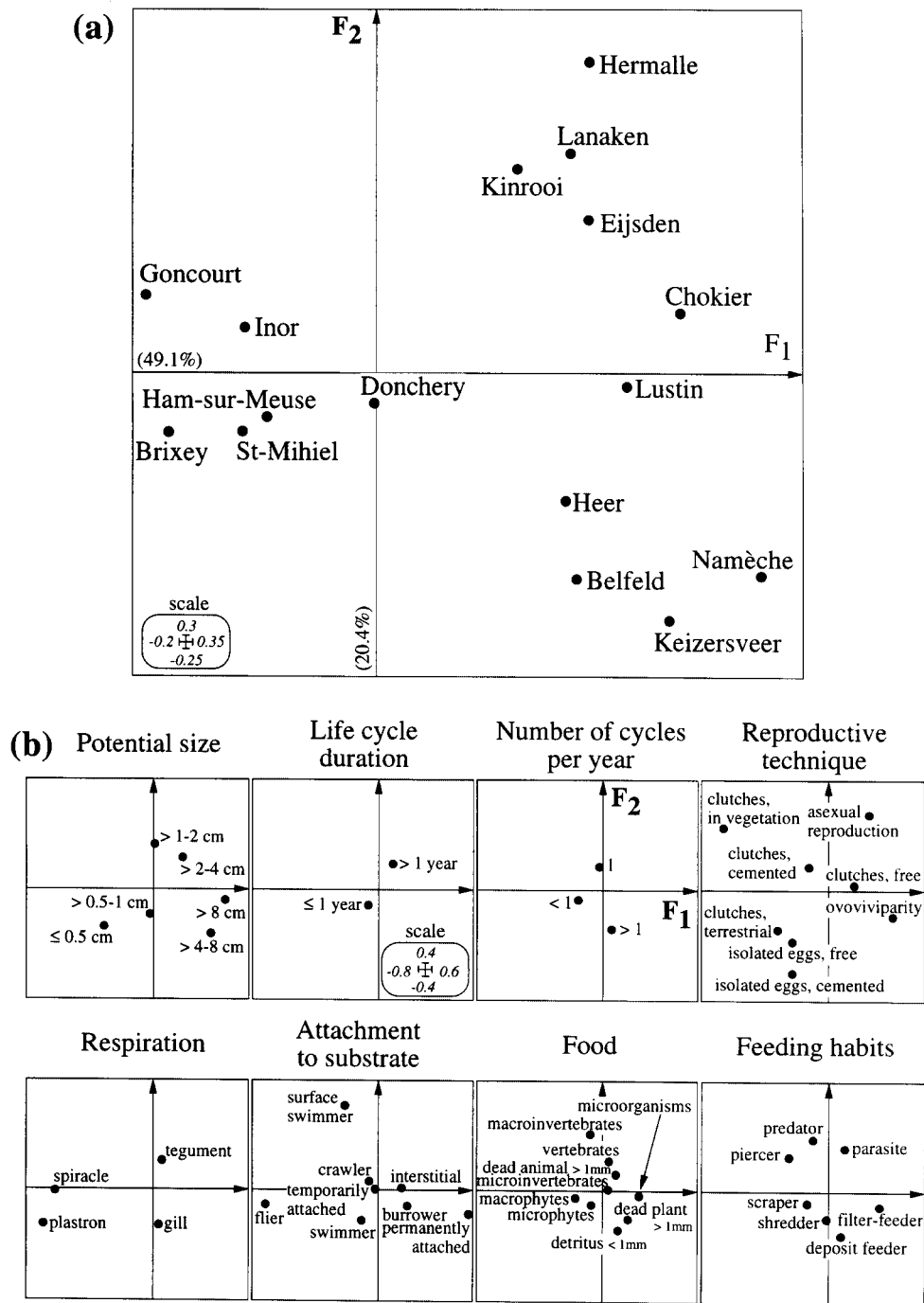


Figure 7. Co-structure between biological traits and abundances of taxa by co-inertia analysis. (a) Ordination of 16 stations on the first factorial plane. (b) Ordination of biological trait modalities on the first factorial plane. Only results of the eight most relevant traits for the co-structure are presented. Explained variance (%) is indicated for each axis

Figure 6. Co-structure between physico-chemical variables and abundances of taxa by co-inertia analysis. (a) Projection of physico-chemical variables on the first factorial plane. (b) Locations of taxa on the first factorial plane. Framed labels correspond to taxa having the same location or being in a same area of the plane

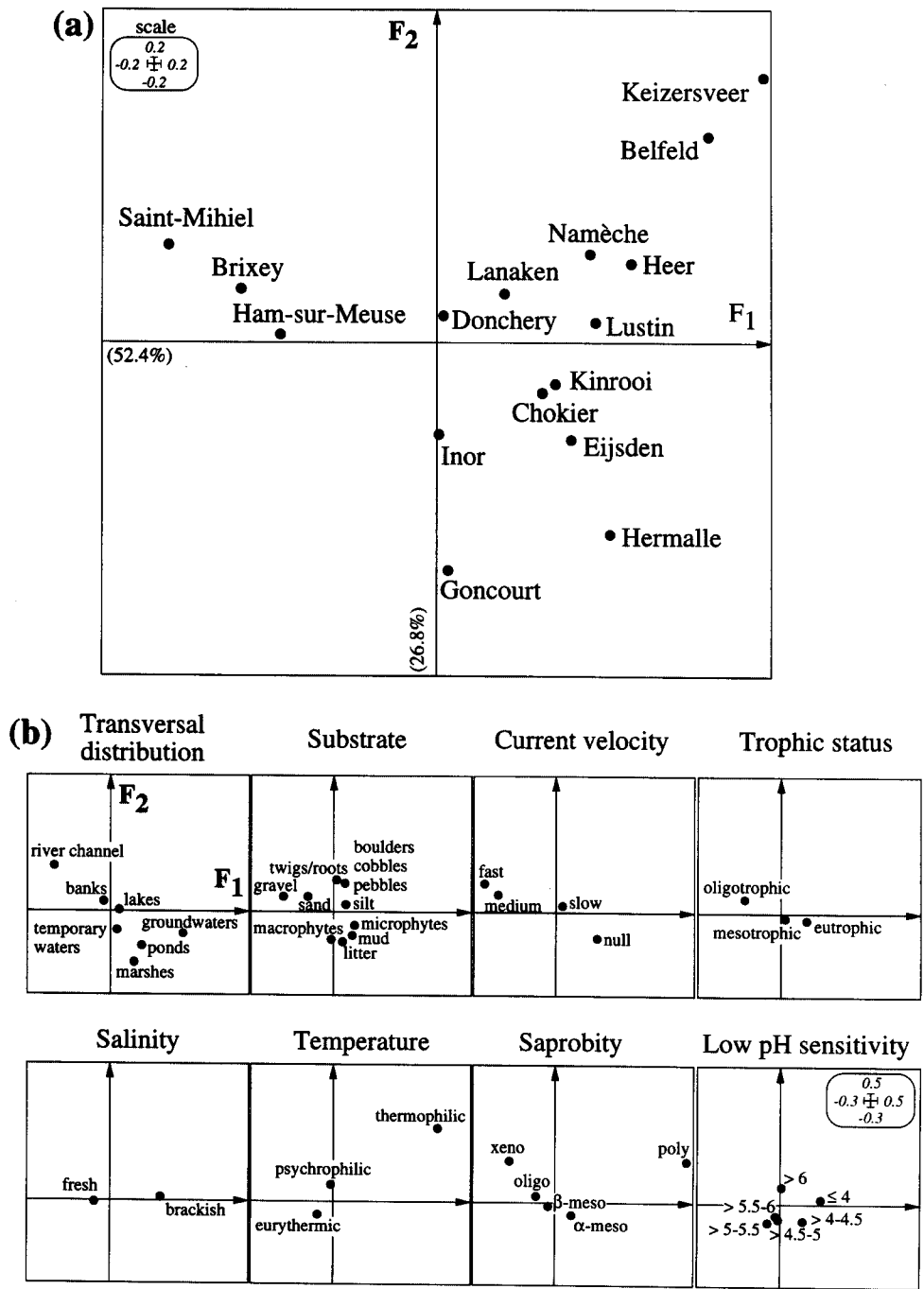


Figure 8. Co-structure between ecological traits and abundances of taxa by co-inertia analysis. (a) Ordination of 16 stations on the first factorial plane. (b) Ordination of ecological trait modalities on the first factorial plane. Only results of the eight most relevant traits for the co-structure are presented. Explained variance (%) is indicated for each axis

were treated using fuzzy correspondence analysis (FCA; Chevenet *et al.*, 1994) to investigate relationships within each set of traits (results were not developed in this paper). Then, we used co-inertia analysis to demonstrate a common structure between spatial distribution and biological/ecological attributes of taxa.

In each case, we evaluated the statistical significance of the co-structure between each couple of arrays by a random permutation test (e.g. Kazi-Aoual *et al.*, 1995).

RESULTS

Faunal structure

CA clearly illuminated the change of community structure along the longitudinal gradient. Samples were located along the F_2 axis from Goncourt and the French sites to stations of the Belgian and Dutch sectors (Figure 2). This gradient corresponded to a gradual shift from a macroinvertebrate assemblage dominated by insects (mainly Ephemeroptera and Trichoptera in riffle habitats; Coleoptera, Heteroptera and Odonata in pool habitats) to a community dominated by crustaceans and molluscs (Figure 3). Faunal variations along F_1 axis seemed to be essentially related to more-or-less lotic/lentic characteristics of sites. At the negative side of F_1 axis, Brixey, St Mihiel and Ham-sur-Meuse assemblages included taxa with rheophilous characteristics (such as *Leuctra*, *Euleuctra geniculata*, *Rhyacophila*, *Hyperrhyacophila*, *Brachycentrus subnubilus*, *Hydropsyche pellucidula*, *Riolus*, Simuliidae). At the positive side, Goncourt, Eijsden and Hermalle exhibited benthic assemblages with taxa more representative of lentic or stagnant environments.

B.M.W.P. and I.B.G.A. (a version of the normalized French biological index, adapted to large rivers (Gay Environnement and Agence de l'Eau R.M.C., 1997)) indices displayed the same longitudinal pattern (Figure 4). The high value of biotic indices in French sites referred mainly to a high taxonomic richness. In contrast, Plecoptera (except Leuctridae) and most of the more pollution-sensitive trichopteran families were absent, even in the upper reaches. Two transition zones, between Ham-sur-Meuse (France) and Namèche (Walloon Belgium) corresponded to a drastic decrease in index values. Between Namèche and Lanaken (Flemish Belgium), the macroinvertebrate fauna was poor and rather homogeneous. New taxa then appeared downstream of Lanaken (*Lymnaea stagnalis*, *Bathynomphalus contortus*, *Hypania invalida*, *Haementeria costata*, *Theromyzon tessulatum*) and recent exotic invaders (e.g. *Corophium curvispinum*, *Corbicula* and *Dikerogammarus villosus*) proliferated.

Faunal structure vs. physico-chemical structure

We assessed environmental (i.e. physico-chemical) gradients, and the extent to which they induced concordant patterns of taxonomic composition among benthic macroinvertebrate assemblages in sampling locations, using co-inertia analysis. The random permutation test indicated that combinations of physico-chemical characteristics and combinations of macroinvertebrate taxa were not randomly distributed among stations (estimated $p < 0.0001$). The optimal correlation between the first axis scores and the second axis scores of taxa (respectively equal to 0.949 and 0.927), indicated that the first two axes were potentially important in explaining the variability in sampling sites. These axes accounted for 63.7 % (F_1) and 18.4 % (F_2) of the total variability. Taxa were arranged along F_1 axis (Figure 6(b)), mainly according to oxygen, pH, conductivity, N-nitrates, N-ammonium and 'discharge' (i.e. a measure of observed summer hydraulic conditions as the mean summer discharge/mean annual discharge ratio—Figure 6(a)). From the right part towards the left part of the F_1 – F_2 plane, the distribution of variables illustrated a contrast between (1) psychrophilic or eurythermic taxa (mainly insects colonizing Brixey and Ham-sur-Meuse habitats—Figure 5) living in clean, saturated waters with rather high pH values (8.1–8.3) and thermophilic organisms (mainly Crustacea, Mollusca, Oligochaeta, Achaeta and Turbellaria collected in downstream sites) able to live in N- ($0.25 < \text{N-NH}_4^+ < 0.65 \text{ mg L}^{-1}$; $0.11 < \text{N-NO}_2^- < 0.20 \text{ mg L}^{-1}$) and P- ($0.4 < \text{P}_{\text{total}} < 0.7 \text{ mg L}^{-1}$) contaminated environments. In the higher right part of the plane, a particular assemblage collected in the furthest upstream station (Goncourt) tolerated high conductivity ($830 \mu\text{S cm}^{-1}$) and elevated chloride concentration (147 mg L^{-1}).

A simple way to compare the physico-chemical ordination and the faunal ordination of stations is to plot the standardized physico-chemical and faunal scores together on a factorial map and to link the two

positions of a given location by an arrow (Figure 5). Hence, it was possible to discuss the link between the faunal structure and the physico-chemical characteristics of sampling locations. Both structures were rather similar (in general, arrows were short). Nevertheless, most of the stations of the Heer-Eijsden stretch (except Namèche) exhibited longer vectors, illustrating some mismatch between the two structures. Furthermore, two groups of stations (Heer/Lustin and Inor/Donchery/Ham-sur-Meuse) displayed close physico-chemical characteristics (solid circles of arrows began in the same area), but fairly different faunal organization (arrows pointed to different directions and their ends were well separated). As a result, major faunal differences among these two groups of stations could not be explained by physico-chemical variables.

Faunal structure vs. bio/ecological trait structure

The co-structure between spatial distribution and both biological and ecological traits of taxa was highly significant ($p < 0.0001$). Communities of French sites differed clearly from communities of other sites (Figure 7(a) and Figure 8(a)) according to a biological (Figure 7(b)) and ecological (Figure 8(b)) trait ordination. The biological traits highlighted size (small to large), reproductive traits, respiration (aerial to aquatic), substrate relation (swimmer and/or crawler to interstitial or burrower) and feeding habits (piercer and scraper to filterer or deposit feeder). In contrast, the ecological traits featured saprobity of taxa (xeno- to polysaprobic), transversal distribution (from running to standing waters), current velocity (fast to null), and trophic status (oligo- to eutrophic) of freshwaters as 'significant' factors determining the ordination of communities.

The trait analysis underlined the role of temporary habitats—where some small-sized, short-lived organisms with a high dispersal potential have the ability to rapidly develop—in structuring the summer macroinvertebrate community of quasi-natural and/or unpolluted sites of the uppermost French sector. These sites exhibited the highest habitat heterogeneity and then supported the most diverse community, both in terms of systematic distribution (Figure 4) and trait combination (Figures 7 and 8). In such environments, stenoeic organisms with quite different combinations of bio/ecological traits can temporarily coexist within the same substrate mosaic.

Downstream from Ham-sur-Meuse, we observed a higher proportion of organisms having a mix of characteristics assumed to adapt them to frequent disturbances (through more generations per year, resistance forms, asexual reproduction or ovoviviparity) or features that remove or reduce the impact of environmental fluctuations (through firm attachment to substrate, but high dispersal abilities). The low substrate heterogeneity and stability, as a joint result of channelization, embankment and commercial navigation, led to a more simple, but less stable functional organization. As a result, the community is more vulnerable to invasive species.

DISCUSSION

Even if the concept of 'river health' (often seen as being analogous with 'human health' when applied to the evaluation of river condition—Resh *et al.*, 1995) remains subject to considerable debate (see, for example, Steedman, 1994; Meyer, 1997; Bunn *et al.*, 1999; Karr, 1999; Norris and Thoms, 1999), it is clear that the assessment of 'river health' involves comparisons (Norris and Thoms, 1999). In this way, appropriate metrics of 'river health', including measures of structure and function both of the biotic and of the physico-chemical components, may be compared between sites, keeping in mind that conditions constituting ecological health of rivers (i.e. biogeographic processes in the regional climatic and geological context) vary geographically.

Applying this approach to the Meuse River, we concluded that this lowland stream may be considered as a 'healthy river' in the French stretch, exhibiting both a high biodiversity and a 'reasonably good' water quality (except for Goncourt). A dramatic decline in the stream integrity was observed in the middle reaches. Two transition zones, between Ham-sur-Meuse (France) and Namèche (Wallon Belgium), highlighted the influence of a high degree of human impact on stream integrity. This sector was influenced

by some domestic effluents and by industrial pollution (Sambre confluence, Namur urban area—Figure 1). The main changes of water quality were an increase of organic pollution and eutrophication shown by a greater concentration of NH_4^+ , NO_2^- and total P and a lower dissolved oxygen concentration (see also Descy *et al.*, 1988). Furthermore, regulation for navigation and ship traffic influenced instream conditions via multiple processes involving a decline of both benthic habitat mosaic heterogeneity and littoral habitat stability. Indeed, channelization changed the characteristics of invertebrate habitats through channel straightening and eradication of pool-riffle sequences, together with a reduction of the substrate mosaic heterogeneity (Boon, 1988). Unpredictable pulses of turbulence and elevated suspended solids following passage of commercial navigation vessels, especially in large sublinear waterway sections (i.e. Namèche and Heer), may negatively affect riparian habitats and their macroinvertebrate communities (Miller and Payne, 1998; Vanden Bossche *et al.*, 1999; Clarke and Wharton, 2000). In addition, embankment construction has led to an artificial channel reducing the availability of littoral refugia that lessen the impact of both natural (e.g. unpredictable patterns of discharge) and anthropogenic (navigation) disturbances on the biota (Townsend, 1989; Townsend and Riley, 1999). This combination of factors contributed to a drastic decrease in biotic indices corresponding to a dramatic reduction of stenotopic taxa in macrobenthic assemblages. Thus, taxonomic richness was the lowest in the extensively straightened, deepened and embanked Heer-Eijsden sector, but increased in the non-canalized river section (including Kinrooi) situated downstream where small numbers of more habitat-sensitive organisms (e.g. *Hydroptila sp.*, *Ceraclea sp.*) were found. In this way, although there was a drastic, sequential downstream alteration of benthic assemblages along the Meuse River, rare specimens of habitat-sensitive invertebrates (mainly Trichoptera) still occurred in the lower reaches, and indicated that a partial recovery of communities may be predicted if restoration and protection of disturbed habitats (especially riparian) take place.

ACKNOWLEDGEMENTS

This study was supported by the International Commission for the Protection of the Meuse River (C.I.P.M.). The authors would like to thank the 'Agence de l'Eau Rhin-Meuse', 'G.R.E.B.E' (France), 'Centre de la Recherche de la Nature, des forêts et du Bois' (Walloon Belgium), 'Vlaamse Milieu-maatschappij' (Flemish Belgium), 'Institute for Inland Water Management and Waste Water Treatment/RIZA' and 'Vallenduuk' (Netherlands) teams for their fieldwork and co-operation. Dr J.P. Descy and all the expert members of the sub-group MI-2 'ecological quality' of the scientific committee of the C.I.P.M. made extensive and constructive comments on the results of this study and are gratefully acknowledged.

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