Bull. Environ. Contam. Toxicol. (1992) 48:428–434

Environmental Contamination and Toxicology

New Diversity Index for Assessing Structural Alterations in Aquatic Communities

Julio A. Camargo

Centro de Investigación y Tecnología del Instituto Nacional de Investigaciones Agrarias (CIT-INIA), Valdeolmos, Madrid, Spain

Gradual changes in environmental factors (e.g., flow, dissolved oxygen, water temperature and food resources) along the longitudinal profile of river systems exert a direct control on the population dynamics of aquatic organisms, resulting in characteristic biological communities within this ecological succession (Illies and Botosaneanu 1963; Hawkes 1975). In this way, a natural river may be considered as a functional continuum (Vannote et al. 1980). Nevertheless, many human activities are causing major environmental impacts on freshwater ecosystems, breaking the functional continuum and modifying the structure of aquatic communities.

Structural alterations in biological communities are frequently examined by quantifying changes in species diversity. The species diversity is a function of the number of species present and the evenness with which the individuals are distributed among these species (Margalef 1958; Lloyd and Ghelardi 1964; Pielou 1966; Hurlbert 1971), and thereby a right measure of species diversity should take account both the number of species and their relative abundances (Goodman 1975). Shannon's and MacArthur's indices are the most popular diversity indices (Magurran 1988) and have been extensively used for assessing structural alterations in aquatic communities during water pollution studies (Washington 1984). However, Shannon's and MacArthur's diversity indices appear to be more sensitive to relative abundances of species and less sensitive to the number of species (Balloch et al. 1976; Hughes 1978; Magurran 1988), giving little weight to rare species. MacArthur's diversity index is derived from Simpson's dominance index (Simpson 1949).

In this paper is described the performance of a new diversity index to assess structural alterations in aquatic communities downriver from disturbance points (e.g., discharge of pollutants, sewage effluents and dams). This diversity index is derived from Camargo's dominance index (d'), which represents a new perspective on dominance in natural communities. The value of Camargo's dominance index tends to increase with the number of subordinate species. A species i is considered as dominant if its relative abundance (p_i) is higher than (1/S) and as subordinate if $p_i < (1/S)$, S being the number of species present (species richness) in the biological community. The values of other dominance indices (Simpson 1949; McNaughton 1967) tend to decrease with the number of subordinate species.

Present address: Department of Biology, Colorado State University (CSU), Fort Collins, CO 80523, USA

MATERIALS AND METHODS

This new diversity index is sensitive to the number of species present and the whole spectrum of species proportions. Its value (D') is the product obtained by multiplying species richness (S) and species evenness (E'):

$$D' = S\,E' \qquad \text{(equation 1)}$$

Because a high value of species evenness implies similar relative abundances among species and, therefore, a low value of species dominance (Washington 1984), the species evenness (E') is estimated as the complement of Camargo's dominance index (d'):

$$E' = 1 - (\Omega/S) \qquad \text{(equation 2)}$$

where Ω represents the absolute difference between species with regard to their relative abundances and is calculated according to the following equation:

$$\Omega = \sum_{h}^{K} | p_{ih} - p_{jh} | \qquad \text{(equation 3)}$$

where p_{ih} is the relative abundance of a species i in a biological community h, p_{jh} is the relative abundance of a species j in the same community h, and K is the maximum number of possible binary subtractions between species, being $K = S(S-1)/2$. In this way, the mathematical expression of this new diversity index (equation 1) may be rewritten as:

$$D' = S - \Omega \qquad \text{(equation 4)}$$

When all species have the same relative abundance, the value of Ω is equal to 0, and therefore the species evenness (E') reaches its maximum value of 1 (equation 2) and the value of species diversity (D') becomes equal to the value of species richness (S) (equations 1 and 4). In this sense, the species diversity (D') may be interpreted as a measure of species heterogeneity in biological communities and its reciprocal value may be considered as a measure of species uniformity (U'):

$$D'\,U' = 1 \qquad \text{(equation 5)}$$

This new diversity index was applied to a field study in order to verify its suitable functional character. The data used in this paper were collected in the upper Río Tajuña (Central Spain, Tajo Basin) in July of 1986. Four sampling sites were selected along the study area (Figure 1). A reference station (S-1) was placed upstream from the fish farm. Second (S-2), third (S-3) and fourth (S-4) stations were respectively placed about 0.01, 0.15 and 1 km downstream from the trout farm effluent. S-3 was situated just below a small man-made waterfall (1.8 m in height). The stream bottom was mainly stony with cobbles and pebbles at all sampling sites, except S-2 where it was covered by a thick layer of organic sediment. Five samples of the benthic riffle macroinvertebrate community were collected at each sampling station, using a Hess cylindrical sampler which enclosed a sampling area of 0.1 sq m and was equipped with a 0.5 m net with a mesh size of 250 µm. All samples were preserved in 4% formalin until laboratory analysis. Specimens were identified to species or genus, except aquatic earthworms and some midge larvae (identified to family).

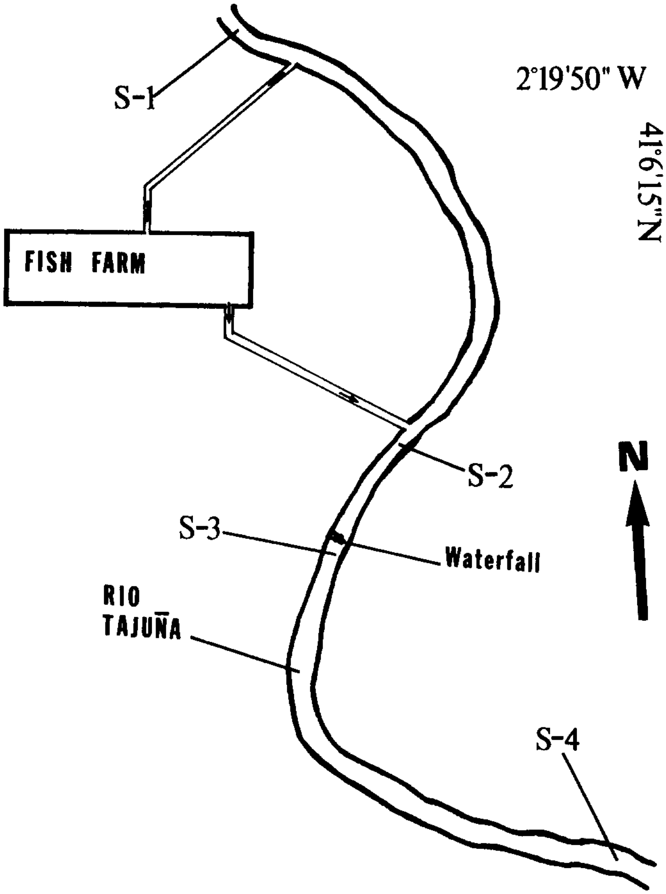

Figure 1. General diagram of the fish farm showing the location of sampling sites along the Río Tajuña (Central Spain, Tajo Basin).

The following biological parameters and indices were estimated using data in Table 1: the total density (N), the species richness (S), the species dominance (d'), the species evenness (E'), the species diversity (D'), the species uniformity (U'), the Shannon's diversity index (H') (Shannon 1948), the MacArthur's diversity index (D) (MacArthur 1972), the Chandler Biotic Score (CBS) (Chandler 1970), and the Biological Monitoring Working Party score system (BMWP) (Armitage et al. 1983). The Shannon's diversity index was calculated with natural logarithms.

RESULTS AND DISCUSSION

Plecopterans, ephemeropterans, coleopterans, trichopterans, amphipods and planarians decreased their abundances or were absent downstream from the fish farm effluent, whereas leeches, simuliids, chironomids and tubificid worms increased their abundances with regard to the reference station (Table 1). Similar changes in zoobenthic composition have been found in other freshwater

Table 1. Mean (n=5) densities (individuals/sq m) for each taxon collected at sampling sites.

	S-1	S-2	S-3	S-4
Polycelis sp.	20	0	0	0
Polycelis felina	62	0	0	0
Tubificidae	226	1640	362	116
Lumbriculidae	22	0	0	0
Helobdella stagnalis	0	70	194	32
Glossiphonia complanata	2	0	0	0
Erpobdella sp.	18	44	388	208
Bythinella sp.	358	0	0	0
Ancylus fluviatilis	112	0	72	24
Planorbis sp.	0	48	20	36
Pisidium sp.	0	108	20	54
Echinogammarus longisetosus	792	0	16	0
Ephemera danica	64	0	0	0
Ecdyonurus sp.	38	0	0	0
Baetis rhodani	32	0	260	538
Ephemerella ignita	94	0	0	0
Paraleptophlebia submarginata	8	0	0	0
Nemoura sp.	2	0	20	6
Leuctra sp.	36	0	0	0
Isoperla sp.	16	0	0	0
Perla marginata	10	0	0	0
Sialis sp.	0	10	0	0
Elmis maugetti	36	0	0	0
Esolus angustatus	242	0	26	0
Limnius wolkmari	202	0	4	0
Riolus cupreus	24	0	0	0
Haliplus sp.	0	0	0	58
Rhyacophila meridionalis	10	0	0	0
Agapetus fuscipes	54	0	0	0
Hydroptila sp.	22	0	34	128
Ithytrichia sp.	30	0	12	0
Hydropsyche pictetorum	14	0	22	50
Plectronemia conspersa	4	0	0	0
Lepidostoma hirtum	18	0	0	0
Sericostoma baeticum	44	0	0	0
Tipula sp.	0	0	12	0
Eusimulium sp.	12	0	548	872
Odagmia ornata	34	0	536	646
Ablabesmyia sp.	4	0	0	0
Cricotopus sp.	58	97	856	356
Eukiefferiella sp.	20	130	628	372
Orthocladius sp.	54	0	0	0
Thienemaniella sp.	0	0	26	40
Chironomus thummi	0	3743	107	0
Pentapedilum sp.	0	363	20	0
Polypedilum sp.	50	67	148	66
Micropsectra sp.	0	106	298	232
Tanytarsus sp.	0	40	428	308
Ceratopogonidae	0	0	22	26
Empididae	0	0	134	18
Athericidae	20	0	0	0
Anthomyidae	0	0	10	0

Table 2. Values of biological parameters and indices estimated at sampling sites.

	S-1	S-2	S-3	S-4
Total density (N)	2864	6466	5223	4186
Species richness (S)	38	13	28	21
Species dominance (d')	0.648	0.763	0.614	0.571
Species evenness (E')	0.352	0.237	0.386	0.429
Species diversity (D')	13.376	3.081	10.808	9.009
Species uniformity (U')	0.075	0.325	0.093	0.111
Shannon's index (H')	2.625	1.309	2.660	2.485
MacArthur's index (D)	8.547	2.463	11.490	9.174
BMWP biotic index	168	19	64	53
CBS biotic index	2052	271	870	678

macroinvertebrate communities exposed to this type of organic pollution (Mantle 1982; Markmann 1982), the dominant development of tubificid worms and red chironomids (containing haemoglobin and other respiratory pigments for regulating their oxygen uptake) being favored just below fish farm outlets. Muñoz (1989) monitored the alterations in physicochemical conditions upstream and downstream from this trout farm during the summer of 1986, and found that the concentration of nitrogen and phosphorus compounds, such as total ammonia, nitrite and ortho phosphorus, increased significantly below the fish farm effluent, whereas the concentration of dissolved oxygen decreased down to a value of 2.7 mg/L. However, the siltation of suspended solids (mainly organic matter) as an apparently anaerobic sludge deposit on the stream bottom at S-2 would be the primary cause of structural alterations in the macrobenthic community at this sampling station.

The values of biological parameters and indices estimated at each sampling station are presented in Table 2. Values of species richness (S), Camargo's diversity index (D'), and BMWP and CBS biotic indices were higher at the reference station (S-1) than at downstream sampling sites, exhibiting higher values at S-3 than at S-4 and their lowest values just below the trout farm effluent (S-2). Shannon's (H') and MacArthur's (D) diversity indices had their highest values just below the waterfall (S-3) and their lowest values at S-2, the MacArthur's index exhibiting a higher value at S-4 than at S-1. The species evenness (E') had its highest value at S-4 and its lowest value at S-2, exhibiting a higher value at S-3 than at S-1. On the contrary, values of total density (N), species dominance (d') and species uniformity (U') were higher just below the trout farm effluent (S-2) than at other sampling stations, the total density and the species uniformity exhibiting their lowest values at S-1 and the species dominance exhibiting its lowest value at S-4.

Linear correlation coefficients between species richness, diversity indices and biotic indices are presented in Table 3. All coefficients are positive. The species

Table 3. Correlation matrix (n=4) for the spatial variation of species richness (S), biotic indices (BMWP and CBS), and diversity indices (D', H' and D) estimated along the study area.

	S	D'	H'	D	BMWP	CBS
S	1.000					
D'	0.957[a]	1.000			a = $P < 0.05$	
H'	0.801	0.939	1.000			
D	0.647	0.821	0.957[a]	1.000		
BMWP	0.958[a]	0.866	0.645	0.427	1.000	
CBS	0.946	0.851	0.626	0.400	0.999[a]	1.000

richness (S) exhibits its lowest coefficients with Shannon's (H') and MacArthur's (D) diversity indices and its highest coefficients with Camargo's diversity index (D') and with BMWP and CBS biotic indices. Moreover, values of linear correlation coefficients between biotic indices and D' are higher than those between biotic indices and H' and D diversity indices.

Because species richness and biotic indices exhibit their lowest coefficients of linear correlation with Shannon's and MacArthur's indices, and values of these two diversity indices are higher at S-3 than at the reference station (S-1), Camargo's index (D') appears to be a more sensitive diversity index for assessing structural alterations in aquatic communities. Furthermore, Camargo's diversity index is more sensitive to changes in the species richness than Shannon's and MacArthur's diversity indices. However, diversity indices are insensitive to changes in species composition, and therefore they cannot replace biotic indices during pollution studies in order to assess the degree of water quality degradation. In this way, both diversity and biotic indices should be complementarily used in this kind of ecological studies.

On the other hand, the lower values of species dominance (d') estimated at S-3 and S-4 with regard to the reference station (S-1) would indicate that intermediate environmental perturbations can generate a reduction in the concentration of dominance in biological communities, the value of species evenness becoming higher. In addition, the fact that values of all diversity and biotic indices are higher at S-3 than at S-4 (Table 2) is probably due to a significant recovery of environmental conditions, such as dissolved oxygen concentrations and redox potential, just below the man-made waterfall. In this sense, it is concluded that small waterfalls may improve the stream's self-purification of organic pollution generated by inland fish farms, the recovery of macrobenthic community structure being accelerated.

Acknowledgments. I thank Professor J.V. Ward for his facilities in order to write this manuscript. The idea for the performance of this new diversity index came while I was writing my dissertation in Spain. The actual work was completed at Colorado State University while I was supported by a postdoctoral grant from the National Institute for Agrarian Research (INIA) in Spain. The Department of Animal Health (CIT-INIA) provided logistical support during the field study.

REFERENCES

Armitage PD, Moss D, Wright JF, Furse MT (1983) The performance of a new biological water quality score system based on macroinvertebrates over a wide range of unpolluted running-water sites. Water Res 17: 333-347

Balloch D, Dames CE, Jones FH (1976) Biological assessment of water quality in three British Rivers the North Esk (Scotland), the Ivel (England) and the Taf (Wales). Water Pollut Control 75: 92-114

Chandler JR (1970) A biological approach to water quality management. Water Pollut Control 69: 415-421

Chutter FM (1972) An empirical biotic index of the quality of water in South African streams and rivers. Water Res 6: 19-30

Goodman D (1975) The theory of diversity-stability relationships in ecology. Q Rev Biol 50: 237-266

Hawkes HA (1975) River zonation and classification. In: Whitton BA (ed) River ecology. Blackwell Scientific Publications, Oxford, pp 313-374

Hughes BD (1978) The influence of factors other than pollution on the value of Shannon's diversity index for benthic macroinvertebrates in streams. Water Res 12: 359-364

Hulbert SH (1971) The nonconcept of species diversity: a critique and alternative parameters. Ecology 52: 577-586

Illies J, Botosaneanu L (1963) Problèmes et méthodes de la classification et de la zonation écologique des eaux courantes, considerées surtout du point de vue faunistique. Verh Int Verein Limnol 12: 1-57

Lloyd M, Ghelardi RJ (1964) A table for calculating the equitability component of species diversity. J Anim Ecol 33: 217-225

MacArthur RH (1972) Geographical ecology. Patterns in the distribution of species. Harper and Row, New York

Magurran AE (1988) Ecological diversity and its measurement. Princeton University Press, Princeton

Mantle GJ (1982) Biological and chemical changes associated with the discharge of fishfarm effluents. EIFAC Technical Paper 41: 103-112

Margalef R (1958) Information theory in ecology. Gen Syste 3: 36-71

Markmann PN (1982) Biological effects of effluents from Danish fish farms. EIFAC Technical Paper 41: 99-102

McNaughton SJ (1967) Relationships among functional properties of Californian grassland. Nature 216: 168-169

Muñoz MJ (1989) Indice de calidad y toxicidad de agua para salmonidos. Doctoral Dissertation No 77. INIA (Spain)

Pielou EC (1966) Species-diversity and pattern diversity in the study of ecological succession. J Theoret Biol 13: 131-144

Shannon CE (1948) A mathematical theory of communication. Bell System Tech J 27: 379-423

Simpson EH (1949) Measurement of diversity. Nature 163: 688

Vannote RL, Minshall GW, Cummins KW, Sedell JR, Cushing CE (1980) The river continuum concept. Can J Fish Aquat Sci 37: 130-137

Washington HG (1984) Diversity, biotic and similarity indices. A review with special relevance to aquatic ecosystems. Water Res 18: 653-694

Received April 12, 1991; accepted September 30, 1991.