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The use of water chemistry and benthic diatom communities for qualification of a polluted tropical river in Costa Rica

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Abstract: The water quality of several sections of a tropical river subjected to severe pollution was studied through physico-chemical water analysis and benthic diatom assemblages. The methodology follows the concept of differential species groups and that of its modification for the groups of nutrient- differentiating species for rivers rich in both oxygen and inorganic nutrients. The trophic indication of the latter authors corresponded clearly with the results of chemical observations made in this study. The most abundant species found in this river were *Navicula goeppertiana*, *Gomphonema parvulum*, *Gomphonema* sp. aff. *pumilum*, *Nitzschia palea*, *Nitzschia amphibia*, *Nitzschia clausii* *Nitzschia inconspicua*, *Navicula seminulum*, *Navicula* sp. aff. *cryptocephala*, *Navicula schroeterii* var. *escambia*, *Cymbella sinuata* and *Surirella* sp. aff. *roba*. These species are known to be tolerant to organic pollution and eutrophication. Therefore we may conclude that diatoms are useful for biological monitoring of disturbed tropical rivers.

Key words: Tropical river, Costa Rica, organic pollution, water chemistry, diatoms, differential species groups, numerical vegetation analysis.

In the natural environment, the quality of the river water, reflected by different types and origins of dissolved and suspended compounds, is largely determined by the surrounding land, climate and geology of the catchment area. In populated areas river water quality is determined by human practices: deforestation, farming, industrial and domestic sewage discharge, which cause changes in colour, suspended solids, pH, temperature, nutrients and run-off characteristics.

The causes and effects of pollution in tropical rivers have been studied by several researchers, particularly with respect to particulate and suspended matter (Gibbs 1967, King and Ekeh 1990), the chemical dynamics in waters related with organic matter content, nutrient loading and pH (*e.g.* Talling 1957, Talling and Talling 1965, Gibbs 1967, Imevbore 1970, Ramírez 1986). Other studies of tropical environments have followed changes of benthic invertebrate communities (Vilela and Souza 1991) and benthic algae (Venkateswarlu 1968, 1969), respectively. Only a few studies relate diatoms of tropical and subtropical rivers to the degree of organic pollution (Patrick 1964, Podzorski 1984, Guerrero and Rodríguez 1991), even though diatoms are supposed to be sensitive indicators of organic pollution (Patrick 1973, Van Dam 1974, Lange-Bertalot 1979, Schoeman and Haworth 1986, Steinberg and Schiefele 1988). Diatoms are excellent for biological monitoring because they have a high reproductive rate, they colonize substrates easily, and they react quickly to contaminants (Cox 1991).

The purpose of this study is to compare diatom communities in a polluted river in Costa Rica (Río Grande de Tárcoles) with similar studies from temperate areas. The specific methodology applied is that of differential species groups according to Lange-Bertalot

(1978, 1979) and Krammer and Lange-Bertalot (1986) and its modification for nutrient rich, but oxygen saturated, running waters by Steinberg and Schiefele (1988). The former was developed in large, slow-flowing rivers, in which nutrient-rich conditions are mostly correlated with reduced oxygen saturation. However in fast-flowing mountain streams and rivers, nutrient-enriched waters are often oxygen saturated. This also applies to R. Virilla and R. Tárcoles. Steinberg and Schiefele (1988) showed that for the latter situation differential species groups must be subdivided into groups of species that benefit from higher nutrient concentrations (eutraphent species) and those that tolerate organic pollution. Results obtained using these methods are compared with numerical grouping of the species and the samples respectively. This approach to classification of running waters has already been applied to temperate rivers by several authors, using macrophytes and macroalgae (Holmes 1983), macrozoobenthos (Braukmann 1987, Wright *et al.* 1984), and macroalgae and microalgae respectively (Pipp and Rott 1993).

THE STUDY SITES

Hidrology and climate: The Río Grande de Tárcoles drains a catchment area as large as 2169 km^2 in the Central Valley of Costa Rica (Fig. 1A). The basin is located between two geographical areas: Valle Central and Pacífico Central. It is surrounded by the Central American Mountain Range with a westward slope to the Pacific coast. Both areas have a seasonal tropical climate, with a rainy and a dry season, average temperatures higher than 18°C, and an annual precipitation of 1500-2000 mm (Instituto Meteorológico Nacional 1991). Most rainfall occurs between May and November, dry season occurs from December to April. The decrease of the rain during June-July is due to a peculiar decline in precipitation, the so-called "veranillo" (Fig.2A).

The annual pattern of discharge reflects the change between the rainy and dry season (Fig. 2B). The annual mean discharge near the mouth of R. Tárcoles ranges from 22 to 60 $m^3.s^{-1}$ during the dry season and 100-200 $m^3.s^{-1}$ in the rainy season. The discharge peak occurs in October.

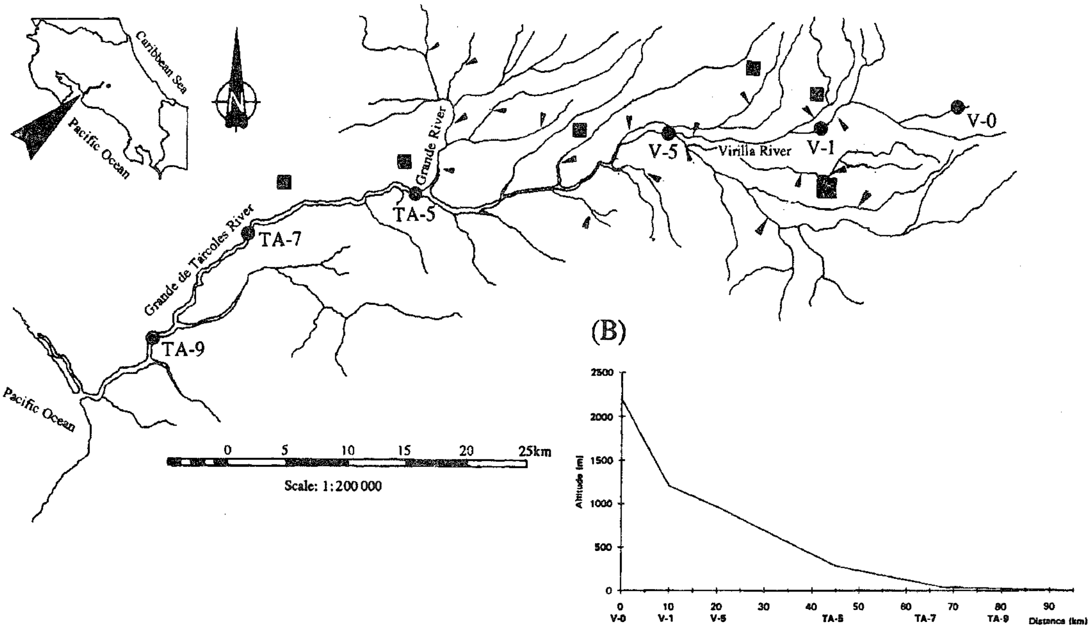


Fig. 1. A) Río Grande de Tárcoles basin with sampling sites (V-0 to TA-9), as well as the main cities (squares) and the most important sewage effluents (arrows), B) Longitudinal profile of the sampling sites.

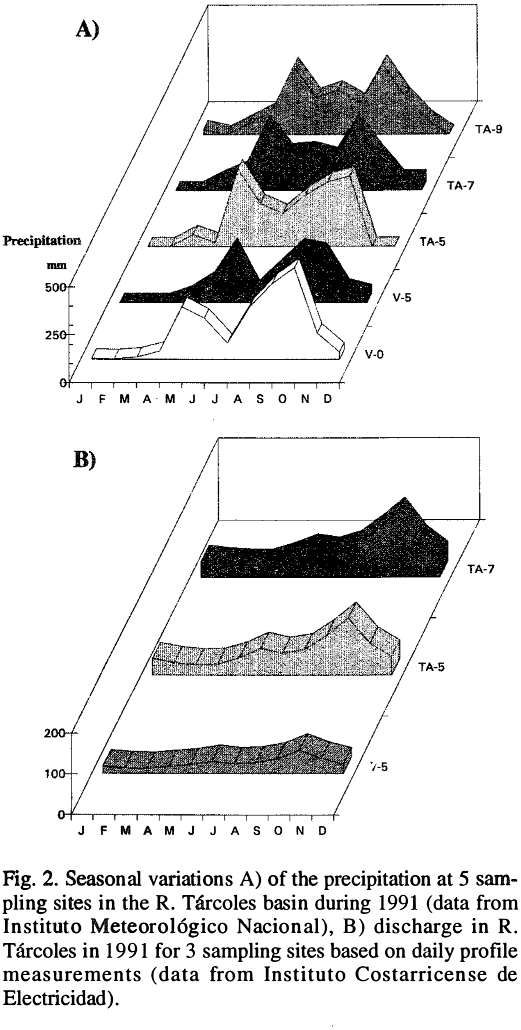


Fig. 2. Seasonal variations A) of the precipitation at 5 sampling sites in the R. Tárcoles basin during 1991 (data from Instituto Meteorológico Nacional), B) discharge in R. Tárcoles in 1991 for 3 sampling sites based on daily profile measurements (data from Instituto Costarricense de Electricidad).

Topography and geology: The R. Tárcoles is formed by the confluence of the Río Virilla, one of the main tributaries flowing down from the East through important cities, meeting the Río Grande in the western Central Valley to form the R. Tárcoles the remaining 40 km, its total length is 98 km. The gradient (Fig.1B) is high in the upper part of the basement draining areas between 2200 and 1200 m a.s.l. (2.1%), moderate in the middle part (0.7%) and low over the last 30 km section (0.1%). The highest elevation of the catchment (2200 m a.s.l..) is located in the foothills of the Central Mountain Range (Cordillera Central), amid dense forest cover. This forest gradually gives way to cleared, agricultural land mixed with increasing portions of urban and industrial areas of the Central Valley (1170-25 m a.s.l.). The population of this region constitutes 57% of the total of inhabitants of the country, where 63% is urban and 37% is rural (Deutsche Gesellschaft für Technische Zusammenarbeit 1991).

Along most of its length, the R. Tárcoles is turbulent and swift, with a resultant stone- covered river bed. Its waters are muddy and usually transports suspended sediments year-round. In the upper R. Virilla, natural riparian vegetation prails, whereas in the middle and lower portions the banks are rocky and bereft of riparian vegetation. In the lower sampling points, most of the river substrate is exposed to the sun all day long.

The R. Tárcoles watershed is underlain by complexes of volcanic-sedimentary material and intrusive rocks produced by different geological processes that to place during the Superior Cretacic period (Siu 1983). Poás and Barva volcanoes have discharged a type of lava called "intercanyon lava" and tuffs called "glowing avalanche deposits", both filled the canyons and were deposited along the river bed, together with post- avalanche lavas, ash, and pyroclastics as well.

Human impacts: The river system is influenced by two main types of water pollution: point sources from untreated municipal and industrial waste water, and non-point sources from agricultural and local domestic sewage input. R. Tárcoles basin is severely polluted by untreated debris from coffee processing and domestic sewage, especially during the dry season (Ramírez 1986, Deutsche Gesellschaft für Technische Zusammenarbeit 1991). Other important effluents include the raw sewage of leather tanneries (Chacón *et al.* 1982), paper mills, a distillery, and textile factories (Deutsche Gesellschaft für Technische Zusammenarbeit 1991). While an earlier study of metal pollution focussing on dissolved metal concentrations (Ramírez *et al.* 1985) found very low values for Zn, Cu, Pb and Cr (< 10 $\mu g.l^{-1}$) in several rivers of the Tárcoles basin, Fuller *et al.* (1990) reported levels of Cr, Pb and Zn in fine-grain bed sediments downstream of leather tanneries reaching 50 to 80 times the background concentrations measured in uncontaminated tributaries to R. Virilla upstream the larger cities. In addition, the high deforestation brought on by agriculture, cattle farming and urbanization, enhances soil erosion, which is severe throughout the whole catchment.

The sampling points: Six sampling points were selected and named according to a 6-year study conducted by the Servicio Nacional de Acueductos y Alcantarillados de Costa Rica between 1980 and 1986. The abbreviations V-0, V-1, V-5 indicate sampling points situated in R. Virilla, and TA-5, TA-7, TA-9 correspond to sites in R. Tárcoles. Criteria for site selection: (1) distribution along an altitudinal gradient between the Virilla headwaters and the mouth of R. Tárcoles, and (2) comparison of river sections upstream and downstream of the sewage effluents from main tributaries (Fig. 1A). While conducting some samplings, other selected tributaries near the site V-5 (R. Torres and R. Bermúdez, in Tables and Figs. abbreviated as BER) and the site TA-5, respectively (Cacho stream), were sampled as well. The main physical, hydrological and morphological features of each sampling site are detailed in Table 2.

MATERIAL AND METHODS

Samples were collected monthly between January and December 1991 from the 6 main sites, Río Torres was sampled once, and the Río Bermúdez and Cacho stream were sampled twice. Four liter water samples were collected twice from surface water as close to the centre of the river as possible following the river from the highest to the lowest site within the same diurnal time sequence each month. Water samples were returned on ice to the laboratory and stored at 4°C for 12 hours before analyses were made.

Information on precipitation was obtained from daily readings taken by the Instituto Meteorológico Nacional (1991) at altitudes comparable to the sites V0, V-1, V5, TA-5, and TA-7. The temperature was measured with a centigrade thermometer. Daily recordings of river discharge were provided by the Instituto Costarricense de Electricidad (1990-1991) near the sampling sites V-5, TA-5 and TA-7. The discharge values mentioned for V-1, R. Bermúdez and R. Torres were taken from Ramírez (1986).

For suspended sediments, one aliquot of 10 or 20 ml was taken from each sample and filtered through preweighed 1 cm GF/A2 Whatman filters. Filters were dried at 120°C for 2 hours, cooled in a desiccator and weighed in an analytical balance. The turbidity was measured with a HACH-Turbidimeter Model Nr.2100A and given as U.N.T. units. The conductivity of the samples was measured with a

TABLE 1

Criteria for river classification

Water quality class	Oxygen deficit(%)	BOD$_5$ (mg.l^{-1})	TP (μgP.l^{-1})	NH$_4$-N (μgN.l^{-1})	Saprobic level
I	-	0.0- 0.5	-	-	ultraoligosaprobic
I-II	< 15	0.5- 2.0	<35	<80	oligosaprobic
II	< 30	2.0- 4.0	36- 81	81-190	ß-mesosaprobic
II-III	< 50	4.0- 7.0	82-196	191-470	ß- α-mesosaprobic
III	< 75	7.0-13.0	197-261	471-620	α-mesosaprobic
III-IV	< 90	13.0-22.0	262-327	621-780	α-meso-polysaprobic
IV	> 90	>22.0	>327	>780	polysaprobic

(B) Relative portions of differential species groups:

Water quality class	Sensitive taxa	Moderately tolerant	Highly tolerant
II or better	>50%	10-50%	<10%
II-III	10-50%	>50%	<10%
III	<10%	>50%	10-50%
III-IV	<10%	10-50%	>50%
IV	<10%	<10%	>90%

(A) Physico-chemical criteria following Hamm (1969) and Dworski (1982), (B) Classification according to relative portions of differential species groups (Lange-Bertalot 1978, 1979, Krammer and Lange-Bertalot 1986)

TABLE 2

Physical, hydrological and morphological features for the river sections sampled in the R. Tárcoles basin in 1991

Site 1)	Altitude (m a.s.l)	Air temp. (°C)	Water temp (°C)	Channel width (m)	Discharge (m^3.s^{-1})	Ann. precip (mm)	Susp. sed (mg.l^{-1})	Turbidity (U.N.T.)	Conduct. (μS.cm^{-}
Main river sections:									
V-O	2200	15-18	14-16	1-2	n.d.	1952	2-20	2-8	86-142
n		(10)	(10)				(9)	(9)	(9)
V-1	1200	19-26	19-24	20-25	0.3-1.2	1402	17-424	20-410	56-165
n		(10)	(10)				(9)	(9)	(7)
V-5	960	21-34	22-25	30-40	13-58	1379	60-230	23-82	130-305
n		(10)	(10)				(9)	(9)	(9)
TA-5	280	27-35	22-25	10-30	29-142	2166	42-640	60-190	120-185
n		(10)	(10)				(9)	(9)	(9)
TA-7	40	22-30	22-25	40-60	31-158	2582	35-1150	17-200	110-190
n		(10)	(10)				(18)	(18)	(9)
TA-9	25	25-37	24-26	25-50	n.d.	1852	10-282	19-180	120-160
n		(10)	(10)				(9)	(9)	(9)
Tributaries to V-5:									
Torres	960	22-23	22-24	10-20	0.02-0.04	1379	112-525	320	320-386
n		(2)					(2)	(1)	(2)
BER	960	21-31	17-24	3-5	0.1-0.3	1379	74-190	55-70	185-470
n		(3)					(2)	(2)	(3)
Tributary to TA-5:									
Cacho	280	27-33	23-26	0.5-1	n.d.	2166	9	n.d.	240-265
n		(2)					(2)		(2)

Numbers indicate absolute values or ranges, numbers in brackets indicate numbers of measurements; n.d.=not determined; site abbreviations see text.

YSI conductivity bridge Model 31, and expressed as μS.cm^{-1} at 25°C. The pH was measured in situ using a digital Barnand Co. LCD pH meter. and a Cole-Parmer type-electrode. Upon return to the laboratory the samples were filtered through Whatman GFC filter paper. Only samples tested for ammonium, alkalinity and chloride were processed without prior filtering. The chemical analyses used are detailed in Standard Methods for the Examination of Waste Water (American Public Health Association 1975). Total phosphorus was determined by the method used by Ebina *et al.* (1983). Dissolved oxygen was measured according to the Winkler method. Values for percentage saturation were calculated using calibration tables with correction made for differences in temperature and altitude. For measurement of Biochemical Oxygen Demand, the samples were incubated for 5 days and thermostatically controlled at 20°C. The values for oxygen saturation, BOD, and total phosphorus and ammonium found in the present study have been used to determine the chemical water quality of the R. Tárcoles basin using various indices commonly applied to rivers from the temperate region.

Identification and quantification of diatoms: Diatom samples were scraped from five stones using a knife and a toothbrush. The samples were taken approximately one to two meters from the bank; due to the swift current, it was impossible to sample stones from the middle portion of the river bed. From each stone, two samples were removed and preserved with some drops of formalin (20%). Diatom frustules were cleaned in boiling 2N HCl, potassium permanganate and peroxide. The acid and permanganate solution was removed by repeated centrifugation and washing with distilled water. Cleaned subsamples (four subsamples from each sample) were dispersed on cover glasses, dried on evaporation plates, and embedded in the diatom resin Naphrax. The diatom frustules were identified and quantified under 1000x oil immersion. A total of 400 diatom valves were identified in each sample. Individuals lying on the girdle side were also

TABLE 3

Chemical variables for the river sections in the R. Grande de Tárcoles basin in 1991

Site	pH	Alkalinity (meq.l^{-1})	Cl (mg l^{-1})	Oxyg sat. (%)	BOD_5 (mg l^{-1})	NO_3-N (mg l^{-1})	NO_2-N (mg l^{-1})	NH_4-N (mg l^{-1})	SRP (µg l^{-1})	TP (µg l^{-1})
Main river sections:										
V-O	5.4-7.6	0.2-0.9	2.5-12.0	103-111	0.3-1.5	0.4-11	0.0-0.0	0.0-1.4	0-400	194-339
mean±SD	6.4±0.5	0.3±0.2	7.6±2.3	106±3	0.8±0.2	0.8±0.2	0.0±0.0	0.4±0.2	200±100	261±60
n	(10)	(18)	(18)	(18)	(18)	(16)	(16)	(18)	(18)	(4)
V-1	7.0-7.5	0.5-1.3	0.7-8.2	97-112	4.0-24.5	0.7-3.1	0.0-0.2	0.1-2.3	200-700	1471-2284
meant±SD	7.0±1.0	1.1±0.4	8.0±5.0	108±6	10.7±6.0	1.9±0.8	0.0±0.1	0.4±0.8	400±200	1858±332
n	(10)	(20)	(20)	(20)	(20)	(18)	(20)	(20)	(18)	(6)
V-5	6.8-7.7	0.7-2.7	1.9-24.0	74-114	3.5-37.0	2.1-7.6	0.1-2.1	0.3-3.7	300-3800	542-1219
mean±SD	7.2±0.3	3.8±0.7	13.2±6.1	100±4	11.9±9.7	4.7±1.7	0.8±0.8	1.5±1.0	1300±1200	819±289
n	(10)	(20)	(20)	(20)	(20)	(18)	(20)	(20)	(20)	(6)
TA-5	6.9-7.8	0.9-1.7	3.6-13.0	91-106	6.1-26.0	2.0-6.0	0.0-1.2	0.1-1.5	100-800	735-1607
mean±SD	7.2±0.2	1.2±0.5	11.0±3.3	98±9	10.3±6.4	4.5±1.6	0.6±0.4	0.08±0.4	500±200	1171±435
n	(10)	(20)	(20)	(20)	(20)	(18)	(20)	(20)	(20)	(6)
TA-7	7.2-7.8	1.3-1.7	8.6-13.0	73-107	3.1-18.0	2.6-9.3	0.0-2.2	0.0-2.0	455-1100	1432-1626
mean±SD	7.5±0.2	1.2±0.4	11.5±1.7	94±9	6.6±4.2	5.5±2.2	0.6±0.6	1.0±0.7	693±200	1529±97
n	(10)	(20)	(20)	(20)	(20)	(18)	(20)	(20)	(20)	(8)
TA-9	7.0-7.7	1.6-2.1	9.6-15.0	78-107	2.0.9.4	3.6-9.9	0.0-1.2	0.0-2.7	313-1224	738-1355
mean±SD	7.3±0.2	1.4±0.5	10.7±2.4	87±9	4.7±2.1	6.2±2.0	0.5±0.3	0.6±0.8	653±300	909±291
n	(10)	(20)	(20)	(20)	(20)	(18)	(20)	(20)	(20)	(6)
Tributaries to V-5:										
Torres	7.4±7.6	2.1-2.5	14.9-21.0	91-106	14.0-17.0	5.8-6.5	0.2-0.9	1.5-2.1	1020-2900	n.d.
mean±SD	-	-	-	94±8	15.5±1.5	6.0±1.1	-	2.0±0.8	1800±969	
n	(2)	(2)	(2)	(4)	(4)	(4)	(2)	(4)	(4)	
BER	7.2-8.4	1.2-1.7	15.1-22.0	39-86	9.6-31.0	0.6-3.6	0.1-0.2	3.3-4.2	1700-2000	2950-2980
mean±SD	7.4±0.2	2.1±0.9	18.4±9.5	58±20	23.5±9.9	1.1±1.3	0.2±0.0	3.7±0.4	1800±140	2968±13
n	(3)	(4)	(4)	(6)	(6)	(6)	(4)	(4)	(4)	(4)
Tributary to TA-5:										
Cacho Str.9	7.9-8.2	1.2-2.9	6.1-6.7	93-100	1.6	0.4-1.3	0.0	0.0-0.2	200-300	n.d.
mean±SD	-	2.1±0.8	6.4±0.3	95±7	-	-	0.0	0.1±0.1	0.1±57	
n	(2)	(4)	(4)	(4)	(2)	(2)	(4)	(4)	(4)	

(Numbers are ranges, arithmetical means and standard deviations; numbers in brackets show number of chemical measurements, n.d. = not determined; site abbreviations see text).

counted. Taxonomy is based mainly on Patrick and Reimer (1966, 1975) Krammer and Lange-Bertalot (1986, 1988, 1991a, 1991b) and Lange-Bertalot and Krammer (1989).

Biological water quality classification: Benthic diatom species composition was used for classification of biological water quality, following the method of differential species groups by Lange-Bertalot (Lange-Bertalot 1978, 1979, Krammer and Lange-Bertalot 1986). This classification system recognizes three groups of species according to their tolerance to organic pollution: (1) highly tolerant species which can survive in highly polluted (alpha-mesosaprobic to polysaprobic) environments, (2) moderately tolerant species, which resist less polluted conditions (beta to alpha-mesosaprobic), but disappear in severely polluted waters and (3) pollution sensitive species, which only occur in oligotrophic and katharobic situations. The species belonging to these groups found so far in temperate regions are listed in Krammer and Lange-Bertalot (1979, 1986) and they are assumed to be cosmopolitan species.

Calculation of water quality class was based on the relative frequency of species belonging to each of the differential species groups in a sample (Table 1B). In most cases classification according to Table 1B was made without doubts. Samples containing equal portions of each of the 3 differential species groups were assigned intermediate water quality class II-III / III. Samples dominated by highly tolerant species, yet with more sensitive species than moderately tolerant ones were classified as water quality III / III-IV, assigning more weight to the portion of highly tolerant species, for which classification is more reliable.

Classification of the species of this study into the seven groups according to Steinberg and Schiefele (1988) is shown in Tables 4 and 5 and used in the discussion, but because the categorization into pollution tolerant and eutraphent species is only available for species from a few alpine rivers and streams, calculation of water quality classes in Table 6 is based on Lange-Bertalot's system only (Lange-Bertalot 1979, Krammer and Lange-Bertalot 1986).

Statistical analysis: Diatom communities were defined according to the relative abundance of species in all 47 samples using numerical vegetation analysis. Species with relative

TABLE 4

List of diatoms found in R. Virilla and R. Tárcoles basin in 1991

Abrev.	Species	L. B.	S & S	V - 0	V - 1	V - 5	T A 5	T A 7	T A 9
	Achnanthes exigua Grunow	ht							2
	Achnanthes helvetica (Hustedt) Lange-Bertalot								
	Achnanthes inflata (Kützing) Grunow								
achn lanc	*Achnanthes lanceolata* (Brébisson) Grunow	t	eu	5	2	2			
achn macu	*Achnanthes maculata* Hustedt								
achn minu	*Achnanthes minutissima* Kützing	s	hs	5	5	5	4	4	
	Achnanthes sp. aff. *ricula* Hohn & Hellermann			5	2	2	2	2	2
	Achnanthes rupestoides Hohn			2					
	Achnanthes subhudsonis Hustedt			2	2	3	2	2	
	Amphora sp. aff. holsatica Hustedt								
	Amphora montana Krasske				2	4	2	2	2
	Amphora pediculus (Kützing) Grunow		s						
cocc plac	*Cocconeis placentula* Ehrenberg	s	eu	3	5	5	2	3	2
	Cyclotella meneghiniana Kützing							4	
	Cyclotella sp. I								
cymb sile	*Cymbella silesiaca* Bleisch	t	eu	5	2			2	2
cymb sinu	*Cymbella sinuata* Gregory	s	hs	4	4	4	3	5	3
cymb tumi	*Cymbella tumida* (Brébisson) Van Heurck			2					
	Diatoma mesodon (Ehrenberg) Kützing		s	2					
dipl subo	*Diploneis subovalis* Cleve								
	Epithemia sorex Kützing								
	Epithemia sp.								
	Eunotia sp. aff. *incisa* Gregory								
	Fragilaria brevistriata Grünow				2				
	Fragilaria capucina var. *capucina* Desmazières	s		2			2	2	2
	Fragilaria capucina var. *gracilis* (Ostrup) Hustedt								
	Fragilaria capucina var. *rumpens* (Kützing) Lange-Bertalot				2			2	
	frag capv *Fragilaria capucina* var. *vaucheriae* (Kützing) Lange-Bertalot	t	eu		2				
	Fragilaria fasciculata (Agardh) Lange-Bertalot	t						2	
	Fragilaria goulardii (Brebissom) Lange-Bertalot								
	Fragilaria pinnata Ehrenberg	s	eu		2				
frag ulna	*Fragilaria ulna* (Nitzsch) Lange-Bertalot	ht		2	3	2		2	3
	Frustulia weinholdii Hustedt								
	Gomphonema sp. aff. *grovei* M. Schmidt								
	Gomphonema mexicamum Grunow								2
	Gomphonema olivaceum (Hornemann) Brébisson		eu						
gomp parv	*Gomphonema parvulum* Kützing	ht	mt	2	3	5	5	4	4
gomp parl	*Gomphonema parvulum* var. lagenula (Kútzing) Frenguelli								

	Gomphonema rhombicum Fricke			3				2	2
	Gomphonema sarcophagus Gregory								
gomp puml	*Gomphonema* sp. aff. *pumilum* I (Grunow) Reichardt & Lange-Bertalot	ht		3	4	4	3	5	4
	Gomphonema sp. aff. *pumilum* 2 (Grunow) Reichardt & Lange-Bertalot				2	2	2		2
	Gomphonema subclavatum Grunow								
	Gomphonema truncatum Ehrenberg								
gyro scal	*Cyrosihma scalproides* (Rabenhorst) Cleve				3				
	Melosira sp.								
navi arve	*Navicula arvensis* var. *mayor* Lange-Bertalot	t		4	2	4	3	3	2
navi atom	*Navicula atomus* (Kützing) Grunow	ht	mt	2	2	2			2
navi capi	*Navicula capitatoradiata* Germain	t	s	3	4	5	2	3	2
	Navicula chilena Lange-Bertalot					2			
	Navicula cohnii (Hilse) Lange-Bertalot						2		
	Navicula contenta Grunow		s	4	2		2	2	2
	Navicula cryptotenella Lange-Bertalot	t	hs	4	3	2	3	3	3
	Navicula elginensis var. *elginensis* (Gregory) Ralfs								
navi erif	*Navicula erifuga* Lange-Bertalot			2		2	3	4	3
	Navicula exilis Kützing								
navi goep	*Navicula goeppertiana* (Bleisch) L. Smith	ht	ht	4	5	4	5	5	3
	Navicula gregaria Cholnoky	t	t	2					
	Navicula laevissima Kützing								
	Navicula minima Grunow	ht	ht	2	2			2	2
	Navicula sp. aff. *modica* Hustedt							2	2
	Navicula molestiformis Hüstedt								
	Navicula mutica var. *ventricosa* (Kützing) Cleve & Grunow	s		2			2		
navi pupu	*Navicula pupula* Kützing	t	eu					2	
	Navicula schroeterii var. *escambia* Patrick	ht		3	5	3	4	5	4
navi semi	*Navicula seminulum* Grunow	ht	ht	3	3	4	2	3	2
	Navicula subfasciata var. *subfasciata* Patrick				2				
navi subm	*Navicula subminuscula* Manguin	ht		2	2	2	3	3	5
	Navicula sp. aff. *submuralis* Hustedt								
navi viri	*Navicula viridula* (Kützing) Ehrenberg	t		2	4	5		2	
	Navicula sp. 1				2	3		3	5
	Navicula sp. 3								
nitz amph	*Nitzschia amphibia* Grunow	ht		2	2	3	5	4	5
	Nitzschia brevissima Grunow								
nitz clau	*Nitzschia claussi* Hantzsch	t		4		3	5	3	2
nitz diss	*Nitzschia dissipata* (Kützing) Grunow		eu		2				
nitz font	*Nitzschia fonticola* Grunow	s		4					
	Nitzschia fossilis Grunow								
	Nitzschia frustulum (Kützing) Grunow	s		3	2	4	4	2	3
nitz inco	*Nitzschia inconspicua* Grunow	t		3		2	5	5	5
	Nitzschia levidensis var. *salinarum* (W. Smith) Grunow								2
	Nitzschia linearis (Agardh) W. Smith	s	eu	3	5	3		2	
nitz pale	*Nitzschia palea* (Kützing) W. Smith	ht	mt	3	5	5	5	5	3
	Nitzschia palea var. *debilis* (Kützing) Grunow		ht						
	Nitzschia linearis paleacea Grunow	t	t		2		2		
	Nitzschia sp. aff. *pura* Hustedt								
	Nitzschia subacicularis Hustedt							2	
	Nitzschia sublinearis Hustedt	s	s		2		2		
	Nitzschia subrobusta Lange-Bertalot						2		
	Nitzschia tropica Hustedt								
	Pinnularia appendiculata (Agardh) Cleve			2					
	Pinnularia braunii (Grunow) Cleve								
rhoi abbr	*Rhoicosphenia abbreviata* (Agardh) Lange-Bertalot	s	eu	2	5	3	2	2	2
	Stauroneis prominula (Grunow) Hustedt								
	Surirella angusta Kútzing							3	
suri roba	*Surirella* sp. aff. *roba* Leclercq			5	2				

Abbreviations of species names used in Table 5. Maximum abundance of species (abundance classes: <1% is not given, 2= 1-5%, 3=5-10%, 4=10-20%) and classification of species acc. to Lange-Bertalot (=L.B.; ht = highly tolerant, s = sensitive) and acc. to Steinberg and Schiefele resp. (= S&S; mt = most tolerant, ht = highly tolerant, 1 = moderately tolerant, s = sensitive, hs = highly sensitive, eu = eutraphent).

TABLE 5

Vegetation table of diatoms of R. Tárcoles due to minimun variance clustering of samples

Sample group No.					1	1	1	1	1	1	1	2	2	2	2	2	2	3	3	3	3	3	4	4	4	4	4	5	5	5	5	6	6	6	6	6	6	7	7	7	8	8	8	8	9	9	9	9	10	10	10
Sampling site					T	B	V	T	T	T	T	T	T	T	T	T	T	T	T	T	T	V	V	V	V	V	V	T	T	T	V	T	V	T	T	T	V	B	V	V	V	V	V	V	T	V	T	V	V	V	V
					A	E	-	A	A	A	A	A	A	A	A	A	A	A	A	A	A	-	-	-	-	-	-	A	A	A	-	A	-	A	A	A	-	E	-	-	-	-	-	-	A	-	A	-	-	-	-
					5	R	1	7	5	5	7	9	9	7	5	9	9	9	5	9	5	5	1	0	0	0	5	7	7	7	0	5	5	7	5	7	0	R	5	1	5	1	1	1	7	1	9	5	0	0	0
Sampling date					N	N	N	M	A	D	N	J	D	S	J	M	J	A	J	M	J	N	D	N	D	J	D	J	D	O	O	M	A	M	M	J	S	S	S	S	M	M	J	J	A	A	N	J	J	A	M
(Month)					o	o	o	a	p	e	o	u	e	e	e	a	u	p	u	a	u	o	e	o	e	u	e	u	e	c	c	a	p	a	a	u	e	e	e	e	a	a	u	u	p	p	o	u	u	p	a
					v	v	v	r	r	c	v	n	c	p	p	y	l	r	n	r	l	v	c	v	c	n	c	n	c	t	t	r	r	y	y	l	p	p	p	p	r	r	l	n	r	r	v	l	l	r	r
Diversity					l											h						h					l	h		l							h		h							h				l	
Species		LB	SS																																																
Frag	capv	t	eu	1						1						1		1				1	1	1	1	1		1	1	1	1											1	1			1					1
Cymb	tumi	-	-	1											1	1					1	1		1	1	1		1	1	1	1									1			1	1			1				1
Nitz	diss	-	eu	2												1																1								1	1	1		1		1					
Gyro	scal	-	-	2	1				1	1							1	1					1	1														1	1	1		1	1	1		1	1	1			
Dipl	subc	-	-	2																								1										1		1				1							
Navi	pupu	t	eu	2															1						1	1		1	1									1	1		1		1						1		
Nitz	font	-	eu	3												1		1						1	1			1			1													1							2
Achn	lanc	t	eu	3	1					1	1	1	1		1	1	1		1			1	1	1	1	2	1				1	1		1									1	1		1	1		1	1	3
Achn	minu	s	hs	4	2	1	1		2	3	1	1	1	2	1	1	1		1			1	3	4	4	4	6	1	3	2	2		1		1	1	1	1	1	1	1	1	2	1	1	1	1	1	1		
Cymb	sinu	s	hs	4	1	1	1	1		2	1	2	1	1	1	1		1	1		1	1	3	3	2	1	3	3	3	6	2				1		1	1	1	1	1	1	3	1	1	1	1				1
Cymb	sile	t	eu	4		1	1			1				1	1	1	1		1		1		1	1	1	1	1	1	1	1	5							1	1	1		1	1	1	1	1	1	1			1
Suri	roba	-	-	4	1			1	1																	1										1	1	1		1		1			1	1			4	6	3
Navi	goep	ht	ht	4	5	5	4	4	4	4	6	2	1	2	3	3	2	1	1	1	1	2	1	3	1	1	1	2	1			2	2	3	1	1	1	1	2	1					1		1	3	1		1
Achn	macu	-	-	4																																															1
Navi	capi	t	s	5		1	1		1	1		1		2	1	1	1	1	1			1	1	1	1			1	1					1	1		1	4	3	3	4	2		2	1	2	1	1	2		
Navi	viri	t	-	5					1	1				1	1	1							1											1	1		1	3	2	1	4	3		1		1					1
Rhoi	abbr	s	eu	5	1		1			1			1		1	1			1			1	1	1	1	1	1	1	1	1				1			1	1	1		1	1	1	4		1	1		1		
Cocc	plac	s	eu	5	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1			1	1		2	1	2		4	4	4	3	1	1	1	1	2	1	1
Comp	puml	ht	-	5	1		1	3	1	1	1	1	2	1	1	1	1	2	1	1	2		1	1	1	1		1	3	1			1	1	1	1	1	1	1	1	1	1	1	3	4	3	3	3	2	1	1
Navi	semi	ht	ht	6	1		1	2	1	1			1	1	1	1	1		1	1	1	1	1	1	1	2		1	1		1	1	1	1	1	1	1				1	2	1	1	1	2	1	3	1		2
Navi	arve	t	-	6				1				1		1	1		1	1	1	1	1	1	1			1		1		1		1	2	1	1	1	1	1	1					1	1	1	1	3	2	1	1
Comp	parl	-	-	6					1						1	1	1	1		1		1				1		1			1	1			1	1		1	1	1				1		1		2			1
Nitz	clau	t	-	6	1	2	1	1		1	1		1	2	1	1	1		1	1	3	1	1		1		1	1						1	3	1	3	1	1	1	1							2	1		
Navi	erif	-	-	6			1							1		2	2	1			1				1								1	1	2	2	1	1	1	1				1	1	1					
Navi	atom	ht	mt	6	1						1		1	1	1		1	1	1	1	1	1	1		1		1		1	1		1	1	1	1		1							1	1	1	1	1	1		
Frag	ulna	ht	eu	6			1	1	1			1		1	1	1	1		1	1	1		1	1					1			1			1			1	1		1	1	2	1	1	1		1	1		1
Gomp	parv	ht	mt	7	1	1	1	2	2	1			1	1	2	1			1		2	2	1	1	1	1	1	1	1	1	1	3	4	1	2	1	1	1	1	1	1	1		1	3	2	3	3	1	1	
Nitz	pale	ht	mt	7	1	1	1	1	1	1	1	1	1	2	2	2	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	5	4	4	4	3	2	2	3	1		1			2	1	1	1	1	1	1
Nitz	amph	ht	-	8	1	1	1	3	2	1	1	2	1	1	2	2	2	4	4	4	4	3	1	1	1	1	1	2	1			2	1	3	2	2	1	1	2	1		1		1	3	1		1	1	1	1
Nitz	inco	t	s	8	1	1	1	1	1	1		4	4	4	4	2	3	3	4	3	2	1	1		3	1	1	1	3	1	1			1	1	1	1		1			1			1		1	1	1		1
Navi	subm	t	ht	8	1			1	2	1		1	3		1	1	2	1	1	4	1	1	1		1			1	1		1	2	1	1	1	2	1	1	1	1	1	1		1	1		1	1	1	1	1

(10 groups, diversity = species diversity of samples: h=very high, 1=very low) and species (8 groups) resp. Only the 31 most discriminating species acc. to Jancay's ranking (see methods) are displayed, together with their classification by Lange-bertalot (LB) and Steinberg and Schiefele (SS) resp. (Abbreviations see Table 4). Abundance class: 1 = 1-5%, 2 = 6-10%, 3 = 11-20 %, 4 = 21-40%, 5 = 41.60%, 6 = >60%).

TABLE 6

Water quality of the sampling points from the R. Tárcoles basin in 1991 according to physico-chemical variables and diatoms

Site	Altitude (m.a.s.l.)	Season	Oxygen deficit	BOD_5	TP	NH_4-N	Diatoms
Main river sections:							
V-0	2200	Rainy	I	I-II	(II-II) IV	II-II-III	II-II-III
		Dry	I	I-II	IV	II-III-III	III
V-I	1200	Rainy	I	II-III	IV	I-II-IV	III
		Dry	I	III-IV-IV	IV	I-II-II-III	III-IV
V-5	960	Rainy	I-I-II	III	IV	(II-III) IV	II-III
		Dry	I-II-II	III-IV	IV	(II-III) IV	III-IV
TA-5	280	Rainy	I	II-III	IV	II-III-III-IV	III-IV
		Dry	I-II-II	III-IV-IV	IV	III-IV	III-IV-IV
TA-7	40	Rainy	I	II-II-III	IV	II-III-IV	II-III
		Rry	I-II	II-III	IV	III-IV	III-IV-IV
TA-9	25	Rainy	I-I-II	I-II-II	IV	III-IV-IV	III-III-IV
		Dry	I-II-II	II-III	IV	II-II-III	III-IV
Tributaries to V-5:							
Torres	960	Rainy	-	III-IV	IV	IV	-
		Dry	II	IV	IV	IV	-
BER	960	Rainy	II-II-III	III-IV	IV	IV	III-III-IV
		Dry	III	IV	IV	IV	-
Tributary to TA-5:							
Cacho	280	Dry	I	I	III	I-II	-

abundance lower than 1% were excluded. Percentage data were not transformed. Similarity of pairs of samples/species was calculated using van der Maarel's similarity index (van der Maarel *et al.* 1978). The sample and species groups shown in Table 5 were obtained by minimum variance clustering with MULVA4, a program package written in FORTRAN for multivariate analysis (Wildi and Orloci 1990). The discriminating species, i.e. species significantly more abundant in one or several sample clusters, were found by Jancey's ranking, a modification of Fisher's analysis of variance, also with MULVA4. A secondary cluster analysis based solely on the discriminating species yielded the sample groups and species groups displayed in Table 5.

RESULTS

Air and water temperature: The variability of water temperature was lower than the variability of air temperature. A higher downstream water temperature is reveled in Fig. 3 and Table 2, with significantly lower values in the headwaters (14-16°C) than near the mouth of the river (24-26°C). Neither, the water nor the air temperature were markedly different between the dry and rainy season, however the highest temperature was registered in the former.

Flow regime, suspended load and turbidity: The lowest run-off occurred from January to April. An initial increase in discharge is recorded at the beginning of the rainy season (April-May), causing a minor peak in June, followed by a constant rise from August to the highest level in October (Fig. 2B). Discharge also increases in the river valley downstream (Table 2).

In most cases the seasonal changes in suspended sediments coincide with changes in precipitation and discharge. V-0 showed the lowest concentrations in contrast to downstream sampling points, where concentrations were highly variable (Table 2). Water turbidity at V-1 and in the lower sites (TA-5 to TA-9) showed a much wider range (10-1150 U.N.T.) than in the headwaters (2-20 U.N.T.). High values were recorded particularly at the first rise of water level in June and during the maximum discharge in October or November (Table 2).

Physical and chemical features: At many sampling stations the water was slightly basic, although at V-0 lower values in the acid range were recorded (Table 3). At V-0 pH values showed seasonal variability with the minimum values (5.4) at the end of the dry season, an increase during May and June, and a second minimum in the "veranillo" (6.2). At the other sampling sites there was no clear change of pH values from dry to rainy season (Fig. 3).

Alkalinity also varied over time and space. Similar to the pattern of pH-values, V-0 presented the lowest alkalinity (average 0.3 meq.l^{-1}) while V-5 indicated a slightly basic character and the highest variability (average 1.8 meq.l^{-1}). At this point the tributaries R. Torres and R. Bermúdez contribute to the high levels. The annual alkalinity minima parallel the maximum discharge and maximum precipitation in October and November (compare Figs. 2 and 3). The conductivity ranged from 56 to 470 µS. cm^{-1}. The highest values in the R. Bermúdez, R. Torres and in V-5, may indicate the accumulation of solute - rich ions from waste waters (Table 2).

Concentrations of chlorides were high, with annual averages increasing from 7.6 mg.l^{-1} at V-0 to 13.2 mg.l^{-1} at V-5 (maximum 24 mg.l^{-1}), and maximum values in R. Bermúdez (average 18.4 mg.l^{-1}, Table 3).

Nutrient concentrations: Among all the sites, V-0 and Cacho stream showed the lowest nutrient values (Table 3), but with conspicuous concentrations in phosphorus (approx. 200 µg.l^{-1}). Downstream from the headwaters the concentrations rise considerably with maxima at V-5 (due to addition of nutrients by highly polluted tributaries) or TA-7 (Table 3). In general, the results indicate high concentrations of nutrients, especially for SRP, total phosphorus, and nitrate.

Seasonal patterns are different for the different variables and are inconsistent from sampling site to sampling site, but generally one

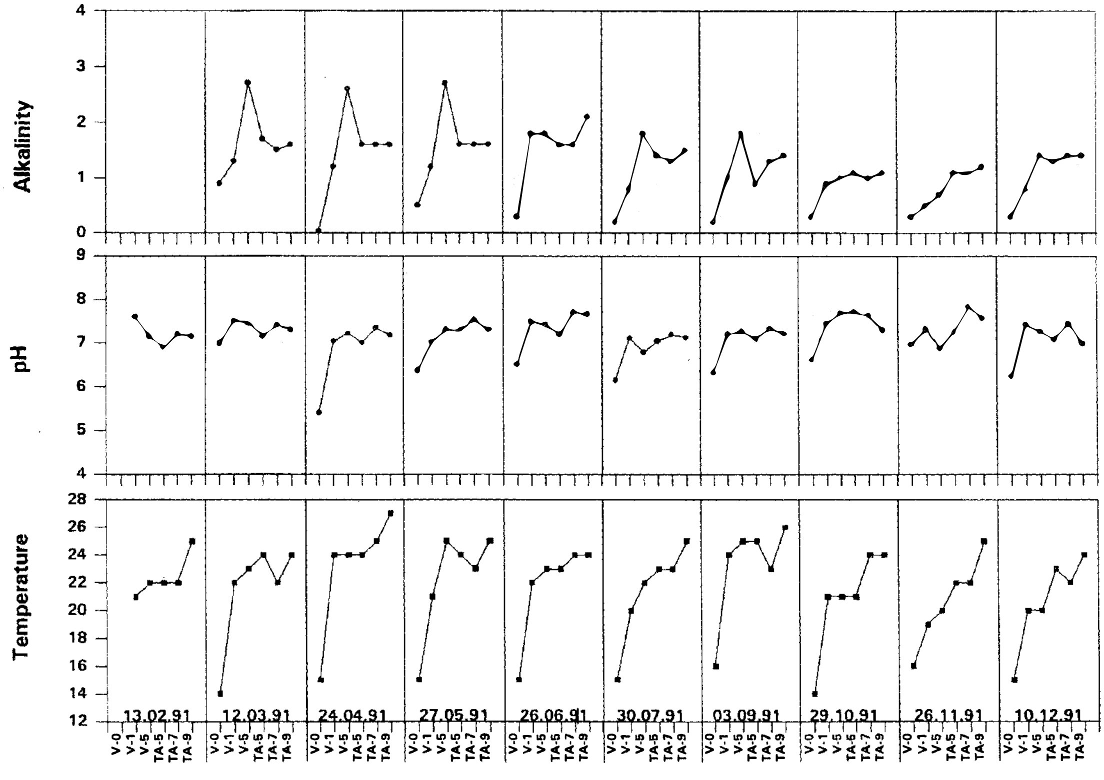


Fig. 3. Longitudinal and temporal variations of alkalinity, pH and water temperature for all different sampling sites in R. Virilla and R. Tárcoles.

peak at the end of the dry season and/or a smaller peak at maximum discharge can be observed (Figs. 4 and 5). Minimum concentrations at maximum discharges, which could be interpreted as a consequence of dilution, were not observed.

Soluble reactive phosphorus was lowest at V-0, and showed a relatively constant pattern throughout the entire sampling period (Fig. 4A), with the exception of the peak values found at site V-5 in March and April (3.8 $mg.l^{-1}$). The highest levels of all data were found in tributaries, e.g. in Río Virilla, Río Torres and R. Bermúdez near sampling point V-5 (Table 3). Large quantities of floating foam were observed throughout the sampling period on those sites, suggesting contamination by detergents in factory and domestic wastewater.

Annual averages of total phosphorus were 1.5 to 2.5 times higher than values for SRP, with peak values at V-5 and R. Bermúdez. As total phosphorus was not measured at every sampling occasion, observations on seasonality are not available.

Ammonium nitrogen (Fig. 4B) was highest at V-5 and in the tributaries entering R. Tárcoles near this site. Annual variability is very high, with maxima in April or June and in October. With the exception of V-0 and Cacho stream, where nitrate levels were low year-round, nitrate concentrations showed an increase either during the dry season with maxima in March or April or at the beginning of the rainy season and a decline as compared with the end of the rainy season in October or November (Fig. 5A). Nitrite as a metastable form of nitrogen is the lowest fraction of inorganic nitrogen measured, with maximum values during dry season (Fig. 5B).

Dissolved oxygen and BOD: In most cases the average oxygen concentration is near or above saturation (Table 3). In all cases, oxygen concentrations were slightly higher during the rainy season, suggesting a transfer of oxygen

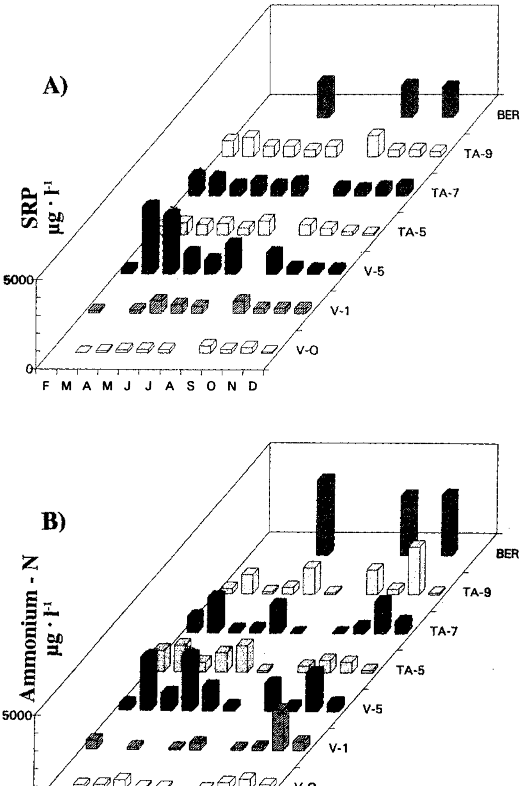


Fig. 4. Seasonal variations of macronutrients at the different sampling stations in R. Virilla and R. Tárcoles and a tributary to station V-5 (R. Bermudez), A) Soluble reactive phosphorus, B) Ammonium-Nitrogen.

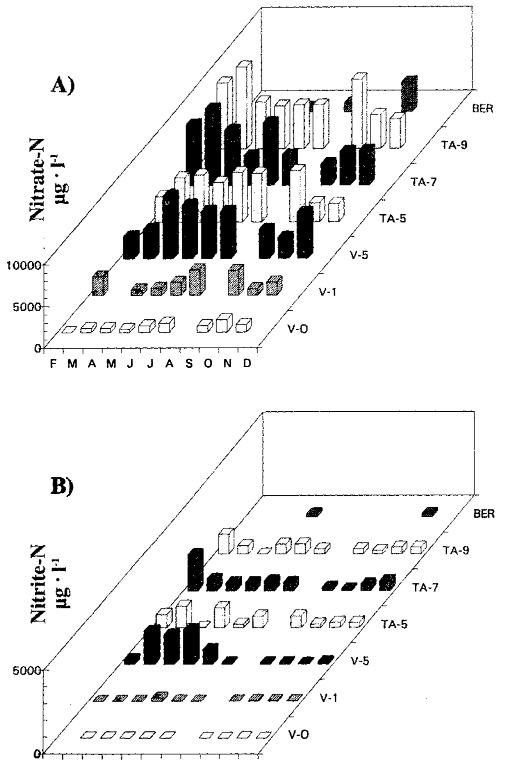


Fig. 5. Seasonal variations of nitrogen compounds at the different sampling stations in R. Virilla and R. Tárcoles and a tributary to station V-5 (R. Bermúdez). A) Nitrate, B) Nitrite.

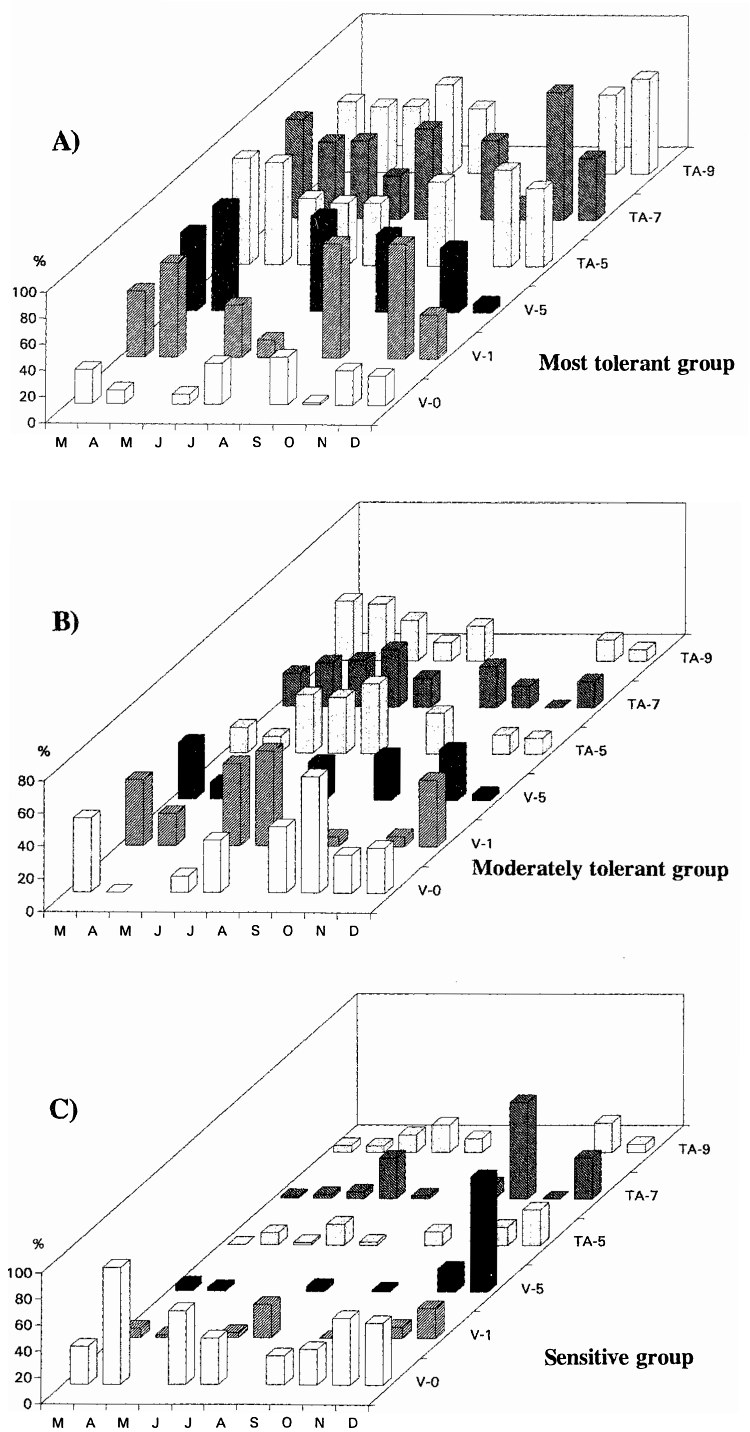
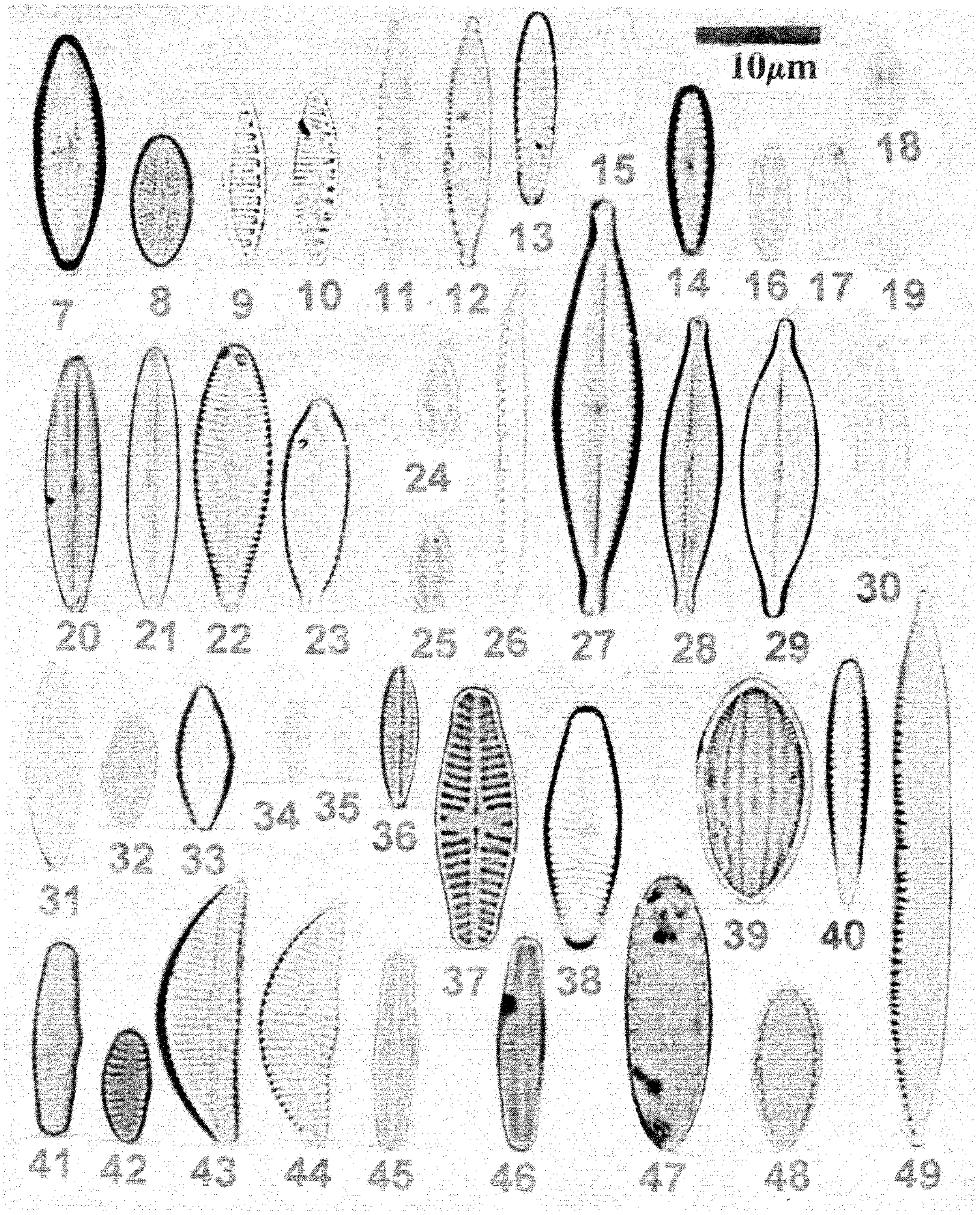
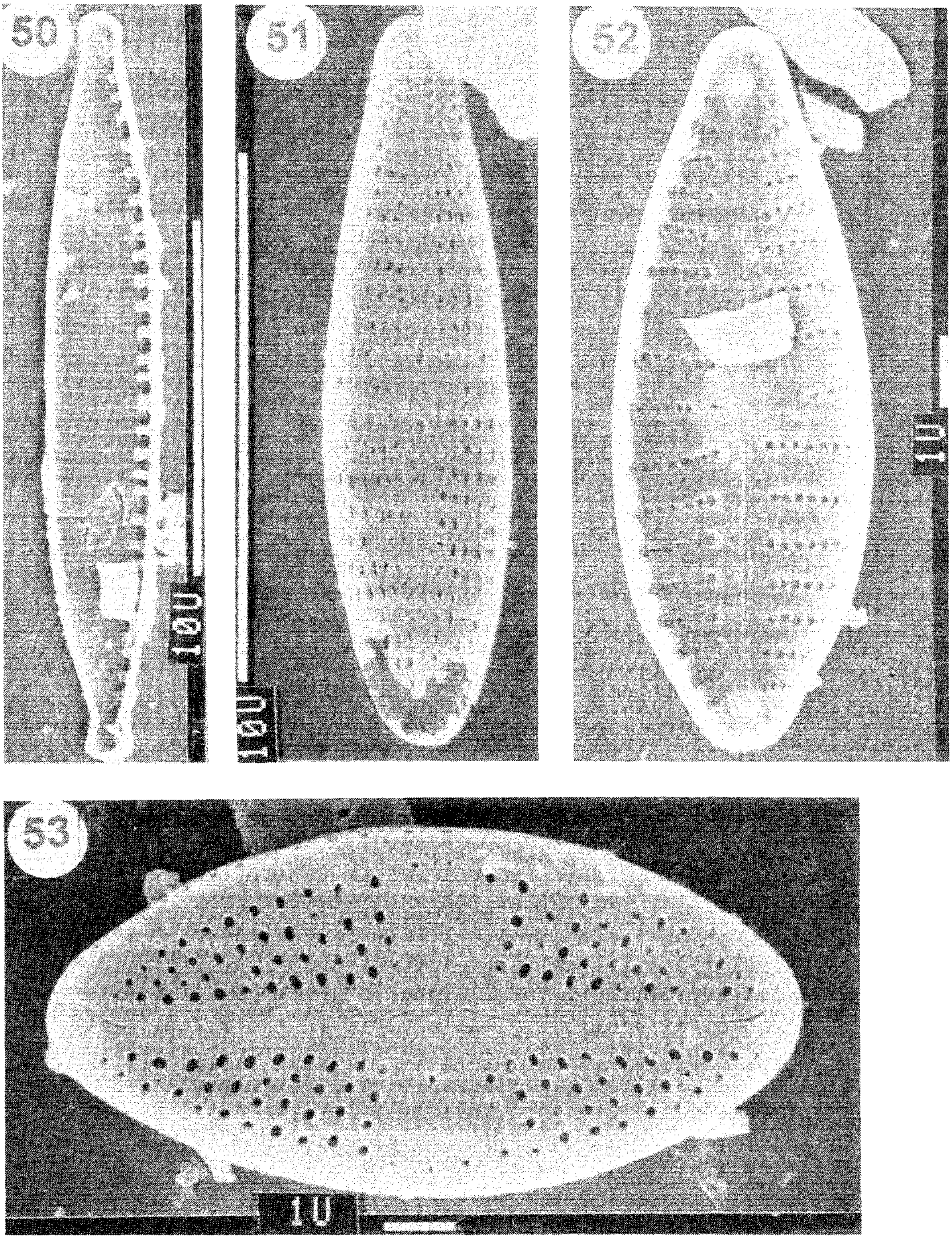


Fig. 6. **Seasonal variations of the relative portions of the 3 differential diatom species groups acc. to Lange-Bertalot** at the different sampling stations in R. Virilla and R. Tárcoles in 1991.



Figs. 7-49. Light micrographs of representatives of the differential species groups (black bar = 10 μm). A) highly tolerant against organic pollution - Figs. 7-14, 16-25; B) moderately tolerant group - Figs. 15, 26-29, 32-38; C) eutraphent species group - Figs. 39-40, 44-45; D) sensitive species group - Figs. 41-42, 45-49 and E) not classified but common on the polluted sites - Figs. 29-30. Figs. 7-8 *Navicula goeppertiana*, Figs. 8-9 *Nitzschia amphibia*, Figs. 10-11 *Nitzschia palea*, Figs. 13-14 *Gomphonema* sp. aff. *pumilum*, Fig. 15 *Navicula arvensis*, Figs. 16-17 *Navicula seminulum*, Figs.18-19 *Navicula atomus*, Figs. 20-21 *Navicula schroeterii*, Figs. 22-23 *Gomphonema parvulum*, Figs. 24-25 *Navicula minima*, Fig.26 *Nitzschia clausii*, Fig. 27 *Navicula capitatoradiata*, Figs. 28-29 *Navicula* sp. aff. *cryptocephala*, Figs. 30-31 *Navicula* sp., Fig. 32 *Navicula subminuscula*, Fig.33 *Fragilaria capucina* var. *vaucheriae*, Figs. 34-35 *Nitzschia inconspicua*, Fig. 36 *Navicula cryptotenella*, Figs. 37-38 *Achnanthes lanceolata*, Fig. 39 *Cocconeis placentula*, Fig. 40 *Rhoicosphenia abbreviata*, Figs. 41-42 *Cymbella sinuata*, Figs. 43-44 *Cymbella silesiaca*, Figs. 45-46 *Achnanthes minutissima*, Figs. 47-48 *Surirella* sp. aff. *roba*, Fig. 49 *Nitzschia linearis*.



Figs. 50-51. SEM photographs of the most characteristic highly tolerant species. Fig. 50 ***Nitzschia palea*****, Fig. 51** *Gomphonema* sp. aff. *pumilum*, Fig. 52 *Gomphonema parvulum*, Fig. 53 *Navicula goeppertiana*.

from the atmosphere favoured by high turbulence in mid-stream.

The biochemical oxygen demand is low upstream (V-0), and increases downstream at V-1, V-5, and TA-5 (Table 3). Increasing self purification processes as well as dilution from clean tributaries may lead to a reduction in the BOD at the lowest sampling sites. The seasonal variability of BOD suggests a slight increase in V-1, V-5, and TA-5 during the dry season due to the accumulation of sewage and to low dilution rates (see also Table 6).

Diatom species composition, communities and classification: A total of 95 diatom taxa were observed in the samples (Table 4). The genera containing the most species is *Navicula* (25 species), *Nitzschia* (17), *Gomphonema* (10) and *Achnanthes* (9). Distribution data in Table 4 largely correspond to the mathematical grouping of species shown in Table 5. Some characteristic diatom species for the places studied are shown in Figs. 7-53.

In spite of high turbidity and pollution, considerable quantities of benthic diatoms have been found in 47 out of the 51 samples. The four samples containing less than 20 frustules each came from V-0 (May), V-5 (June and October) and TA-5 (October). All the species found to be abundant in R. Virilla and R. Tárcoles are cosmopolitan species, and well known in temperate regions. Only some of the rare species, such as *Fragilaria goulardii* and *Gomphonema mexicanum* are reported to be more frequent in the tropics (Krammer and Lange-Bertalot 1986).

Many of the species dominating at any one of the sites also occurred at all sampling sites (Table 4). Thus the sites differ more according to the relative proportions of species than to their presence or absence. Seasonal distribution patterns were only observed for some species (Table 5); further patterns may be detected with absolute quantification.

Samples are moderately species-rich, mostly containing 25 to 35 species and a maximum of 45 species. Samples are characterized by 3 to 5 species of 10 to 20 (30) % relative abundance. Maximum diversity was observed mostly during the rainy season in V-0, V-5 (twice), TA-7 and TA-9, and once in dry season (V-1, April). Lowest diversity was shown by samples from V-0 in April, TA-7 in October and V-5 in December.

Cluster analysis also fails to show altitudinal and/or seasonal differences in species composition (Table 5), but multivariate methods do reveal similarities between samples and dates. First, groups No. 1, 2, 3, 5 and 6 are distinct from one cluster of samples V-1 and V-5 (group No. 8) and two sample clusters mainly represented V-0 (groups No. 4 and 10). Second, four clusters mainly contain samples taken at one season: Groups No. 1, 5 and 7 rainy season, group No. 10 dry season and "veranillo".

The sample groups described above are characterized by one or several species groups, especially by the respective discriminating species. Thus clusters of samples from R. Tárcoles are characterized by the dominance of *Navicula goeppertiana, Nitzschia inconspicua* and *Nitzschia amphibia,* while sample clusters representing mainly samples from R.Virilla are dominated by *Achnanthes minutissima, Cymbella sinuata* and *Surirella* sp. aff. *roba.*

Biological classification: Because these species are largely cosmopolitan, 25 species could be assigned to Lange-Bertalot's groups of highly tolerant (12 species out of 19 listed in Krammer and Lange-Bertalot 1986) and moderately tolerant (13 species out of 38) species (Table 4). All the following highly tolerant species are frequent in R. Tárcoles: *Navicula goeppertiana, Gomphonema parvulum, Navicula seminulum, Navicula subminuscula* and *Nitzschia palea,* with highest abundance in the lower sections of the river. Among the moderately tolerant species, only *Nitzschia amphibia* (mostly in the lower sections) and *Nitzschia clausii* (all along the river) reach higher frequencies. The following species, which Lange-Bertalot regarded as pollution -sensitive, are frequent in our study: *Achnanthes minutissima, Amphora montana, Cocconeis placentula, Cymbella silesiaca, Cymbella sinuata, Nitzschia frustulum,* and *Rhoicosphenia abbreviata.*

The latter-most species mentioned above and several others are also regarded as pollution - sensitive by Steinberg and Schiefele (1988) (*Achnanthes minutissima, Cocconeis pediculus, Cymbella sinuata and Navicula cryptotenella*), or as moderately sensible but eutraphent (e.g. *Cocconeis placentula, Cymbella silesiaca, Nitzschia dissipata, Rhoicosphenia abbreviata*; for classification of other species see Table 4).

Species groups yielded by cluster analysis also reflect pollution tolerances of species, as illustrated in Table 5. While groups No. 6, 7 and 8 comprise highly tolerant and some moderately tolerant species, groups No.1 to 5 consist of pollution-sensitive and eutraphent species.

The relative portions of the three differential species groups displayed in Fig. 6 clearly show differences in water quality of sampling sites: only V-0 contained considerable amounts of sensitive species throughout the year. At all the other sampling sites the largest frequency was reached by highly tolerant species, followed by moderately tolerant species. Aside from V-0, the moderately tolerant group was most important in June/July, in some cases also in March, while sensitive species were common in October (TA-7) and December (V-5).

Water quality of R.Tárcoles in 1991, as obtained from Fig. 6 and Table 1B, ranged from water quality class II (V-0, November) to IV (TA-7, November). Most frequently, quality classes II-III, III and III-IV were given. The ranges of water quality classes for each sampling site given in Table 6 show a clear difference between sampling sites, with V-0 being the relatively unpolluted site (quality class II-III during the rainy season and III during the dry season) and TA-5 being the most polluted site (III / III-IV during the rainy season and III-IV / IV during the dry season) and TA-7 showing the widest range of water quality classifications (II-III / III to III-IV / IV). In most cases water quality was slightly better during the rainy season than during the dry season.

DISCUSSION

The river section studied comprises one representative headwater stream and several sections of the largest river in the Central Valley in Costa Rica. This research yields information on the biotope quality of some main sections of a large catchment area and should be supplemented by a careful regional sampling network in order to render information on the water quality of the Río Grande de Tárcoles basin.

When these rivers begin to rise in the rainy season, erosion increases suspended sediment load and turbidity. An enhancement of nutrient concentrations and BOD in each sampling site takes place simultaneously, reflecting the increased discharge of untreated waste water. The whole R. Tárcoles basin is affected by the raw sewage from coffee plantations and factories, untreated domestic and industrial waste water, as reflected in the high amounts of nutrients and BOD. Later on the rainy season, water quality improves as the initial surge subsides. V-0 and the small Cacho tributary are the only slightly polluted reference sites.

Nutrient concentrations are generally high. The irregular spatio-temporal distribution of nutrient concentrations (Figs. 4 and 5) suggests effects of both punctual sampling and variable hydrologic conditions. The positive relationship between flow and nitrate level observed in the first rainy months, may be related to nitrification processes due to the oxidation of ammonium caused by high turbulence during this period of the year (Ramírez 1986, Stachowicz 1990). On the other hand, because it is very soluble, nitrate may also originate from agricultural fertilizer (Mason 1991). Nitrate concentrations may also be enhanced by high deforestation and consecutive erosion and leaching processes of soil material along all the R. Tárcoles catchment basin. The decline of this nutrient at the end of the rainy season may be the result of dilution process.

The high quantity of ambient phosphorus (soluble reactive phosphorus and total phosphorus) at all the sampling points suggests a high background of this nutrient. Pringle *et al.* (1990) and Pringle and Triska (1991) reported the presence of high phosphorus concentrations in several unpolluted streams that drain the volcano area in the Caribbean lowlands of Costa Rica. Similar results have been obtained from studies in lakes and rivers in other tropical countries (Talling 1957, Talling and Talling 1965, Golterman 1973, Payne 1986). These authors suggest that erosion of rock phosphate is the main natural phosphate source in waters from volcanic regions. The Tárcoles river basin, just as tecto-volcanic basins, is comprised of volcanic-sedimentary material. This geological formation may provide a high concentration of phosphate to streams and groundwater reserves flowing down from the Irazú, Poás and Barva volcanoes draining into R. Virilla and R. Tárcoles (Echandi-Echeverría 1983). This postulated natural source of phosphate may obscure the effects of anthropogenic phosphates.

High oxygen contents (Table 3) were caused by the high gradient and turbulence, and can lead to erroneous interpretations of the results. If we consider the values of oxygen given in the limnosaprobic ranges, all the sampling points except R. Bermúdez should be classified as water quality class II or better (Table 6). This interpretation does not reflect the true pollution levels. Therefore, oxygen content is an inappropriate indicator of water quality classification. Oxygen does, however, influence the diatom community despite high concentrations of nitrate, ammonium, and BOD.

Among the chemical parameters used by several authors for the water quality classification of large, slow flowing European rivers (Table 1A), only methods based on BOD and ammonium could be successfully applied to R. Tárcoles (Table 6). According to total phosphorus, all sampling points except Cacho stream (III) and V-0 have to be classified as water quality class IV. This Phosphorus-based assessment is therefore in stark contrast to oxygen based classification.BOD is also considered as an appropriate criterion for classification of the sampling sites, with Cacho stream and V-0 as the least saprobic sites (I-II) and V-1, TA-5 and Bermúdez showing the highest saprobic level (III-IV / IV). Saprobic levels of samples from the dry season were slightly higher at each sampling site. Another reasonable criterion is ammonium which generally yielded slightly worse classifications than BOD. Sampling sites V-5, R. Bermúdez and R. Torres showed the highest degree of pollution (water quality class IV). The seasonal pattern of ammonia is not as consistent at each sampling site as that of BOD.

The method proposed by Lange-Bertalot (1978, 1979) provides a meas of assessing water quality from the relative proportions of three diatom species groups based on their tolerance towards organic pollution. Because this method was developed for slow-moving European rivers, we must verify their applicability to tropical systems, which have high background nutrient levels and clearly lotic conditions.

This study reveals that diatoms are found at all investigated sites and, despite high fine sediment deposition, suitable samples for analysis could be obtained at 80% of the sites. We can thus conclude that this method can be used for biological monitoring of tropical environments. To a large extent, the species spectrum comprises cosmopolitan species, so that qualifications from temperate systems can be applied t tropical environments. However the actua classification of species into different grades o tolerance is different from the studies of Lange-Bertalot because nutrient levels are generally high and the oxygen content is elevated due to the highly uneven terrain and the swift current of the river.

Therefore the classification system of Steinberg and Schiefele (1988), defining an extra group of species preferring nutrient enriched, but oxygen saturated conditions (termed eutraphent species), can be applied even more successfully to the description of the water quality of R. Tárcoles. This system requires data on the nutrient requirements of a larger portion of the dominating species. As illustrated in Tables 4 and 5, most of the tolerant or definitively sensitive species, according to Lange-Bertalot, are termed eutraphent species by Steinberg and Schiefele (1988). High abundance of eutraphent species help to distinguish eutrophic sampling sites and/or occasions (sample clusters 8 and 9) from saprobic situations, where they form only a small portion of the community. *Achnanthes minutissima* and *Cymbella sinuata* are the only species classified as sensitive by both Lange-Bertalot and Steinberg and Schiefele; these species characterize those samples which were given water quality class II-III or better based on both BOD and NH_4.

Remarkably, none of the oligotraphent species according to Steinberg and Schiefele (1988) have been found in this study. *Achnanthes minutissima* and *Cymbella sinuata*, the only sensitive species reaching high percentages all along R. Tárcoles, find optimal conditions in nutrient poor, highly aerated, and slightly alkaline water (Krammer and Lange Bertalot 1988), but they are found relatively often in polluted sites as well (Van Dam 1979, Maier and Rott 1990). For *Achnanthes minutissima* it is necessary to consider a taxonomic problem as well: *Achnanthes minutissima* var. *saprophila* reaches its maximum in highly polluted waters (Kobayasi and Mayama 1982), while *Achnanthes minutissima* var. *jackei* is known to be sensitive to pollution (Krammer and Lange Bertalot 1986). In the present study, this species could not be identified to the variety level, which may hinder correct classification of this species.

This study confirms the classifications by both Lange-Bertalot and Steinberg and Schiefele. *Navicula capitatoradiata* is more appropriately considered a tolerant species, due to its maximum abundance in VA-5, while for *Navicula cryptotenella* seems to be only sensitive (not highly sensitive as in Steinberg and Schiefele). From the species which were found frequently in this study and which have not been assigned till now, we suggest that *Surirella* sp. aff. *roba* and *Achnanthes* sp. aff. *ricula* are pollution sensitive and prefer oligotrophic conditions, while *Gyrosigma scalproides* and *Navicula erifuga* as sensitive but eutraphent.

It is evident from both chemical and biological water quality classifications that the river downstream from V-0 is heavily loaded with nutrients and organic pollution from domestic sewage, treatment plants, factories and agriculture. These pollutants are reflected in the high percentage of tolerant species (Fig. 6). Classification according to diatoms in most cases corresponds to classification according to ammonium, and yields lower water quality classification than BOD, because of the high level of eutraphent species found.

Margalef (1958), Johansson (1982), demonstrated that in water quality conditions better than alpha-mesosaprobic, environmental factors other than nutrient load and biochemical oxygen demand determine the species composition of any component of the biota. Diatom communities of unpolluted Austrian streams and rivers were most closely related to stream order and altitude (*i.e.* mainly temperature, discharge regime, and geology (Pipp and Rott 1993), but ambient light, chemical compounds other than carbonates, and competition and predation are important as well (*e.g.* Chessman 1986, Ward 1986).

Information on the requirements of diatoms under tropical conditions is scarce. Venkateswarlu's (1969) results from Moosi River near Hyderabad (India) correspond to results from R.Tárcoles concerning the occurrence of *Achnanthes minutissima* and *Fragilaria ulna* in well oxygenated, nutrient enriched situations and of *Nitzschia palea* and *Cyclotella meneghiniana* in saprobic situations. Podzorski's study on the reaction of diatoms to environmental change in Broad River, Jamaica (1984) deals with seasonal changes of epiphytic (not epilithic) community structure at one sampling station with similar pH, high conductivity, similar and considerably lower orthophosphate concentrations as compared to R. Tárcoles. An investigation of littoral phytobenthos of a Nicaraguan lake (Guerrero and Rodríguez 1991) also revealed high percentages of *Nitzschia amphibia, Nitzschia palea* and *Navicula goeppertiana* at the most polluted sites, and *Achnanthes minutissima* at the less polluted sites.

Therefore a study of the benthic algae communities of tropical reference sites from the same catchment, or a catchment comparable to R. Tárcoles, would be the next step to be taken to adapt classification methods presented here to runoff from volcanic regions in the tropics, characterized by high water temperatures, high turbidity and high background concentrations of nutrients. In spite of methodological refinements of classification systems, the present study clearly demonstrates the need to take the following practical measures to improve the water quality of R. Tárcoles: establishment or improvement of waste water treatment plants, reduction of raw waste water discharge into the river, reduction of fertilizer use and of coffee processing refuse near the river, and establishment of a corridor of riparian vegetation on both river banks to reduce or prevent soil erosion.

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RESUMEN

La calidad del agua de varias secciones de un río tropical contaminado se estudió considerando factores químicos y biológicos. Los resultados confirman el alto grado de

deterioro de la cuenca del Río Grande de Tárcoles, situación reflejada en el alto porcentaje de especies de diatomeas tolerantes a fuerte descarga de nutrientes y materia orgánica. Especies resistentes a fuertes condiciones de contaminación, especies moderadamente resistentes y especies sensitivas a un sistema acuático deteriorado han servido de base para clasificar diferentes niveles sapróbicos en los sitios estudiados. Para ello se utilizó el concepto de grupos de diatomeas desarollado por Lange-Bertalot (1978, 1979, 1986) y Steinberg and Schiefele (1988). Las especies más abundantes fueron las siguientes: *Navicula goeppertiana, Gomphonema parvulum, Gomphonema* sp. aff. *pumilum, Nitzschia palea, Nitzschia amphibia, N. clausii, N. inconspicua, Navicula seminulum, Navicula* sp. aff. *cryptocephala, Navicula schroeterii* var. *escambia, Cymbella sinuata* y *Surirella* sp. aff. *roba.*

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