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PRIMARY RESEARCH PAPER

Water nutrient concentrations in channels in relation to occurrence of aquatic plants: a case study in eastern Croatia

**Aleksandra Kočić · Tomislav Hengl ·
Janja Horvatić**

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Abstract In this paper we analyzed nutrient concentration in the channels of eastern Croatia and investigated whether certain plant species and associations can be used as direct estimators of water quality. One hundred and twenty-two channel sites were visited and water samples taken for laboratory analysis (pH and concentrations of sulfate, chloride, ammonium, nitrate, and total phosphorus). At each site, macrophyte vegetation was recognized and its occurrence recorded. Three groups of analyses were performed: (a) principal component analysis to describe habitat characteristics of the investigated channels, (b) stepwise regression analysis to build estimation models for nutrient concentrations, and (c) geostatistical analysis including fitting of variograms and interpolation of values over the whole area of interest. High values of water nutrients in the eastern Croatian channels were reported (90% intervals): 5.3–29.4 for nitrates, 27.8–54.2 for sulfates, 0.1–0.4 for total P, and 0.18–0.34 mg l^{-1} for ammonium. Water nutrient concentrations can be successfully mapped over the channel network in eastern Croatia using geostatistics (regression kriging). The nutrient concentration variables required log transformation prior to regression or variogram analysis because their distributions were distinctly skewed towards lower values. Species were found to be a more successful estimator of nutrient concentrations than plant associations. In all cases, species had a higher adjusted *R*-square value, ranging from 0.302 (ammonium) to 0.485 (sulfates). Additional load of nutrients in water could lead to the disappearance of the more-sensitive species *Lemna trisulca*, *Riccia fluitans*, and *Ricciocarpus natans* and the spread of *Potamogeton pectinatus*, *Glyceria maxima*, and *Glyceria fluitans*. Further studies are needed to develop strategies for incorporating permanent monitoring networks to observe environmental changes and succession of vegetation.

Keywords Sulfates · Nitrates · Ammonium · Stepwise regression · Kriging · Croatia

Introduction

The chemical environment of many aquatic habitats has changed during the last century due to intensification of agricultural use, urban expansion, and water pollution (Riis & Sand-Jensen, 2001). Large nutrient

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A. Kočić (✉) · J. Horvatić
Department of Biology, J. J. Strossmayer University,
Trg Lj. Gaja 6, 31000 Osijek, Croatia
e-mail: aleksandra_kocic@yahoo.com

T. Hengl
Institute for Biodiversity and Ecosystem Dynamics,
Faculty of Science, University of Amsterdam, Nieuwe
Achtergracht 166, 1018 Amsterdam, WV, Netherlands

inputs, especially overenrichment with phosphorus and nitrogen, have accelerated eutrophication, which has become a widespread problem in rivers, lakes, estuaries, and coastal oceans (Carpenter et al., 1998). The effect of anthropogenic nutrient enrichment on river plants has been demonstrated in many studies (Demars & Harper, 1998; Schneider & Melzer, 2003). It is increasingly important to observe changes, including those in the nutrient condition, in aquatic systems. These changes impact the water pollution and the distribution and status of overall biota. However, monitoring water pollution can often be expensive and time consuming. Thus biologists hope to discover simple and affordable indicators of water quality, i.e., certain plants or plant communities.

Aquatic plants are an essential part of many freshwater aquatic ecosystems. Their status is a direct indicator of environmental conditions because such plants grow in close contact both with the water that surrounds them and the sediments in which they are rooted (Brönmark & Hansson, 1998). The development of aquatic plants is dependent upon a variety of abiotic and biotic factors, the major ones being current velocity (Haury, 1996; Janauer, 2001; Daniel et al., 2006), substrata (Baattrup-Pedersen & Riis, 1999), water depth (Riis et al., 2001; Bouldin et al., 2004), light (Bini et al., 1999), overall water quality (Haury, 1996), and nutrients (Dawson & Szoszkiewicz, 1999; Thiebaut & Muller, 1999). If all habitat conditions are known, the distribution of plant species and communities can be successfully predicted (Guisan & Zimmermann, 2000). Thus, it should be possible to use the occurrence of plants as an estimator of environmental conditions. Despite being aware that certain species can be used as bioindicators, there is a need for reliable and systematic guides to estimate water nutrient concentrations in the field by recognizing and describing the macrophytes.

In recent years, there has been increasing interest in assessing the spatial distribution of aquatic vegetation (Tremp, 2007), nutrients in the water (Smith et al., 1997; Yuan, 2004), and the associated environmental risks. The researches has been focused on methodological advances and the application of concepts and technologies that have shown operational in similar land applications, e.g., for monitoring of stream networks (Sauquet, 2006; Peterson et al., 2006).

Likewise, our objective in this paper was to analyze the nutrient concentrations of channels in eastern Croatia and to explore the possibilities of using geostatistical analysis with nutrient concentrations data. Furthermore, we wanted to investigate whether certain plant species and communities can be used as direct estimators of water nutrient concentrations and to suggest strategies for establishing permanent environmental monitoring networks.

Materials and methods

Study area

The target area was the channel system in eastern Croatia (Fig. 1). It covers about 4500 km^2 with altitude ranging from 75 to 99 m a.s.l. The water in the channel system is controlled by three rivers: the Danube, the Drava, the Sava, and their tributaries. In the past, the area was covered by alluvial forests and marshes and was under the constant impact of flood water. During the 19th century, the marshy and flooded area was considerably reduced by melioration activities. Today, the flooded area has been reduced by 50% and the marshes can be observed only in isolated localities. The northeastern part of the investigated area corresponds to the Croatian Baranja region, and lies within the triangle between the Danube and Drava rivers. In the corner between the Danube and Drava rivers is a large floodplain, the Natural Park Kopački Rit. The southern part of the research area represents the largest complex of Slavonian oak forests in Croatia. Networks of rivers can be found inside these forests, including the Bosut River with its tributaries, the Biđ, the Spačva, the Studva, and the Berava, which all have a slow current velocity, and a meandering and shallow course.

Field sampling

Prior to the field work, we systematically allocated 122 observation sites on 1:50,000 topographic maps. The sites were selected to determine the water nutrient concentrations of channels in eastern Croatia. They included rivers and channels situated within both forested areas (44 sites) and agricultural land (78 sites) to reflect a gradient of land use and anthropogenic influence. The sites were also selected to represent river order gradients of water courses. The

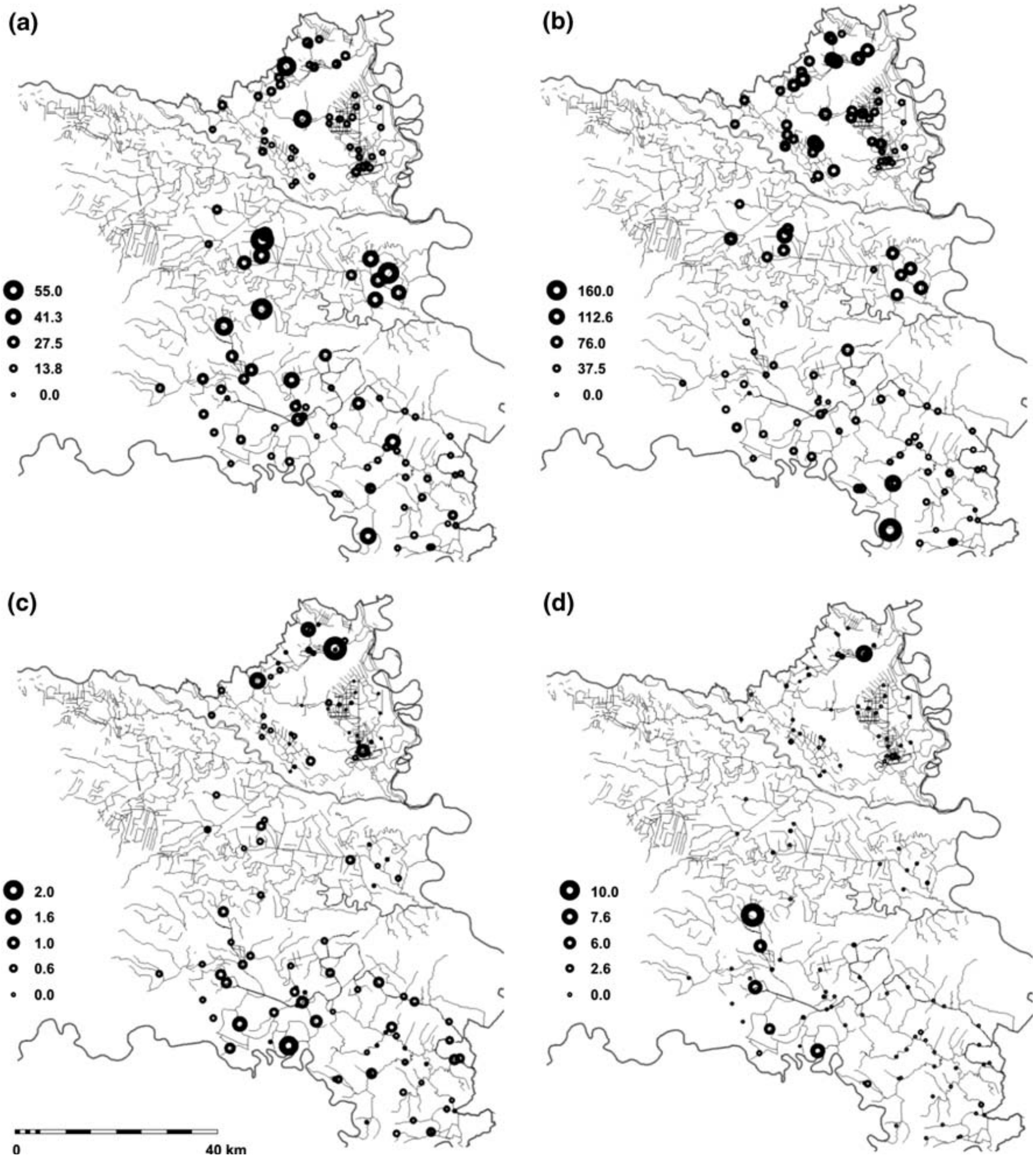

Fig. 1 The measured concentrations (mg l^{-1}) of: (**a**) nitrates, (**b**) sulfates, (**c**) total phosphorus, and (**d**) ammonium in the investigated sites of channel network in eastern Croatia

preselected *XY* locations were exported to a portable global positioning system (GPS) unit and then used for navigation in the field. These locations were visited in July and August in 2005 and 2006.

The following environmental variables were recorded for each channel site: the width and depth of the channel, as well as the geographical variables easting, northing, and altitude (recorded by the GPS device). As additional estimators available for the whole area of interest we used a digital elevation model (DEM) derived from the 90 m spatial resolution Shuttle Radar Topography Mission DEM and the mean annual enhanced vegetation index (EVI) derived from the 250 m resolution moderateresolution imaging spectroradiometer (MODIS) imagery. The EVI image can be used to represent the green biomass of area, i.e., vegetation cover. Higher values of the EVI indicate more dense vegetation, while urbanized areas typically show the small values. Although the spatial resolution of the MODIS images is relatively coarse, the advantage of the MODIS images is that they have a very high temporal resolution (16 days) and hence can be used to parameterize the vegetation/land use dynamics. The DEM and the EVI are standard exhaustive predictors used for geostatistical mapping of environmental variables (Hengl, 2007; Hengl et al., 2007). The SRTM DEMs can be obtained from the Consortium for Spatial Information (http://www.srtm.csi.cgiar.org) and the MODIS imagery from the The Land Processes Distributed Active Archive Center (http://lpdaac.usgs.gov).

For the chemical analysis in the laboratory, water samples were collected from each channel site just below the water surface. Acidity (pH) was determined by a pH-meter and the concentrations of sulfates, chlorides, ammonium, nitrates, and total phosphorus by spectrophotometry (Shimadzu UV-VIS 1601) using standard methods (APHA, 1998).

Surveys were conducted from a boat or from the bank. The percentage cover occupied by each species was determined visually and converted to a simple scale for subsequent analysis, as follows; + = a few scattered specimens (mean coverage 0.1%); 1 $\leq$ 5% coverage (mean 2.5%); 2 = 6–25% (mean 15%); 3 = 26–50% (mean 37.5%); 4 = 51–75% (mean 62.5%); 5 = >75% (mean 87.5%) (Braun-Blanquet, 1964), from the 50 m reference channel length. The percentage abundance of each submerged species was also recorded based on vegetation samples taken from the boat with a sampling rake and from direct observation through the water surface (Parsons, 2001). All the field data were collected by the same person, thus ensuring that the estimates were standardized. Within the channels, a total of 89 species were identified. The obligate submerged and amphibious plants (Sand-Jensen et al., 1992; Riis & Sand-Jensen, 2002), which totalled 48 species, were included in the analysis. Even though occasionally observed within the streams, terrestrial plants were excluded due to their land-related habitat. For the taxonomic nomenclature of vascular plants we used the Flora Europaea (Tutin et al., 1968–1993) and for their identification we used the keys of Casper & Krausch (1980) and Preston (1995). In survey sections 50 m in length, dominant phytocoenosa was taken as the plant association of the site. The size of vegetation relevés were 10–50 m^2. The vegetation was classified on the basis of the abundance of characteristic species according to the system devised by Braun-Blanquet with stands of *Spirodela polyrhiza* as the only exception. Because of the conspicuous dominance of *Spirodela polyrhiza* in deep and wide channels and the lack of characteristic species in some relevés, these were syntaxonomically nonclassifiable so we marked them separately as stands. A detailed description of aquatic plant associations in Croatia with characteristic species can be found in Topić (1989).

Data analysis

We performed three groups of analyses using the 122 point samples: (a) principal component analysis to describe the habitat characteristics of the investigated channels, (b) stepwise regression analysis to build estimation models for water nutrient concentrations, and (c) geostatistical analysis including fitting of variograms and interpolation over the whole area of interest. In addition, the environmental variables were compared between agricultural and forested land using *t*-tests (Table 1).

A principal components analysis (PCA) ordination of the habitat variables was performed using the STATISTICA 7.0 software (StatSoft) to describe habitat characteristics of the investigated channels. Stepwise multiple regression models were built in *R* statistical computing environment (http://www.r-project.org) to quantify the relationships between the aquatic macrophyte taxa and macrophyte communities. A stepwise multiple regression algorithm iteratively removes predictors that are insignificant and finds an optimal subset of predictors (Jongman et al., 1995). This allows one to detect the most promising indicators of nutrient concentrations and reduce future field work. The distributions of the values of nutrients were all highly skewed, with relatively small numbers of sites having higher values. Such data is obviously not well suited for linear regression analysis (Hengl, 2007). To account for this problem, all nutrient concentrations variables were log transformed. The observed species were

Table 1 Summary of the environmental variables of channels in eastern Croatia (mean, range in parentheses) in agriculture and forestry areas

Parameters	Agriculture	Forestry	Total	*P*-values
Width (m)	4.9 (1.0–12.0)	22.8 (2.0–80.0)	11.1 (1.0–80.0)	<0.001
Depth (m)	0.7 (0.1–2.6)	1.3 (0.1–4.5)	0.9 (0.1–4.5)	<0.001
Altitude (m)	82.4 (76.0–99.0)	81.5 (75.0–93.0)	82.1 (75.0–99.0)	ns
pH	7.6 (7.2–8.5)	7.9 (7.4–8.9)	7.7 (7.2–8.9)	<0.001
Sulfate (mg l^{-1})	50.3 (11.0–95.0)	32.3 (7.0–162.8)	43.8 (7.0–162.8)	<0.001
Nitrate (mg l^{-1})	14.0 (1.9–55.0)	8.2 (0.4–32.9)	11.9 (0.4–55.0)	<0.01
Ammonium (mg l^{-1})	0.7 (0.0–13.4)	0.4 (0.0–5.4)	0.6 (0.0–13.4)	ns
Total P (mg l^{-1})	0.3 (0.0–3.2)	0.4 (0.0–1.2)	0.3 (0.0–3.2)	ns
Chloride (mg l^{-1})	44.5 (14.0–147.6)	35.4 (20.0–122.4)	41.2 (14.0–147.6)	<0.01
EVI	193.6 (161.0–238.0)	203.7 (174.0–234.0)	197.2 (161.0–238.0)	<0.001

The environmental variables were compared between agricultural and forested land using *t*-test. ns = no significant differences between variables

supplemented by physical variables of habitat such as depth, width, altitude (from a digital elevation model), and enhanced vegetation index (EVI), as an estimate of the mean annual biomass. We ran the stepwise regression first by using the value of the mean coverage of species and then by using the presence/absence values of plant associations as predictors.

For each nutrient, we fitted a variogram for residuals and interpolated the values over the 100 m grid using the regression kriging technique (Hengl et al., 2007) as implemented in the gstat package of *R*. Originally, we wanted to use detailed maps of the occurrence of the plant species available for the whole area of interest as the only predictors of the water nutrient concentrations. Because we only worked with the sampled occurrences, we limited the regression models to only two raster layers of the DEM and EVI. These layers are available over the entire area and therefore can be used to predict the value of an environmental variable. First, by modeling the relationship between the nutrients and the DEM and EVI at the sample locations, and then by applying it to unvisited locations using the known value of the auxiliary variables at those locations. For more details about the regression kriging computational steps see Hengl (2007).

Results

Measured concentrations of nitrates, sulfates, total phosphorus, and ammonium at the investigated sites of channel networks in eastern Croatia are shown in Fig. 1. The mean width of the investigated channels varied from 4.9 m in agriculture to 22.8 m in forestry areas ($P < 0.001$). Channels in forestry land were on average deeper (1.3 m) than those in agricultural land (0.7 m, $P < 0.001$). The forested areas are characterized by higher pH ($P < 0.001$) and lower concentrations of chlorides ($P < 0.01$), nitrates ($P < 0.01$), and sulfates ($P < 0.001$) than in the water in agricultural land areas (Table 1).

Principal component analysis (PCA) shows the general structure of the environmental variables of the investigated channels in eastern Croatia (Fig. 2). The first four axes of the PCA with eigenvalues greater than 1 accounted for 63.3% of the total inertia of the data set. The axis scores indicated the first axis (26.2% inertia) as the gradient from generally deeper (+0.74) and wider (+0.72) channels with a higher pH (+0.66) mainly of forested area to shallow, narrow channels with a higher amount of nitrates (−0.59) and sulfates (−0.69), which are indicators of intensive agriculture. The relation of the first axis with geographical position (northing and easting) showed that the eastern part of the investigated area towards the Danube, Sava, and Bosut rivers belong to the group of deeper and wider channels, while the northern part of the investigated area is under the influence of intensive agriculture. The second axis (14.1% inertia) corresponded to phosphates (−0.79), ammonium (−0.58), and northing (+0.59) and described a gradient of nutrient concentrations from higher to lower amounts of nutrients (total

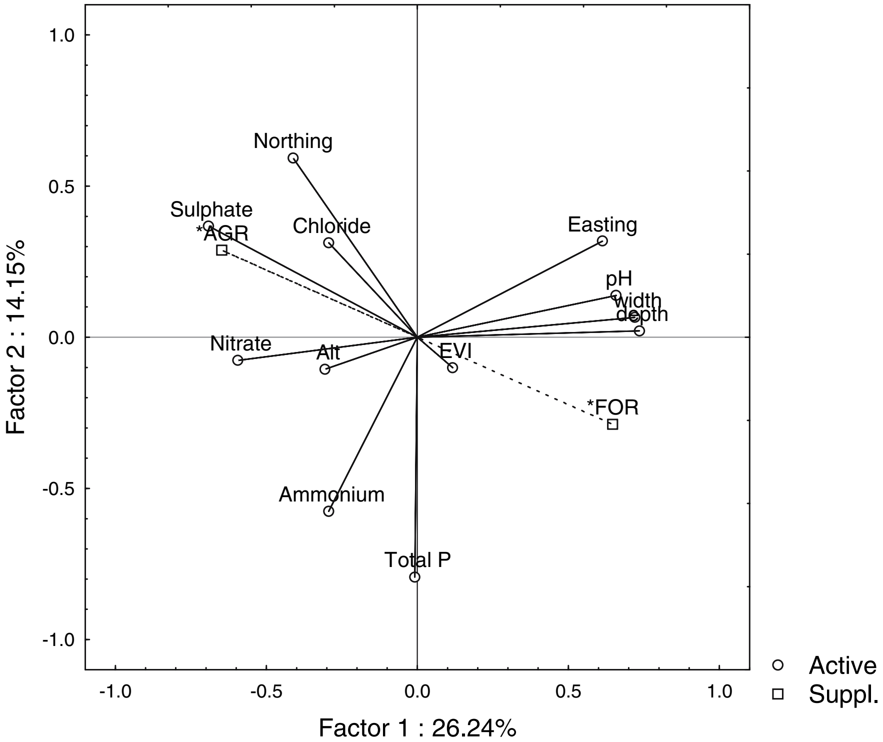

Fig. 2 Representation of the first factorial plan of the principal component analysis involving the physical and chemical variables of the habitat as active (Active) variables and agriculture (AGR) and forestry (FOR) area as supplementary (Suppl.) variables

phosphorus and ammonium). The third axis (13.1% inertia) was determined by altitude (−0.77) and the mean annual enhanced vegetation index (EVI) (−0.72) while the fourth axes (9.8% inertia) was determined by pH (+0.42), chlorides (+0.61), and nitrates (+0.44).

The stepwise regression analysis showed a similar relationship of the investigated variables as the PCA (Fig. 2, Table 3). The models also showed a weak but significant correlation between the altitude and EVI with the nutrients (Table 3). Despite the small range of altitude (75–99 m a.s.l.) in the investigated area, a higher amount of nitrates exhibited a positive correlation with altitude. The high values of total phosphorus in the investigated sites indicated hypereutrophic conditions (OECD, 1982) (Fig. 1c), and showed a negative relationship with values of EVI (Table 3).

Further geostatistical analysis of the nutrient concentrations of channels indicated that all nutrients showed a significant spatial autocorrelation (Fig. 3), even after the use of auxiliary predictors. Only for total phosphorus, we were not able to fit a variogram but used a pure nugget variogram (Fig. 3c). In general, the point measurements of nutrient concentrations are suitable for geostatistical analysis and mapping applications. The remaining questions are which geostatistical techniques are most appropriate for this and how to extend the number of predictors. The final maps showing the distribution of nutrients over the channel system interpolated using regression kriging are shown in Fig. 4.

The investigated channels were colonized predominantly by free-floating species *Lemna minor*, *Spirodela polyrhiza*, submerged *Ceratophyllum demersum*, and by the plant association *Lemno-Spirodeletum polyrrhizae*. The most significant stepwise multiple regression models were fitted for pH, sulfates, and nitrates (Table 2). The associations *Ceratophylletum demersi*, *Trapetum natantis*, *Riccietum fluitantis*, and stands of *Spirodela polyrhiza* were indicators of lower amounts of nitrates. *Myriophyllo-Nupharetum* was an indicator of lower amounts of nitrates and sulfates. In addition, the plant association *Trapetum natantis* was correlated with a higher pH and this was the characteristic association of the wide channels in the forestry areas. The results showed that plant associations are weak estimators of the total phosphorus and ammonium (adjusted *R*-squared value of the models in Table 2). Nevertheless, we

Table 2 Stepwise multiple regression between environmental variables and macrophyte associations

Associations	pH	Nitrate	Sulfate	Chloride	Ammonium	Total P
Class: Lemnetea W. Koch et Tx. 1954						
Order: Lemnetalia W. Koch et Tx. 1954						
Alliance: Lemnion W. Koch et Tx. 1954						
Ass. Lemno-Spirodeletum polyrrhizae W. Koch 54			2.56*			
Ass. Lemnetum trisulcae Knapp et Stoffers 62						−2.77**
Ass. Spirodelo-Salvinietum Slav. 50						
Ass. Riccietum fluitantis Slav. 56		−2.48*				−2.37*
Class: Potamogetonetea Tx. Et Prsg. 1942						
Order: Potamogetonetalia W. Koch 1926						
Alliance: Potamogetonion W. Koch 1926						
Ass. Ceratophylletum demersi Hild 56		−2.67**				
Ass. Potamogetonetum pectinati Carstensen 55					3.23**	2.38*
Alliance: Nymphaeion albae Oberd. 1957						
Ass. Myriophyllo-Nupharetum W. Koch 26		−3.88***	−2.99**			
Ass. Trapetum natantis Muller et Gors 60	2.98**	−2.46**				
Class: Phragmitetea Tx. et. Prsg. 1942						
Order: Phragmitetalia W. Koch em. Pign. 1953						
Alliance: Phragmition W. Koch 1926						
Ass. Scirpo-Phragmitetum W. Koch 26						
Ass. Glycerietum maximae Hueck 31			2.72**	2.14*		
Ass. Typhetum latifoliae G. Lang 73			1.99*			
Order: Nasturtio-Glycerietalia Pign. 1953						
Alliance: Glycerio-Sparganion Br.-Bl. et. Siss. 1942						
Ass. Glycerietum fluitantis Eggler 33					2.44*	
Stands of *Spirodela polyrhiza*		−2.70**				
Altitude						
Width	7.41***					
Depth					−2.55*	
EVI						
R^2_{adj}	0.547	0.298	0.386	0.033	0.170	0.148

Correlation coefficients are given. Values marked with asterisks are significant at $P < 0.05$ (*), $P < 0.01$ (**), and $P < 0.001$ (***) levels; empty case: $P > 0.1$

can see that the plant associations *Lemnetum trisulcae* and *Riccietum fluitantis* are significantly correlated with a lower amount of total phosphorus, *Potamogetonetum pectinati* with a higher amount of total phosphorus and ammonium, and *Glycerietum fluitantis* with a higher amount of ammonium (Table 2).

The stepwise multiple regression models of chemical variables using species and environmental variables as predictors (Table 3) showed similar relationships as in the case of plant associations. The best-fit models were for pH, sulfates, and nitrates. Species associated with a higher amount of nitrate grew predominantly in shallow channels and were associated with agricultural areas (Table 1). The species *Glyceria maxima*, *Myriophyllum spicatum*, and *Sium latifolium* were related with a higher amount of sulfates, and the species *Sparganium erectum*, *Sium latifolium*, and *Wolffia arrhiza* with a higher amount of nitrates. The occurrence of *Ceratophyllum demersum*, *Hippuris vulgaris*, *Myriophyllum verticillatum*, *Najas marina*, *Ricciocarpus natans*, *Sagittaria sagittifolia*, *Bulboschoenus maritimus*, and filamentous algae were connected with lower amounts of sulfates, and *Ceratophyllum demersum*,

Table 3 Stepwise multiple regression between environmental variables and macrophyte taxa

Species	pH	Nitrate	Sulfate	Chloride	Ammonium	Total P
Acorus calamus L.						
Alisma plantago-aquatica L.						2.71**
Bolboschoenus maritimus (L.) Palla			−3.18**	−2.28*		
Butomus umbellatus L.						
Callitriche stagnalis Scop.						
Ceratophyllum demersum L.		−3.34**	−2.83**			−2.70**
Chlorocyperus glomeratus (L.) Hay.					3.02**	
Elodea canadensis L. C. Rich.						
Filamentous algae	4.94***		−2.81**			
Glyceria fluitans (L.) R. Br.					2.68**	2.38*
Glyceria maxima (Hartm.) Holmb			3.15**			
Hippuris vulgaris L.	−2.25*		−2.57*			−2.91**
Hydrocharis morsus-ranae L.	−2.51*			−2.30*		
Lemna gibba L.						
Lemna minor L.						
Lemna trisulca L.				2.50*		−4.0***
Marsilea quadrifolia L.	3.45***					
Mentha aqutica L.						
Myriophyllum spicatum L.			2.52*			
Myriophyllum verticillatum L.		−2.87**	−2.50*	−2.46*		
Najas marina L.		−2.40*	−3.17*		2.33*	
Nuphar lutea (L.) Sibth. & Sm.	−2.74**	−2.56*				
Nymphaea alba L.						
Nymphoides peltata Kuntze						
Oenanthe aquatica (L.) Poiret						
Phragmites australis (Cav.) Trin. ex Steud				2.51*		
Polygonum amphibium L.					2.11*	
Potamogeton crispus L.						
Potamogeton natans L.		−2.03*				
Potamogeton pectinatus L.					3.82***	2.52*
Ranunculus aquatilis L.						
Ranunculus circinatus Sibth						
Riccia fluitans L.		−2.61*				−2.85**
Ricciocarpus natans L.			−2.06*			−2.9**
Rorippa amphibia (L.) Besser						−2.42*
Sagittaria sagittifolia L.			−2.02*	−2.31*		
Salvinia natans (L.) All.						
Schoenoplectus lacustris (L.) Palla						
Sium latifolium L.		2.18*	3.58***	3.23**		
Sparganium erectum L.		2.39*				
Spirodela polyrhiza (L.) Schleid						
Stratiotes aloides L.				−2.66**		
Trapa natans L.	2.82**					
Typha angustifolia L.						

Table 3 Stepwise multiple regression between environmental variables and macrophyte taxa

Species	pH	Nitrate	Sulfate	Chloride	Ammonium	Total P
Typha latifolia L.	−2.11*					
Utricularia vulgaris L.						
Veronica anagallis-aquatica L.						
Wolffia arrhiza (L.) Horkel ex Wimm.		3.13**				
Width	4.50***		−3.05**			2.29*
Depth		−4.66***			−2.84**	
Altitude		2.89**				
EVI						−2.25*
R^2_{adj}	0.601	0.428	0.485	0.225	0.302	0.338

Correlation coefficients are given. Values marked with asterisks are significantly at the $P < 0.05$ (*), $P < 0.01$ (**), and $P < 0.001$ (***) levels

Myriophyllum verticillatum, *Najas marina*, *Nuphar lutea*, *Potamogeton natans* and *Riccia fluitans* with lower amounts of nitrates. Species associated with a higher amount of ammonium (*Chlorocyperus glomeratus*, *Glyceria fluitans*, *Potamogeton pectinatus*, *Najas marina*, *Polygonum amphibium*) were located in shallower channels (Table 3). With regard to the distribution of total phosphorus, *Potamogeton pectinatus*, *Alisma plantago aquatica*, and *Glyceria fluitans* were related to high values of total phosphorus, while *Ceratophyllum demersum*, *Lemna trisulca*, *Hippuris vulgaris*, *Rorippa amphibia*, *Riccia fluitans*, and *Ricciocarpus natans* were indicators of lower values of total phosphorus.

The comparison of the regression coefficients obtained from these models confirmed that species are more suitable indicators of nutrient concentrations than associations—the adjusted *R*-squared value is always 50–100% higher if species versus associations are used as predictors (Table 2, Table 3).

Discussion

The results of this case study have shown that the water nutrient concentrations in the channels have reached high levels (Table 1, Fig. 2). In the nutrient-enriched conditions the submerged vegetation is replaced by free-floating communities because eutrophication promotes the growth of epiphytes and nonrooting macrophytes (Bini et al., 1999). An increase of the amount of nutrients favors biological diversity to some extent; however, a further increase of nutrients in water may lead to a decrease of overall biodiversity, the disappearance of some plant communities, and spreading of others (Heegaard et al., 2001). The positive relationship of nitrates and sulfates with the agricultural area confirms the results obtained in numerous studies. For example, in the research of Yuan (2004) there was a strong autocorrelation of nitrate concentration with agricultural activity in the watershed. Heegaard et al. (2001) found that high sulfate concentrations were associated with lowland areas of intensive agriculture and were probably related to fertiliser application. Also, in our case study, the high values of total phosphorus were correlated with the low values of mean annual EVI, i.e., urban land use. This coincides with the results of Johnson et al. (1997), who showed that elevated phosphate loading is related to urban land use. According to Smith et al. (1997), fertilizer application is highly significant in the final total phosphorus model. The next step to improve our maps of nutrients, especially the map of total phosphorus, would be to include additional maps of land use and locations of the sources of pollution (industry lines, wastewater system, etc.).

The results of the statistical analysis for this case study showed that plant species are good indicators of the water nutrient concentrations. For example, the disappearance of the species *Lemna trisulca*, *Riccia fluitans*, *Ricciocarpus natans* as well as plant associations *Lemnetum trisulcae* and *Riccietum fluitantis* can be an indicator of higher amounts of nutrients (mainly total phosphorus). Landolt (1986) confirmed that accelerated eutrophication might eventually lead

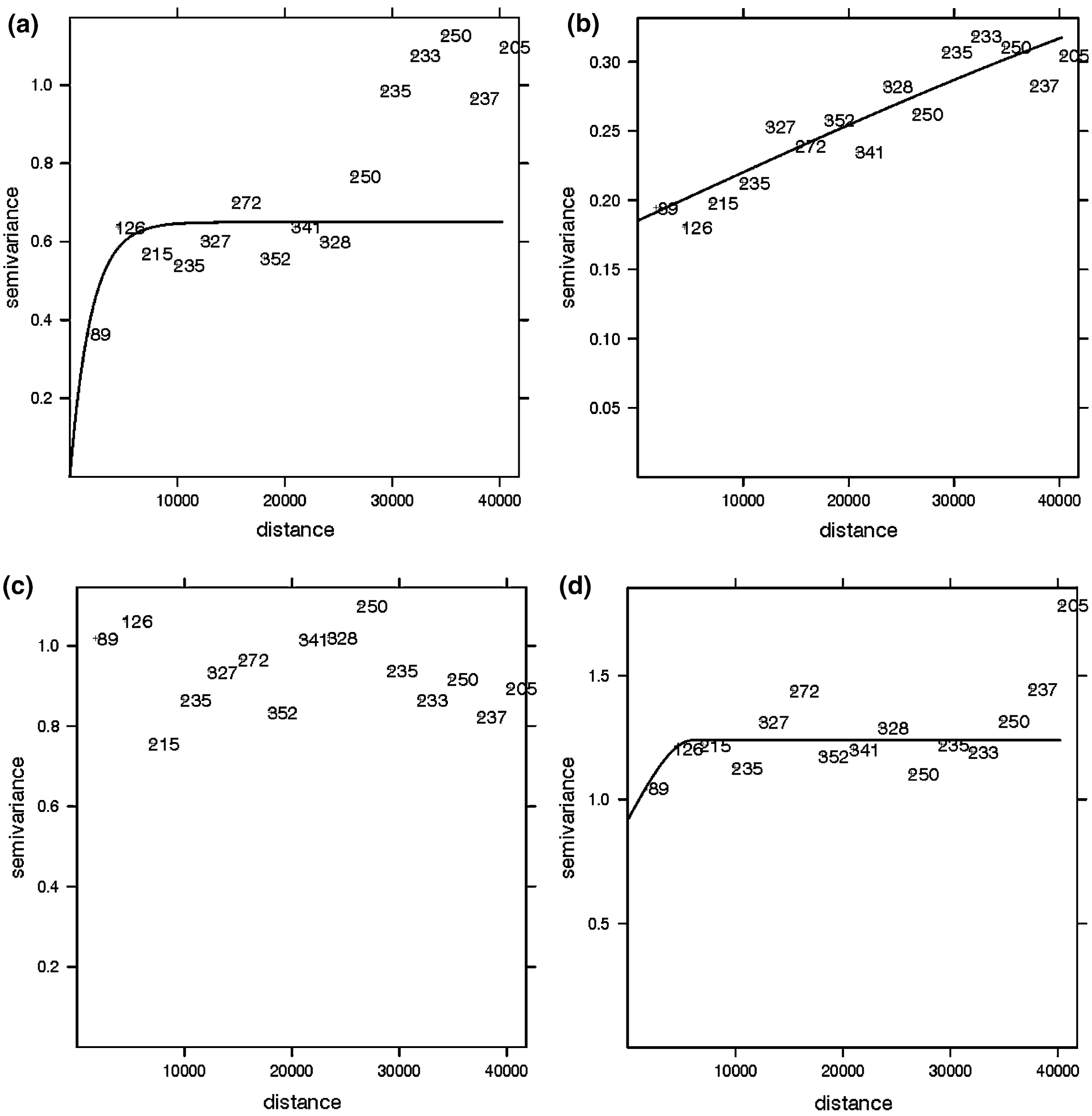

Fig. 3 Variogram models ($n = 122$) fitted for (**a**) nitrates, (**b**) sulfates, (**c**) total phosphorus, and (**d**) ammonium in the channel network of eastern Croatia; all were fitted automatically in the gstat package. The measured concentrations were log transformed prior to variogram modeling

to the disappearance of more-sensitive species such as *Lemna trisulca*, *Riccia fluitans*, and *Ricciocarpus natans*. According to Topić (1989), the submerged species *Najas marina* occurred in shallow, stagnant and very warm water. In our investigation this species was found in water with a lower amount of nitrates and sulfates, but a higher amount of ammonium. This could be due to the decline of the oxygen concentration and anaerobic processes that cease bacterial nitrification and cause the accumulation of ammonia in warm condition (Wetzel, 2001). Similarly, *Potamogeton pectinatus* was an important species for the indication of habitats with higher amounts of ammonium and total phosphorus. It is able to tolerate high trophic levels and its domination indicates the most trophic habitats (Demars & Harper, 1998). *Nuphar lutea* was observed frequently in deeper waters with a lower amount of nitrates and a lower pH. Szankowski & Klosowski (1999) confirmed that a plant community with *Nymphaea alba* and *Nuphar lutea* occurs in

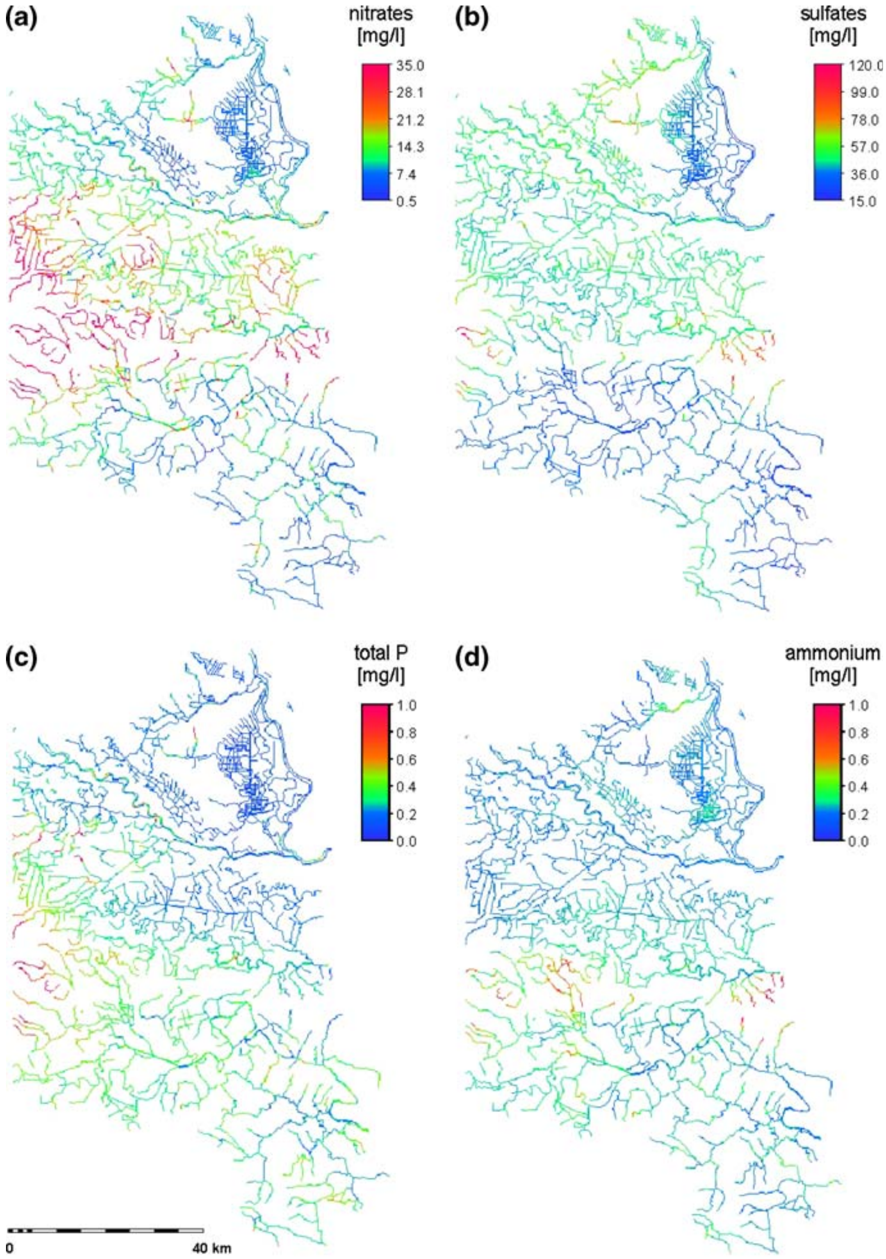

Fig. 4 Interpolated maps of nutrient concentrations: (**a**) nitrates, (**b**) sulfates, (**c**) total phosphorus, and (**d**) ammonium in the channel network of eastern Croatia

a wide range of habitats, while subassociation with *Nuphar lutea* occurs in Poland in water with a lower amount of nitrates and lower pH. A *Glyceria maxima* was related to shallow and narrow channels with a higher amount of sulfates. In the eastern Croatian channels, this species was dominant because of its tolerance to polluted water and increased eutrophication. Topić (1989) reported that the association *Glycerietum maximae* is very common on the channels with waste waters in the surroundings of Kopački Rit in Croatia.

The distribution of plant species and associations in the eastern Croatian channels can be closely connected with nutrients but also with other habitat conditions. For example, in the investigated channels the submerged species *Ceratophyllum demersum* was correlated with lower amounts of nitrates, sulfates, and total phosphorus. On the contrary, many authors indicate that *C. demersum* forms highly dominant biomasses in the most eutrophicated conditions in lakes and rivers (Nurminen, 2003). In our case, this contradiction can be explained by the important rule of channels' morphometry in the distribution of *C. demersum*. The channel size was the overriding factor that obscured water quality relations. We agree with Demars and Harper (1998) that future surveys should select sites where physical parameters are homogenous, i.e., using the homogeneous river section method (Kohler & Janauer, 1995; Tremp, 2007). Otherwise, to compare habitats of different nutrient status it is fundamental to bear in mind the channels' morphometry (Toivonen, 1985).

It is evident from our results that species (Table 3) can be more successfully connected with the nutrient concentrations than plant associations (Table 2). According to Janauer (2001) associations have limited relevance for the differential indication of trophic status and so individual species seem more promising. There are several reasons for these phenomena. Firstly, in spite of the favored phytosociological approach, plant communities as classified by Braun-Blanquet (1964), are manmade concepts subject to uncertainties. Secondly, plant communities are dynamic entities undergoing constant temporal and spatial changes in floristic composition caused by site conditions and competition between plants. Despite the less significant relations between chemical data and plant communities, in some cases phytosociological methods do seem suitable for the detection of further anthropogenic enrichment in lowland, nutrient-rich catchments (Demars & Harper, 1998). Since each species reacts individually to separate environmental variables, they may also react to other variables that have not been measured, and detailed knowledge regarding their behavior could be of great advantage for the assessment of ecosystem changes.

In our study, the geostatistical analysis and regression models were limited to only two raster layers, the DEM and the EVI. To confirm the indicative capabilities of plants by geostatistical analysis, a complete inventory of aquatic vegetation should be produced so that detailed maps of plant species occurrence, available for the whole area of interest, could be used as predictors of nutrient concentrations. There are many factors that are also important determinants of water quality and plant composition but that have not been investigated in this study. Therefore, in order to gain a better understanding of spatial and temporal changes in water nutrient concentrations and species composition, as well as the relation between them, there is a need to establish a permanent monitoring network.

Conclusions

Additional loads of nutrients in channels of eastern Croatia could lead to the disappearance of the more-sensitive species *Lemna trisulca*, *Riccia fluitans*, and *Ricciocarpus natans* and the spreading of *Potamogeton pectinatus*, *Glyceria maxima*, and *Glyceria fluitans*. Species have been shown to be more successful estimators of nutrient concentrations than plant associations. In addition, nutrients can be successfully mapped over the channel network in eastern Croatia using regression kriging. However, the original nutrient concentrations require transformation prior to regression or variogram analysis because their distributions are distinctly skewed towards lower values. If the transformation is not performed prior to (geo)statistical analysis, the results of the analysis can lead to unrealistic models (overfitting) that are controlled by a few high values.

A complete inventory of aquatic vegetation needs to be produced so that detailed maps of plant species occurrence can be used as predictors of nutrient concentrations. In addition, we propose the initiation of a permanent monitoring network, so that water samples can be periodically collected and used to generate up-to-date maps of nutrient concentrations. Such monitoring networks would also help introduce conservation measures to protect endangered habitats and species.

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