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Dynamics of self-regulatory processes in a lowland river due to seasonal changes in certain hydro-ecological and water quality factors

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ABSTRACT

This study establishes an evaluable system of relationships among the hydromorphological and water quality factors of a temperate, lowland, regulated watercourse. The aim is to investigate the effects of the environmental factors that cause temporal changes in planktonic algal communities. Measured, real-time and modelled water quality and hydrological data sets were compared during the analysis. It is observed that the same factor can have both positive and negative effects in different periods. Different physiological and morphological characteristics determine environmental tolerance. Chlorophytes, which utilize the red light living in the upper layer, closely correlate with water mirror width (top width). Diatoms need dissolved and suspended silicon and are therefore related to the factors that cause sediment mixing and increased salinity (EC). Cyanobacteria and dinophytes are also able to utilize organic matter (mixotrophy and heterotrophic photosynthesis, respectively). They multiply easily when the organic nutrients that are abundant. In the absence of inorganic nitrogen compounds, cyanobacteria are preferred because of their ability to directly or indirectly take up the N_2 molecule. Hydraulic changes have a significant impact on water quality and life processes, including biodiversity.

1. Introduction

A river (and its floodplain) is an independent and unique natural entity whose character is determined by several factors, which can be grouped according to their nature as hydromorphological, hydrophysical, hydrochemical or aquatic biological. In order to reconstruct regulated watercourses, it is necessary to assess the environmental parameters that fundamentally determine the ecological status of rivers. This study examines the relationships between some hydroecological and water quality factors. Its basic theory is that eutrophication and self-purification are related to water quality and hydrological parameters. It does not only depend on the concentration and or amount of environmental factors. Different physiological and behavioral characteristics of algal groups create different ecological relationships. The same factors can have a stimulating and inhibiting effect. These relationships need to be studied in a holistic system. Such studies can be used for water quality protection, water revitalization, river valley reconstruction, the reintegration of watercourses into nature, the rehabilitation of aquatic and wetland habitats and more during design and construction work (Pregun, 2016).

Surface watercourses are dynamically structured hydromorphological systems in space and time, where the longitudinal dimension plays a prominent role. Changes in the direction of one-way water transport over time are determining hydrological factors. The complex, diverse geomorphological pattern of riverbeds significantly increases habitat diversity (Larned et al., 2011). Bed geometry can be considered static in the long or short term, while water quality parameters are dynamic variables (Pregun, 2009). Useful information can be obtained by modelling structural indicators (horizontal, vertical longitudinal pattern, mosaicism) and their spatial and temporal changes (Bockelmann et al., 2004; Pregun et al., 2008).

In restored riverbeds, sediment deposition and the formation of features such as point bars and reefs increase due to altered sediment transport capacity and enhanced habitat diversity (Škarpich et al., 2019). Literature reviews have indicated that the reintegration of watercourses into nature is always beneficial (Shields Jr et al., 2003; Mitsch et al., 2008; Lu et al., 2019). In classical river morphological research, the most significant independent variables have included the slope of the riverbed and the water surface level, the water flow, the quantity and quality of the transported sediment, the material of the riverbed and the shore, aquatic and coastal vegetation and human interventions (West, 1978; Richards, 1982; Schumm, 1985; Nanson and Knighton,

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1996; Knighton, 1998). The most common human effects (in addition to water pollution) are hydrotechnical interventions that radically transform hydraulic conditions (Dynesius and Nilsson, 1994). Recently, the study of the dynamic processes of water and sediment transport and their relationship with factors such as heavy metal and xenobiotic accumulation, and habitat diversity has become more and more important. (Szabó et al., 2020; Kurwadkar et al., 2021).

For the hydrological characterization of riverine habitat types and organisms, classical hydrobiology primarily uses water velocity (e.g. rheophilic, rheophobic and rheobiont species). Based on recent research, the most characteristic hydraulic descriptors of water movement (Froude number, Reynolds number) are suitable for characterizing aquatic macrophyte habitats (Harper et al., 2000; Kemp et al., 2000; Devi and Kumar, 2016).

The relationship between macroinvertebrate habitats, water quality and hydromorphological features has also been investigated (Shi et al., 2019). Morphology and bed sediments have an important effect on the pattern of larger and sessile organisms, such as macrophytes and macroinvertebrates (Mueller et al., 2014).

The restoration of hydromorphology increases diversity at all habitat levels (Staentzel et al., 2019). Significant results have been attained from decades of research into phytoplankton functional groups. In the case of stagnant waters, algae are divided into well-defined functional groups. However, river algae are not to be able clearly classified yet. All river algae belong to codon D in this system (Reynolds et al., 2002; Padisák et al., 2003; Padisák et al., 2009; Kruk et al., 2010). Group D is characterized by shallow, nutrient-rich, regularly flushed, turbid waters. D-algae tolerate regular, continuous water movement well, but are sensitive to depleted nutrient content.

The theory of competitive exclusion (Hardin, 1960) states that species coexist permanently as much as the number of significant factors limiting the multidimensional space defined by them. Previous research has shown a much higher number of species in permanently coexisting communities than the number of factors influencing reproduction; this is the plankton paradox (Hutchinson, 1961).

During real succession processes, environmental factors are constantly changing in space and time. According to the intermediate disturbance hypothesis, taxon diversity is greatest when the aquatic community is subject to moderate disturbance (Connell, 1978; Fisher et al., 1998). Today, we know of several forms of lasting coexistence that also explain the plankton paradox (Wilson, 2011). Interventions in the longitudinal dimension of watercourses (e.g. cutoffs) are accompanied by an increase in extreme events (Tharme, 2003; Somlyai et al., 2019).

The article focuses on the following goals: 1. Group formation and reduction of redundancy within the studied ecological factors 2. Investigation of the significant relationships of ecological factors 3. Relationships between the studied algae divisions and hydraulic, pHysical and chemical environmental factors.

2. Material and methods

2.1. Monitoring station and water quality parameters measured

The River Berettyó is a strongly modified lowland river, its hydrogeochemical character is calcareous, with medium-fine bed material, and medium river basin (100–1000 km^2). The river belongs to the Tisza River catchment, which is a part of the Danube river system. The total original river length was 364 km, the existing length is 198 km, and the studied, most regulated Hungarian section is 75 km. The hydrotechnical interventions was due to drainage of wetlands and termination of the backswamps water supply. The river bends have been cut through of the upper section, so its length was reduced by nearly half. The water-quality of the stream fluctuates between poor and good status; the most hazardous factors are the high organic matter content (TOC and BOD_5), the low oxygen content and the salt content (electric conductivity). The macroinvertebrate bioindicators show better environmental conditions than physical–chemical properties, because the river connects to the network of semi-natural channels, which function as a system of ecological corridors. (Pregun, 2016).

Hydrophysical and hydrochemical data were measured at the MS-3 water quality monitoring station operated by the Trans-Tisza Environmental, Nature Protection and Water Inspectorate (left overbank, Berettyó River, Pocsaj, Hungary; 66,172 river-km), which is currently under renovation (Fig. 1).

The long-term time series was derived from time interval data from 01 November 2002 to 07 July 2007. Analyses of water quality and hydraulic time series were performed in seasonal groupings (Table 1). A summary of the uniform basic instrumentation is given in Table 1. The measured parameters, their abbreviations and their explanations can be found in the "Glossary", Chapter 6.

2.2. Statistical methods

Data sets were analysed by correlation analysis, stepwise regression analysis and factor analysis. The preliminary correlation analysis demonstrated correlations between the data sets of certain factors (e.g. algae and hydraulic data). The factor analysis was performed using a principal component analysis. Environmental variables with a factor weight above 0.4 were analysed. Varimax rotation isolated and identified background variables well. The purpose of the factor analysis was twofold: 1) to examine the principal components and the background variables that explain them; and 2) to reduce redundancy. The number of principal components was determined according to the Eigen rule. The data set was deemed suitable for the factor analysis based on the Kaiser-Meyer-Olkin and Bartlett tests. SPSS and Excel programmes were used for the data analysis (Table 2).

2.3. Hydraulic model and bed morphology

In order to establish the Berettyó hydraulic model, it was necessary to survey and correct the bed morphological data. Originally, the Hungarian Water Management Scientific Research Institute (VITUKI) surveyed the typical cross sections of the Hungarian section of the Berettyó in the early 1970s (148 XS, 74.5 km long section). A verification of the data as well as an assessment of Manning's n bed roughness conditions is ongoing. Field geometrical measurements of the Berettyó were performed on the entire Hungarian section of the watercourse (measurement accuracy 0.2 m). The studied section is the Hungarian upper part of the river, between 74.01 and 68.234 rkm (rkm: river-kilometre, distance from the estuary) 5776 m long, and contains 13 measured XS. The water quality monitoring and hydrological measuring station operated at 68,234 rkm (latitude 47.278°N; longitude 21.798°E). The HEC-RAS programme was used for modelling (Fig. 2). Models based on bed morphological and hydrological data are able to satisfactorily estimate hydraulic parameters (Downs and Thorne, 2000; Mouton et al., 2007; Brunner, 2010; Pregun, 2016).

3. Results: Analyses of seasonal time series

3.1. Spring

The main factors of the first principal component are water transport, kinematic factors, bed geometry and electrical conductivity. The negative factor weight of electrical conductivity (EC) can be explained by the dilution caused by the increasing water flow. The second principal component contains the dynamic parameters, the determining factors being the Froude number and the slope of the water surface. Shear, hydraulic radius, Reynolds number and speed are displayed with opposite signs. The Froude number indicates subcritical flow conditions. Algae belong to the third principal component, and there was no direct or indirect competition among them. In the fourth principal component, the positive ammonium and dissolved oxygen (DO) as well as the

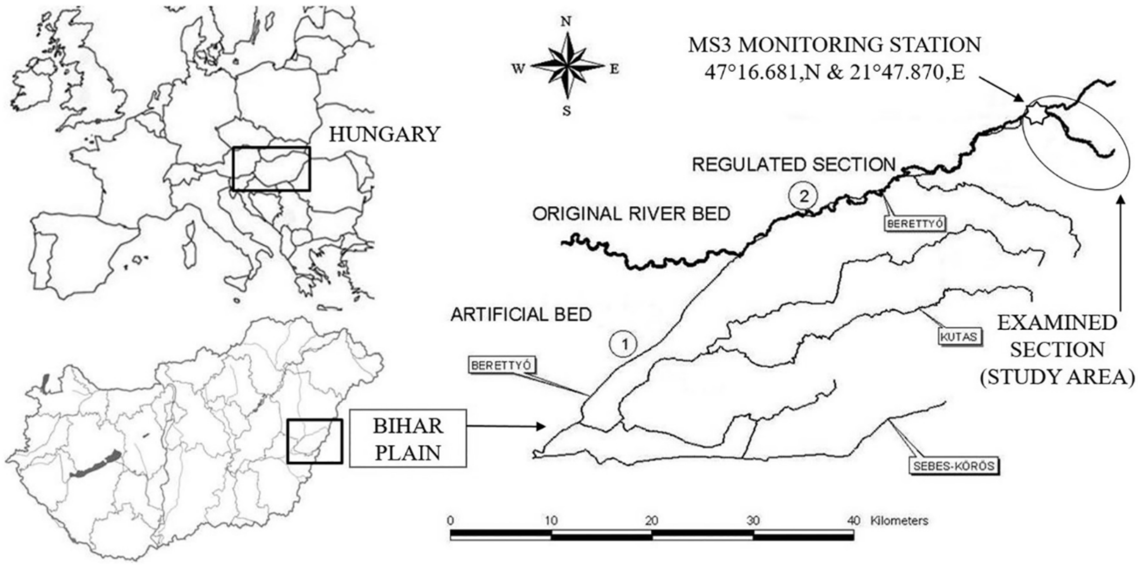

Fig. 1. The geographical location of the examined river section in the Berettyó sub-basin.

negative total organic matter content have opposite signs, indicating that the oxygen-intensive process of ammonification reduces the amount of organic matter. The nitrification process stops below 10 °C, is slow between 10 and 15 °C, so ammonia accumulates at low temperatures.

The fifth principal component indicates the one-way relationship between temperature and turbidity; pH is opposite to them, i.e. the hydrogen ion concentration increases with temperature and turbidity. Turbidity is displayed but at a low value. The stepwise regression shows that the relationship of turbidity to organic matter, Froude number, ammonia, and dinophytes is as follows: $R = 0.80$; -0.85; -0.90; 0.91. According to these findings, organic matter plays a significant role in the formation of turbidity (Tables 3, 4).

3.2. *Summer*

The relationship between EC and kinematic factors is broken as the significance of dilution decreases due to low water flow. In the third major component, chlorophytes, diatoms, EC and T are positively related, with turbidity opposite and weak. The proliferation of diatoms indicates that enough silicon was available at that time. The uptake of Si reduces turbidity, so its value is weak and opposite. Chlorophytes utilize the red rays of the spectral range, so they live only in the uppermost layer. Given that the biomass of diatoms is much more significant, the shading of chlorophytes is not significant. The fourth principal component indicates the opposite relationship between DO and total organic carbon (TOC), so ammonification continues. However, there is no positive relationship between NH_4 and DO in summer (NH_4 is in the fifth principal component). This is because at higher temperatures ($T >$ 8–10 °C), the nitrification process starts and NH_4 is converted to nitrate.

A significant portion of TOC is an organic decomposition product. As the TOC concentration increases, the EC also increases and the pH decreases. TOC is highest in summer, while the DO concentration is lowest. The main reasons for low oxygen content are the oxygen demand of aerobic biodegradation processes, high temperature and reduced water flow. Due to the smaller water surface, the diffusion of atmospheric oxygen is also reduced. Oxygen deficiency is only partially compensated by the photosynthetic activity of algae. Cyanobacteria are associated with a weak factor weight to DO and pH.

In the fifth principal component, ammonium and dinophytes are in a significant, one-way, negative relationship. These include cyanobacteria with a positive sign and turbidity with a weaker but detectable value. In summer, the ammonia content is relatively low, although there is considerable organic matter for ammonification. At higher temperatures and enough oxygen presence nitrification reduces the ammonia concentration. The resulting oxidized nitrogen forms are mainly taken up by diatoms and chlorophytes, their biomass being dominant. Turbidity is highest in summer and this (more specifically, dissolved) Si can contribute to the proliferation of diatoms. The available silicon forms are abundant based on these results. In the third principal component, the relationship between turbidity and the diatom–Chlorophyta groups is negative because of their high light demand. Turbidity has a greater negative effect on Chlorophytes than on diatoms. For diatoms, turbidity also plays a favourable role (Si). Dinophytes and cyanobacteria are at a relative disadvantage in the deeper layers due to shading, although they also have the highest bioproduction in summer. In addition, they are capable of producing heterotrophic energy. The proportion of dinophytes is lowest in summer, probably due to the lack of nitrogen forms that they can absorb. Many species of cyanobacteria can uptake molecular nitrogen. In a nitrogen-poor environment, they are capable of producing significant organic matter, which can contribute to turbidity. This may explain the weak but evaluable relationship between cyanobacteria and turbidity.

3.2.1. *Autumn*

Most explanations of variance are still included in bed geometry and water transport in the first principal component. Ammonia joins the hydrodynamic factors in the second major component at the end of the vegetation period. There is a positive relationship with the Froude number and the opposite with the Reynolds number. The physico-chemical parameters are in the third major component, with the exception of TOC. PH and temperature have the highest factor weights. Oxygen and ammonia are associated with positive pH, while electrical conductivity is associated with negative temperature. All algal groups have the lowest biomass in autumn. Dinophytes, cyanobacteria and oxygen content together form the fourth major component, in a positive relationship. Chlorophytes, diatoms and TOC are in the fifth component. The TOC concentration is then the lowest; the factor weight is weak but evaluable.

3.2.2. *Winter*

There is a significant change in the factor structure. The principal component that contains the group of dynamic factors ranks third and does not include the Reynolds number. In the other seasons, this factor was included in the first principal component containing the kinematic

Table 1
Seasonal averages, maxima, minima and standard deviations of the examined water quality parameters.

Hydromorphological & Hydraulic Parameters													
Stat.	QTot (m^3/s)	WSElev (m)	Slope (m/km)	Area (m^2)	Vel (m/s)	WP (m)	Width (m)	Shear (N/m^2)	Power (N/ms)	Mann_n ($s/m^{1/3}$)	HR (m)	*Fr*	*Re*
Spring													
Min.	1.18	96.02	0.32	6.60	0.29	11.03	10.45	1.87	1.35	0.036	0.62	0.12	179.21
Max.	84.90	100.21	1.56	184.25	0.62	123.91	120.79	7.73	5.62	0.048	1.63	0.21	951.14
Mean	12.47	97.38	0.54	30.92	0.45	24.86	23.46	5.00	2.92	0.045	1.22	0.14	573.65
SD	13.57	0.98	0.34	27.80	0.08	20.15	19.67	1.44	1.10	0.004	0.28	0.02	210.37
Summer													
Min.	1.05	95.95	0.27	5.93	0.28	10.69	10.17	1.77	1.34	0.036	0.58	0.11	158.38
Max.	82.20	100.33	1.76	201.51	0.61	127.45	124.19	7.17	4.87	0.048	1.71	0.20	938.77
Mean	6.84	96.75	0.93	19.17	0.39	17.87	16.85	3.73	2.30	0.047	0.98	0.15	403.76
SD	10.79	0.87	0.54	24.51	0.08	16.67	16.23	1.55	0.85	0.003	0.31	0.02	206.99
Autumn													
Min.	1.05	95.95	0.38	5.93	0.28	10.69	10.17	1.80	1.33	0.038	0.58	0.12	158.38
Max.	35.10	98.86	1.76	65.77	0.61	50.68	48.51	7.61	5.41	0.048	1.56	0.18	911.17
Mean	3.92	96.46	0.96	12.18	0.37	13.46	12.61	3.32	2.01	0.048	0.88	0.15	338.68
SD	4.10	0.47	0.50	7.96	0.05	4.54	4.28	1.18	0.73	0.001	0.21	0.02	142.01
Winter													
Min.	1.36	96.13	0.37	7.77	0.31	11.55	10.91	2.24	1.34	0.036	0.70	0.11	216.95
Max.	64.90	99.74	1.50	131.51	0.62	102.44	99.73	7.75	5.67	0.048	1.57	0.20	936.20
Mean	8.37	97.03	0.67	21.46	0.43	18.10	16.90	4.79	2.78	0.047	1.15	0.14	518.81
SD	8.25	0.74	0.42	15.81	0.07	10.74	10.38	1.56	1.04	0.003	0.28	0.02	206.28

Physical-chemical parameters								Biological parameters					
Stat	T (°C)	pH (0/0)	EC (µS/cm)	DO	Turb	TOC (mg/L)	NH_4 (mg/L)	Chlorophytes (µg/L)	Cianobacteria (µg/L)	Diatoms (µg/L)	Dinophytes (µg/L)	AlgTot (µg/L)	Tox (T-index)
Spring								Spring					
Min.	0.52	7.19	81.79	0.60	17.63	0.00	0.00	0.00	0.00	0.11	0.01	0.06	0.04
Max.	22.62	8.22	823.33	16.86	796.88	29.13	0.82	47.08	6.73	6.22	5.52	62.26	352.92
Mean	12.26	7.81	571.50	8.31	86.32	7.70	0.21	1.63	0.68	1.38	0.45	3.39	9.66
SD	5.48	0.21	122.77	2.68	107.93	6.10	0.13	4.64	0.86	0.87	0.46	4.94	27.65
Summer								Summer					
Min.	13.74	7.01	299.96	2.12	32.56	0.07	0.00	0.01	0.00	0.05	0.00	0.71	0.04
Max.	29.70	8.07	1745.27	12.58	900.67	28.34	0.80	10.52	4.46	13.87	2.98	23.64	50.67
Mean	21.23	7.58	680.52	6.79	130.08	9.54	0.24	1.91	0.98	2.24	0.67	4.94	8.69
SD	2.56	0.22	232.64	1.60	148.28	7.29	0.16	1.88	0.89	2.10	0.56	3.61	11.61
Autumn								Autumn					
Min.	2.98	7.38	318.38	2.59	25.58	0.07	0.00	0.00	0.00	0.00	0.00	0.03	0.04
Max.	29.88	8.45	1524.00	12.38	190.17	28.34	2.87	44.98	7.18	10.64	1.45	62.26	22.63
Mean	13.96	7.83	673.58	8.05	48.51	6.90	0.25	1.16	0.55	1.25	0.29	2.71	2.86
SD	6.16	0.16	143.36	2.61	26.37	5.32	0.44	4.44	0.92	1.31	0.29	5.47	4.38
Winter								Winter					
Min.	−0.28	7.36	251.75	2.48	25.21	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.04
Max.	15.70	10.43	879.00	29.61	512.88	28.43	1.78	32.42	6.05	9.33	3.67	46.10	32.33
Mean	2.88	8.01	593.52	10.27	62.67	8.40	0.32	2.37	0.58	0.97	0.40	2.82	4.61
SD	2.49	0.34	103.50	4.66	64.85	8.11	0.29	6.48	0.98	0.91	0.51	6.23	6.87

Measurement Principles & Methods			
Water quality parameter	Measurement Unit	Range	Operating principle
Water Temperature	C°	0–50	Digitalis
pH	dimensionless	0–14	Potentiometry
Dissolved Oxygen	mg/l	0–20	Voltammetry
Electric Conductivity	µS/cm	0–2000	Conductometry
Turbidity	NTU	0–500	Light Reflection
Ammonium-Ion	mg/l	0–10	Photometry
TOC	mg/l	0–20	UV Accelerated Oxidation
Chlorophyll-A	µg/1	0,1<	Fluorimetry
Biomonitor (Toxicity Meter)	T-index	0–100	Daphnia/Alga

factors and in the second principal component containing the dynamic indices. Its average value (~ 520) reaches the weakly turbulent flow state. The viscosity value increases at low temperatures, so the dynamic significance of the Reynolds number decreases. There is an inverse exponential relationship between viscosity and temperature, so the linear analysis shows no correlation. All algae are together in the second major component, along with the dissolved oxygen with a low negative factor weight. This indicates that photosynthetic oxygen production is not significant. Oxygen concentration is high due to low temperature. The nitrification process stops below 8–10 °C. This temperature slows down but does not stop the ammonification processes, thus increasing the ammonium concentration. A comparison of the first and fifth principal components shows that conductivity decreases significantly with dilution. The reduced conductivity cannot be compensated by the

Table 2
Examination of the suitability of the data set for factor analysis.

Seasons	KMO MSA*	Bartlett's Test**
Spring	0.75 (middling)	0.00
Summer	0.75 (middling)	0.00
Autumn	0.82 (meritorious)	0.00
Winter	0.78 (middling)	0.00

* Explanation of Kaiser-Meyer-Olkin Measure of Sampling Adequacy:
0 to 0.49 unacceptable.
0.50 to 0.59 miserable.
0.60 to 0.69 mediocre.
0.70 to 0.79 middling.
0.80 to 0.89 meritorious.
0.90 to 1.00 marvellous.
** Explanation of Bartlett's Test of Sphericity:
The test compares the matrix of Pearson correlations to the identity matrix. The test is significant if the result is less than 0.05.

increase in the ammonium concentration.

4. Discussion

A factor analysis (using the principal component analysis method) was used to divide the examined environmental factors into several functional groups, specifically bed geometry and kinematics, hydrodynamics, photosynthetic assimilation (Constructivity), heterotrophic dissimilation (Destructivity) and other physical and chemical factors (Table 3, Fig. 3). The hydrodynamic characteristics differ from kinematics and bed geometry. Hydrokinetics describes water movements without causality, while hydrodynamics studies the energetic and dynamic relationship system of water movements.

Factors of bed geometry, kinematics and water transport are always the first major components. Most of the factors are strongly linearly correlated with each other. This should be taken into account during stepwise regression (Table 4). Dynamic factors are the second major component in spring, summer and autumn. The Reynolds number and mean water velocity are included in both principal components, with a strong factor weight in the first and a weak but detectable factor weight in the second. The group of dynamic factors is in the third main component in winter, so its importance by this time has decreased. The Reynolds number and mean water velocity are included only in the first principal component, among the kinematic factors (see below). The second main component consists of algae and dissolved oxygen in winter. As a basic condition, the main representative of the kinematic-geometric factors is the maximum width of the water surface, while the main representative of the hydrodynamic factors is the Froude number. The main factors of the first main component are the bed geometry data and the kinematic characteristics of water transport (water flow, velocity, etc.). The explanation of variance ranges from 40 to 45%. The factor weight of the water width is high in all cases (0.94–0.98). The width and the surface of the water are essential for non-living and living processes. Water width affects, among other aspects, light conditions, photosynthetic oxygen production, metabolic processes, water temperature and gas exchange between the water body and the atmosphere. The Froude number (the relationship between the forces of inertia and the accelerating forces) is the most important representative of the dynamic factors. Its factor weight is 0.90–0.94 from spring to autumn, decreasing to 0.8 in winter. The hydrodynamic characteristics are in the second principal component from spring to autumn, with 14–16% explained variance. In winter, they are found in the third principal component, with 11% explained variance. There is a significant correlation ($R = 0.68$) between the maximum water width and the Froude number in the high water period in spring, but they always belong to a separate main component. The Reynolds number (the ratio of inertia forces to viscous forces) is between 200 and 1000. This indicates laminar ($Re < 580$) and slightly turbulent ($580 < Re < 2320$) flow. The factor weight of the Reynolds number in the first principal component is always large (~ 0.8). It can also be found among the hydrodynamic factors with a lower factor weight (~ 0.4), but only during spring, summer and autumn, when they are in the second main component. The Reynolds number is only in the first principal component in winter, when it weighs a lot (0.9). There is no strong connection between the Froude and the Reynolds number. The regression coefficient is 0.16 in spring and 0.19 in winter; these are high water periods. In low water periods, in

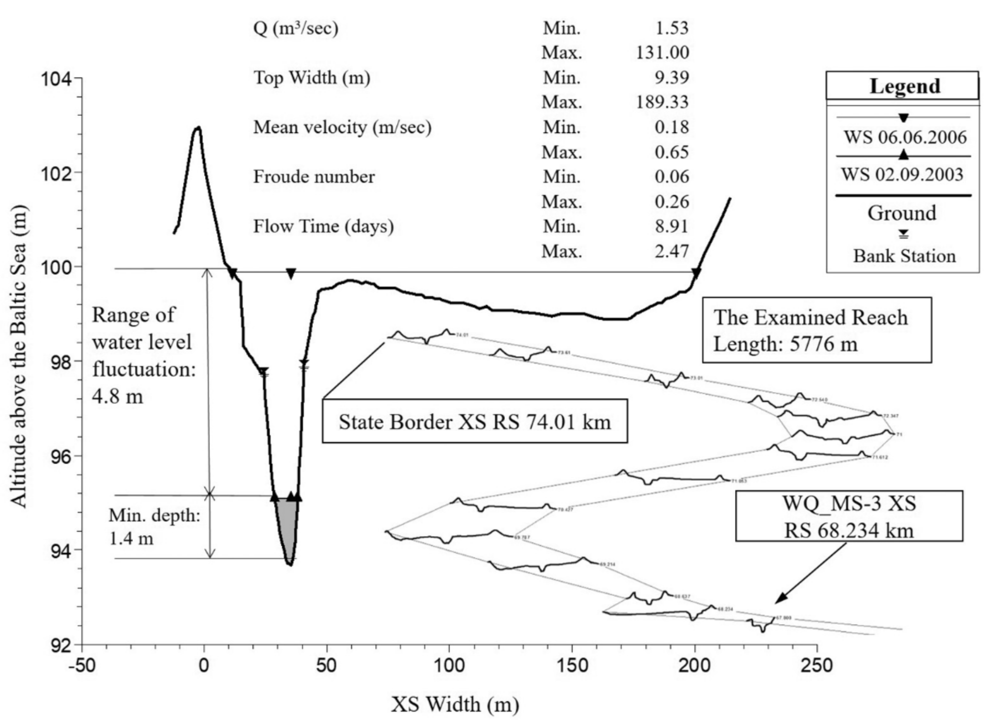

Fig. 2. The examined section of the Berettyó with the characteristic cross-sections and the basic hydrological-hydraulical data.

Table 3
Results of seasonal factor analyses (The factor-structure, factor weights and explained variance).

Spring (84.22)*				
1 (41.69)**	2 (16.34)	3 (13.28)	4 (6.53)	5 (6.38)
Geometry, Kinematics	Dynamics	Constructivity***	Destructivity***	Physio-chemical factors
QTotal (0.98)****	Shear (0.70)		NH_4 (0.78)	t (0.66)
Area (0.97)	HR (0.69)		DO (0.68)	Turb (0.43)
WP (0.95)	*Re* (0.55)			
Width (0.94)	Vel (0.44)			
WSElev (0.93)				
Vel (0.88)		Chlorophytes (0.93)		
Power (0.84)		Cyanobacteria (0.86)		
Re (0.82)		Diatoms (0.75)		
HR (0.70)		Dinophytes (0.75)		
Shear (0.69)				
Mann_n (−0.94)				
EC (−0.79)	*Fr* (−0.93)			
DO (−0.43)	Slope (−0.80)			
Slope (−0.41)	t (−0.56)		TOC (−0.54)	pH (− 0.84)
Summer (85.64)				
1 (40.31)	2 (16.25)	3 (11.05)	4 (10.24)	5 (7.79)
Geometry, Kinematics	Dynamics	Constructivity	Physio-chemical factors	Destructivity
Width (0.98)	Shear (0.60)	Diatoms (0.91)	DO (0.80)	
WP (0.98)	HR (0.59)	Chlorophytes (0.75)	pH (0.76)	Cyanobacteria (0.54)
Area (0.96)	*Re* (0.49)	t (0.48)	Cyanobacteria (0.43)	Turb (0.45)
QTotal (0.96)	Vel (0.46)	EC (0.46)		
WSElev (0.92)				
Power (0.91)				
Re (0.84)				
Vel (0.80)				
HR (0.75)				
Shear (0.75)	*Fr* (−0.94)			
	Slope (−0.84)			NH_4 (−0.82)
Mann_n (−0.97)	t (−0.52)		TOC (−0.76)	Dinophytes (−0.58)
Slope (−0.41)	EC (−0.47)	Turb (−0.48)	EC (−0.42)	
Autumn (82.14)				
1 (40.22)	2 (14.72)	3 (10.93)	4 (8.56)	5 (7.70)
Geometry, Kinematics	Dynamics	Physio-chemical factors	Destructivity	Constructivity
WP (0.95)	Shear (0.59)	pH (0.75)		
Width (0.95)	HR (0.55)	DO (0.47)		
Area (0.95)	*Re* (0.47)	NH_4 (0.42)		
QTotal (0.94)	Vel (0.40)			
WSElev (0.89)				
Power (0.81)			Dinophytes (0.82)	Chlorophytes (0.85)
Re (0.79)			Cyanobacteria (0.74)	Diatoms (0.80)
Vel (0.78)			DO (0.64)	TOC (0.49)
Turb (0.77)				
HR (0.72)				
Shear (0.70)				
	Fr (−0.90)			
Mann_n (−0.94)	Slope (−0.80)	t (−0.88)		
EC (−0.53)	NH_4 (−0.58)	EC (−0.51)		
Winter (86.28)				
1 (44.17)	2 (16.40)	3 (11.31)	4 (7.54)	5 (6.87)
Geometry, Kinematics	Constructivity	Dynamics	Physio-chemical factors	Physio-chemical factors
QTotal (0.99)	Chlorophytes (0.97)	Turb (0.72)		NH_4 (0.85)
WP (0.98)	Cyanobacteria (0.97)	HR (0.51)		EC (0.42)
Width (0.97)	Dinophytes (0.96)	Shear (0.44)		
Area (0.97)	Diatoms (0.68)			
WSElev (0.94)				
Power (0.93)			pH (0.83)	
Vel (0.92)			t (0.80)	
Re (0.90)			TOC (0.40)	
Shear (0.87)				
HR (0.83)				
Mann_n (−0.94)				
EC (−0.67)		*Fr* (−0.80)		
Slope (−0.57)	DO (−0.47)	Slope (−0.67)		DO (−0.62)

Explanation:
*Spring (84.22): Season and total explained variance;
**1 (41.69): principal component number and explained variance;
***Constructivity: the photosynthetic assimilation; Destructivity: the heterotrophic dissimilation
**** QTotal (0.98):WQ factor and factor weight.

Table 4
Seasonal relationships of algal groups and hydraulic-physical-chemical water quality parameters based on the results of Stepwise Regression Analyses.

Spring				Summer			
Algae	Independent Physical-Chemical Parameters	R(1)	R(tot)	Algae	Independent Physical-Chemical Parameters	R(1)	R(tot)
Chlorophytes	Width, DO, -NH_4, t, pH	0.20	0.47	Chlorophytes	t, DO, —Turb, -TOC, NH_4, Width, -Vel, EC	0.55	0.89
Cyanobacteria	Width, Turb, t	0.54	0.66	Cyanobacteria	*Re*, t, Tox, -Vel, DO, NH_4	0.76	0.88
Diatoms	EC, *Re*, *Fr*, -Vel	0.32	0.58	Diatoms	EC, DO, -*Fr*	0.52	0.6
Dinophytes	-pH, *Re*, t	0.29	0.37	Dinophytes	TOC	0.30	–

Autumn				Winter			
Algae	Independent Physical-Chemical Parameters	R(1)	R(tot)	Algae	Independent Physical-Chemical Parameters	R(1)	R(tot)
Chlorophytes	Low Significance Correlations	–	–	Chlorophytes	-Vel	0.43	–
Cyanobacteria	TOC, Tox	0.78	0.80	Cyanobacteria	Width, DO, -pH	0.80	0.84
Diatoms	TOC, —*Fr*, Tox, —Turb, Width, -Vel, -EC	0.61	0.80	Diatoms	Width, -pH, -NH_4, *Fr*	0.50	0.61
Dinophytes	Turb, EC, *Re*, -NH_4, pH	0.44	0.70	Dinophytes	-*Fr*, -pH, t, —*Re*, -EC, NH_4, —Tox, Vel	0.28	0.66

Explanation: R(1) the regression component of the first step; R(tot) the regression component of the final step

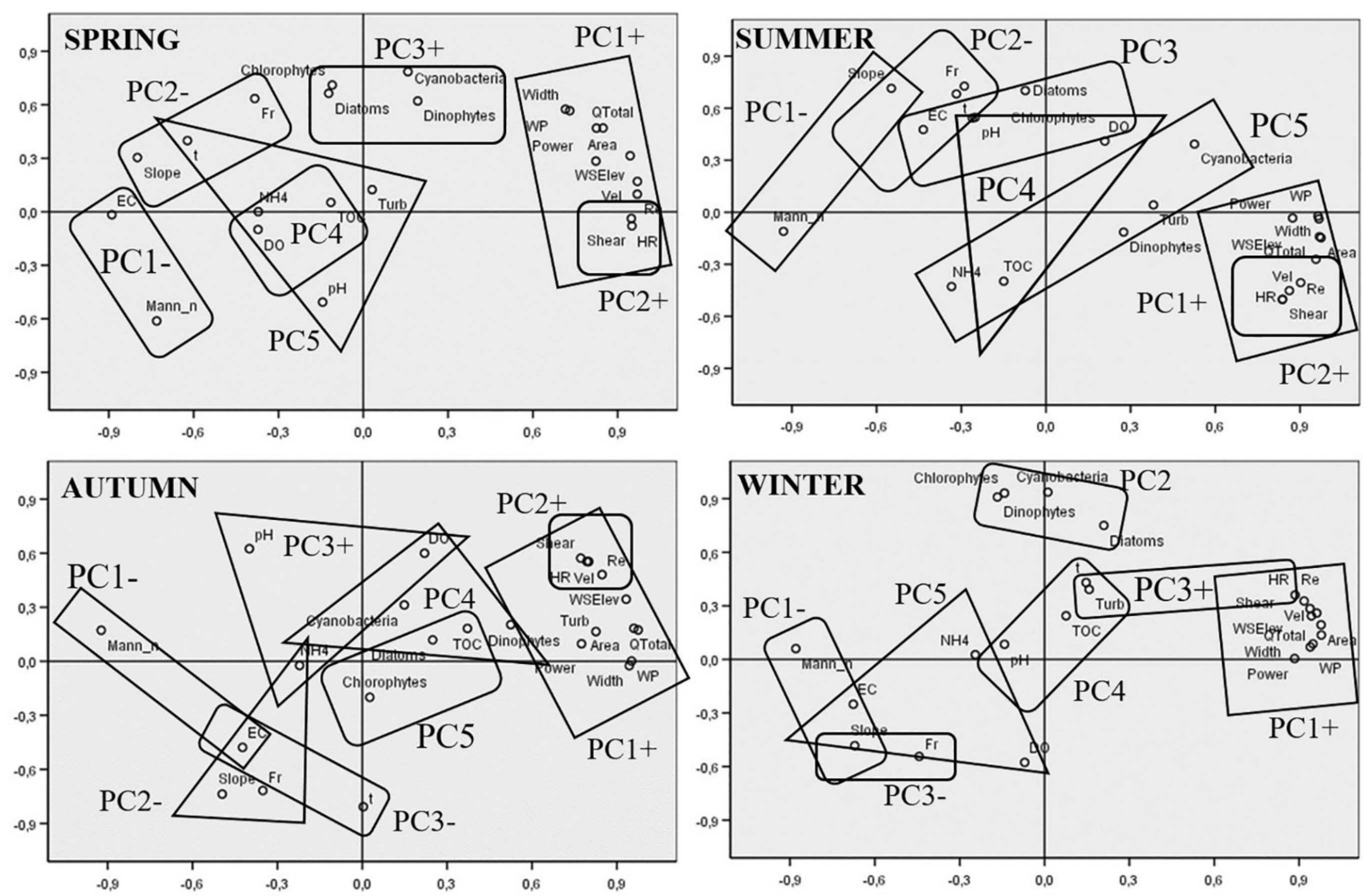

Fig. 3. Representation of the five-dimensional abstract spatial relationship of water quality factors in two dimensions. Explanations: PC1+: Principal Component 1, positive values. (To be read in conjunction with Tables 3 and 4.)

summer and autumn, the regression coefficients are 0.40 and 0.47; the flow is mainly laminar. The dissolved oxygen concentration is then the lowest. The negative factor weight of EC can be explained by the dilution caused by increasing water flow. Manning's bed roughness is negative because flooding increases the proportion of areas with lower values. The border associations of the coastal zone are formed by bush willows, while the outer part of the floodplain is covered with grass.

To study the relationship between algae and non-living physico-chemical factors, a linear regression, including stepwise analysis, was used in addition to the factor analysis. Algae are always relatively strongly correlated with each other, even when separated by principal component analysis. Therefore, in examining each algal group and the physicochemical environmental factors, I excluded the other algal divisions.

Different algal groups respond differently to different environmental factors. The complementary relationships between different internal properties and changing external environmental influences determine the spatial and temporal structure of algal communities. Chlorophytes can use red light for photosynthesis. Red light is absorbed within a few cm of water, so planktonic chlorophytes live only in the upper layer.

Diatoms have an external silicate skeleton. They are more tolerant of impurities, but silica is a limiting factor because it is necessary for their skeletal formation (Casabianca et al., 2018). Chlorophytes and diatoms are autotrophic photosynthesizers. If adequate light conditions and inorganic nutrient sources are available, they will have high biomass production.

All cyanobacteria as well as several species of dinophytes are capable of heterotrophic metabolism (half of the known Dinophyta species are obligate heterotrophic and are therefore not considered algae). In the case of unfavourable light conditions and/or higher turbidity, if sufficient biodegradable organic matter is available, these algae have an advantage over chlorophytes and diatoms. Some species of cyanobacteria can absorb molecular nitrogen, either directly through their own enzyme systems or indirectly through symbiont bacteria. This property gives them an advantage when the concentration of inorganic dissolved nitrogen in the absorbable form is low.

The algae are in the same main component in spring and winter. This principal component is the third in spring and the second in winter for the explanation of variance (it swaps places with dynamics in winter). Dissolved oxygen is associated with weak and negative values for algae in winter, so their role in the oxygen balance is negligible. In summer and autumn, the algae are divided into two groups, Diatoms with Chlorophytes, Dinophytes with Cyanobacteria are always present, and there is a positive relationship between them. In summer and autumn, the algae are divided into two groups, Diatoms with Chlorophytes, Dinophytes with Cyanobacteria which are always present and have a positive relationship between them.

The results of the applied linear statistical methods (correlation, regression and principal component analyses) do not indicate direct or indirect competition. The total biomass production of algae was highest in summer, then the diatoms dominated. Diatoms, dinophytes and cyanobacteria produce the highest seasonal yields. Chlorophytes have the highest biomass production in winter, followed by summer. In winter, the amount of all algae is low, but the biomass productivity and the proportion of chlorophytes are the highest. The intensity and the time of sunlight decrease in winter and shift towards the red-colour spectral range. These light conditions are more favourable for chlorophytes, which thus become dominant. Chlorophytes utilize red light, live in the upper water layer and can therefore have a shading effect. The hydrokinetic and hydrodynamic processes are mainly physically determined. However, there are multi-factorial relationships between chemical and biological water quality factors and independent physical variables. The metabolic processes of the aquatic community depend on temperature in different ways. The ammonification process begins above 0 °C, although much more slowly than at higher temperatures. Nitrification processes that convert ammonia to oxidized forms start at 8–10 °C, so the ammonia content of the water is highest in winter. Colder water has a higher gas-dissolving capacity (Henry's law), so it has the highest oxygen content in winter. The oxygen demand for ammonification is available, but ammonium accumulates due to the inactivity of nitrifying organisms. This is why there is no relationship between temperature and ammonia content in winter. Ammonification and nitrification are oxygen demanding processes. Above 0 °C, the ammonification process reduces the TOC and DO content and increases the ammonium concentration (NH_4). Nitrification reduces the ammonia and DO concentrations, but the process only works above 8–10 °C. For this reason, there is a significant positive relationship between NH_4 and DO in the spring, while TOC contrasts with them, with a weaker factor weight. DO and TOC always belong to the same main component in spring and summer, with significantly opposite values.

5. Conclusions

Through a time series analysis of properly selected hydrogeomorphological, hydraulic, physical, chemical and biological water quality factors, we can attain an idea of the hydroecological relationship system of a regulated watercourse. External environmental factors play an important role in regulating the balance of algal communities. Continuous, spatial and temporal changes in hydroecological factors are essential to maintain a state of moderate disturbance. A changing environment always favours communities with different tolerance spectra. This condition lasts for a short time owing to continuous environmental changes and therefore no group of algae develops long-term dominance.

The studied groups of algae have different physiological and morphological characteristics. They tolerate spatially and temporally varying factors in a multifactorial environment differently. They have a characteristic relationship with factors such as light, turbidity, conductivity and temperature. Diatoms and chlorophytes are capable of autotrophic assimilation, i.e. photosynthesis and dissimilation. Some species of cyanobacteria and dinophytes are capable of heterotrophic assimilation. Several cyanobacteria are capable of direct or indirect nitrogen uptake from the atmosphere. The parameters of the multi-factorial environment have different effects on algal groups. Indeed, the same factor can be inhibitory or stimulatory in different periods. No direct competition can be detected among the individual algal groups.

Chlorophytes that utilize red light are highly dependent on the width of the water surface (top width). Consequently, they mainly live in the upper layer of the water body. The tolerance spectrum of diatoms is less narrow in terms of light. Diatoms, on the other hand, are important for dissolved and colloidal forms of silicon and are therefore associated with agitation and salinity (EC). Certain species of cyanobacteria and dinophytes capable of mixotrophy and heterotrophic photosynthesis can utilize organic matter. These algae can multiply in waters loaded with biodegradable organic matter. Cyanobacteria that take up molecular nitrogen are preferred under nitrogen-poor conditions. These correlations are stronger in the rising and peaking stages of the vegetation period, in spring and summer.

The photosynthetic activity of algal communities is the basis of the aquatic food web. Maintaining phytoplankton biodiversity is therefore paramount. Ensuring a steady water discharge alone will not solve the problems faced. River rehabilitation also requires the restoration of the natural hydrological regime and the range of temporal water level fluctuations.

6. Glossary, explanation & abbreviations of the studied hydroecological factors in alphabetic order (name & unit)

- AlgTot: abundance of total algae (μg/L)
- Area: area of wetted cross section active flow (m^2)
- Chlorophytes: abundance of Chlorophytes (Chlorophytes) (μg/L)
- Conveyance (Q): discharge of water flow in cross section. (m^3/s)
- Cyanobacteria: abundance of blue-green bacteria (Cyanobacteria) (μg/L)
- Diatoms: abundance of Diatoms (Chrysophyta, Bacillariophyceae) (μg/L)
- Dinophytes: abundance of Dinoflagellates (Dinophytes) (μg/L)
- DO: dissolved oxygen (mg/l)
- EC: electric conductivity (μS/cm)
- *Fr*: Froude number: ratio of inertial forces to acceleration forces for the wetted channel (dimensionless)
- HR: Hydraulic radius – wetted area divided by perimeter for wetted cross section (m)
- Mann_n: river bed roughness, for the main channel (Manning's-n) ($s/m^{1/3}$)
- NH_4: ammonium content (mg/l)
- pH: H^+ activity
- Power: total stream power (N/ms)
- *Re*: Reynolds number – the ratio of inertial forces to viscous forces for the wetted channel (dimensionless)
- Shear: shear stress in total wetted cross section (N/m^2)

- Slope: slope of the water surface or slope of the energy gradeline (m/m)
- t: water temperature (°C)
- TOC: Total Dissolved Carbon (mg/l)
- Turb: turbidity – Nephelometric Turbidity Unit) (NTU)
- Vel: average velocity of flow in total cross section (m/s)
- Width: top width of the water surface in wetted cross section (m)
- WP: wetted perimeter – the circumference of the wetted cross-section except top width (m)
- WSElev: water surface elevation, altitude above the level of the Baltic Sea. (m)

CRediT authorship contribution statement

Csaba Zsolt Pregun: Conceptualization, Methodology, Software, Data curation, Writing – original draft, Visualization, Investigation, Supervision, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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