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Periodic signals of climatic variables and water quality in a river- eutrophic pond- wetland cascade ecosystem tracked by wavelet coherence analysis

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Abstract –Lakes are sensitive to changes in their environmental boundary conditions that can be indicated in the periodic behavior of water quality variables. The present work aims to assess the degree to which common annual periodic behavior is present (1994-2010) in the meteorological parameters (global radiation, air temperature, cloud cover), streamflow; and five primary nutrients (e.g. total phosphorus, nitrate-nitrogen) as possible indicators of ecosystem vulnerability in four different ecosystems using wavelet coherence analysis. The cascade system is located in the mouth of a shallow river where the water flows through a eutrophic pond then a disturbed/undisturbed macrophyte covered wetland reaching a large shallow lake. The results highlight the differing abilities of the elements of the cascade of ecosystems to follow seasonality. The changes in water quality (nutrient cycle) in the eutrophic pond most closely mirror meteorological seasonality. The vulnerability of the wetland ecosystem was expressed by its decreased capacity to follow seasonal changes due to high algae loads and additional inflows. Moreover, the wetland proved to be weak and unstable regarding phosphorus and nitrogen retention. With the successful application of wavelet coherence analysis to the "black-box" cascade system the study sets an example for the implications of the method in such combined or stand-alone natural/partially-constructed ecosystems.

Keywords: ecosystem management, eutrophication, Kis-Balaton Water Protection System, macrophyte cover, meteorological driving effect, nutrient retention, vulnerability

1. Introduction

Water, and especially fresh water, is one of the most critical natural resources which is highly endangered by climate change and anthropogenic activity (Vörösmarty et al., 2000). It has been documented that environmental (Reynolds, 1984) and anthropogenic factors (Kovács et al., 2010) govern and may indeed corrupt the capacity of freshwater ecosystems to follow seasonal changes. In the moderate climate zone aquatic ecosystems, e.g. rivers (Wong et al., 1978) and shallow lakes are per se susceptible to eutrophication (Padisak, 1992), while even constructed wetlands (Kadlec, 1999) tend to follow seasonal changes in hydrometeorology as far as the variables describing their quality and/or quantity are concerned. This phenomenon is mirrored in the seasonal behavior of e.g. runoff (Dettinger and Diaz, 2000), concentrations of nitrogen (Exner-Kittridge et al., 2016) and phosphorus forms (Istvánovics, 1988), or phytoplankton biomass (Reynolds, 1984) through the changing temporal-, light- and hydrologic conditions. In all of these cases, these various characteristics hold vital information about the ecological state of the systems, i.e. of the shallow lakes, rivers, constructed/natural wetlands.

Hitherto, the periodic behavior of a certain water quality variable has usually been studied. There are only a few cases in which sets or groups of parameters, e.g. nutrients, ions, etc. (Kovács et al., 2017), or multiple parameters individually (e.g. chlorophyll-a, sodium-, potassium ions, nitrate-nitrogen) (Kovács et al., 2010) have been assessed together to describe the overall capacity of a habitat or several habitats, to follow the seasonal changes. Although the studies cited present a significant and validated picture of the periodic behavior of freshwater ecosystems, they do not directly explore the relationship - that is, the coherence - of the periodic behavior of water quality variables with meteorology. This present study aims to remedy this shortcoming and explore the direct relationship of water quality parameters (mostly inorganic nutrients) with local climate and streamflow in a cascade system consisting of a shallow river, a eutrophic pond and a wetland with both an undisturbed- and disturbed habitats.

1.1. Study area description

The Kis-Balaton Water Protection System (KBWPS) assessed here functions as a treatment reservoir-wetland system, and was constructed to reduce diffuse nutrient loads reaching Lake Balaton, the largest (surface area approx. 594 km^2) lake in Central Europe. Improving water quality and preserving its good ecological status of the lake is one of the primary goals of European water management (EC, 2000; ICPDR, 2015). The largest tributary to the lake, the River Zala, supplies almost 50% of its water and 35-40% of its nutrient input (Hatvani et al., 2014), therefore significantly affecting its water quality. In the nineteenth century the water level of Lake Balaton and the River Zala was regulated (Lotz, 1988). As a result of this artificial modification, the former wetland areas of Kis-Balaton - located in the Lower Zala Valley - partially dried up and to a great extent became incapable of performing their natural filtering function. Combined with increased agricultural activity (e.g. fertilizer usage) and urbanization (e.g. waste water production) in the course of the 20th century, these changes resulted in the continuous deterioration of Balaton's water quality (Hatvani et al., 2014; 2015; Somlyódy et al., 1983) and occasionally led to considerable economic losses in the tourism sector (Istvánovics et al., 2007). To halt and reverse these negative trends, comprehensive measures for nutrient reduction were taken (Hatvani et al., 2015; Somlyódy et al., 1983) resulting in a 50-60% decrease in biologically available nutrients (Padisák et al., 2006a).

An important part of these measures, the Kis-Balaton Water Protection System (KBWPS) was created in two constructional phases. The remains of the former Kis-Balaton Wetland at the mouth of the River Zala (**Fig. 1**) were revitalized, and in Phase I, an 18 km^2 reservoir was inundated, commencing operation in 1985. With average depth of ~1 m and a water residence time of approx. 30 days (Hatvani, 2014), this has become an algae-dominated "eutrophic pond" (**Fig. 1**). In it, summer phytoplankton biomass (chlorophyll-a concentration) exceeds 200 mg m^{-3} and is dominated by cyanobacteria. About 80% of the phosphorus (P) loads are bound in algae and sediment (Mátyás et al., 2003). In 1992 Phase II was put into operation, though up to 2014 only a part of it (16 km^2) was inundated. This area (the "wetland") is covered by macrophytes (**Fig. 1**). The water residence time here is approximately twice as long as in Phase I (Hatvani, 2014). This "classic wetland" part of the system is covered by reed-dominated macrophytes; euphytoplankton species are therefore scarce, while meroplanktonic species can be found in high number in open water patches (WTWD, 2012).

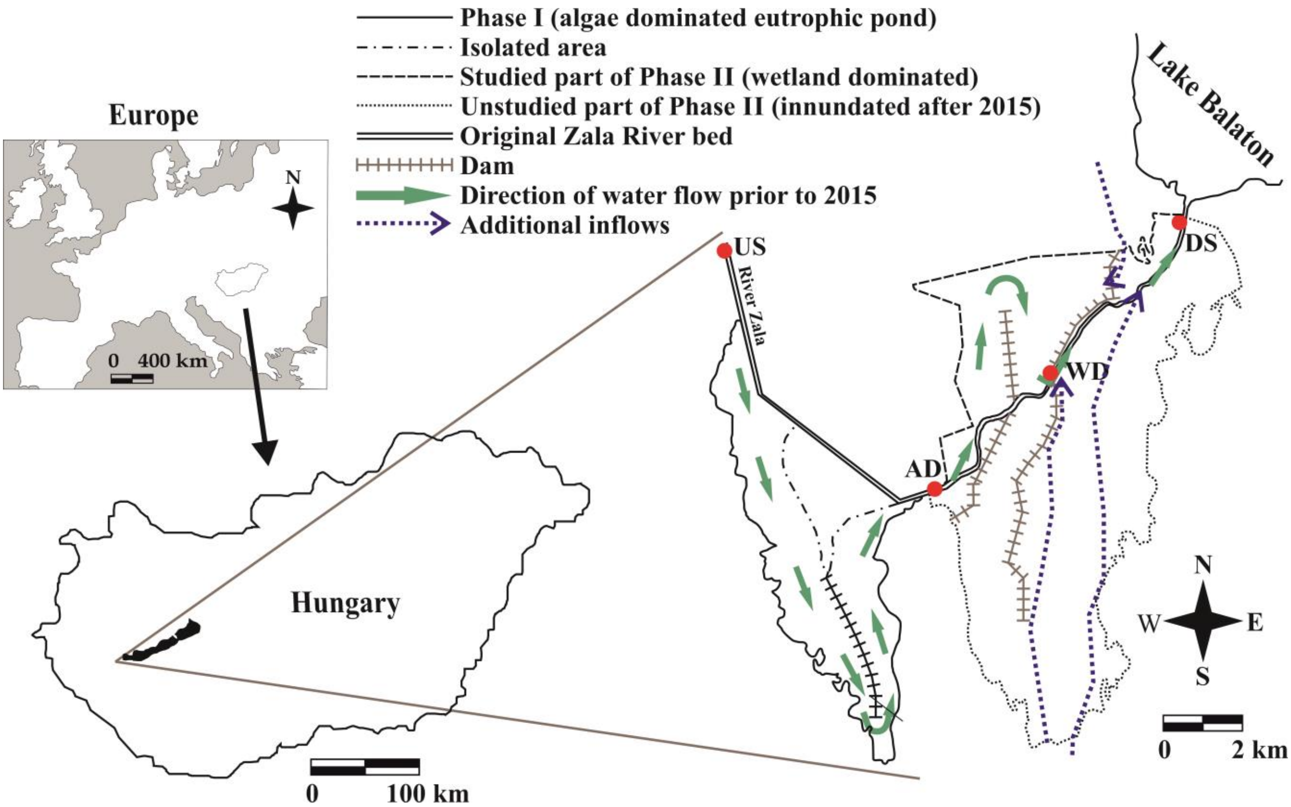

Fig. 1. Location of the study are and the sampling sites (US: upstream, AD: algae dominated, WD: macrophyte dominated, DS: downstream; detailed description in Section 2.2.) marked with red dots (based on Hatvani (2014)). Note, in other studies the sites assessed here (US, AD, WD, DS) are referred to as: Z15, Z11, Kb210, Z27 respectively.

Since the water coming from the River Zala passes through the different ecosystems (habitats) of the KBWPS and changes into lake water, it is suspected that hydrochemical seasonality (Kolander and Tylkowski, 2008; Tanos et al., 2015) - governed mainly by temperature driving the dynamics of biological processes - will be present/corrupted to a different degree in the various habitats mirroring their local characteristics. This is the particular process that is investigated in the present study with state-of-the-art statistical tools using the key link between hydrochemical seasonality and the periodicity of the water quality parameters.

1.2. Study aims

The specific questions of the study were, how are the differences in behavior (e.g. in nutrient retention) of the connected freshwater ecosystems (shallow river, eutrophic pond and an undisturbed/disturbed wetlands) indicated in the change in common periodicity between the daily measured water quality and the meteorological parameters or streamflow? It is to be expected that by exploring the previously mentioned characteristics a far-reaching overall picture may be obtained of the functioning of the cascade system prevailed by a consistent in/anti-phase coherence. This may serve as an example for the assessment of wetlands ecosystems set up with similar mitigation purposes (Cao et al., 2016; Dunne et al., 2015; Martín et al., 2013; Ni et al., 2016) and be a solid foundation laid down for the wider applicability of the methodology in limnology.

2. Materials and methods

2.1. Dataset used

In the study, the daily time series of 5 water quality parameters (WQPs) - nitrate-nitrogen (NO_3-N); total nitrogen (TN); total phosphorus (TP); phosphate-phosphorus (abbreviated as SRP); total suspended solids (TSS, mg l^{-1}) - were examined, along with background meteorological parameters and daily streamflow (Q; m^3 min^{-1}). This latter is the amount of water passing through a cross-section of the assessed system in a given time. The meteorological parameters included were global radiation (GR, J cm^{-2}), air temperature (T, °C), precipitation (mm) and cloud cover (CC, tenths) (Spinoni et al., 2015). The meteorological parameters together with Q will be referred to as independent variables (IVs) in the study. All data were assessed using wavelet spectrum and wavelet coherence analyses (Torrence and Compo, 1998) for the time interval 1994-2010 from four sampling sites of the KBWPS (**Fig. 1)**. The sites were **(Fig. 1)**:

- Upstream, the input of the KBWPS, representing the River Zala, abbreviated in the present study as “US”

- The outflow of the algae-dominated shallow eutrophic pond Phase I., abbreviated in the present study as “AD”.
- The outflow of the macrophyte-dominated wetland habitat, representing the undisturbed wetland, abbreviated in the present study as “WD”
- The downstream outlet of KBWPS, including the outflow water of the wetland and additional external inputs reach the system bringing a 40% excess in streamflow (Hatvani et al., 2014), thus representing a “mixed” wetland habitat (disturbed wetland); abbreviated in the present study as “DS”.

The latter two (WD and DS) will be referred to together in certain places of the paper as Phase II (**Fig. 1**). Please note that for Q at WD, the data was only available from 01.01.1995.

2.2. Methodology

The periodic behavior of the independent variables was evaluated using wavelet spectrum analysis to identify those time intervals lacking annual periodicity. Than to find the direct common periodic signal between the water quality parameters and the independent variables, wavelet transform coherence (WTC) was used, as it was applied e.g. to uncover the relationship between climate indices and streamflow variability (Nalley et al., 2016), to explore the relationship between water levels and chlorophyll-a in Lake Baiyangdian (Wang et al., 2012). This approach was also used, e.g. on stable isotopes in precipitation and temperature (Salamalikis et al., 2016), on speleothems and climate variables (Hatvani et al., 2017), or in assessing low-frequency variability in hydroclimate records from east Central Europe (Sen and Kern, 2016).

Wavelet spectrum analysis is considered as a function localized in both frequency and time with a zero mean (Grinsted et al., 2004); it could also be taken as the convolution of the data and the wavelet function (Kovács et al., 2010) for a time series (X_n, n=1,. . . , N) with a ‘Δt’ degree of uniform resolution (Eq. 1):

$$W_n^X(s) = \sqrt{\frac{\Delta t}{s}} \sum_{n'=1}^{N} X_{n'} \Psi_0 \left[(n'-n)\frac{\Delta t}{s}\right] \quad (1)$$

Here N stands for the length of the time series, ψ_0 the wavelet function and s the scale. In the present case to generate daughter wavelets the Morlet mother wavelet (Morlet et al., 1982) was used as the source function.

Wavelet spectrum analysis provides the basis for wavelet transform coherence, which is able to indicate the common power of two variables, being in this way similar to a correlation coefficient, but localized in the frequency-time space (Grinsted et al., 2004). While wavelet spectrum analysis takes into account one variable in 3D (period, power and its localization in the time-frequency space), wavelet transform coherence does the same but for two variables (in this case, one dependent and one independent) in 4D, because the phase differences, which represent the temporal lags, are included as well.

In the study only the positive signals significant (α=0.01) against a thousand first-order auto regressive AR(1), surrogate time series were considered; for details see Roesch and Schmidbauer (2014). It should be noted that, since the wavelet functions at each scale are normalized, the wavelet transforms of the results are comparable even to other time series (Torrence and Compo, 1998). Three main characteristics of the wavelet transform coherence were used:

(i) the presence of the coherent periods in time, which meant that the significant periodic behavior –coherence - at a certain frequency was transformed into percentages, while taking as 100% the presence of the coherence/period throughout the whole investigated time as in previous studies (Hatvani (2014); Kovács et al. (2010)),

(ii) the maximum global−wavelet power, which is the average cross-wavelet power in the frequency domain (averages over time(Roesch and Schmidbauer, 2014),

and (iii) the phase differences between the pairs of water quality parameters and meteorological parameters which show which series is the leading one in this relationship (Fig. A1).

2.3. Software used

For the calculations R statistical environment was used (R Core Team, 2016): the wavelet spectrum analysis was performed with the `analyze.wavelet` function, while the wavelet transform coherence results were generated with the `analyze.coherency` function of the `WaveletComp` package (Roesch and Schmidbauer, 2014).

3. Results

3.1. Overview of the system

The varying concentrations of the examined water quality parameters indicate the presence of distinct borders between the different habitats/ecosystems. The River Zala brings a fair amount of nutrients (P and N) to the system through the US site, where about half of the TP is SRP, and where TN mostly consists of NO_3-N (Table 1). In the eutrophic pond these nutrients (SRP; NO_3-N) are mostly bound in algae, which in turn form most of the TSS (Pomogyi, 1996); Fig. A2). Thus, the level of TSS does not significantly decrease compared to that of the River Zala (US), due to the change in its composition from inorganic to organic. In Phase II (WD and DS), however the amount of N drops to ~50% and TSS to 20% of the concentrations seen in the eutrophic pond, while P retention in Phase II is clearly low (Table 1). It is known that the level of particulate N increases up to the outflow of the eutrophic pond (site AD) then decreases in the wetland (WD); organic matter is decomposed and filtered out by the macrophyte cover (Fig. 2). Dissolved organic nitrogen (DON) shows values similar to that of particulate nitrogen (PN) up to the outflow of the eutrophic pond and accounts for half of TN; it follows the increase of algae biomass (in this case approximated by TSS). In the wetland, DON slightly decreases, but not to the same degree as the nitrate-nitrogen. Therefore, at the downstream outlet of the wetland to Lake Balaton (DS; Fig. 1) N is in dissolved state, but it is not nitrate-nitrogen, rather DON.

Table 1. Descriptive statistics of the water quality parameters (WQPs) at the different sampling locations (SLs), where M denotes the mean, SD the standard deviation R the range in mg l^{-1}, and CV the coefficient of variation in % (1994-2010). The number of measurements was equally 6209 for each site and variable.

	SLs/WQPs	SRP	TP	NO_3-N	TN	TSS
M	**US**	0.10	0.19	2.01	3.20	33.74
	AD	0.02	0.17	0.42	2.84	24.05
	WD	0.12	0.17	0.22	1.62	3.49
	DS	0.10	0.16	0.27	1.73	5.44
R	**US**	0.80	3.14	7.83	10.84	3157.00
	AD	0.49	0.83	4.00	12.06	170.00
	WD	0.56	1.07	2.88	12.34	77.00
	DS	0.50	0.86	3.45	8.32	117.00
±SD	**US**	0.06	0.13	0.69	0.97	92.71
	AD	0.03	0.12	0.60	1.43	16.30
	WD	0.10	0.12	0.34	0.60	3.94
	DS	0.08	0.11	0.35	0.62	6.25
CV	**US**	0.59	0.71	0.34	0.30	2.75
	AD	1.73	0.72	1.44	0.51	0.68
	WD	0.81	0.70	1.53	0.37	1.13
	DS	0.83	0.68	1.31	0.36	1.15

The highest degrees of variability (CV > 100%) are reported for TSS in the River Zala (US), and SRP and NO_3-N in the eutrophic pond (AD), and again TSS and NO_3-N in Phase II (WD and DS; Table 1).

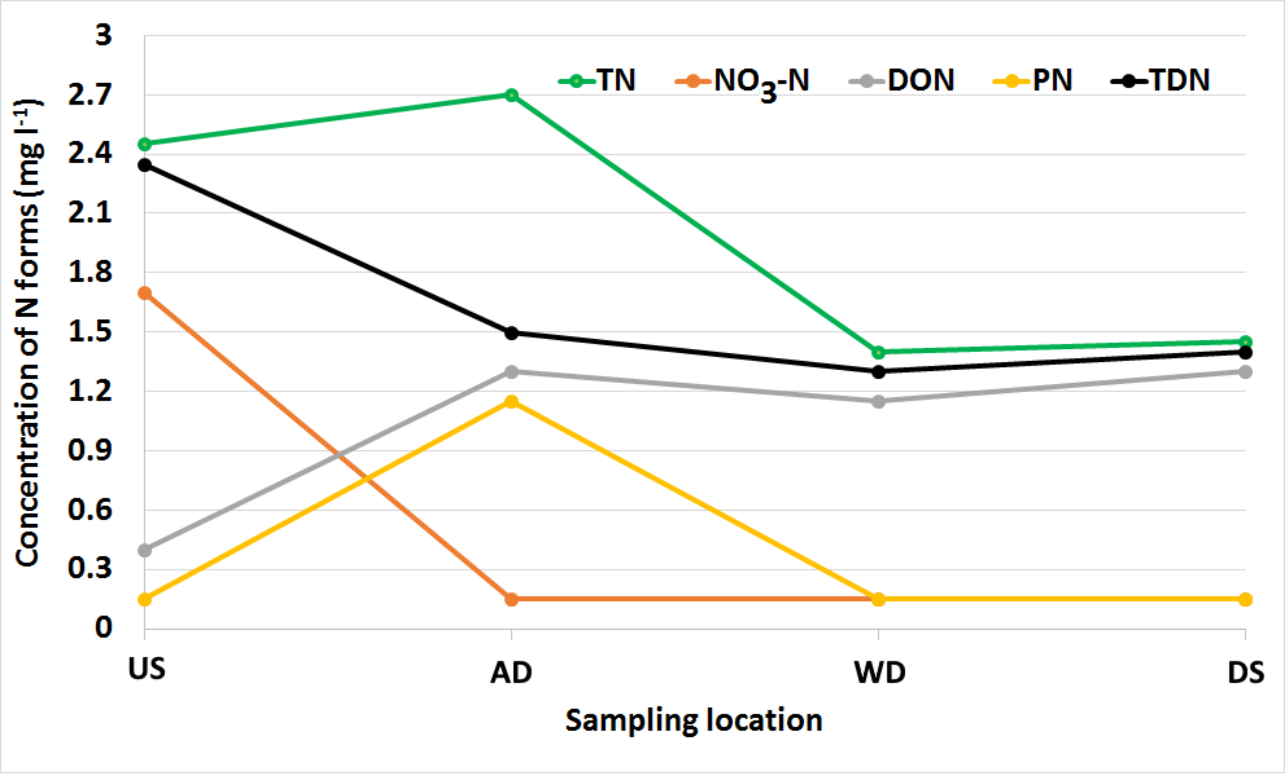

Fig. 2. Average annual (2011) concentrations of TN: total nitrogen; NO_3-N: nitrate-nitrogen; DON: dissolved organic nitrogen; PN: particulate N and TDN: total dissolved N; based on data taken from WTWD (2012)

3.2. Periodic behavior of the meteorological parameters

As expected, wavelet spectrum analysis indicated a strong and significant annual periodicity throughout the whole investigated period for all (e.g. Fig. 3a) but one of the independent variables. The exception is precipitation (Fig. 3b). In the power spectrum density graph of precipitation major gaps were observed in its annual periodicity, e.g. between ~2000 and ~2002 (Fig. 3b). In addition, it indicated the weakest global wavelet power in the one-year period band (Table 2). Thus, due to its more intermittent and weak seasonality, it was omitted from the wavelet transform coherence analyses to avoid misleading and unstable results. Regarding the other independent variables, the global wavelet power was highest for T and GR, while the second weakest was for CC. In the case of Q, a clear continuous increase (~34%) can be observed downstream from US to DS.

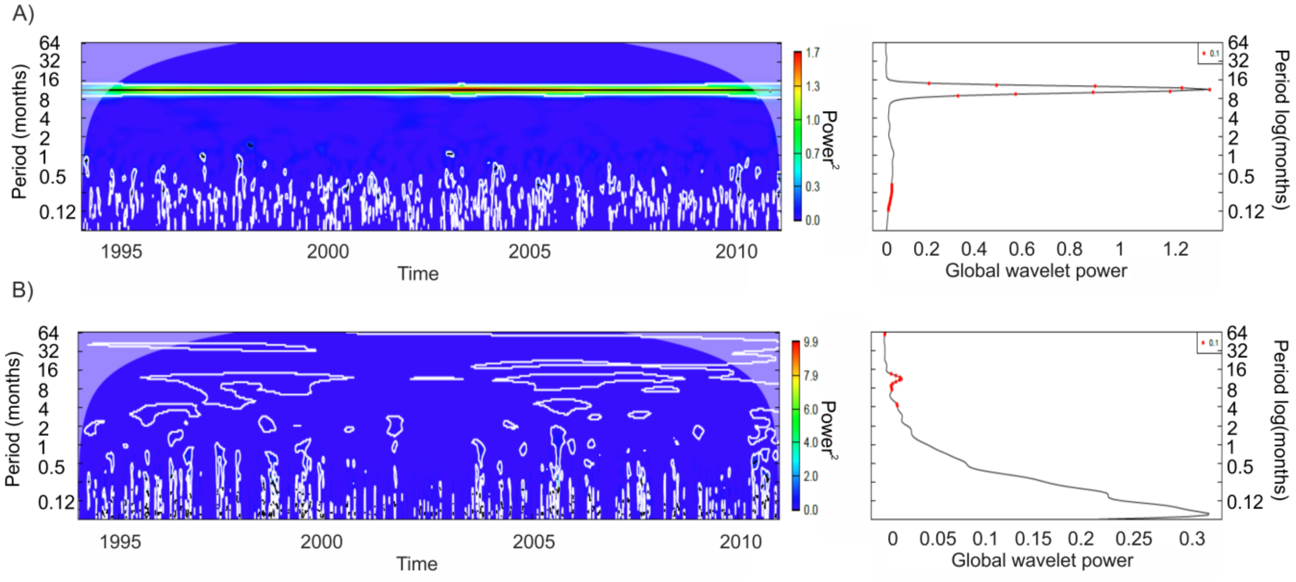

Fig. 3. Power spectrum density (left panels) and time-averaged wavelet power (right panel) graphs indicating the presence of annual periodicity in (a) the temperature and (b) precipitation time series at the US sampling site location for 1994-2010. The white contours in the left panels and the red dots in the right ones show the 90% confidence levels calculated against a thousand AR (1) surrogates. It should be noted that wavelet spectrum analysis coherence and wavelet transform coherence produce edge artifacts, since the wavelet is not completely localized in time, thus the introduction of a cone of influence (COI; dimmed area on the left panels) is suggested, in which edge effects cannot be ignored (Torrence and Compo, 1998).

Table 2. Global wavelet power of the independent variables at the one-year period for the different sampling site locations (1994-2010; for streamflow (Q) at the WD site location 1995-2010)

WQPs/SLs	US	AD	WD	DS
CC	0.18	0.18	0.19	0.18
GR	1.25	1.25	1.25	1.25

Precipitation	0.03	0.03	0.03	0.03
T	1.35	1.40	1.40	1.35
Q	0.23	0.25	0.33	0.35

3.3. Common presence of the annual period and maximum global power

As the main step, pairs were set up using the water quality parameters and the independent variables and their coherence was examined using wavelet transform coherence. Results showed that most of the corresponding water quality parameters and the independent variables pairs have a significant common annual periodicity over the entire studied time interval. In the frequency bands other than those corresponding to the annual period, the global wavelet powers of the coherences were always noticeably weak and/or insignificant (α=0.01; as an example, see later Fig. 4a).

This coherence in annual periodicity was most powerful between the P forms and the independent variables (especially GR and T; Table 3). At the US site SRP, and in the eutrophic pond TP, gave a higher global wavelet power at the one-year period band. These powers reached their maxima after the year 2000 (see later Fig. 4). The coherence of P forms with streamflow was the weakest at US and in the AD area, while it was the highest and of the same magnitude in the two sampling locations (WD and DS) of Phase II of the KBWPS. It should be noted that, in general, TP displayed the strongest coherences in the system (avg. global power = 0.70).

Regarding the N forms, the global wavelet power of TN was of the same magnitude at US and in Phase II (WD and DS); it was strongest at AD with GR and T. In the meanwhile, for NO_3-N, the picture was somewhat similar to that of TN, but more balanced. However, coherence was still highest at AD.

In the case of TSS in general, weak coherences were observed in the system, avg. global power = 0.26 except at AD (Table 3). Its coherence with e.g. CC at US and in Phase II (WD and DS) was <0.08, making it hard to draw solid conclusions. The highest degrees of coherence were to be seen at AD, where the coherence of the WQPs with CC and Q increased as well. TSS here had nearly as high a degree of coherence with GR and T as did the TP (Table 3). The weakest coherences in general for TSS were seen at WD (avg. power=0.07).

Table 3. Global wavelet powers of the WQPs and the independent variables (IVs) for 1994-2010. In the case of streamflow (Q), at the WD sampling location, for 1995-2010. The darker red shades indicate higher powers, the darker blue shades smaller ones.

		Sampling location			
WQP	**IVs**	**US**	**AD**	**WD**	**DS**
SRP	**CC**	0.35	0.15	0.40	0.40
	GR	0.95	0.40	1.10	1.10
	T	1.00	0.48	1.20	1.20
	Q	0.39	0.19	0.53	0.53
TP	**CC**	0.23	0.38	0.40	0.40
	GR	0.60	1.10	1.10	1.15
	T	0.60	1.10	1.20	1.20
	Q	0.25	0.47	0.54	0.55
NO$_3$-N	**CC**	0.25	0.32	0.30	0.28
	GR	0.67	0.80	0.72	0.78
	T	0.68	0.90	0.75	0.80
	Q	0.27	0.39	0.38	0.43
TN	**CC**	0.15	0.26	0.15	0.14
	GR	0.39	0.78	0.39	0.40
	T	0.42	0.79	0.42	0.40
	Q	0.15	0.29	0.27	0.19
TSS	**CC**	0.08	0.34	0.04	0.07
	GR	0.25	0.95	0.10	0.18
	T	0.25	0.95	0.10	0.18
	Q	0.10	0.40	0.05	0.10

From the independent variables side, the weakest coherences were observed between the WQPs and CC, and, secondly, with Q. On average, the global wavelet powers were the lowest US (0.4) and highest at site AD (0.57), while they were of the same magnitude in Phase II (0.51 and 0.52 for WD & DS respectively).

3.3.1. Absence of coherence between the WQPs and the meteorological parameters

Overall, in the whole KBWPS there were 16 occurrences when coherence over an annual scale between the WQPs and the independent variables was interrupted. The absence of annual coherence was only considered if its length was longer than one year, i.e. ~6% of the total investigated time (Table 4). From the perspective of independent variables, these cases were mostly associated with Q (in 12 out of the 17 pairs). Moreover, the highest portion of absence in coherence was usually related to streamflow (~50% of the absence between Q & SRP at AD and Q & TSS at US, WD, DS; Table 4). From the perspective of WQPs these episodes of absence in annual coherence were mostly related to SRP and TSS at AD and WD respectively. With regard to the spatial aspect, the average absence decreased in the eutrophic pond and the wetland with respect to the River Zala, after which it increased again at DS (Table 4).

Table 4. Percentage of the absence of annual coherence for those WQP & independent variable (IV) pairs where the absence was longer than one year (≥ 6 %) of the total time (reference period: 1994-2010; for Q at WD 1995-2010).

		Sampling location			
WQP	**IVs**	**US**	**AD**	**WD**	**DS**
SRP	**CC**		13%		
	GR		11%		
	T		25%		
	Q		56%	7%	
TP			7%		
NO_3-N			20%	11%	
TN		40%	9%	14%	29%
TSS		12%		52%	46%
	T			18%	
Average absence		26%	20%	21%	37%

3.4. Phase differences

From the phase differences on the power spectrum density graphs, it is clear that it was mostly the independent variables that were leading the WQPs (e.g. later in Figs. 4-7). The P forms, for example, were mostly in antiphase with CC and Q and in phase with GR and T in the whole system, just as TSS at US and at site AD (Table 5). It was interesting to observe that while T was leading certain WPQs by 1-2 months (e.g. TP at AD; Fig. 4a), GR was leading these by 2-3 months (Fig. 4b). The only habitat where the phase difference of SRP and the independent variables was changing/inconclusive was in the eutrophic pond (AD). TSS in Phase II seems to tend towards keeping the pattern indicated upstream, but its phase differences become changing and inconclusive. It should be noted, that its powers were the lowest here in the whole KBWPS (Table 3).

Table 5. Phase differences of the WQPs and the independent variables (IVs) for 1994-2010. In the case of Q at sampling location WD, this is for 1995-2010. '-' stands for an antiphase, '+' for an in-phase and IC for an inconclusive/changing phase relationship between the WQPs and the independent variables

		Sampling location			
WQP	**IVs**	**US**	**AD**	**WD**	**DS**
SRP	**CC**	-	-	-	-
	GR	+	IC	+	+
	T	+	+	+	+
	Q	-	-	-	-
TP	**CC**	-	-	-	-
	GR	+	+	+	+
	T	+	+	+	+
	Q	-	-	-	-
NO_3-N	**CC**	+	+	+	+
	GR	-	-	-	-
	T	-	-	-	-
	Q	+	+	+	+
TN	**CC**	IC	-	IC	IC
	GR	IC	+	IC	IC
	T	-	+	IC	IC
	Q	IC	-	IC	IC

TSS	CC	-	-	IC	IC
	GR	+	+	IC	IC
	T	+	+	IC	IC
	Q	-	-	IC	IC

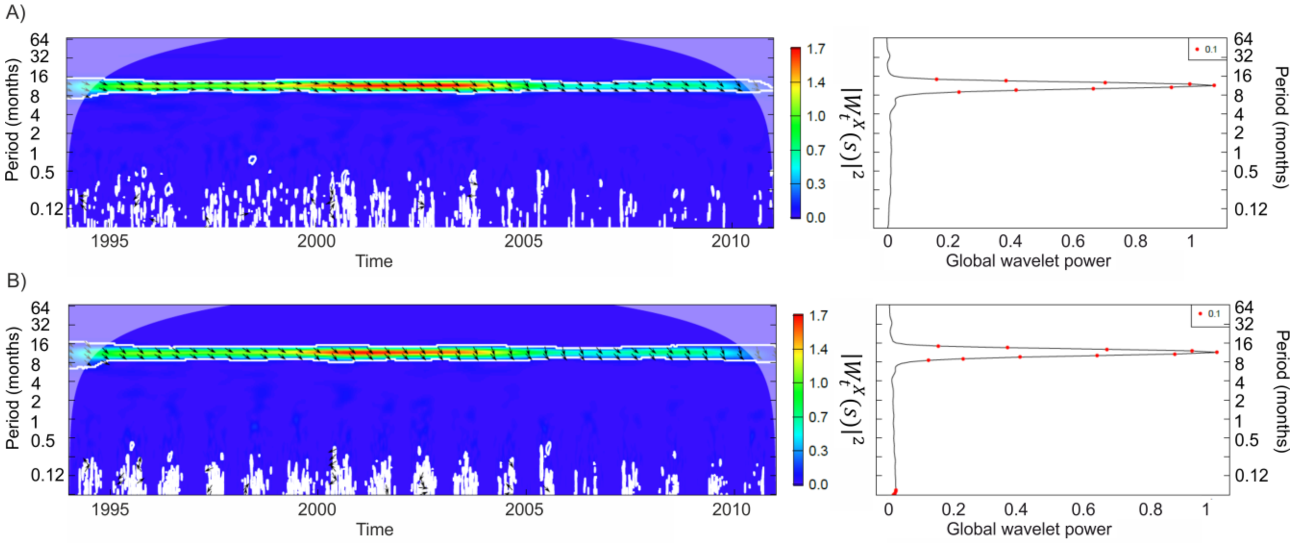

Fig. 4. Time–frequency coherency images (left panel) and time-averaged cross-wavelet power (right panel) of (a) total phosphorus and temperature and (b) global radiation at the AD site. The white contours in the left panels and the red dots in the right ones show the 90% confidence levels calculated against a thousand AR(1) surrogates. The black arrows indicate the phase-angle difference of the parameter pairs. For further details see Rösch and Schmidbauer (2014).

As for the N forms, NO_3-N, displayed a pattern opposite to that of the P forms (except for SRP and GR at AD). It is in antiphase with T and GR and in-phase with Q, while TN is mostly inconclusive, especially in Phase II (Table 5; e.g. Fig. 5a). However, in the River Zala, TN indicates a quasi-persistent antiphase pattern with T, while with GR it was rather hectic (Table 5). It nevertheless showed a quasi-persistent in-phase relationship with T and GR at AD (Fig. 5b). This implies that the N forms besides NO_3-N, organic and particulate, are in-phase with T and GR (Fig. 2).

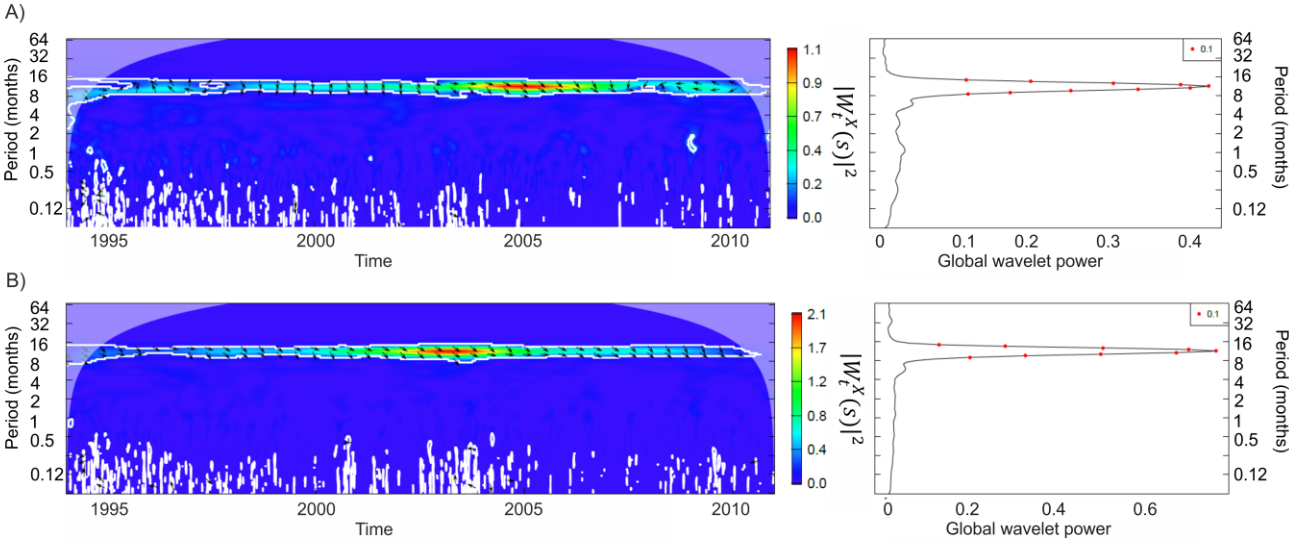

Fig. 5. Time–frequency coherency images (left panel) and the time-averaged cross-wavelet power (right panel) of (a) total nitrogen and temperature at sampling location WD and (b) at sampling location AD. For further details, see the caption to Fig. 4.

4. Discussion

4.1. Overview of the coherences

The annual coherence between the water quality- and climatic variables of a river, eutrophic pond and wetland was directly compared. Since there is no transitional area (ecotone) between the ecosystems, the differences in annual coherence clearly represent the distinct habitats, and are as much as possible. In the whole system, the most important factors driving the coherences between the water quality parameters and independent variables were global radiation/temperature, the setting of the different habitats, and the nutrient loads arriving through the River Zala.

In the River Zala (US), annual coherence was strongest between the P forms, nitrate, and T & GR, while absence of coherence was most characteristic of TN and TSS with Q. This can be explained by the general characteristics of small, shallow rivers like the River Zala, with an average depth of 1.4 m at mean water level (GDWM, 2016). The shading effect of riparian vegetation is a key factor in both the heat budget and nutrient cycles of river sections (Allan and Castillo, 2007; Wetzel, 2001).

The upper section of the River Zala traverses a forested area, its riparian vegetation shades the water, and the dense canopy prevents excessive warming. The lower section of the river, which is represented by sampling location US, is however much less shaded, since it flows through arable land with scarce riparian vegetation (GDWM, 2016) and with high exposure to heat and radiation, causing the strong coherences with the primary meteorological parameters. Moreover, the fact that nitrate had the weakest antiphase relationship with T and GR in the River Zala can be explained by the generally lower rate and less pronounced seasonal variation of denitrification in rivers compared to lakes (Piña-Ochoa and Álvarez-Cobelas, 2006).

The eutrophic pond (AD) was even more exposed to the effects of air temperature and radiation than the River Zala. The water here slows down, the residence time increases and the pond is slightly shallower than the River Zala (average depth 1.1 m (Tátrai et al., 2000)). With regard to P, its main processes can be delineated by the Vollenweider model, which describes the relationship of the trophic state of the system based on P loads and mean depth/retention time (Reynolds, 1992; Vollenweider and Kerekes, 1982). It thus provides ideal conditions for algae to reproduce and consume the SRP in the water (Hatvani et al., 2014) arriving via the River Zala. This is the reason for the lowest SRP values in the whole system (avg. = 0.02 mg l^{-1}; Table 1) being found in the eutrophic pond. In the meanwhile, an opposite process is also present here: with the increase of temperature, the internal P loads of the eutrophic pond increase as well, P is released from the sediment (Istvánovics et al., 2004), especially in drier and warmer years (Chambers and Odum, 1990). This should account for the high degree of coherence between TP (including bounded P in algae cells: “algae-P”) and T & GR in the particularly warm and dry years after 2000 (Fig. 4). These previously discussed processes acting simultaneously (peaking at the same time in the growing season) are responsible for the inconclusive phase difference of SRP and independent variables and the decreased power and occasional absence of their annual coherence. Moreover, since TSS consists mostly of algae in the eutrophic pond (Pomogyi, 1996), it comes as no surprise that the power of its coherence with GR and T was as high as that obtaining between TP and GR & T, because TP consists of "algae-P". The same notion is true for the N forms as well, especially TN. It predominantly represents the algae – the organic N fraction (Fig. 2) - of the eutrophic pond (Wetzel, 2001). At the same time, inorganic N (nitrate and nitrite) decreased in concentration as SRP, where nitrite was already present in small portions. TSS only indicated a strong coherence with the independent variables where it consists mostly of algae; this occurred only in the eutrophic pond.

The waters arriving from eutrophic pond slow down even more and reach the undisturbed- and the disturbed wetland habitat of the KBWPS. Due to the excess loads (see Section 1.1 and Fig. 1), the disturbed "mixed" wetland habitat shows the characteristics of both a classic wetland and a stream. The latter observation manifested itself in the similarity of the disturbed wetland to the River Zala with regard to the global wavelet powers and the absence of annual coherences. In the case of the phase differences, however, the disturbed wetland resembles the classic wetland, indicating that despite the additional inputs both (i.e. the whole of Phase II) are decomposition dominated (Istvánovics et al., 1997), with much lower P retention capacity than the eutrophic pond (Somlyódy, 1998). TN here consists of both organic and inorganic forms, mainly characteristic of processes such as phase changes. Thus, meteorological factors are unlikely to drive TN concentrations. Moreover, the shading of the macrophytes is also a major factor here in controlling the biological processes. It has been documented that shading is a factor in dampening the capacity of a wetland to indicate seasonal changes (Kovács et al., 2010). It is suspected that the lowest global wavelet power of TN and TSS and the significant gaps in their annual coherence with the independent variables are because of the previously mentioned phenomena. The coherence with the independent variables and the concentration of TSS (Table 1) slightly increases as the additional inputs reach the system. On the one hand, the gaps in annual coherence of TSS and the independent variables were present in the undisturbed wetland because of the mostly low concentrations of TSS (Table 1; Fig. A2) as in macrophyte dominated constructed wetlands (Dunne et al., 2012). While, on the other hand, the gaps between TSS and Q at the output of the system were present due to the unbalanced additional inputs (e.g. Fig. A2) from natural streams, constructed canals and fish ponds (drained three times a year, but irregularly) to Phase II of the KBWPS.

In general, the average percentage of absences in coherency between the water quality parameters and the independent variables decreases as the waters' residence time increases from the River Zala, up to the undisturbed wetland (Section 3.3.1; Table 4). Then, with the additional 40% temporarily irregular input of streamflow downstream of WD, the average percentage of absence increases to values higher than those witnessed in the river. Besides the increased residence time, in the algae dominated eutrophic pond, the cyclic planktonic eutrophication (Wetzel, 2001) played a major role in increasing the ecosystem's capability to follow/indicate meteorological seasonality. A similar pattern was observed by Kovács et al. (2010) in their assessment of annual periodicity using wavelet spectrum analysis on a wider set of weekly sampled parameters for a shorter period (1993-2007). Although in their study the undisturbed wetland showed a higher percentage of absence of annual periodicity (59.1%) than the eutrophic pond (40.9%), still, the disturbed wetland did display a higher absence in annual periodicity (68.2%) than the river (63.6%), as in the present case. The reason for the difference between the obtained absence in periodicity lies not only in the different time interval and applied methodology, but in the fact that the present study focused solely on the nutrient forms and the closely related TSS. The observation that the irregular excess loads arriving to the disturbed wetland corrupt its capability to indicate the seasonal changes emphasizes wetlands' exposure to anthropogenic activity (Brinson and Malvárez, 2002). This vulnerability becomes even more pronounced with climate change (Finlayson, 2016).

4.2. Phase differences

4.2.1. Inconclusive phase differences of P forms and TSS

The pattern of the phase differences concurs with the previously discussed observations; nevertheless, it does provide excess information on the functioning of the system by describing the possible temporal shift between the common annual coherence of the water quality parameters and the independent variables. In the eutrophic pond, TSS for example behaves similarly to TP, being in-phase lead by T (by 1-2 months) and by GR (by 2-3 months), indicating that TSS is composed mostly of algae (Fig. 4), which corresponds to the delay between the weekly average maxima of GR and T. Unsurprisingly, the delay between the two meteorological variables was 7 weeks in the investigated time period, with the GR maxima occurring in the 24th week, i.e. mid-June. By mirroring this meteorologically forced relationship, it underlines the capability of the methodology (phase differences) to follow fine changes even under the annual scale. As for TP, in the eutrophic pond it is most likely to occur in particulate form because of the algae, while in Phase II its wavelet transform coherence results resemble that of SRP, since it is dissolves in the water.

The inconclusive/confusing phase differences between SRP and the independent variables in the eutrophic pond can be explained by the changes in the concentration of P forms through the year, where SRP displayed almost no increase in summer (Fig. A3) due to the continuous algal uptake. Moreover, these inconclusive/confusing phase differences of SRP and T & GR occur for the most part after the year 2000, as was the case of TSS in Phase II. This was a well-documented dry period in the region (Padisák et al., 2006b). In these years, although external nutrient loads decreased, the internal loads acted in the opposite way (Hatvani et al., 2014) due to the higher T and GR. These counter-processes caused e.g. the phase differences of SRP and T to become meaningless, since according to the arrows (Fig. A4), around 2004 T should have been leading SRP by almost 6 months. In the case of TSS, the inconclusive phase differences in Phase II are presumably caused by the generally low concentrations near the level of detection (Fig. A2) and the hectic inputs from the canals.

4.2.2. Inconclusive phase differences of N forms

Upstream, in the River Zala, NO_3-N dominated (Table 1; Figs. 2, 6a) the N forms, with slightly lower concentrations in summer, mostly because the higher exposure of the river section to radiation increases biological activity, thus denitrification (Mulholland et al., 2008). It should be noted, however, that the dissolved organic fraction of TN (Fig. 2) is able to modify the phase differences of TN, and this was especially so in the dry years around 2000 (Fig. 7a). It happened to such an extent that TN was not able to display a pattern (decrease with T and GR in the summer) as clear as in the case of nitrate (Fig. 7b).

In the algae dominated eutrophic pond TN changed its phase with reference to the River Zala, and displayed a clear in phase pattern with T and GR. This occurred because, in the eutrophic pond, as GR and T increase in the growing season, the inorganic N uptake of algae also increases proportionately (Reay et al., 1999). This process decreases the nitrate concentrations (Fig 6b), thus leaving the TN loads at a similar level as the input from the river (Table 1; Figs. 2 and 6b).

Then the water arrives to the macrophyte covered wetland dominated habitat, where decomposition processes are prevailing (Kovács et al., 2010; Wetzel, 2001), especially in the growing season. Because of the decomposition of algae, oxygen availability is low (Istvanovics, 2002), thus, temperature becomes the most important factor in organic matter loss (Brinson, 1981). If the waters of the River Zala were to enter the wetland directly, probably all N forms would show an opposite/antiphase relationship with T and GR, i.e. lower values in the growing season and higher in winter. This is indeed the case for nitrate (Table 5; Fig. 6c,d), but not for TN, the levels of which do not drop in parallel to this. However, PN is retained by wetlands (Romero et al., 1999) thus decreasing the TN output in the KBWPS accordingly. Unfortunately, in summer organic N is continuously resupplied from the decomposition of algae. Therefore, despite the seasonal increase of denitrification (Seitzinger, 1988) and the N uptake of the macrophyte cover (Dvořáková Březinová and Vymazal, 2016) with water temperature, these opposite-tending processes disrupt the periodic characteristic of

TN in the wetland area. Nevertheless, a net decrease in the output of TN from the KBWPS is observed due to the previously discussed processes (Table 1); it is just not observable in the seasonal cycle.

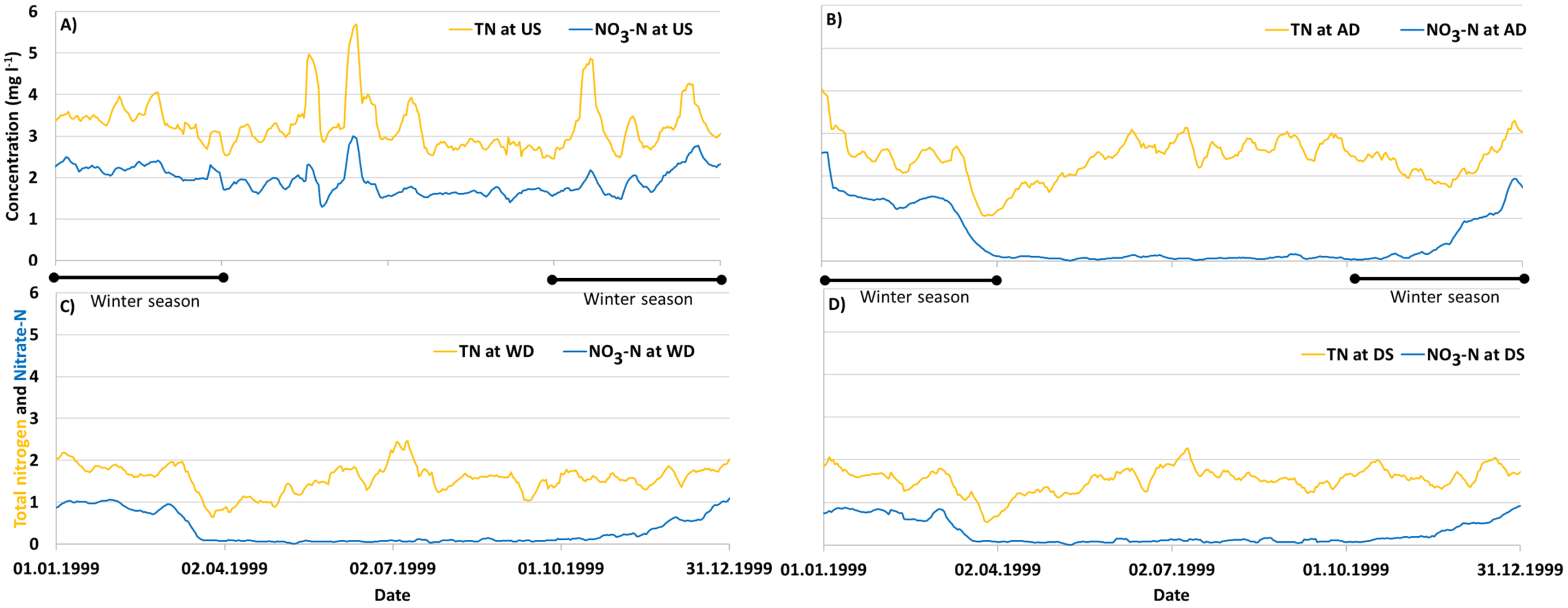

Fig. 6. Centered 7 day moving average of (a) total nitrogen and nitrate-nitrogen in the River Zala, (b) the eutrophic pond, (c) the undisturbed wetland and (d) the disturbed wetland in 1999. The black lines indicate the winter seasons.

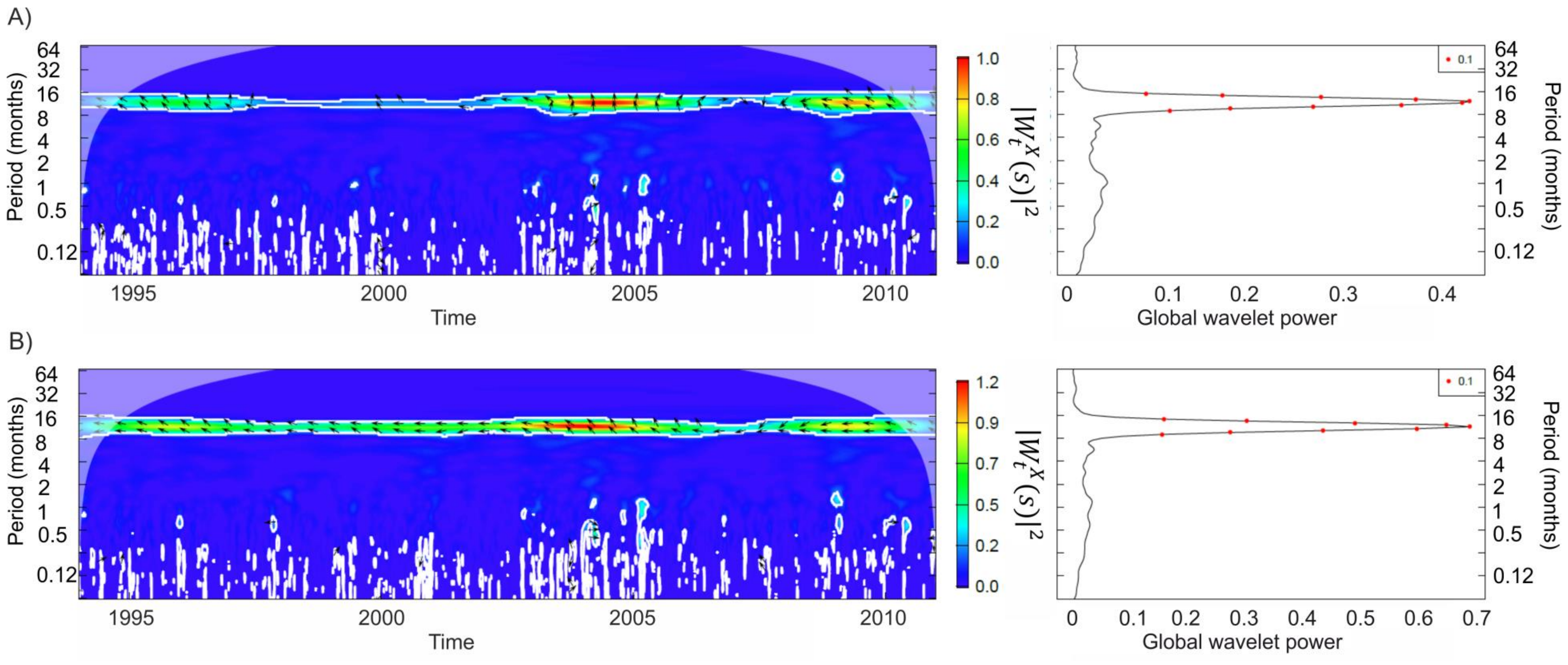

Fig. 7. Time–frequency coherency images (left panel) and time-averaged cross-wavelet power (right panel) of (a) total nitrogen and (b) nitrate-nitrogen with temperature in the River Zala (US). For further details, see the caption to Fig. 4.

5. Conclusions

The water quality variables of a cascade-like engineered ecosystem consisting of a shallow river, a eutrophic pond, and an undisturbed/disturbed macrophyte covered wetland were assessed to track the capacity of the system to indicate meteorological seasonality. In particular, the annual coherence of the water quality parameters and meteorological parameters (including streamflow) indicated the explicit differences in the functioning of the different habitats of the assessed system and these were shown to be in concurrence with previously documented knowledge. It was also pointed out that the eutrophic pond is more capable of mirroring meteorological changes. In the meanwhile, continuous upstream- (from the eutrophic pond) and temporarily irregular additional nutrient inputs (from the southern watershed) tend to counteract the characteristic processes of the wetland (including macrophyte shading). Taken together, these decrease its capacity to indicate seasonality, as seen in the pond upstream. Moreover, it was found that in this particular setting, the wetland is less suitable/unstable in terms of nitrogen retention, and can only decrease the incoming waters' phosphorus concentrations to a small degree, most probably due to the excess- and the high algae loads.

With the successful application of wavelet transform coherence to the "black-box" cascade, where the boxes represent different ecosystems without any transition areas (ecotone) in between them, a promising example is set for the wider application of the method in limnology. The present paper provides a more precise overall picture on the previously discussed behavior of the cascade system, which was designed to restrain the nutrients brought by the River Zala responsible for a fair part of Lake Balaton's eutrophication.

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Appendices

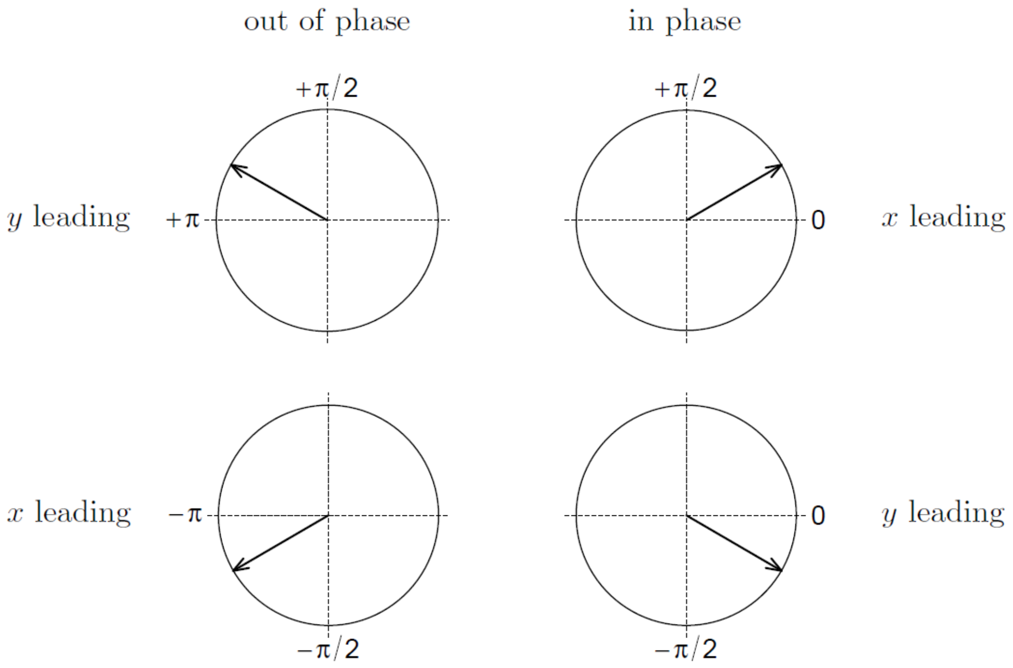

Fig. A1. The full set of possible phase-differences and their interpretation taken from (Roesch and Schmidbauer, 2014) based on (Conraria and Soares, 2011), where the phase differences are shown as arrows in the image plot of cross-wavelet power. In the present study the water quality parameter was always the first (x) while the meteorological parameters were the second (y) components of the calculation. In a practical sense for an annual period, the upper left figure would indicate that the meteorological parameter is leading the water quality one in antiphase and with about 2 months; upper right: water quality parameter leading the meteorological one with 2 months in-phase; lower right: water quality parameter antiphase leading the meteorological one with 2 months and lower left: meteorological parameter leading the water quality one with about 2 months in-phase.

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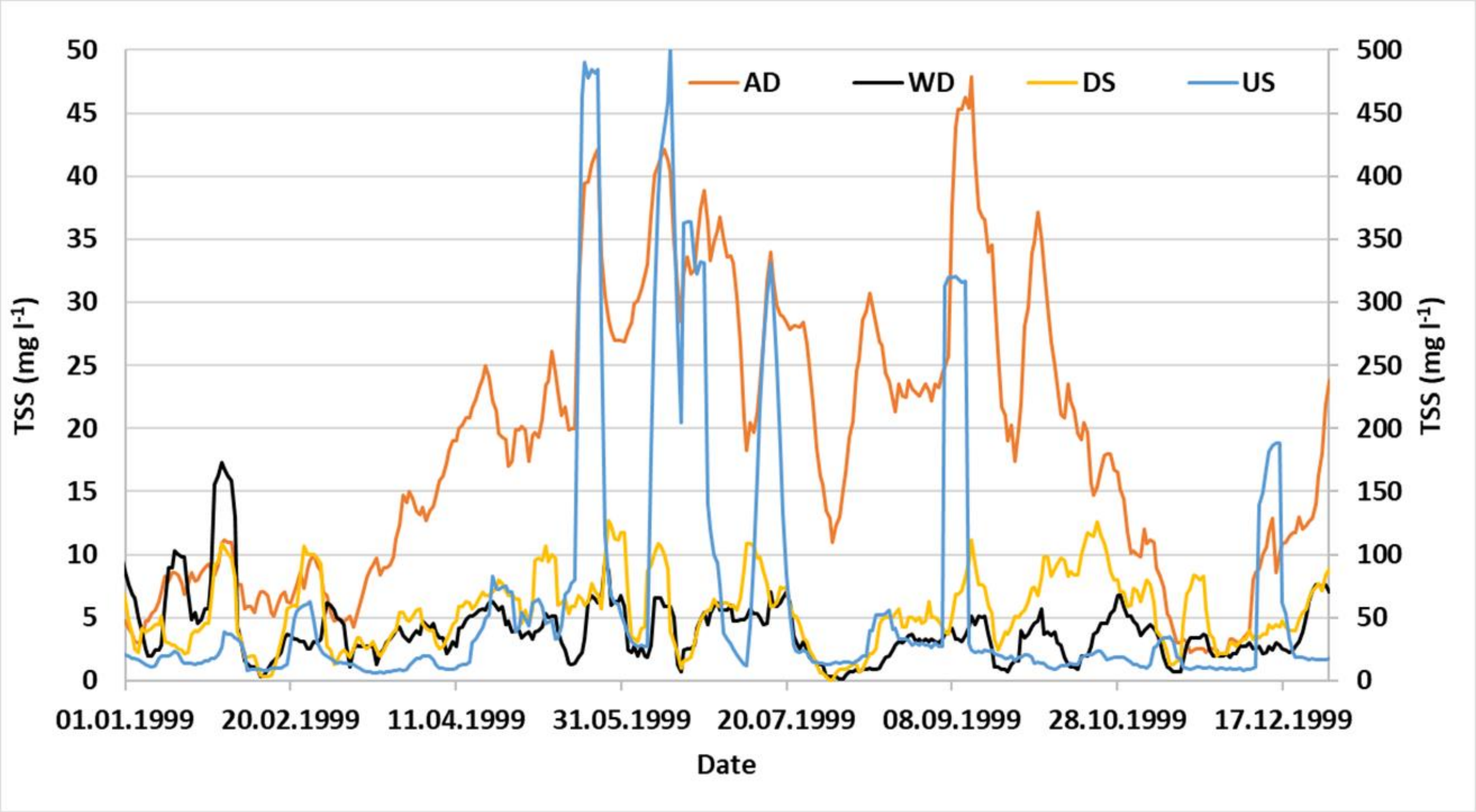

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709 **Fig. A2. Centered 7 day moving average of the concentration of total suspended solids in the different habitats of the KBWPS for 1999**

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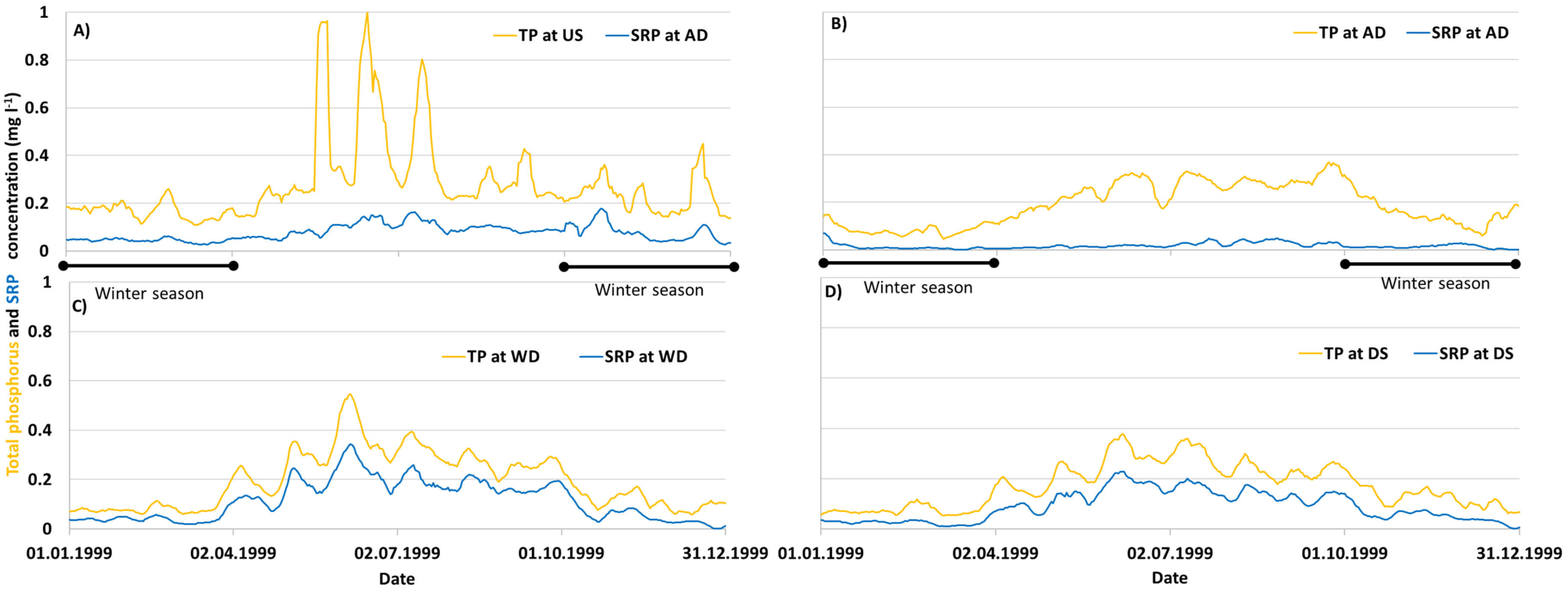

Fig. A3. Centered 7 day moving average of (a) total phosphorus and soluble reactive phosphorus in the River Zala (US), (b) the eutrophic pond (AD), (c) the un-disturbed- (WD) and (d) the disturbed wetland (DS) in 1999. The black lines indicate the winter seasons.

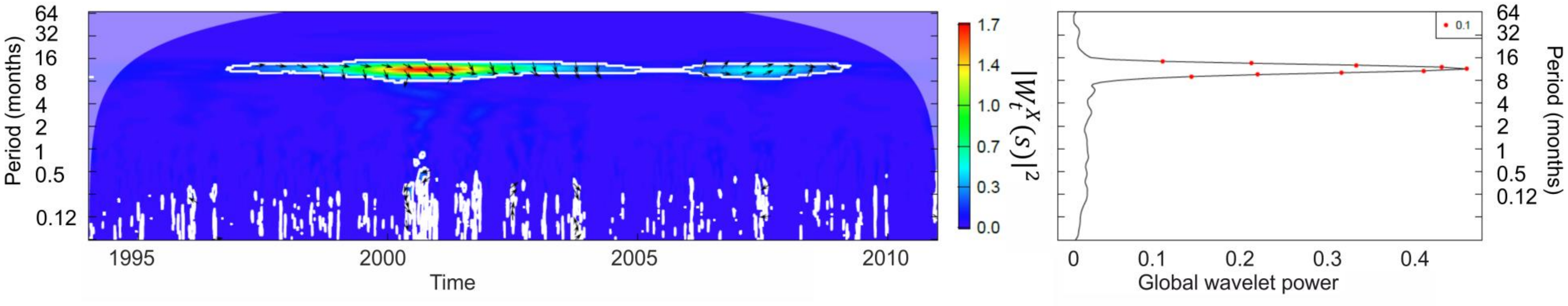

Fig. A4. Time–frequency coherency images (left panel) and time-averaged cross-wavelet power (right panel) of soluble reactive phosphorus and temperature at sampling location AD. For further details, see the caption of Fig. 4.