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SHORT COMMUNICATION

Relationship among physicochemical conditions, chlorophyll-*a* concentration, and water level in a tropical river–floodplain system

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Abstract

The free-flowing Usumacinta River maintains an average annual water-level fluctuation of 6.7 m. This study evaluated relationships between 14 physicochemical and biological variables and key factors in four water-level conditions in a river–floodplain system. The analysis incorporated intra-annual variation in all variables, with each selected in accordance with multiple statistical and physicochemical criteria. Possible correlations were examined as a function of various physicochemical and biological factors at each water level. Within the study area, defined by a temporal gradient in principal component 1, the yearly river overflow above the bankfull stage is characterized by water with a low level of total suspended solids. Data on riverine wetlands suggest that seasonal changes are key to determining intra- and inter-annual chlorophyll-*a* levels and water clarity. However, opposite trends are observed for high and low water-level conditions. Nutrient enrichment cannot be taken as the key physicochemical factor of water level, under either water-level conditions, due to the lack of a temporal gradient in principal component 2 and the high biochemical variability of nitrate and orthophosphate levels. In conclusion, the hypothesis was accepted for the production of phytoplankton biomass and light attenuation at low and high water levels, as both were dependent on intra-annual changes. The increases in chlorophyll-*a* related to the minimal variability at the lowest water level open the opportunity to gauge this relationship as a possible environmental predictor for river–floodplain systems.

Keywords Inorganic nutrients · Intra-annual variation · Lateral connectivity · Physicochemical processes · Usumacinta basin

Introduction

River–floodplain systems are ecologically valuable due to the hydrobiological interactions that take place among water level, biogeochemical cycles and biota distribution (Junk 2002). The structure and ecological functions of these ecosystems depend mainly on water-level fluctuations and the interconnections between rivers and their floodplains (Junk 2002; Sánchez et al. 2015a).

The free-flowing Usumacinta River boasts the fifth highest runoff amount into the Western Atlantic and feeds a reservoir that could potentially serve as the largest water reserve in Mexico (Wetzel 2001; CONAGUA 2011; Sánchez et al. 2015a). The Usumacinta is characterized by marked intra-annual variation in water level, which ranges from 11.5 to 18.2 m above mean sea level (Fig. 1), according to calculations based on data obtained from the Banco Nacional de Datos de Aguas Superficiales (BANDAS) government database (https://app.conagua.gob.mx/bandas/). A high biodiversity of phytoplankton and aquatic fauna has been

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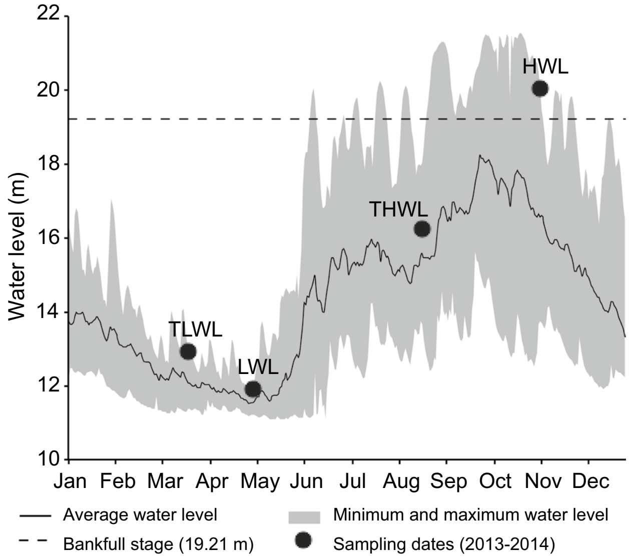

Fig. 1 Historical average of daily water level of the Usumacinta River (2003–2015) and sampling dates. THWL = transition to high water level, HWL = high water level, TLWL = transition to low water level, LWL = low water level

recorded throughout the Usumacinta river–floodplain (e.g., Macossay-Cortéz et al. 2011; Barba-Macías et al. 2015; Esqueda-Lara et al. 2016). However, invasive non-native species and changes in soil use and farming activities have been reported in the Usumacinta river–floodplain (Kolb and Galicia 2012; Sánchez et al. 2015b; Barba-Macías and Trinidad-Ocaña 2017).

Intra-annual water-level fluctuations in the Chaschoc River–floodplain system, measured during this study, allow it to be permanently connected to the Usumacinta River. In most river–floodplain systems that are surface hydraulically connected, like the Chaschoc and Usumacinta, intra-annual variations in water level are more significant than inter-annual variations (Junk 2002). Several reports related intra-annual physicochemical and biological variations in water level to various dominant abiotic and biotic processes in the aquatic environment. For example, during periods of water-level transition (defined by increasing or decreasing depth) and high water-level (when exceeding the bankfull stage) increases in inorganic nutrient levels, organic matter decomposition, and light attenuation have been reported to be due to processes caused by the spatial–temporal variability of the river–floodplain system (e.g., Peng and Effler 2013; Brito et al. 2014). By contrast, changes in the production of phytoplankton biomass have been reported by various authors as the dominant factor determining water level during periods of low water level in some river–floodplain systems (e.g., Brito et al. 2014; de Souza et al. 2017). Referencing the marked intra-annual water-level fluctuation observed in this study, the hypothesis held that variation in the chlorophyll-*a*, physical, and chemical variables is related to at least one dominant process during each of the water-level conditions under consideration (low water level—LWL, transition to high water level—THWL, high water level—HWL, and transition to low water level—TLWL). To test this hypothesis, intra-annual variation in 14 variables related to inorganic nutrient enrichment (nitrogen and phosphate compounds), organic matter decomposition, light attenuation, and production of phytoplankton biomass was monitored under the four water-level conditions. This research was performed in the floodplain of the Usumacinta basin over a 1-year period (2013–2014).

Materials and methods

Study area

The Chaschoc River–floodplain system (17°50′04.7″–17°45′38.7″N, 91°45′30.5″–91°42′25.8″W) is located 130 km upriver from the Usumacinta River mouth in the Southern Gulf of Mexico. At the LWL, permanent aquatic ecosystems occupy approximately 1212.44 ha. During periods of HWL, river overflow can result in a flooded area of up to 13,202.47 ha (Fig. 2). Average low and high water levels can differ by 4–10.2 m (Supplementary material).

Vegetation in the study area includes seasonally flooded forest and riparian vegetation dominated by eight species, as well as freely floating and floating-leaved macrophytes, each one represented by two species (Macossay-Cortéz et al. 2011). Submersed rooted macrophytes, common in other

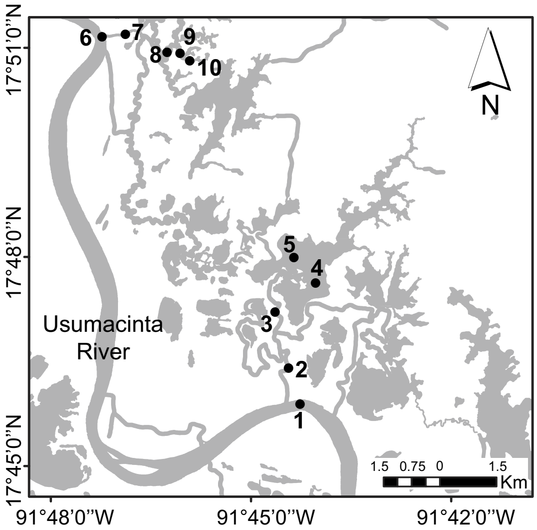

Fig. 2 Map of the Chaschoc River–floodplain system, filled circle = sampling sites

river–floodplain systems interconnected with the Usumacinta River, were absent (Macossay-Cortéz et al. 2011).

Sample collection

Analyses of intra-annual variation included 14 physical, chemical, and biological variables in the water of the Chaschoc River–floodplain system during each of four water-level conditions: THWL in August 2013, HWL in November 2013 when the Usumacinta River overflowed above the bankfull stage (Fig. 1), TLWL in March 2014 and LWL in May 2014. Water level (m) was measured only as a referential value for each of the four conditions (Supplementary material).

Ten sampling sites were established in the river–floodplain of the Chaschoc (Fig. 2), with three replica samples acquired per site, for each of the four water-level conditions. Water temperature (WT) in °C, electrical conductivity (EC) in $\mu S\ cm^{-1}$, turbidity (Turb) in NTU, Secchi disk depth (SD) in m, pH, concentrations ($mg\ L^{-1}$) of ammonium (NH_4), nitrate (NO_3), nitrite (NO_2), orthophosphate (PO_4), and total phosphorus (TP), Chl-*a* in $\mu g\ L^{-1}$ and the percent dissolved oxygen saturation (DO Sat) were recorded at the mid-water level at each site. Biochemical oxygen demand (BOD_5) in $mg\ L^{-1}$ and chemical oxygen demand (COD) in $mg\ L^{-1}$ were estimated for samples composed of sub-samples obtained from the three replicas at each site. Each variable was quantified in accordance with the methods of APHA (1998) and USEPA (1971), totaling 1520 records.

Statistical analyses

Data analysis consisted of four steps: (1) determine intra-annual variation of each variable, (2) initially select variables based on statistical and physicochemical criteria, (3) refine variable selection to group them by water-level condition and interpret the key factors in the water column, and (4) integrate variables based on physicochemical and biological factors under each water-level condition. Intra-annual variation in the variables was estimated based on mean water levels calculated from each of the three replicate data sets acquired at each sampling site, and on single data points for Chl-*a* and other physical and chemical variables obtained from composite samples (mixed replicates from each site) (Supplementary material). The data did not show a normal distribution (Shapiro–Wilk; $p < 0.05$) or homogeneity of variance (Bartlett; $p < 0.05$). Therefore, analyses were performed using nonparametric tests (Wilcoxon; $p < 0.05$). Initial selection of the physicochemical variables and of Chl-*a* was carried out with Spearman's nonparametric correlation test ($p < 0.05$) to eliminate redundant variables. Subsequently, six additional physicochemical variables were eliminated based on their environmental effects. For the second variable selection step, principal components analysis (PCA) was applied to the values of each standardized variable (z-value), based on a correlation coefficient matrix, to determine the intra-annual distribution in the eight remaining variables for each of the four water-level conditions. For simplification, principal components (PCs) with eigenvalues less than unity were eliminated from the PCA (Legendre and Legendre 2000), and variables with absolute eigenvector values greater than 0.4 were considered to have made significant contributions to the PCs (Weilhoefer et al. 2008). Finally, the physicochemical and biological variables that were significant for each PC were grouped by water-level condition and taken as key factors in the water column contributing to a corresponding process. The inorganic nutrient enrichment, organic matter decomposition, light attenuation, and production of phytoplankton biomass were initially the corresponding processes considered. Statistical analyses were carried out using JMP software (ver. 10.0; SAS Institute, Cary, NC, USA).

Results and discussion

Chl-*a* levels and all other chemical and physical variables differed significantly among the four water-level conditions during the study period (Wilcoxon, all $p < 0.05$; see Supplementary material). These results can be explained by changes in water levels in river–floodplain systems and natural intra-annual variation therein (Mayora et al. 2013; Tubatsi et al. 2014). Water levels of the Chaschoc have historically exceeded those of the bankfull stage (Fig. 1). The average difference between the LWL and HWL water levels in the Chaschoc River–floodplain system, of 6.2 m (Supplementary material), favors lateral connectivity among areas that are seasonally inundated. Similar fluctuations in Chl-*a* levels and other physicochemical variables have been reported in other hydraulically non-perturbed river–floodplain systems (Zalocar de Domitrovic 2003; Townsend 2006; Mayora et al. 2013).

The TP and Turb data were omitted from the analysis due to their correlation with PO_4 levels ($p \leq 0.008$); this relationship has been frequently reported in other wetlands (Liu et al. 2016). Four of the twelve remaining included variables were also removed, where for example intra-annual variations in pH, EC and WT, as well as low concentrations of NO_2 (Supplementary material), were not associated with significant changes in the physical or chemical condition of the water. Indeed, the annual ranges of pH, EC and WT were within the limits of slightly alkaline, limnetic and tropical

Table 1 Eigenvectors, eigenvalues and variance in principal components analysis

Variable	PC1	PC2	PC3
COD	**0.446**	0.092	0.000
BOD_5	0.101	0.055	**0.645**
SD	**− 0.437**	0.053	0.354
NH_4	0.099	0.320	**− 0.616**
NO_3	− 0.121	**0.675**	0.140
PO_4	0.359	**0.453**	0.098
DO Sat	**0.473**	**− 0.445**	0.067
Chl-*a*	**0.471**	0.159	0.213
Eigenvalue	2.490	1.549	1.394
Explained variance (%)	31.1	19.4	17.4
Accumulated variance (%)	31.1	50.5	67.9

The eigenvectors highlighted in each component are in bold

waters. PCA was applied to the eight remaining variables (Table 1).

No variable was discarded during PCA. The first three PCs of the PCA were retained because they had an eigenvalue greater than 1 significant variation (χ^2; $p < 0.0001$), and explained 67.9% of the variance in the data (Table 1). DO, Sat, Chl-*a*, and COD were positively associated with the first component, while SD was negatively associated. The second component was defined positively by NO_3 and PO_4, but negatively by DO Sat. The third component showed a positive relationship with BOD_5 and a negative relationship with NH_4 (Table 1).

The four water-level conditions were interpreted according to the first three PCs. LWL group was mainly explained by PC1 (Fig. 3). This water-level condition included the maximum values of DO Sat (≥ 137%) with 30% of the Chl-*a*

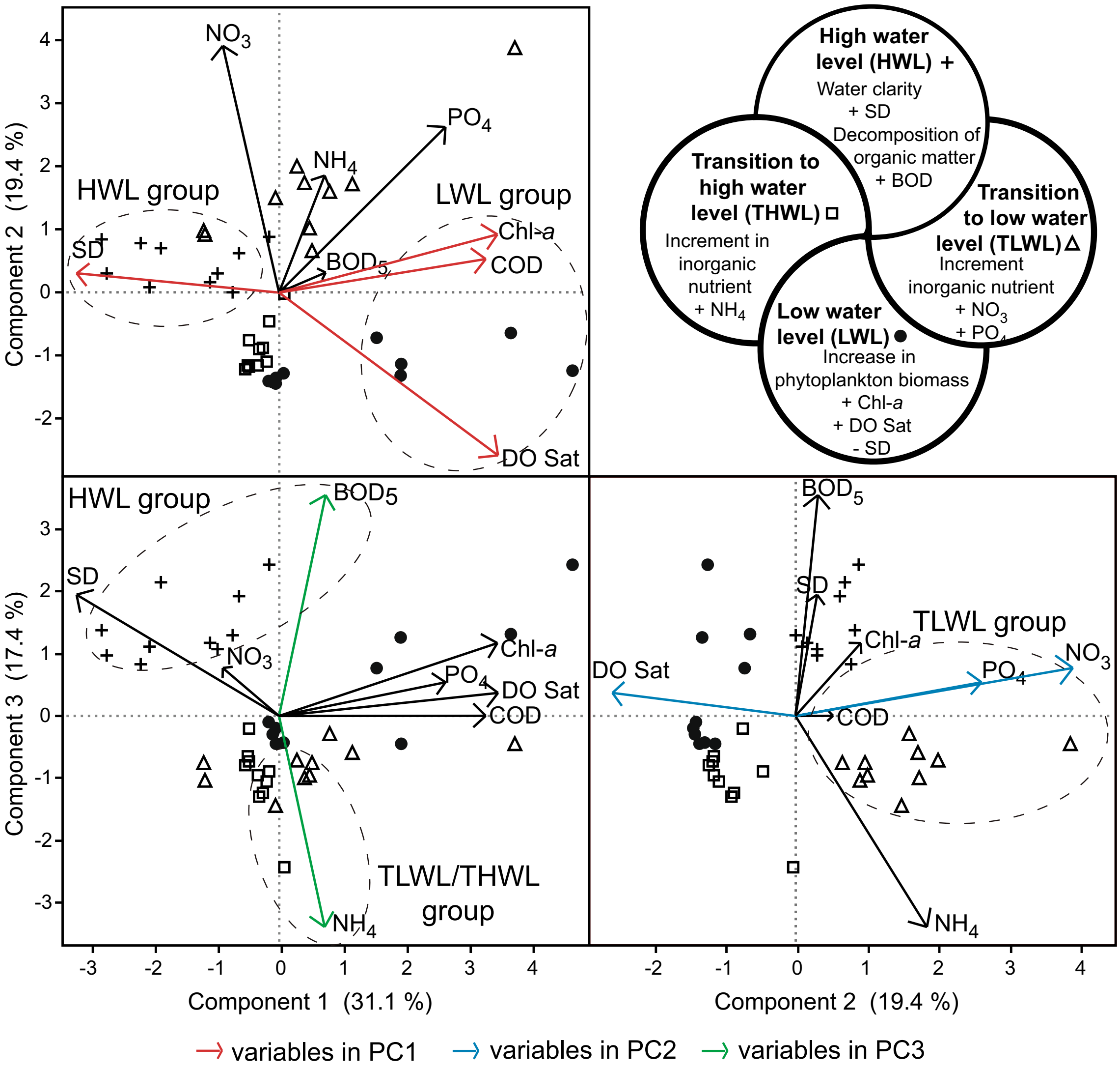

Fig. 3 PCA bi-plots (variables and samples) and conceptual diagram of the variability in Chl-*a* and physical and chemical variables as a function of the intra-annual water level in the Chaschoc River–floodplain system

values > 25 µg L^{-1} and 70% of the COD values being greater than 20 mg L^{-1}; this coincides with the minimum values of SD (< 0.3 m). Chl-*a* values greater than 25 µg L^{-1} indicate hypereutrophized environments according to OECD (1982). Moreover, Chl-*a* levels under LWL conditions were 45.1 µg L^{-1} greater than under THWL conditions, while DO Sat and COD were 256% and 91 mg L^{-1} greater under HWL conditions, respectively. Moreover, SD values were 1.3 m lower relative to HWL conditions. The distribution of these four variables and the samples along the PC1 axis help explain a temporal gradient with increases in Chl-*a* levels and decreasing water clarity among the four water-level conditions.

TLWL group was mainly explained by PC2 (Fig. 3). For TLWL, all NO_3 values, and 40% of the PO_4 values, were greater than 1 mg L^{-1} and 0.31 mg L^{-1}, respectively. DO Sat values (≤ 110%) were lower than those for LWL. In addition, PC3 showed a slight difference (0.35 mg $L^{-1)}$ in NH_4 levels between TLWL and HWL (Fig. 3). Thus, the distribution of nutrients and samples along the PC2 and PC3 axes indicated enrichment, which helps explains the water conditions at TLWL.

THWL group was partially explained by PC3 (Fig. 3), where the NH_4 concentration (0.49 mg L^{-1}) was slightly greater than for both the HWL and LWL conditions. However, the increase in NH_4 levels was not large enough to be interpreted as nutrient enrichment.

For HWL group, the maximum SD and BOD_5 values (Supplementary material) could be explained by the PC1 and PC3 axes, respectively (Fig. 3). For HWL, SD was 1.5 m greater than the value for LWL, and BOD_5 was 11.6 mg L^{-1} higher than for THWL. Therefore, water clarity and organic matter degradation were key factors for HWL.

The increase in Chl-*a* levels was recorded under LWL conditions in the Chaschoc points to the possibility of correlating phytoplankton assimilation with the availability of inorganic nutrients (e.g., Shuhaimi-Othman et al. 2007; Wang et al. 2018). Nutrient input in the study area may be from runoff during TLWL. High Chl-*a* levels have been frequently reported under LWL conditions in river–floodplain systems (Mayora et al. 2013; Brito et al. 2014; Roach et al. 2014). However, increases in Chl-*a* levels are particularly noticeable when both physicochemical variability and phytoplankton dynamics show an association with marked fluctuations in water level (Townsend 2006; Zuijdgeest et al. 2016). This is because flood pulses favor organic matter decomposition, availability of phosphate compounds, and their assimilation by phytoplankton, the latter being characterized by high values of DO Sat and Chl-*a* at LWL (Tockner et al. 2000; Townsend 2006; Weilhoefer et al. 2008; Wang et al. 2018). The yearly overflow of the Chaschoc above the bankfull stage (Fig. 1), which can increase water levels by up to 6.2 m, can be correlated with temporal gradients in Chl-*a* levels, as indicated by PC1. This implies that seasonal increases in Chl-*a* are key inter-annual factors determining water level. Moreover, both intra- and inter-annual variations in water level, which are related to increasing Chl-*a* levels during low-water periods, may be crucial for maintaining the ecological condition of the Chaschoc River–floodplain system. It is likely that water-level fluctuations help the ecosystem maintain its capacity to process excess inorganic nutrients and Chl-*a* through the activity of its biota. For example, high nutrient concentrations (NO_3 and PO_4) under TLWL result in high levels of Chl-*a* and, consequently, high values of DO Sat and minimum SD (< 0.3 m) under LWL. These coincide with a high phytoplankton diversity, also recorded for LWL in the study area (Esqueda-Lara et al. 2016), which may be indicative of favorable ecological conditions. However, studies on the relationships between physicochemical processes and phytoplankton size (Palijan 2017) remain to be conducted for the Chaschoc River–floodplain system.

Increasing levels of inorganic nutrients (N and P) have also been linked with falling and rising water levels during both transition conditions (i.e., Brito et al. 2014). Under THWL and TLWL, maximum concentrations of NH_4 (≤ 0.51 mg L^{-1}) remained low due to its fast oxidation, and therefore not associated with high values (≥ 1 mg L^{-1}) recorded in other ecosystems (Peralta et al. 2014; de Wilde et al. 2015). The NO_3 and PO_4 concentrations observed for TLWL were greater than 1 mg L^{-1} and 0.310 mg L^{-1}, respectively, which are relatively high for aquatic ecosystems according to the OECD (1982) and Zhu et al. (2015). However, NO_3 and PO_4 concentrations often exhibit high variability within very short time frames under conditions of transitional water level. Such high variability is typically explained by interactions between hydrogeomorphic and biogeochemical processes (de Wilde et al. 2015). Therefore, the observed variability in NO_3 and PO_4 concentrations, and the lack of a gradient in PC2, indicates that nutrient enrichment in the Chaschoc River–floodplain system cannot be the dominant physicochemical process during transitions in water-level conditions.

Under HWL conditions, increases in SD and BOD_5 have been observed in other ecosystems (Tockner et al. 2000; Roach et al. 2014; Tubatsi et al. 2014; Zuijdgeest et al. 2016). The decomposition of organic matter has been correlated with water-level fluctuations and flooding, since organic matter in the floodplain can be transported very rapidly, but generally requires more time to degrade. The increase in the SD gradient during the inundation of 11,990.03 ha in the Chaschoc River–floodplain system can be explained by a low monthly average sediment load from 1951 until 1980 in the Usumacinta River, which was at least 50% lower than its average value during water discharge (Muñoz-Salinas and Castillo 2015). This latter report is consistent with the low levels of total suspended solids (<37.5 mg L^{-1}; unpublished data) that were measured in the present study. Similar to increases in Chl-*a* levels, water clarity can be dependent on other intra- and inter-annual factors, since the Chaschoc system is fed with water containing low levels of total suspended solids and the bankfull stage is exceeded every year (Fig. 1). However, water clarity and increases in Chl-*a* levels were opposing key factors, as revealed by the same PCs but under extreme water-level conditions. The contrasting Chl-*a* conditions between the hypertrophic values (>25 µg L^{-1}) at LWL and mesotrophic values (4.9–7.9 µg L^{-1}) at HWL (Supplementary material) highlight the possible relationship between this rise in production of phytoplankton biomass with the minimal short-term variability in water depth recorded by Tockner et al. (2000) during the LWL. Under a global warming scenario, the relationship between the production of phytoplankton biomass and the lowest water level in river–floodplain systems has been linked to the rise in surface water temperature, eutrophication, and cyanobacteria abundance (Jeppesen et al. 2015; Kraemer et al. 2017).

Conclusion

In the Chaschoc River–floodplain system, the production of phytoplankton biomass and light attenuation were interpreted with increases in Chl-*a* levels and water clarity under LWL and HWL conditions, respectively, as demonstrated by a temporal gradient in PC1. Historically, intra-annual variation has resulted in water levels exceeding the bankfull stage every year, where the water has low amounts of total suspended solids. Moreover, both key factors have been frequently reported in several floodplain ecosystems. In contrast, nutrient enrichment during both water-level transitions correlated with isolated observations of high NO_3 and PO_4 concentrations. These correlations were not linked to a historical background, although nutrient enrichment has been observed in other riverine wetlands. The inherent hydrogeomorphic traits of individual ecosystems, combined with regional variations therein, result in pronounced physicochemical variation in the water column during transitional water-level stages versus under HWL or LWL conditions. The agreement with the minimal short-term variability in water level observed under LWL conditions and the increases in Chl-*a* levels as a key factor during the same water-level conditions for different riverine wetlands open the opportunity to gauge the relationship between the lowest water level and Chl-*a* as a possible environmental predictor of permanent hydraulic connected wetlands. The recurrence of this relationship in similar geomorphic river–floodplain systems located in regions with different climate patterns should be tested by a meta-analysis before it may be used as a predictor for anthropogenic ecological impacts, such as modifications of the hydraulic connectivity and climate change. The restriction at the lowest level will minimize the effect of the ample Chl-*a* variation, both on the intra- and inter-annual scales.

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Compliance with ethical standards

Conflict of interest The authors declare that have no conflict of interest.

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