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## **Water-level fluctuation enhances sediment and trace metal mobility in lake littoral**

Nathalie Lécivain<sup>1</sup>, Bernard Clément<sup>1</sup>, Aymeric Dabrin<sup>2</sup>, Juliette Seigle-Ferrand<sup>3</sup>, Damien Bouffard<sup>4</sup>,  
Emmanuel Naffrechoux<sup>5</sup>, Victor Frossard<sup>6</sup>✉

<sup>1</sup>Univ Lyon, Université Claude Bernard Lyon 1, CNRS, ENTPE, UMR5023 LEHNA, F-69518, Vaulx-en-Velin, France

<sup>2</sup>Irstea, UMR 5553 RiverLy, centre de Lyon-Villeurbanne, 69625 Villeurbanne Cedex, France

<sup>3</sup>UMR LECA, Université Savoie Mont-Blanc, 73376 Le Bourget du Lac, France

<sup>4</sup>Eawag, Swiss Federal Institute of Aquatic Science and Technology, Surface Waters - Research and Management, Kastanienbaum, Switzerland.

<sup>5</sup>UMR LCME, Univ. Savoie Mont-Blanc, 73000 Chambéry, France

<sup>6</sup>UMR 42 CARRTEL, Université Savoie Mont-Blanc, 73376 Le Bourget du Lac, France

✉Corresponding author: [victor.frossard@univ-smb.fr](mailto:victor.frossard@univ-smb.fr)

## **Abstract**

Water-level fluctuation (WLF) is a widespread management action in lakes and reservoirs whose impacts on contaminant fate have seldom been investigated. We used near shore hourly measurements (n = 2122) of turbidity (contaminant proxy) and water velocity (sediment resuspension proxy) to track high-frequency contaminant dynamics during a 0.6 m change in water level observed in autumn 2017 in a large French lake. Simultaneously, discrete trace metal measurements highlighted that trapped sediment was more contaminated and finer than surficial sediment supporting that suspended particles (measured by turbidity) were a preferential medium for contaminant mobility. General additive models involving tensor products revealed the enhancement of wind-speed and river discharge effects on turbidity with water draw down. The decrease of the explained deviances by the models over time-lags indicated short time-scale response of turbidity to external forcing. Three of the four major turbid events occurred at the lowest water-level and were concomitant of sediment resuspension as well as precipitation events and / or river flood suggesting a complex interplay among in-lake and watershed processes at controlling sediment mobility during the WLF. These results shed in light that WLF can affect lake littoral hydrodynamic cascading up to the enhancement of contaminant mobility. Sediment resuspension may be an overlooked feature of WLF increasing contamination risk and exposure for littoral organisms with widespread ecological consequences due to the large number of water-level regulated ecosystems.

## **Keywords**

water-level fluctuation, trace metals, turbidity, resuspension model, lake littoral

## 1. Introduction

The fate of contaminants in aquatic ecosystems depends on physical transport and mixing as well as geochemical processes both acting at different time scales that remain difficult to capture in the field. Discrete and passive sampling (e.g. Diffusive Gradient in thin film) provide time-average insights on local contamination yet masking real-time contaminant behavior (Lécrivain et al. 2018, Bretier et al. 2019). Recent approaches such as electroanalytical methods progressively open the way for real-time monitoring of contaminants while their implementation remain currently limited to short time-scales (i.e. hours to days, Garnier et al. 2006) or necessitate stringent monitoring systems (Superville et al. 2015). Contaminant bioavailability modeling accounting for physical and chemical characteristics of sediment, water and contaminant can make valuable predictions for an array of contaminants but necessitate a high number of parameters at work (e.g. partitioning coefficients) and still a consequent environmental monitoring (Di Toro et al. 2005; Paquin et al. 2002, Brix et al. 2017).

Alternatively, turbidity, measured as nephelometric turbidity units (NTU), is among the most basic environmental integrative information that can be recorded at high-frequency. It quantifies the cloudiness of water related to the amount of suspended particles that are a preferential medium for adsorbed contaminant (Chiffre et al. 2015; Kalnejais et al. 2007). The ability of particles to adsorb contaminant change with particle grain size due to changes in specific surface area (Martincic et al. 1990) (Sutherland 2003) and suspended particles tend to contain much higher contamination than the bulk sediment they originate due to smaller grain size (Kalnejais et al. 2007). Turbidity can also inform on the dynamics of dissolved contaminants as soluble contaminant from soils or sediment generally co-occur with particle resuspension events (Cantwell et al. 2002; Feters et al. 2016). For instance, Bretier et al. (2019) recently reported a sharp increase of Mn, Ni, Co and As dissolved concentrations concomitantly with high suspended particulate matter (i.e. high turbidity) triggered by sediment release from a dam flushing event in the Upper Rhône River. Consequently, the consideration of the size of suspended particles in complement to turbidity (i.e. the overall particle concentration) could provide valuable indicators for tracking contaminant fate in freshwaters overtime. Rather than estimating the actual contamination that can be obtained by relevant discrete sampling,

these indicators could enable the assessment of the relative changes in contaminant mobility and ultimately biota exposure to contaminant overtime (Weltens et al. 2000).

We investigated high-frequency (hourly measurements) dynamics of littoral turbidity and water velocity along with external forcing (i.e. precipitation, wind speed, river discharge) during a water-level fluctuation event (WLF,  $\Delta\text{depth} = 60$  cm) that occurred in autumn 2017 in the largest natural French lake (Lake Bourget). A sediment resuspension model quantifying the occurrence of grain size-specific sediment resuspension events was derived from water velocity (Soulsby and Whitehouse 1997, Graham et al. 2016). Complementarily, discrete measurements of trace metals (TM) were performed at three occasions (before-during-after WLF) among two different matrices (surficial and trapped sediments) to assess the actual contamination of the littoral and its possible variation during the WLF.

The overarching aim of this study was to evaluate the dynamic of suspended particles (i.e. turbidity) as a proxy for TM dynamic during the WLF tackled through the following working hypotheses:

- 1) The low water-level during the WLF should foster wind-induced sediment resuspension (Cózar et al. 2005; Hofmann et al. 2008), increasing turbidity and metal mobility.
- 2) The effects of external forcing on turbidity should modulate by the WLF and increased for low water-level.
- 3) The occurrence of high turbidity events should be associated to sediment resuspension events indicating that in-lake processes may be responsible for turbidity. Alternatively, watershed processes (i.e. export of suspended particles) should be involved.

Overall, these investigations were expected to provide insights regarding the influence of WLF on contaminant dynamics, an often overlooked feature of WLF within lake littorals.

## 2. Materials and methods

### 2.1. Lake Bourget and study sites

Lake Bourget is the largest French natural lake (44.5 km<sup>2</sup>, 45.43°58.2'N 5°51'59.1'E) sheltered within the limestone mountains of the Epine and Bauges. The catchment area of the lake is 560 km<sup>2</sup> and covered by forests (45 %), agricultural areas (22 %), grazing fields (12 %), urban areas (13 %) and water bodies (8 %) (CISALB 2009). The littoral sediment contained by a mixture of contaminants exerting low but heterogeneous toxicity. Higher contaminant concentrations were reported in the southeastern region of the lake mostly resulting from local watershed run-offs (Lécrivain et al. 2018; Lécrivain et al. 2019). We selected this southeastern region for the study area. This area is characterized by a ~ 5 % gentle slope close to the outlet of a small arm of the Tillet River, one of the main tributary of the lake (45°40'00.6"N 5°53'39.0"E) (Appendix 1). Three study sites distant of 20 m to each other were retained along a littoral transect (Appendix 1). The shallowest site (S<sub>0.7</sub>) was located ~ 10 m away from the shoreline at 0.7 m depth and the two other points (S<sub>1.5</sub> and S<sub>2.5</sub>) at ~ 30 m and ~ 50 m from the shoreline at depths of 1.5 m and 2.5 m respectively. The experimental design as well as physico-chemical monitoring among the study sites are presented in Appendix 2.

### 2.2. Trace metal contamination

TM discrete measurements were performed at three temporal steps over the WLF. On the 2017/08/31, step 1 provided information before the water-level dropped down. On 2017/10/19, step 2 provided information at the lowest level. Finally, on 2018/04/24, step 3 provided information resulting from the water-level increase (step 3).

Triplicates of TM measurements were performed at each site among two different matrices: surficial and trapped sediments. Sediment traps were deployed two weeks prior sampling sessions to ensure sediment accumulation. After sampling, the surficial and trapped sediments were placed in pre-washed polyethylene bottles, transported to the laboratory in coolers, sieved at 2 mm to remove macro-debris and stored at 4°C during a maximum of 24 hours.

Prior to the measurements, bulk sediments were mineralized in a microwave oven (CEM/MARS Xpress, 2 mL of ultra-pure HNO<sub>3</sub> + 6 mL of ultra-pure HCl, 180 °C for 30 min, filtration on a 0.45-

$\mu\text{m}$  Whatman<sup>TM</sup> filter and dilution of the residue in 25 mL of ultra-pure water). The sediment grain size spectra were quantified using a Malvern Mastersizer 2000G. TM concentrations were then estimated by atomic absorption spectrometry (AAS). The total sediment contents of Cd, Cr, Cu, Ni and Pb were measured in a graphite furnace at 1500 °C, and the total sediment content of Zn was measured with an air-acetylene flame (Perkin Elmer, model PinAAcle 900T). The detection limits were as follows: Cd = 2.5  $\mu\text{g kg}^{-1}$  DM, Cr = 10  $\mu\text{g kg}^{-1}$  DM, Cu = 3.5  $\mu\text{g kg}^{-1}$  DM, Ni = 17.5  $\mu\text{g kg}^{-1}$  DM, Pb = 12.5  $\mu\text{g kg}^{-1}$  DM, Zn = 375  $\mu\text{g kg}^{-1}$  DM. Certified reference material (River sediment LGC6 187) was used for standardization, and triplicate measurements were done to ensure that analytical errors were under 2%.

### *2.3. Turbidity and external forcings*

Water turbidity was measured at hourly frequency using an Aqua Troll 600 multiparameter probe located at site S<sub>1.5</sub> to quantify the amount of particles present in the open water. We performed 2-point calibration at 10 NTU and 100 NTU for turbidity measurements using In Situ's turbidity standards and a new calibration was performed at the beginning of each new step. Hourly measurements for wind speed and precipitation were collected from the meteorological station of Météo-France Chambéry-Aix-73329001 (Appendix 3). Hourly discharges of the Leysse River were extracted from the national station of La Motte-Servolex-V1315020 (<http://hydro.eaufrance.fr/>, Appendix 3). The flood plume of the Leysse River typically flows North-East toward the studied area (Vinçon-Leite et al. 1998) and the discharges of both the Leysse River and the Tillet River (nearby the study area) exhibit similar hydrological regimes and only information from the Leysse River were considered here.

### *Sediment resuspension model*

The local sediment resuspension was quantified by the dimensionless Shields mobility parameter ( $\theta$ , Soulsby and Whitehouse 1997). The Shields parameter was derived by combining sediment information (modal grain size and density) with water current velocity data obtained at site S<sub>2.5</sub> with an acoustic Doppler current profiler (ADCP, AQUADOPP Profiler 2MHz) set up for recording hourly

velocity over 2 m depth. We used velocity data at 70 cm above the sediment. This height was chosen as an optimal distance from the bottom where the logarithmic velocity profile is well developed.

The dimensionless mobility Shields parameter is obtained as follows:

$$\theta = \frac{\tau_b}{(\rho_s - \rho_w) \times g \times d} \quad (1)$$

where  $\tau_b$  is the bottom shear stress ( $\text{kg m}^{-1}\text{s}^{-2}$ ),  $\rho_s$  is the particle density ( $2600 \text{ kg m}^{-3}$ ),  $\rho_w$  is the water density at the sediment surface ( $1000 \text{ kg m}^{-3}$ ),  $g$  is the gravitational acceleration ( $9.81 \text{ m s}^{-2}$ ) and  $d$  is the sediment mean particle diameter (taken as the modal lake and trapped sediment particle sizes of  $159 \mu\text{m}$  and  $127 \mu\text{m}$  respectively, Appendix 4).

The bottom shear stress ( $\tau_b$ ) represents the product of water density and the square of the shear bed velocity ( $u_*$ ):

$$\tau_b = \rho_w \times u_*^2 \quad (2)$$

The bottom shear stress is estimated using the water current velocity data,  $U$  ( $\text{m s}^{-1}$ ), assuming a logarithmic velocity profile above the sediment bed:

$$u_* = \frac{k \times U(z)}{\ln(\frac{z}{z_0})} \quad (3)$$

where  $z$  is the distance between the sediment and the current velocity measured by the ADCP in meters (here  $70 \text{ cm}$ ),  $k$  is the von Karman's constant ( $0.4 \text{ m s}^{-1}$ ),  $z_0$  is the roughness height ( $5 \times 10^{-3} \text{ m}$ , Bouffard and Lemmin 2013).

In order to estimate the resuspension potential of the sediment particles, the Shields parameter was confronted to a dimensionless critical value ( $\theta_{cr}$ ), above which sediment resuspension was expected according to (Soulsby and Whitehouse 1997) as follows:

$$\theta_{cr} = \frac{0.3}{1 + 1.2 \times D_*} + 0.055 \times (1 - \exp^{-0.02 D_*}) \quad (4)$$

where the dimensionless grain size ( $D_*$ ) is expressed as follows:

$$D_* = d \sqrt{\frac{3 \times g \times (\frac{\rho_s}{\rho_w} - 1)}{v^2}} \quad (5)$$

where  $v$  is the kinematic viscosity ( $\text{m}^2 \text{s}^{-1}$ ).

## 2.5. Statistical analyses



Mann-Whitney tests were used to estimate the significance of the difference in TM concentrations among surficial and trapped sediment. Generalized additive models (GAM, Hastie and Tibshirani 1990, Wood 2006) were selected to analyze the relationships between turbidity and the external forcing. GAMs are flexible non-parametric models that accommodate for nonlinear relationships between variables and can support different distributions of the response variable. The extent of nonlinear relationship among variables is quantified through the estimated degree of freedom (edf) where edf = 1 indicate linear relationship and edf higher than 1 indicate progressively higher nonlinear relationship. A first GAM was computed considering water pressure as single variable to identify the general influence of WLF on turbidity. A second GAM that considered the three external forcing was fitted to assess their respective influence on turbidity. A last GAM involving tensor product smooths (Wood 2006) was finally fitted to address the possible modulation of WLF on the relationships between turbidity and the external forcing. The tensor product smooths allow the smooth relationship between turbidity and the external forcing to change nonlinearly with WLF. The tensor product interaction terms in the GAM reflected how the relationship between turbidity and the external forcing can be modulated by WLF. Tensor product interaction terms are suitable to model responses to interactions of variables with different units, which is the case in this study, and have been shown to provide fruitful insight among complex ecological interactions (e.g. Bacheler et al. 2009, Kvile et al. 2016). The possible time-lag response of turbidity to the external forcing was investigated by fitting the last GAM with delayed external forcing from 0 to 48 hours (i.e. responses variables were modeled against external forcing previously recorded from 0 hour (instantaneous) to 48 hours). We considered four knots and cubic regression splines to construct the smoothing splines and fitting the GAM and their performances were assessed by the proportion of deviance explained. Turbidity was  $\log_{10}$ -transformed prior the analyses and a Gamma distribution was considered for  $\log_{10}$ -transformed turbidity as it was a continuous variable bounded down 0 and clearly diverging from a normal distribution due to its right-skewness.

All statistical analyses as well as graphical displays were performed using R 3.6.3 (R Development Core Team 2020) and the packages *mgcv* (Wood and Augustin 2002, Wood 2006), *ggplot2* (Wickham 2009).

### 3. Results

#### 3.1. WLF, turbidity and water velocity dynamics

The water level drawdown started in September, stabilized during October and was followed by the water level increase in November (Fig. 1A). Over the three-months survey, background turbidity was mostly below 10 NTU (Fig. 1B). We however distinctly identified four major turbid events occurred (i.e.  $> 100$  NTU, maximum turbidity  $\sim 3500$  NTU) spanning from few days to several weeks (Fig. 1B). Water velocity was low over most of the study period (i.e.  $< 0.05$  cm s<sup>-1</sup>) and short higher velocity events were punctually recorded both in September and October with intensity reaching up to 0.15 cm s<sup>-1</sup> (Fig. 1C). During the two first weeks of November, the water velocity was more fluctuating and reached higher level than during the previous months and the highest water velocity of 0.18 cm s<sup>-1</sup> was recorded.

#### 3.2. Trace metal contamination

Surficial and trapped sediments mostly corresponded to fine sand according to Wentworth's (1922) classification although they differed in the mode values of grain size with surficial sediment being coarser (159  $\mu$ m) than the trapped one (127  $\mu$ m) (Appendix 4). Most TM significantly differed among these two types of sediment with concentration significantly higher for the trapped sediment than for the surficial one except for Cr and Ni that did not exhibit significant differences in their TM concentration (Fig. 2). When significant, the extent of TM enrichment for trapped sediment compared to the surficial one varied among TM from  $\sim 15$  % enrichment for Cd to  $\sim 100$  % enrichment for Cu.

#### 3.3. Turbidity, WLF and external forcings

The univariate GAM highlighted significant changes in turbidity along with WLF (Fig. 3A, Table 1). The pattern was nonlinear with an overall increase in turbidity with decreasing water level. Differently, a multivariate GAM indicated that turbidity did not significantly varied with precipitation but significantly linearly increased with both wind speed and river discharge (Fig. 3B to D, Table 1). Nevertheless, this multivariate GAM explained a limited proportion of the overall turbidity variability (i.e. 5.3% of the total deviance). A multivariate GAM accounting for the interactions between WLF and the significant external forcing was then fitted and its explanatory power was greatly higher (i.e.

35.2 % of the total deviance) than without considering interaction with WLF (Table 1, Fig. 4). This feature highlighted the role of external forcing on turbidity by WLF. The effect of wind speed appeared stronger at low water levels with higher slope compared to higher water levels (Fig. 4A). Similarly, the positive and nonlinear relationship linking discharge and turbidity was identified for low water levels while it was nonlinearly negative at high water levels (Fig. 4B). For both external forcing the higher predicted turbidity was identified for the lower water levels.

The multivariate GAM accounting for WLF interaction was fitted for increasing time-lags of the external forcing (Fig. 5). The proportion of deviance explained remained steady for the five first time-lags prior decreasing progressively up to 48h time-lags. The explanatory power of the multivariate GAM was hence the highest when considering no or short-term delay for the external forcing.

#### 3.4. Resuspension events

Over the three months of the study, the mean water velocity was  $3 \pm 2 \text{ cm s}^{-1}$  with several episodic events reaching velocity of about  $15 \text{ cm s}^{-1}$  and a maximal velocity of  $18 \text{ cm s}^{-1}$  by mid-November (Fig. 6A). These results shed in light the highly hydrodynamic constraints of the littoral of this large lake. The water velocity allowed computing the Shield parameter informing of the initiation of sediment resuspension for specific sediment grain sizes (Fig. 6B). When considering the mode value of surficial sediment grain size, three sediment resuspension events occurred over the studied period. By the end of September, the first resuspension event was not related to a turbid event while for the second and third resuspension events the onsets of turbid events could be identified. Three complementary sediment resuspension events would occur considering mode of trapped sediment (Fig. 6B). The first one was concomitant with the onset of the longer turbid event spanning from the end of October to early November and by the end of this turbid event a second resuspension event was suggested by the Shield parameter. The third resuspension event for the mode of trapped sediment occurred close to the last resuspension event for lake sediment mode values during the third turbid event. Considering the water velocity recorded during the studied period, the number of resuspension events decreased exponentially with sediment grain size (Fig. 6C). The highest sediment grain size that could be resuspended (i.e. a single resuspension event) had a diameter of  $230 \mu\text{m}$  and the number of resuspension events started to sharply increase for sediment finer than  $50 \mu\text{m}$  diameter.



## 4. Discussion

### 4.1. Turbidity as a contaminant proxy

Turbidity was especially variable over the study period and three of the four major turbid events recorded occurred during the lowest water-level period while the overall positive effect of water drawdown on turbidity could be more precisely quantified using a GAM. These results enabled to validate the hypothesis of an increasing turbidity as long as the water-level was lowered during the WLF. Further, the higher TM concentrations measured in trapped sediment compared to those in surficial sediment, likely related to their finer grain-size spectra (Martincic et al. 1990; Zhang et al. 2002, Sutherland 2003), supported the hypothesis that suspended particles were a preferential medium for TM mobility. Turbidity could hence be a relevant proxy to inform of the amount of TM within the open-water of lake littoral (Yao et al. 2016, Nasrabadi et al. 2016). As a consequence, WLF may foster TM exposure of the littoral biota as along with particle-adsorbed TM, dissolved TM have been shown to increase with turbidity (Brétier et al. 2019). The contamination risk of TM for the littoral biota would be enhanced during the lowest water-levels of WLF representing an adverse effect on littoral organisms of this management action. Complementary investigations such as TM sequential extraction (Lécrivain et al. 2019) and / or quantifying TM dissolved concentrations may complement our approach to better decipher TM exposure and their bioavailability for the littoral biota (Eggleton and Thomas 2004, Atkinson et al. 2007; Fetters et al. 2016, Nasrabadi et al. 2018).

### 4.2. Modulation of turbidity by water-level fluctuation

Among the external forcings considered, wind speed and river discharge had significant positive effects on turbidity yet their explanatory power (i.e. deviance explained) remained limited when considered additively. Their positive influence on turbidity was expected as both wind speed and discharge can either trigger sediment resuspension (Zheng et al. 2013) or support the input of sediments from the watershed (Hofmann et al. 2008) and two main reasons may explain their limited explanatory power. First, these measurements were performed at the closest long term monitoring stations from the studied sites (i.e. a distance of few km) possibly limiting the accuracy of these

variables actually acting at the study area. Second, other factors that were not accounted for such as upwelling may also have been involved in littoral variation of turbidity. Accounting for the interactions of wind speed and river discharge with WLF through the use of the tensor products in GAM to model their effects on turbidity drastically increased the explanatory power of the GAM. This result indicated that WLF would effectively modulate the effects of external forcings on turbidity. More precisely the water drawdown increased the effects of the external forcings on turbidity which amplifies the amount of suspended particles highlighting direct influence on WLF on contaminant mobility.

The decrease of deviance explained by the GAM over successive time lags suggested short time-scale (i.e. hours) response of turbidity to the external forcings. This result supports the relevance for considering high-frequency measurements to address contaminant mobility in lake littoral. Complementarily, the maintaining of rather high deviance explained at larger time-lags indicated that the external forcings may still influence turbidity at longer time-scale (i.e. several days). This result is in accordance with the sinking speed of sediment modal grain size that may be of several days considering turbulent regime in the lake littoral (Appendix 5). In other words, the external forcings would almost instantaneously affect particle and contaminant mobility that would maintain (i.e. delayed effect) for several days which constitutes suitable conditions for biota exposure to contaminant.

#### 4.3. Linking turbidity to in-lake processes

The lake littoral supported high hydrodynamic constraints as shown by the bottom water velocity that regularly exceeded  $10 \text{ cm s}^{-1}$  corresponding to shear stress higher than  $10 \text{ N m}^{-2}$  with maximal values of  $\sim 20 \text{ N m}^{-2}$  (Appendix 6). Such hydrodynamic constraint was of similar magnitude than those reported by Kalnejais et al. (2007) in the Boston Harbor (USA) for which resuspension events due to shear stress contributed up to 60% of the flux of resuspended metal in an average year. The resuspension events increased exponentially as long a sediment grain size decreased with a major inflexion at  $\sim 50 \mu\text{m}$  grain size in diameter. This result may be linked to the noisy variations of low turbidity outside of the major turbid events and explain the grain size spectra of the littoral sediment

(Appendix 4) whose fraction smaller than 100  $\mu\text{m}$  in diameter drastically decreased. The lake littoral hence primarily acts as a transport area for fine sediment to storage compartments in deeper zones (Morales-Marin et al. 2018). This assertion is supported by the finer particle size of deep sediment compared to littoral ones often associated to higher contaminant concentrations.

The major turbid events were mostly associated to sediment resuspension events when considering mode values of trapped and surficial sediment indicating that in-lake processes involving bottom shear stress may explain their onsets. However, most turbid events were also concomitant of high river discharge or precipitation suggesting that watershed processes (i.e. particle export from the watershed) would also be involved in the turbidity variations. For instance, the longest turbid event of several weeks that started by mid-October was associated to a unique resuspension event for the mode of trapped sediment and its duration may then not been only attributable only to in-lake process supporting lake sediment remobilization. The complex interplay between in-lake and watershed processes likely control the onset and duration of turbid events whose relative implication likely varied among turbid events ultimately constraining contaminant mobility. This complexity was tentatively addressed using the GAM considering wind speed (i.e. in-lake process) and river discharge (i.e. watershed process) that may provide useful forecast for turbidity dynamic within the littoral of this large natural French lake.

## **Conclusion**

We showed that WLF may significantly modulate the influence of the external forcing that drove the littoral turbidity. The enhancement of turbidity for the lowest water level associated to higher TM contamination of resuspended sediment provided evidence of the influence of WLF on TM mobility. Biota exposure may hence be amplified as ingestion of suspended contaminated particles is a common contamination pathway for both benthic and pelagic consumers (Weltens et al. 2000, Li et al. 2017) along with passive contamination via dissolved contaminant assimilation. Overall, turbidity may be a suitable proxy for high-frequency monitoring in complement to discrete contaminant measurements in highly dynamic aquatic ecosystems such as lake littoral. Due to the large number of water-level regulated ecosystems affected by WLF and in the perspective of their increasing establishment

313 (Farinotti et al. 2019), the effects of WLF on contaminant fate may have underestimated indirect and  
314 delayed impacts on littoral biodiversity compared to direct and more commonly reported alterations  
315 (Carmignani and Roy 2017; Evtimova and Donohue 2014).

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317

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1 Tables

2

3

4 Table 1: Summary statistics of the GAMs considering only WLF and accounting or not for the WLF in  
5 combination with external forcings (i.e. tensor product smooths) to explain turbidity variability.

Variables	Smooth terms	edf	p-value	Deviance explained
WLF	s(Water-level)	3.0	<0.001	18 %
Forcings without WLF	s(Precipitation)	1.2	0.24	5.3 %
	s(Wind_speed)	1.0	<0.001	
	s(Discharge)	1.0	<0.001	
Forcings accounting for WLF	te(Wind_speed, water-level)	7.1	<0.001	35.2 %
	te(Discharge, water-level)	11.9	<0.001	

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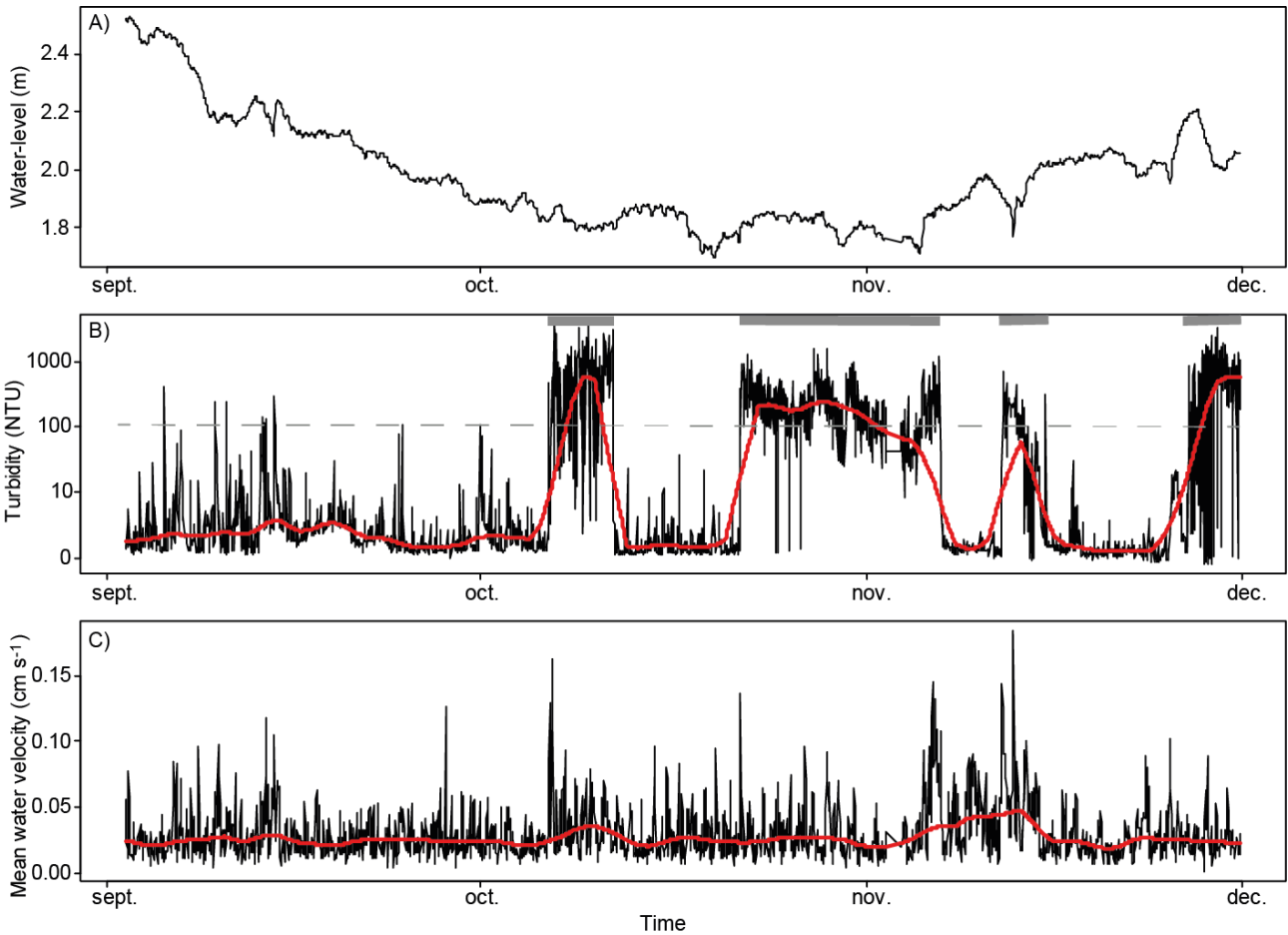


Figure 1: High-frequency dynamic of the littoral of Lake Bourget in autumn and winter 2017. A) water-level (m), B) turbidity (NTU, note the logarithmic-scale) and C) water velocity (cm s<sup>-1</sup>). Red lines represent Lowess-smooth trends (span window = 5% in the data, n= 2122). The horizontal dashed grey line in B) indicates the threshold for a turbid event (turbidity higher than 100 NTU) and grey rectangles report the duration of the turbid events.



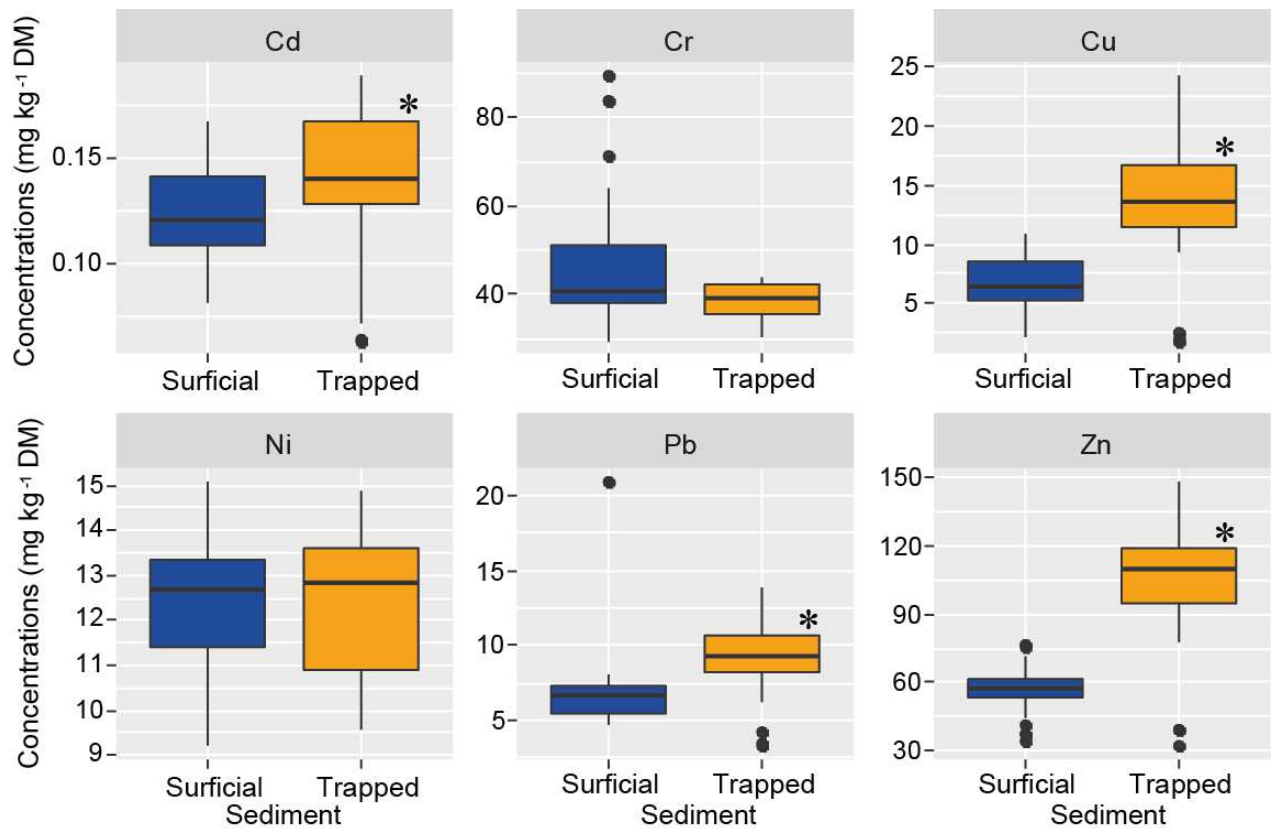
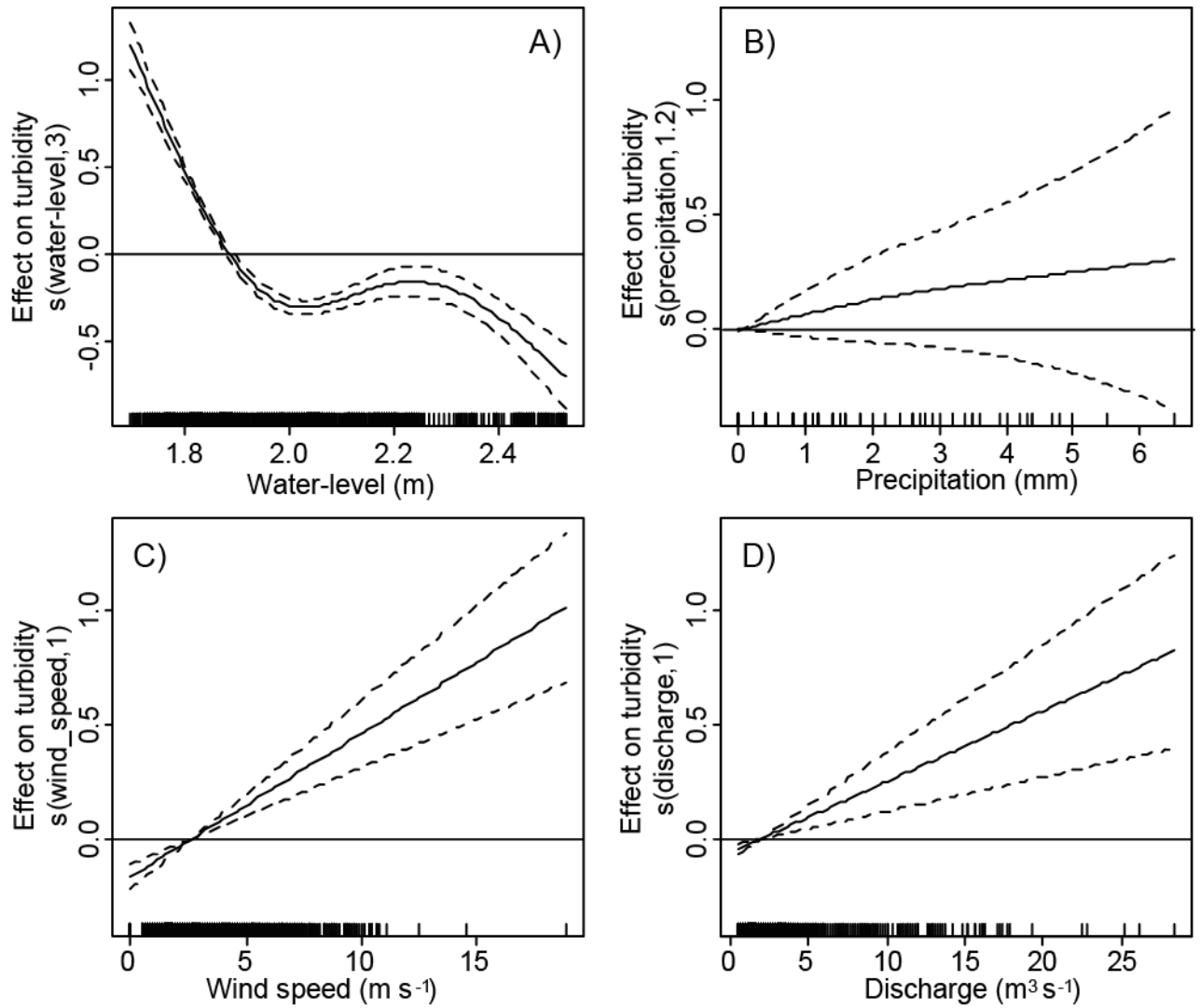
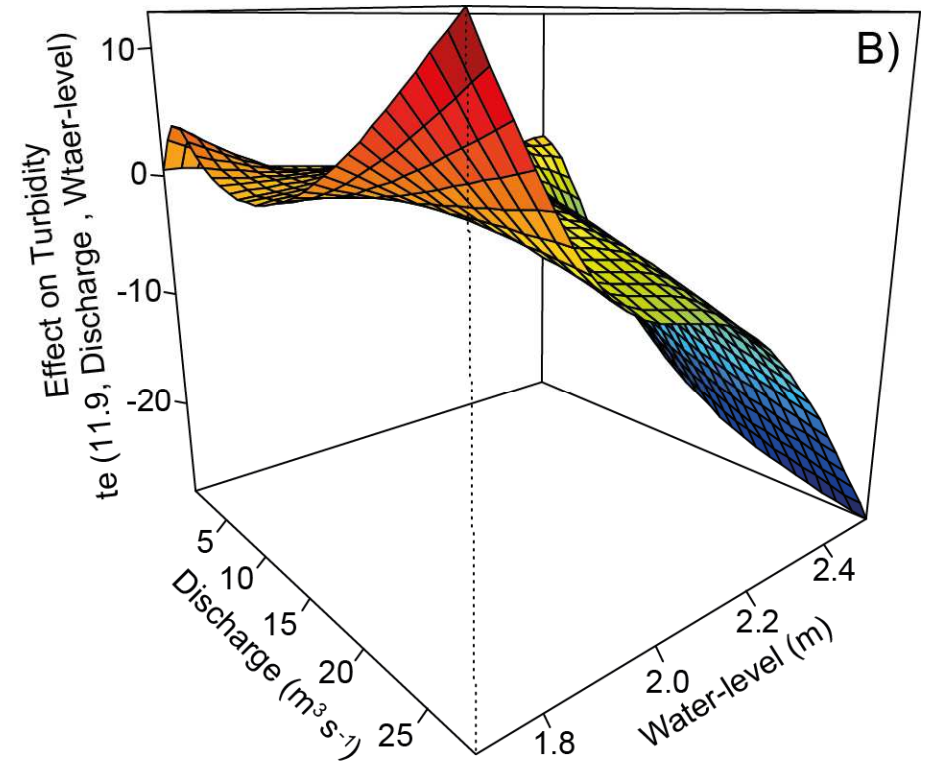
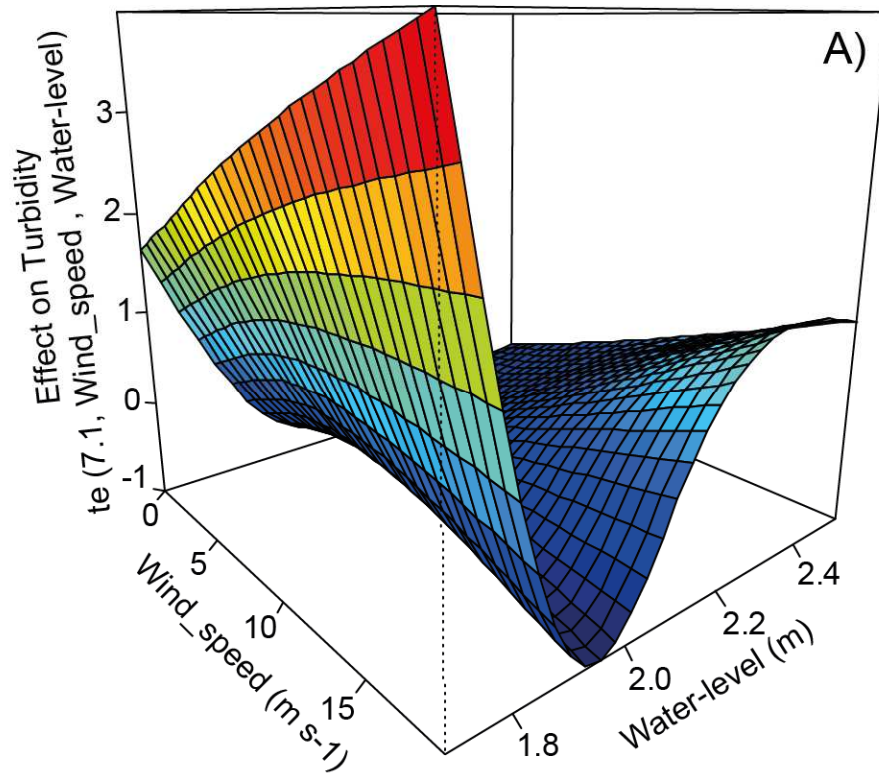


Figure 2: Boxplots of the trace metal concentrations (mg kg<sup>-1</sup> DM) in surficial (n = 27) and trapped (n = 24) sediments. The water-level was too low at S<sub>0.7</sub> to enable trapped sediment sampling explaining the lower sampling size of trapped sediment compared to surficial ones. The black stars indicate significant differences in trace metal concentrations according to Mann-Whitney tests assuming a significant threshold for p < 0.05.



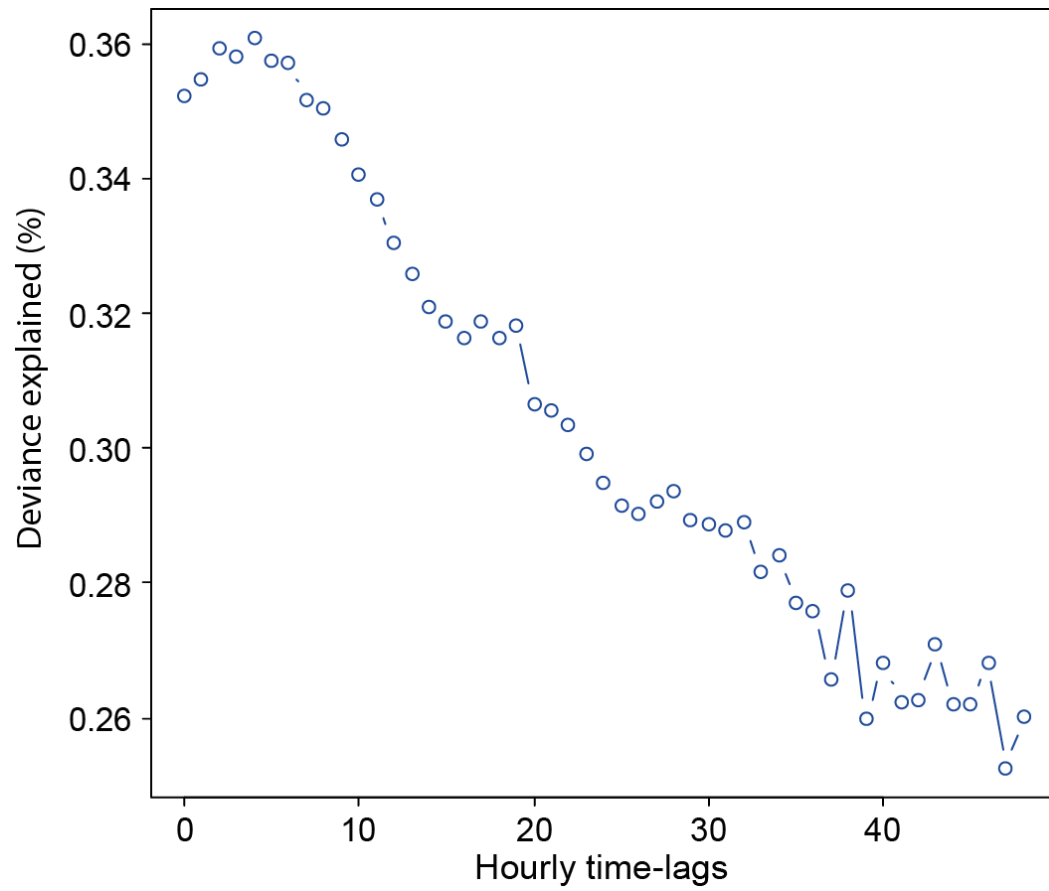
**Figure 3:** A) Smoothing of a simple GAM fitting the turbidity to WLF. Smoothings of a multivariate GAM fitting the turbidity to B) precipitation, C) wind speed and D) discharge. The variable forcing turbidity and the number referring to the edf (i.e. extent of nonlinear relationship) are indicated in vertical brackets. The horizontal back lines indicate whether the variables have positive or negative effects on turbidity.



33

34 **Figure 4:** 3D-tensor product maps (i.e. interaction smooth functions) highlighting the implication of water-level at modulating the relationships between  
 35 turbidity and the external variables: A) wind speed ( $\text{m s}^{-1}$ ) and B) river discharge ( $\text{m}^3 \text{s}^{-1}$ ). The variable constraining turbidity and the number referring to the  
 36 edf (extent of nonlinear relationship) are reported in the vertical brackets.

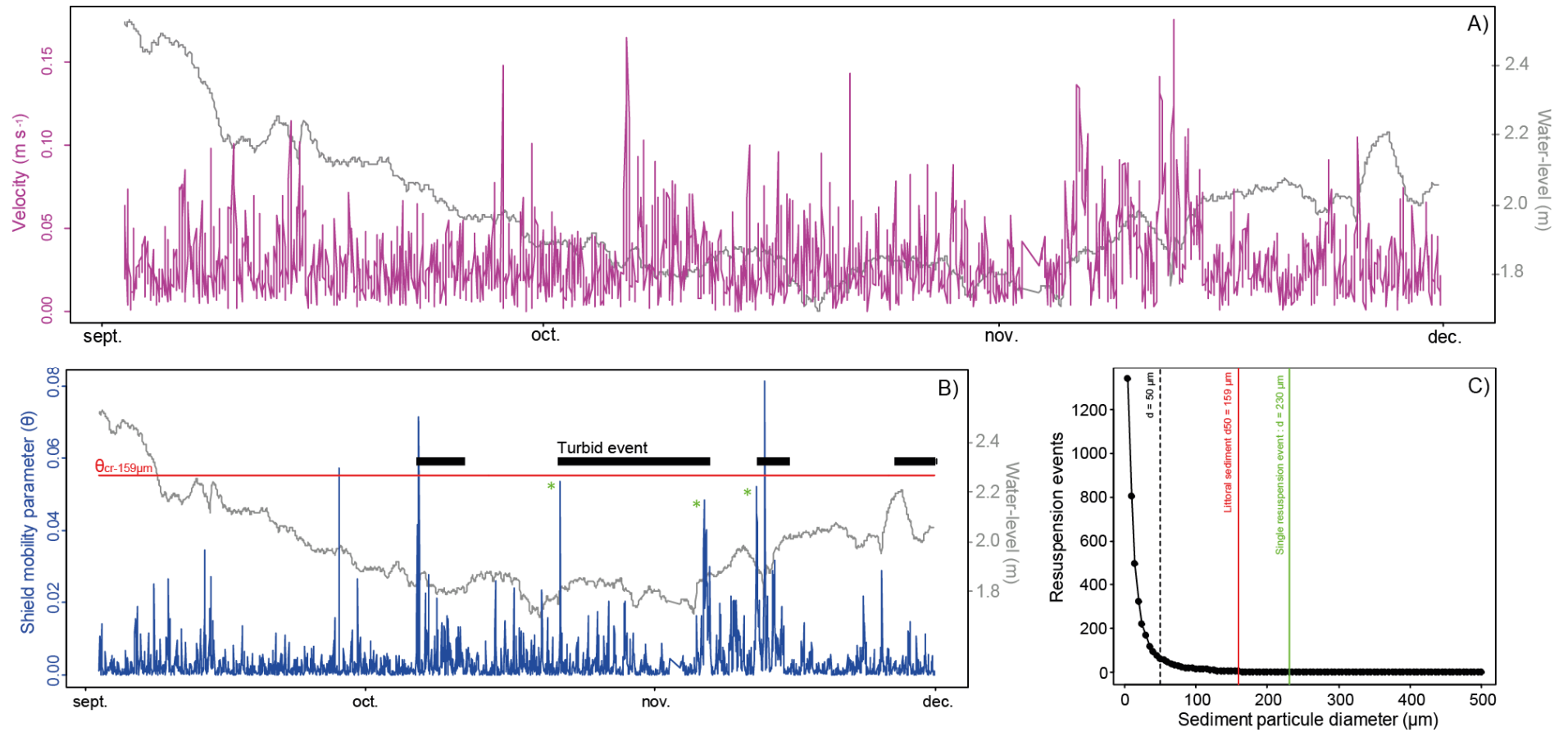
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39 **Figure 5:** Changes in deviance explained of the GAM accounting for the interaction smooth  
40 functions over different hourly time-lags for the external forcings i.e. delayed effects of  
41 external forcings.

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44 **Figure 6:** Sediment resuspension modeling: A) Dynamic of water velocity (m s<sup>-1</sup>). The grey line shows the water-level variations (m). B) Dynamic of the  
 45 Shield mobility parameter ( $\theta$ ). The horizontal red line shows the critical value for the resuspension of the mode grain size of lake sediment ( $\theta_{cr-159\mu m}$ , 159  $\mu m$   
 46 diameter). Green stars indicate additional resuspension events considering the mode grain size of trapped sediment (127  $\mu m$  diameter). The black rectangles  
 47 indicate the turbid events according to Fig. 1.B. C) Number of resuspension events according to sediment diameter ( $\mu m$ ). The vertical lines indicate sediment

48 diameters of interest:  $d = 230 \mu\text{m}$  is the maximal sediment diameter for the occurrence of a single resuspension event,  $d = 159 \mu\text{m}$  is the mode value for lake  
49 that encountered 3 resuspension events (see B of this figure) and  $d = 50 \mu\text{m}$ , below which resuspension events drastically increased, was submitted to 63  
50 resuspension events.