

1 **Title page for submission to Freshwater Biology**

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3 Title: Biogeochemistry of a California Floodplain as revealed by high resolution temporal  
4 sampling

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17 Abbreviated title: Biogeochemistry of a California Floodplain.

18

19 Keywords: floodplain, biogeochemistry, water quality, nutrient cycling, flood pulse

1 **Summary:**

- 2 1. Studies of biogeochemical processes in Mediterranean and semi-arid floodplains are scarce.  
3 For most floodplain studies, the temporal resolution of sampling ranges from several days to  
4 months. The purpose of this study was to examine water quality on a fine temporal scale (< 1  
5 day) during and after flooding to elucidate short-term variations in biogeochemical processes.
- 6 2. We identified three distinct river-floodplain connectivity phases: river-floodplain surface  
7 connectivity (flooding), floodplain draining, and floodplain ponding; and collected 4-hour  
8 composite samples at the floodplain inlet and outlet.
- 9 3. The degree of mixing of from previous floods with new flood pulse water is significantly  
10 influenced by flood magnitude and duration. The extent of mixing in turn impacts floodplain  
11 biogeochemistry and source/sink dynamics for fluxes of dissolved and suspended constituents.
- 12 4. The floodplain was a sink for total and volatile suspended solids, total nitrogen (TN),  
13 ammonium nitrogen ( $\text{NH}_4^+\text{-N}$ ), total phosphorous (TP) and chlorophyll-a; and a source for  
14 nitrate nitrogen ( $\text{NO}_3\text{-N}$ ), orthophosphate ( $\text{PO}_4\text{-P}$ ) and dissolved organic carbon (DOC).
- 15 5. During floodplain draining total nitrogen,  $\text{NO}_3\text{-N}$  and  $\text{PO}_4\text{-P}$  decreased, while  $\text{NH}_4^+\text{-N}$   
16 remained at background levels. During ponding total nitrogen decreased while  $\text{NH}_4^+\text{-N}$ , TP,  
17  $\text{PO}_4\text{-P}$  and DOC increased and  $\text{NO}_3\text{-N}$  remained at background levels.
- 18 6. Diel chlorophyll-*a* cycles were observed during the falling limb of the flood pulses and  
19 during hydrologic disconnection. The diel cycle was most pronounced during floodplain  
20 draining following the larger magnitude flood.
- 21 7. Our results demonstrate that major nutrient transformations occur in the span of several hrs  
22 and highlight the importance of high resolution temporal sampling in floodplain studies.

1 **Introduction:**

2           Until recently, floodplains as critical riverine ecosystem components were largely  
3 overlooked and poorly understood. The last 20 years have seen an increase of scientific and  
4 public interest in large river floodplains, particularly the Danube River in Austria (Heiler *et al.*,  
5 1995; Schiemer *et al.*, 1999; Tockner *et al.*, 1999; Hein *et al.*, 2003), Amazonian rivers such as  
6 the Mapire in Venezuela (Vegas-Vilarubia and Herrera, 1993a, 1993b; Chaco *et al.*, 2005), the  
7 Rhine and Meuse rivers in the Netherlands (Admiraal *et al.*, 1993; Vanderbrink *et al.*, 1993 and  
8 1994) and the Ogeechee River in North America (Wainright *et al.*, 1992; Benke *et al.*, 2000 and  
9 2001).

10           The fundamental concept outlining the relationship between rivers and their floodplains  
11 is the Flood Pulse Concept (FPC; Junk *et al.*, 1989; Tockner *et al.*, 2000). The FPC describes  
12 floodplains as continuously expanding and contracting systems that shift between lotic, lentic  
13 and terrestrial ecosystems, which are intimately linked to the river that floods them. The  
14 reoccurrence of flooding varies greatly between geographic locations and is highly dependent on  
15 the local hydrologic cycle, microclimate and the discharge regime of the river. Flood pulsing is  
16 therefore the major factor influencing floodplain biological production; as well as biotic and  
17 abiotic interactions within and between a floodplain and the river.

18           Currently, floodplain ecosystems exist primarily as isolated habitat patches with limited  
19 connectivity to the rivers that flood them (Ward *et al.*, 1999). However, numerous studies have  
20 revealed the many benefits of floodplains: groundwater recharge (Rodegers *et al.*, 2004), flux of  
21 organic matter between the river and floodplain (Wainright *et al.*, 1992., Hein *et al.*, 2003), flood  
22 and erosion protection (Zedler, 2003), deposition of suspended solids (Craft and Casey, 2000),  
23 increased primary and secondary productivity (Grosholz and Gallo in revision habitat for

1 migrating waterfowl, and spawning and rearing grounds for numerous fish (Sommer *et al.*, 2001a  
2 and 2001b; Ribeiro *et al.*, 2004). In addition, some studies have demonstrated the dynamic  
3 biogeochemical nature of large river-floodplain systems (Furch and Junk, 1993; Tockner *et al.*,  
4 1999; Amoros and Bornette, 2002).

5 Intense river system leveeing, impoundment, channelization and groundwater pumping in  
6 the California Central Valley have devastated the majority of the native riparian forests,  
7 eliminated most of the natural floodplains, and altered the local surface and groundwater  
8 hydraulics. Today, less than 13% of California's floodplains remain, which include active  
9 channels, emergent wetlands and pastures (Hunter *et al.*, 1999). Of the remaining floodplains,  
10 only 3.4% is managed for biodiversity or wildlife uses (Hunter *et al.*, 1999). The complex  
11 hydrology that once defined the Central Valley riparian forests and floodplains has almost  
12 completely disappeared. Restoration of California's river-floodplain systems has received much  
13 attention in the last 10 years, however, the majority of the research has focused on  
14 geomorphology and fisheries.

15 Current California floodplain research demonstrates that floodplain reared fish tend to  
16 have higher apparent growth rates than river channel reared fish (Sommer *et al.*, 2001; Ribeiro *et*  
17 *al.*, 2004). This is due to the higher abundance of prey items (Sommer *et al.*, 2001 and 2004;  
18 Baranyi *et al.*, 2002; Grosholz and Gallo, in revision); longer water residence time (Grosholz and  
19 Gallo in revision) and higher floodplain habitat heterogeneity (Ribeiro *et al.*, 2004). In addition,  
20 floodplains may be of particular importance in California and the Pacific Northwest by providing  
21 spawning and rearing habitat for endangered Salmonids (Sommer *et al.*, 2001 and 2004; Hall and  
22 Wissmar, 2004). However, scientific information regarding biogeochemical processes in lower  
23 and mid-order river-floodplain systems from Mediterranean and semi-arid climate is scarce.

1 Most studies of floodplain water quality have conducted sampling with temporal  
2 resolutions ranging from several days to months (Vegasvilarrubia and Herrera, 1993; Furch,  
3 1993; Castillo, 2000; Baker *et al.*, 2001; Robertson *et al.*, 2001; Amoros and Bornette, 2002;  
4 Schemel *et al.*, 2004). This resolution ignores short term (< 1d) biogeochemical processes, which  
5 may be an important source of variation in nutrient transformations, changes in primary and  
6 secondary producers, and transport of nutrients and organic matter into and out of the floodplain.  
7 In addition, we don't know how flood magnitude and hydrologic residence time influence short  
8 term (<1 d) changes in water quality during the draining and ponding hydrologic connectivity  
9 phases. The purpose of this study was to describe short-term fluctuations in water quality on a  
10 fine temporal scale during and after flooding in order to understand the importance of these  
11 fluctuations for overall water quality and nutrient transformations. Knowledge of water quality  
12 changes can help define the goals for future floodplain restoration efforts, and can aid in the  
13 development of successful management strategies.

#### 14 **Methods:**

##### 15 *Study Site:*

16 The floodplain is located in the lower Cosumnes River watershed at an elevation of 1.5 to  
17 4 m above sea level. It is part of the Cosumnes River Preserve (CRP) which is owned by The  
18 Nature Conservancy and is located in the California Central Valley (Figure 1). The climate is  
19 Mediterranean with a mean annual precipitation of 45 cm yr<sup>-1</sup> occurring between December and  
20 May and followed by a five month dry season from June to October. There are no major water  
21 diversions or impoundments along the Cosumnes River (Andrews, 1999; Kennedy and Whitener,  
22 2000), therefore the river responds to the natural winter and spring watershed hydrology. The  
23 Cosumnes River is a 5<sup>th</sup> order stream with headwaters located at an altitude of 2300 m on the

1 west side of the Sierra Nevada, and transports surface runoff and snowmelt to the San Francisco  
2 estuary (Andrews, 1999). Historically the study site was an alluvial floodplain connected to  
3 anastomosing river channels; however, the river and floodplain remained disconnected for  
4 approximately 75 years due to leveeing of the river channel to allow agricultural practices on the  
5 floodplain.

6 The experimental floodplain was created in the winter of 1995, when CRP managers and  
7 the Army Corps of Engineers breached the levee along the Cosumnes River and allowed 98.5 ha  
8 of agricultural fields in the historic floodplain to flood. The floodplain floods 8 - 12 hr after river  
9 discharge exceeds  $22.1 \text{ m}^3\text{s}^{-1}$  at the Michigan Bar monitoring station, located 40 km upstream of  
10 the floodplain (Florsheim and Mount, 2002). Besides from carving out a pond in the middle of  
11 the upper floodplain, the site has gone through a natural restoration process(Figure 1). The site  
12 has been colonized by willows, cottonwoods and herbaceous vegetation which have created the  
13 habitat heterogeneity that can be observed today. The habitats present include ponds, grasslands,  
14 early successional forests, and an old growth riparian forest.

15 A levee divides the experimental floodplain into an upper and lower floodplain (Figure  
16 1). This study was conducted on the upper floodplain, which has an area of 37.4 ha (Figure 1).  
17 There are two inlet levee breaches that allow water from the Cosumnes River to enter the upper  
18 floodplain, North Breach (NB) and South Breach (SB). Two additional breaches along the levee  
19 that divides floodplain allow water to flow from the upper to lower floodplain, East Breach (EB)  
20 and West Breach (WB).

21 ***Sampling design:***

22 We placed one automatic pump sampler (ISCO 6700) at NB to sample water coming into  
23 the floodplain (inlet), and a second automatic sampler at WB to sample water leaving the

1 floodplain (outlet, Figure 1). The autosamplers were programmed to collect 500 ml of water  
2 every hr. During the rising limb of the first storm we collected 2 hr composite samples, the  
3 remainder of the samples were 4 hr composite samples. We collected samples with autosamplers  
4 starting February 18<sup>th</sup> at 5:00 pm and ending March 13<sup>th</sup>, 2004 at 11:00 am.

#### 5 ***Water Quality Analysis:***

6 Water samples were kept cool and dark prior to analysis. Total suspended solids (TSS)  
7 were analyzed by filtering water through a 0.45 $\mu$ m pre-combusted and weighed glass fiber filter  
8 (GFC-Gelman), drying the filter at 60°C for 24 – 48 hr, weighing it again and taking the  
9 difference between the initial and final weight. Finally, the filter was combusted at 550°C for 2  
10 hr, allowed to cool to room temperature in a desiccator and weighed. The mass lost by  
11 combustion was determined to be the volatile suspended solids (VSS) or organic fraction of TSS.  
12 Unfiltered aliquots for total nitrogen (TN) and total phosphorous (TP) were digested using  
13 persulfate (Stark and Hart,1986). Subsamples for ammonium (NH<sub>4</sub><sup>+</sup>-N), nitrate (NO<sub>3</sub>-N),  
14 orthophosphate (PO<sub>4</sub><sup>3-</sup>-P) and dissolved organic carbon (DOC) analyses were filtered through a  
15 0.2  $\mu$ m polycarbonate membrane (Millipore). TN, NO<sub>3</sub><sup>-</sup>-N and NH<sub>4</sub><sup>+</sup>-N were analyzed using a  
16 conductimetric analyzer (Carlson,1986 and Yu *et al.*,1994). TP and PO<sub>4</sub>-P were analyzed using  
17 a spectrophotometer (Perking Elmel Lambda 38) and the methods described by Clesceri *et al.*  
18 (1998). DOC was analyzed with a Tekmar-Dohrmann UV-enhanced persulfate digestion and  
19 infrared CO<sub>2</sub> detection spectrophotometer (Phoenix 800). Chlorophyll-a (chl-*a*) measurements  
20 were made with ethanol pigment extraction fluorometry as described by Clesceri *et al.* (1998).

#### 21 ***Hydrograph:***

22 We conducted this study between February 18 and March 21, 2004. During this period  
23 we sampled two flood pulses (Figure 2a), the first flood pulse (FP1) started on Feb 18 at

1 approximately 1:00 pm and had an approximate duration of 4 d and 3 hr with a mean discharge  
2 of  $32.4 \text{ m}^3\text{s}^{-1}$  and a peak discharge of  $46.6 \text{ m}^3\text{s}^{-1}$ . The second flood pulse (FP2) began on  
3 February 25 at approximately 7:00 pm, had an approximate duration of 8 d and 19 hr, a mean  
4 discharge of  $48.9 \text{ m}^3\text{s}^{-1}$  and a peak discharge of  $140.2 \text{ m}^3\text{s}^{-1}$ .

5 ***River-floodplain connectivity phases:***

6 Based on continuous water depth sensor data, rating curves for NB, WB and EB (Mount  
7 *et al.*, unpublished data) and a flood pulse water balance for SB, we identified three distinct  
8 surface water connectivity phases: river-floodplain connectivity, floodplain draining and  
9 disconnection (Figure 2; **Error! Reference source not found.**). Connectivity occurs during  
10 flood pulsing (FP1 and FP2), when active exchange of surface water from the Cosumnes River to  
11 the upper floodplain and from the upper floodplain to the lower floodplain takes place. Draining  
12 (DR1 and DR2) occurs when river water is no longer entering the floodplain, but water in the  
13 upper floodplain drains to the lower floodplain. Finally, disconnection refers to the floodplain  
14 “ponding” phase when there is no surface water exchange between the Cosumnes River, the  
15 upper floodplain and the lower floodplain. During this phase, water losses can be attributed  
16 mainly to infiltration and evapotranspiration.

17 ***Connectivity phase regressions:***

18 Using Jump IN 5.1 (SAS Institute) we fitted simple linear and quadratic regressions to  
19 water quality parameters measured at WB (floodplain outlet) during the draining and ponding  
20 connectivity phases in order to discern the relationship of water quality constituents to  
21 hydrologic residence time during a particular phase. We reported the best of the fits based on the  
22  $r^2$  and p values. If neither fit was significant we reported the linear fit.

23 ***Flux Calculations:***



1 Total flux in ( $TF_{\text{phase}}^{\text{IN}}$ ) or out ( $TF_{\text{phase}}^{\text{OUT}}$ ) for each connectivity phase was calculated as  
 2 follows:

$$3 \quad TF_{\text{phase}}^{\text{IN}} = \sum_{t_{\text{start}}}^{t_{\text{end}}} F_{\text{interval}}^{\text{IN}}$$

$$4 \quad TF_{\text{phase}}^{\text{OUT}} = \sum_{t_{\text{start}}}^{t_{\text{end}}} F_{\text{interval}}^{\text{OUT}}$$

5 Where  $TF_{\text{phase}}^{\text{IN}}$  and  $TF_{\text{phase}}^{\text{OUT}}$  are in kg or Mg,  $F_{\text{interval}}^{\text{IN}}$  and  $F_{\text{interval}}^{\text{OUT}}$  are fluxes at a specific 2 or 4  
 6 hr time interval in kg or Mg,  $t_{\text{start}}$  and  $t_{\text{end}}$  are the starting and ending time intervals of a  
 7 particular connectivity phase. We calculated  $F_{\text{interval}}^{\text{IN}}$  and  $F_{\text{interval}}^{\text{OUT}}$  as follows:

$$8 \quad F_{\text{interval}}^{\text{IN}} = (WV_{\text{interval}}^{\text{NB}} + WV_{\text{interval}}^{\text{SB}}) * [C]_{\text{NB interval}}$$

$$9 \quad F_{\text{interval}}^{\text{OUT}} = (WV_{\text{interval}}^{\text{EB}} + WV_{\text{interval}}^{\text{WB}}) * [C]_{\text{WB interval}}$$

10 Where  $WV_{\text{interval}}$   $\text{m}^3$  at the specified breach (NB, SB, EB or WB) during that 2 or 4 hr  
 11 time interval and  $[C]_{\text{NB interval}}$  and  $[C]_{\text{WB interval}}$  are the concentrations of a particular water quality  
 12 constituent at NB and WB during the same 2 or 4 hr time interval.  $WV_{\text{interval}}$  at NB, EB and WB  
 13 was calculated by adding the water volume calculated at a 10 minute time step from the  
 14 beginning to the end of each phase as follows:

$$15 \quad WV_{\text{interval}} = \sum_{t_{\text{start}}}^{t_{\text{end}}} (Q_t * 600)$$

16 Where  $Q_t$  is the discharge in  $\text{m}^3\text{s}^{-1}$  at every 10 minute time interval and 600 is the time  
 17 step between discharge calculations in seconds.

18 For fluxes into the floodplain we used the NB water quality data and rating curve. For  
 19 fluxes out of the floodplain we used the WB water quality data and the WB and EB rating  
 20 curves. Because of the difficulty in generating a rating curve for SB, the water volume at this  
 21 breach during each 2 or 4 hour interval was calculated as:

1 
$$WV_{SB} = WV_{EB} + WV_{WB} - WV_{NB}$$

2 Where  $WV_{SB}$ ,  $WV_{EB}$ ,  $WV_{WB}$  and  $WV_{NB}$  are the water volumes at the SB, EB, WB and  
3 NB respectively.

4 Due to autosampler malfunctions we were not able to collect autosampler samples at the  
5 inlet for the first 36 hrs of the second flood pulse. In order to fill this data gap we interpolated  
6 daily grab sample data collected at the inlet to fill missing values and compare trends between  
7 the two flood events.

8 **Results:**

9 **Water quality analysis:**

10 *Suspended solids:*

11 Suspended solid concentrations were higher at the inlet breach (NB) than at the outlet  
12 breach (WB) during both floods. Inlet suspended solid concentrations were higher during FP1  
13 than FP2, whereas suspended solid concentrations at the outlet were higher during FP2 than FP1.  
14 TSS was highest during the rising limb of both flood pulses, peaking at 221 and 178 mg L<sup>-1</sup> at  
15 the inlet for FP1 and FP2, respectively; and 56 and 62 mg L<sup>-1</sup> at the outlet during FP1 and FP2,  
16 respectively (Figure 3a). During DR1, initial TSS concentrations at the outlet decreased but then  
17 increased as the floodplain continued to drain (Figure 3b). TSS concentrations decreased during  
18 DR2 and ponding by 1.10 mg L<sup>-1</sup> day<sup>-1</sup> and 0.60 mg L<sup>-1</sup> day<sup>-1</sup>, respectively (Figure 3c, d).

19 The VSS proportion of TSS (%VSS) was higher at the outlet than at the inlet during both  
20 floods (Figure 5a). Outlet %VSS ranged from 17 to 90 and from 14 to 57 during FP1 and FP2,  
21 respectively; whereas %VSS at the inlet ranged from 12 to 32 and from 11 to 43 during FP1 and  
22 FP2, respectively. Although TSS at the outlet increased during the second half of DR1, % VSS  
23 decreased approximately 10.7 % day<sup>-1</sup> (Figure 5b). However; while TSS decreased, % VSS

1 increased 3.2 % day<sup>-1</sup> during DR2 (Figure 5c). Initially, %VSS increased during ponding, but  
2 then decreased as hydrologic residence time increased (Figure 5d).

3 *Nitrogen:*

4 TN concentrations were higher at the inlet and outlet during FP1 (Figure 6a). During the  
5 initial hrs of both floods, TN concentrations at the inlet were higher than at the outlet, but as  
6 flooding continued TN at the outlet tracked inlet concentrations. TN concentrations decreased  
7 during DR1, DR2 and ponding at rates of 0.081 ppm day<sup>-1</sup>, 0.061 ppm day<sup>-1</sup> and 0.043 ppm day<sup>-1</sup>,  
8 respectively (Figure 6b, c, d).

9 NO<sub>3</sub>-N concentrations were higher during FP2 than during FP1 at both the inlet and  
10 outlet (Figure 7a); most likely due to watershed flushing. While NO<sub>3</sub>-N concentrations during  
11 FP1 at the inlet and outlet tracked each other closely (0.04 – 0.54 ppm), concentrations during  
12 FP2 at the inlet (0.06 – 0.48 ppm) were lower than concentrations at the outlet (0.02 – 0.51 ppm)  
13 during the rising limb and peak of the flood pulse. However, inlet concentrations were higher  
14 (0.51 – 0.68 ppm) than outlet (0.48 - 0.62 ppm) during the falling limb of FP2. NO<sub>3</sub>-N  
15 concentrations decreased during DR1, DR2 and ponding at a rate of 0.09 ppm day<sup>-1</sup>, 0.14 ppm  
16 day<sup>-1</sup> and 0.004 ppm day<sup>-1</sup>, respectively (Figure 7b, c, d).

17 NH<sub>4</sub><sup>+</sup>-N concentrations were higher at both inlet and outlet during FP1 (0.02 - 0.39 ppm)  
18 than during FP2 (0.01 - 0.34 ppm) (Figure 8a). Concentrations at the outlet were higher during  
19 the rising limb of FP2, but lower than concentrations at the outlet during the falling limb of FP2.  
20 NH<sub>4</sub><sup>+</sup>-N concentrations increased during DR1 at a rate of 0.008 ppm day<sup>-1</sup> (Figure 8b).  
21 Concentrations remained low during DR2 and rapidly increased during the ponding phase at a  
22 rate of 0.028 ppm day<sup>-1</sup> (c, d).

23 *Phosphorous:*

1 TP concentrations were higher at the inlet (0.18 - 0.45 ppm) than the outlet (0.07 – 0.27  
2 ppm) during FP1 (Figure 9a). Inlet TP was higher than outlet TP during the rising limb and peak  
3 of both floods, and concentrations closely tracked each other during the falling limb of FP2 (0.08  
4 – 0.26 ppm) (Figure 9a). TP concentrations decreased during DR1 at a rate of 0.013 ppm day<sup>-1</sup>  
5 (Figure 9b). No change in concentrations was observed during DR2 and ponding (Figure 9c, d).

6 Inlet PO<sub>4</sub>-P concentrations were higher than outlet concentrations during the rising limb  
7 and peak of FP1, but tracked each other during the falling limb of FP2 (Figure 10a). PO<sub>4</sub>-P  
8 concentrations decreased during both draining phases at a rate of 5.6 ppb day<sup>-1</sup> and 5.2 ppb day<sup>-1</sup>  
9 (Figure 10b, c). However, PO<sub>4</sub>-P concentrations increased during the ponding phase at a rate of  
10 4.7 ppb day<sup>-1</sup> (Figure 10d).

#### 11 *DIN:DIP*

12 Dissolved inorganic nitrogen (NO<sub>3</sub>-N + NH<sub>4</sub><sup>+</sup>-N) to dissolved inorganic phosphorous  
13 (PO<sub>4</sub><sup>3-</sup>-P) ratios (DIN:DIP) were higher at the inlet than the outlet during FP1 and the falling  
14 limb of FP2 (Figure 12a). Ratios during FP1 decreased from 21.6 at the inlet and 11.7 at the  
15 outlet during the peak of the flood to 4.8 at the inlet and 3.6 at the outlet at the end of the flood.  
16 Ratios during FP2 were highest during the second smaller hydrograph peak (17.9 and 16.4 at the  
17 inlet and outlet, respectively) due to an increase in NO<sub>3</sub>-N concentrations coupled with a  
18 decrease in PO<sub>4</sub>-P concentrations. The DIN:DIP ratio decreased during the DR1 and DR2 at a  
19 rate of 0.94 day<sup>-1</sup> and 2.77 day<sup>-1</sup>, respectively (Figure 12b, c). However, DIN:DIP increased  
20 during the ponding phase at a rate of 0.17 day<sup>-1</sup> (Figure 12d) suggesting an increase in DIP  
21 limitations.

#### 22 *Dissolved Organic Carbon:*

1           The DOC concentrations were higher at the outlet than at the inlet during the falling limb  
2 of FP1; while during the falling limb of FP2 concentrations at the inlet and outlet tracked each  
3 other (Figure 13a). Outlet DOC concentrations decreased during the first 16 hrs of the floods  
4 from 11.3 to 5.3 ppm during FP1 and from 7.7 to 5.4 ppm during FP2. The highest  
5 concentrations of DOC were observed during the DR2 phase and ranged from 6.3 to 13.5 ppm.  
6 DOC concentrations increased during DR1 at a rate of 0.84 ppm day<sup>-1</sup> (Fig 13b). However,  
7 concentrations during DR2 initially increased and then decreased (Figure 13c). As floodplain  
8 draining increased and water velocities decreased. During ponding DOC increased at a rate of  
9 0.26 ppm day<sup>-1</sup> (Figure 13d).

#### 10           *Chlorophyll-a*

11           During the rising limb of the flood pulses an initial increase and peak in *Chl-a*  
12 concentrations at the inlet and outlet were observed, however, this increase was followed by a  
13 decrease in *Chl-a* during the falling limb of the hydrograph (Figure 14a). *Chl-a* concentrations  
14 during flooding were higher during FP1, and were consistently higher at the inlet than at the  
15 outlet, except for the last 24 hrs of FP2, during which outlet concentrations were slightly higher  
16 than at the inlet.

17           Interestingly, we observed a significant diel pattern in *Chl-a* concentrations during the  
18 falling limb of FP1 and FP2, as well as during the draining and ponding phases. Minimum *Chl-a*  
19 concentrations were observed at night between the hrs of 12:00 am and 5:00 am, and increased  
20 1.5 to 4 fold during the day, peaking between 10:00 am and 4:00 pm. The range of the diel  
21 fluctuations was greatest during DR2 (3.1 - 13.5 ppb) and continued through the ponding period  
22 (Figure 14b, c, d).

#### 23           **Fluxes:**

1           Although concentrations of most constituents were higher during FP1, the larger  
2 magnitude and longer duration of FP2 resulted in larger fluxes from the river to the floodplain  
3 (Table I). During our sampling period the floodplain was a net sink for TSS, VSS, TN,  $\text{NH}_4^+\text{-N}$ ,  
4 TP and Chl-*a* (Table I). During FP1 the floodplain was a sink for all constituents except for  
5  $\text{PO}_4\text{-P}$  and DOC. A total of 48.9 kg of  $\text{PO}_4\text{-P}$  and 3.3 Mg of DOC were exported from the  
6 floodplain during FP1. During FP2, a total of 752 kg of  $\text{NO}_3\text{-N}$ , 0.5 kg of TP and 0.4 Mg of  
7 DOC were exported out of the floodplain. Overall, relatively small proportions of  $\text{NO}_3\text{-N}$ ,  $\text{PO}_4\text{-P}$   
8 and DOC were exported from the floodplain (7.9%, 2.5% and 3.1%, respectively).

## 9 **Discussion:**

### 10 *Impact of flood magnitude and duration on biogeochemical processes:*

11           Flood pulsing resets aquatic floodplain succession and stimulates primary production by  
12 importing dissolved nutrients and organic matter into the floodplain (Ertl, 1985; Junk *et al.*,  
13 1989; Van Den Brink *et al.*, 1993; Tockner *et al.*, 1999; Tockner *et al.*, 2000; Robertson *et al.*,  
14 2001). While studies have directly addressed the impact of flood magnitude and duration on  
15 geomorphological processes (Arscott, 2002; Florsheim, 2002; Fagan and Nanson, 2004) and the  
16 impact of water sourcing on biogeochemical processes (Arscott, Tockner and Ward, 2001;  
17 Brunke, 2003), very few studies such as that by Ryder (2004) and Vandenbrink, Vankatwijk, and  
18 Vandervelde (1994) have addressed the impact of flood magnitude and duration on floodplain  
19 biogeochemistry and aquatic community structure. Several studies suggest that the timing and  
20 temperature of a flood are the major physical factors influencing biological productivity and  
21 nutrient cycling within the floodplain (Amoros and Bornette, 2002; Robertson *et al.*, 2001;  
22 Tockner *et al.*, 2000), and therefore quantification of the flood pulse is essential in order to

1 determine the quantity and quality of habitat that will be available for plants and animals within  
2 the floodplain (Benke *et al.*, 2000).

3         Smaller magnitude floods at this site, such as those with mean  $Q < 36.8 \text{ m}^3 \text{ s}^{-1}$  and lasting  
4 less than 5 days (Gallo, unpublished data) do not completely mix the old floodplain water with  
5 the new flood pulse water. This is apparent by the close tracking of inlet (NB) and outlet (WB)  
6 water quality constituent concentrations, even though dilution of most water quality constituents,  
7 with the exception of  $\text{NO}_3\text{-N}$  was greater during FP2 due to the larger volume of water entering  
8 the floodplain. However, TSS concentrations at the outlet during FP2 did not vary greatly,  
9 suggesting that FP2 had a greater watershed and floodplain flushing effect than FP1. The greater  
10 magnitude and duration of FP2 contributed to enhanced floodplain flushing and thus a more  
11 dramatic resetting of aquatic floodplain conditions. In addition, the lower concentrations of most  
12 water quality constituents following FP2 suggest that the greater magnitude and duration of the  
13 flood reduced pool sizes of nutrients and organic matter available for subsequent biogeochemical  
14 processes.

15         Our study demonstrates that flood magnitude and duration greatly impact the extent to  
16 which the older floodplain water and the newer flood pulse water mix. The extent of mixing in  
17 turn significantly impacts fluxes of dissolved and suspended matter to and from the floodplain,  
18 which subsequently impact floodplain biogeochemistry. Therefore, in low and mid order stream  
19 systems flood magnitude and duration may play a larger role on floodplain biogeochemical  
20 processes than previously perceived.

### 21         *The floodplain as a sink/source of water quality constituents*

22         Exchanges of particulate matter between the river and the floodplain are limited to large  
23 flood events; and floodplains can be sources or sinks for several water quality constituents

1 (Vegasvilarrubia and Herrera, 1993; Tockner *et al.*, 1999; Tockner *et al.*, 2002; Valett *et al.*,  
2 2004). The amount (flood magnitude) and timing of rainfall received in a particular year coupled  
3 with floodplain topography and sediment loads in the river may dictate whether the floodplain  
4 acts as a source or a sink for organic matter (Tockner *et al.*, 1999; Ahearn *et al.*, 2004;). Tockner  
5 *et al.* (2000) suggest that the ability of a floodplain to retain or supply a particular water quality  
6 constituent can alternate depending on the river-floodplain hydrologic connectivity phase and  
7 discharge. During the sampling period, our study site was a sink for TSS, VSS, TN, NH<sub>4</sub>-N, TP  
8 and Chl-*a*; and although it was a source of NO<sub>3</sub>-N, PO<sub>4</sub>-P and DOC, the loads exported from the  
9 floodplain were not significant when compared to the loads imported from the river during flood  
10 pulses. In addition, the floodplain draining phases did not play a significant role in the export of  
11 water quality constituents, mainly due to the small volumes of water exported from the  
12 floodplain during draining. This finding suggests that floodplain flushing events of large  
13 magnitude and long duration are necessary in order to transport food resources, such as dissolved  
14 inorganic nutrients, phytoplankton and zooplankton from the floodplain to the river.

15         Studies show that floodplains act as particulate matter filters and as potential sources of  
16 DOC ([Robertson, et al.](#), 1999; Tockner *et al.*, 1999; Tockner *et al.*, 2002; Valett *et al.*, 2004).  
17 The results from our study agree with these findings. The fluxes and the peak TSS and %VSS  
18 concentrations observed during FP1 and FP2 suggest that the larger and heavier inorganic  
19 particles, as well as some organic material settled out of the water column rapidly, which is  
20 evident by the consistently lower concentrations of TSS at the outlet. Although the net DOC  
21 exported from the floodplain was only 3.1% greater than the influx of DOC ; it is important to  
22 note that in California, only 3.3% of the riparian forests remain (Hunter *et al.*, 1999). The  
23 riparian vegetation, although successfully expanding to the herbaceously vegetated areas at our



1 study site, covers a relatively small percent of the floodplain area (Viers, unpublished data).  
2 Thus, at this time, production of terrestrially derived DOC and particulate organic matter (POM)  
3 and its subsequent export from the floodplain to the Cosumnes River may be minimal. However,  
4 in the future, as restoration of riparian forests in the Central Valley expands and the litter layer  
5 from floodplain forests increases, terrestrially derived floodplain POM and DOC fluxes may  
6 increase.

7 As hydrologic residence time increases, we expect terrestrially derived DOC to be  
8 incorporated into the aquatic foodweb and for production of aquatic DOC to increase. Our data  
9 demonstrate a net export of DOC during FP1, which occurred after a long period of river-  
10 floodplain hydrologic disconnection. However, a larger mass of DOC was exported during FP2,  
11 which was a flood event of larger magnitude and duration. Therefore, we suggest that large  
12 flushing events following long periods of hydrologic disconnection may result in greater export  
13 of aquatic DOC to the river.

14 The ability of a particular floodplain to sequester or supply a specific water quality  
15 constituent to the river may depend on a wide range of factors including current and historical  
16 land use, fire regime, soil type, geomorphology, etc. (Craft and Casey, 2000). Our results are not  
17 consistent with studies that demonstrate that floodplains are sinks for NO<sub>3</sub>-N or sources of Chl-*a*  
18 (Tockner *et al.*, 1999; Valett *et al.*, 2005). This may be partly due to the rapid transformation of  
19 particulate and dissolved organic nitrogen to NO<sub>3</sub>-N in the water column during flooding, and to  
20 the high loads of Chl-*a* flushed from the watershed during the 2004 water year, which followed 3  
21 dry years. In addition, we expect top down pressures on primary producers within the floodplain  
22 to greatly impact Chl-*a* fluxes. We expect in future studies to observe inter-annual variations in

1 the source/sink nature of our study site, which will greatly depend on antecedent condition, flood  
2 magnitude and duration, and successional stage of the terrestrial vegetation.

3         Although the sink/source nature of a floodplain can change according to hydrologic  
4 connectivity and flood magnitude, there is general agreement among studies in the fate of  
5 nutrients deposited in the floodplain following a flood pulse. Studies in numerous river-  
6 floodplain systems demonstrate that changes in floodplain water chemistry are directly related to  
7 hydrologic connectivity, with the floodplain and river having similar concentrations of dissolved  
8 constituents during flooding, which begin to diverge from each other once hydrologic  
9 disconnection ensues (Vegas-Vilarrubia and Herrera, 1993; Heiler *et al.*, 1995; Hein *et al.*, 1999;  
10 Amoros and Bornette, 2002; Schemel *et al.*, 2003; Schemel *et al.*, 2004; Valett *et al.*, 2005). As  
11 the river and the floodplain become hydrologically disconnected systems and areas of standing  
12 water develop within the floodplain, nutrient uptake and organic matter cycling become internal  
13 processes which are regulated by the conditions within each isolated water body (Junk *et al.*,  
14 1986; Heiler *et al.*, 1995; Tockner *et al.*, 2000).

### 15         *Nutrient transformations during floodplain draining and ponding*

16         Most studies have focused on subsurface connectivity (groundwater), river-floodplain  
17 connectivity and river-floodplain disconnection as the three main separate hydrologic  
18 connectivity phases (Heiler *et al.*, 1995; Aspetsberger, *et al.*, 2002; Tockner *et al.*, 2002; de  
19 Domitrovic, 2003; Aoyagui, 2004; Baker and Vervier, 2004). Floodplain to river connectivity  
20 during draining as a separate phase with its own set of biogeochemical processes has received  
21 relatively little attention. This may arise from the short duration of this phase combined with the  
22 large temporal resolution of most studies, and from difficulty in identifying starting and ending  
23 points to floodplain draining, an effort which may be confounded by evapotranspiration and

1 infiltration. The impact of floodplain draining on water quality and subsequent floodplain  
2 processes is largely unknown. However, patterns in our water quality data demonstrate that the  
3 draining and ponding phases have distinct biogeochemical processes, which are due to reduced  
4 water velocities and slower mixing during draining and static hydraulic conditions during  
5 ponding.

6 Our data suggest that nutrients are quickly depleted and/or transformed during the  
7 draining and ponding phases, which is when the surface water from the river no longer impacts  
8 floodplain hydrology or biogeochemistry. During the initial hrs of draining, nutrient  
9 concentrations in the water column reflect the nutrient concentrations during the falling limb of  
10 the flood. However, as water velocities decrease, hydrologic residence time increases and anoxic  
11 conditions develop or continue within the soils, localized biogeochemical processes dominate  
12 nutrient dynamics. Studies demonstrate that following river-floodplain hydrologic  
13 disconnection, floodplain soil and water column respiration, release of dissolved organic  
14 compounds from submerged vegetation and from floodplain soils; primary productivity and  
15 invertebrate biomass increase (Furch *et al.*, 1988; Klinge *et al.*, 1983; Valett *et al.*, 2004,  
16 Grosholz and Gallo in revision).

17 Decreasing NO<sub>3</sub>-N concentrations during the draining phases, coupled with the possible  
18 development of anoxic conditions in the soils due to decreased water velocities and increased  
19 hydrologic residence time suggest appreciable potential for denitrification from floodplain soils,  
20 which is consistent with findings from other studies (Klingensmith and Vancleve, 1993). In  
21 addition, the decrease in NO<sub>3</sub>-N could be coupled with an increase in primary productivity,  
22 which is evident from the higher peaks of Chl-*a* during draining which has been demonstrated in  
23 other floodplain systems (Heiler *et al.*, 1995). Although denitrification and mineralization of

1 leached dissolved organic nitrogen (DON) from submerged detritus and vegetation can lead to  
2 water column increases in  $\text{NH}_4^+$ -N, concentrations remained low most likely due to the high  
3 affinity of primary producers for  $\text{NH}_4^+$ -N. The decreasing concentrations of  $\text{PO}_4$ -P during the  
4 draining phases may be attributed to luxury consumption of biologically available phosphorous  
5 by autotrophs and heterotrophic bacteria, and to adsorption to and subsequent settling of  
6 inorganic particles.

7 By the ponding phase,  $\text{NO}_3$ -N concentrations were near detection limit levels, while  
8  $\text{NH}_4^+$ -N and  $\text{PO}_4$ -P concentrations increased, suggesting nutrient recycling and denitrification.  
9 Increases in  $\text{NH}_4^+$ -N and  $\text{PO}_4$ -P concentrations could also be attributed to the rapid  
10 mineralization of dissolved organic compounds to  $\text{NH}_4$ -N; the leaching of orthophosphates from  
11 the submerged organic matter and a shift of primary producers to nitrogen fixing photosynthetic  
12 algae. In addition, studies have demonstrated that animal activity in the water column and at the  
13 soil-water interface can increase nutrient concentrations via excretion, sediment resuspension,  
14 nutrient translocation and transport (Wilhelm, Hudson, and Schindler, 1999; Tarvainen, Sarvala,  
15 and Helminen, 2002; Vanni, 2002; Tarvainen, et al, 2005). Due to the high abundance of aquatic  
16 macroinvertebrates at our study site (Grosholz and Gallo, in revision), we hypothesize that  
17 animals significantly contribute to changes in nutrient concentrations during the draining and  
18 ponding phases, which is when the floodplain shifts from a lotic to a lentic system.

19 Nutrient concentrations measured at our site during hydrologic disconnection were  
20 similar to concentrations measured by Valett *et al.* (2005) in a floodplain associated with the Rio  
21 Grande, NM, were lower than concentrations measured at the Yolo Bypass, CA by Schemel *et*  
22 *al.* (2004), and were higher than concentrations measured by Vegas-Vilarrubia and Herrera  
23 (1993) in the Mapire System in Vanezuela. When compared to concentrations measured by

1 Tockner *et al.* (2002) in a glacial floodplain of the Val Roseg System, DIP and TP concentrations  
2 at our site were higher while DIN concentrations were similar. These data demonstrate that there  
3 is a wide range of variability in floodplain biogeochemical transformations following river  
4 disconnection.

5 Pulses of allochthonous organic matter into the floodplain during flooding, as well as the  
6 riparian and floodplain vegetation, will have a large impact on nutrient input to the floodplain via  
7 leaching of nutrients from submerged and decaying organic matter (Klinge *et al.*, 1983; Furch *et*  
8 *al.*, 1988; Vegas-Vilarrubia and Herrera, 1993a; Baldwin, 1999). The dissolved organic matter  
9 (DOM) released from flooded litter and vegetation can in turn play an important role in  
10 regulating primary productivity and microbial activity by either enhancing or inhibiting  
11 photosynthetic activity (Robertson *et al.*, 2001) and microbial nutrient utilization (Baldwin,  
12 1999). It is suggested that DOM quality depends on the age of the organic material and  
13 hydrologic residence time. Fresh particulate organic matter submerged for a short period of time  
14 will release the most biologically available DOM, and aged organic matter submerged for a long  
15 time will release the most recalcitrant DOM (Baldwin, 1999). FP2 deposited in the floodplain  
16 more than twice the amount of particulate organic matter (as measured by %VSS) than FP1. The  
17 magnitude of flooding during and after FP2 resulted in extensive submersion of terrestrial  
18 vegetation, suggesting that DOM (as measured by DOC) released during DR2 was more labile  
19 than DOM released following FP1 or during ponding. We hypothesize that labile DOM was  
20 quickly taken up by primary producers and heterotrophic bacteria during the last 48 hrs of DR2,  
21 thus causing a rapid decline in DOC concentrations. The increase of DOC observed during  
22 ponding suggests leaching of recalcitrant DOM.

1           While VSS concentrations did not change during the draining phases, they decreased  
2 during the ponding phase, suggesting that small suspended organic matter such as phytoplankton,  
3 bacterioplankton and organic detritus was transferred into higher trophic levels such as  
4 macrozooplankton, aquatic macroinvertebrates and larval fish.

#### 5           *Short term water quality changes*

6           Because the sampling frequency of most studies has been in the range of several days to  
7 months, then details of biogeochemical processes on floodplains following inundation are not  
8 entirely understood. Our data show that water quality can change rapidly (<4 hrs) as seen in the  
9 diel patterns of Chl-*a* , which are a measure of planktonic photosynthetic organisms. The diel  
10 variations observed in our study, and the peak times in Chl-*a* concentrations are consistent with  
11 patterns found during the decreasing water phases in the Amazonian floodplain lakes Batata and  
12 Mussura (Melo and Huzar, 2000; Melo *et al.*, 2004). During flood events, phytoplankton  
13 productivity decreases due to the amounts of suspended solids in the water column which can  
14 decrease the amount of light available for photosynthesis. Additionally, flood pulses tend to  
15 significantly dilute phytoplankton biomass (Heiler *et al.*, 1995), which in turn significantly  
16 decreases net water column primary productivity. Although the diel variations were observed  
17 during the falling limb of the flood pulses, the diel patterns were most dramatic during the DR2  
18 and ponding phases. We hypothesize that Chl-*a* peaks were highest during DR2 due to the  
19 increased availability of dissolved inorganic nitrogen and dissolved organic compounds (as  
20 measured by DOC) following FP2; which may have alleviated nutrient limitations in the water  
21 column.

22           The increases in Chl-*a* concentrations during the day are indicative of high primary  
23 productivity rates, which have been observed in other floodplain systems (Vegas-Vilarrubia and

1 Herrera, 1993; de Melo and Huzar, 2000; Melo *et al.*, 2004). The nightly decrease in Chl-*a*  
2 concentrations can be attributed to the reduction of photosynthetic activity during the night,  
3 respiration due to cell division and phytoplankton grazing by invertebrates. In past years, the  
4 phytoplankton community during and shortly after flooding has been observed to be dominated  
5 by diatoms, and green algae including *Zygnema sp.*, *Spirogyra sp.*, *Scenedesmus sp.* and  
6 *Ankistrodesmus sp.* (Gallo, unpublished data). However, during periods of very high hydrologic  
7 residence time plankton community dominance shifts to euglenophytes and N-fixing  
8 cyanophytes including *Chlamidomonas sp.*, *Anabeana sp.*, *Nostoc sp* and *Nodularia sp.* (Gallo,  
9 unpublished data). Previous research at this site has demonstrated that the floodplain can support  
10 large populations of planktonic grazers including, chironomids, copepods, cladocerans and  
11 ostracods (Grosholz and Gallo in revision), which can increase their feeding activity at night and  
12 cause a dramatic decrease in phytoplankton biomass in several hrs.

13 Our DIN:DIP ratios suggest that during the draining phases, nitrogen was the limiting  
14 nutrient, particularly following FP1. Nitrogen limitation increased with hydrologic residence  
15 time, however, primary producers may have compensated for inorganic nitrogen limitation  
16 through nitrogen fixation and utilization of dissolved organic nitrogen. N-fixing cyanobacteria  
17 are common photosynthetic organisms in wetlands and have been observed to be the dominant  
18 primary producer in the water column of our site (Gallo, unpublished data). In addition,  
19 numerous studies have demonstrated that when DIN is in short supply, uptake and utilization of  
20 dissolved organic nitrogen by photosynthetic organisms increases (Tyler, McGlathery, and  
21 Anderson 2001 and 2003). The availability of dissolved inorganic phosphorous coupled with the  
22 ability of primary producers to utilize nitrogen from a variety of sources may have enhanced  
23 photosynthetic activity during the draining and ponding phases. Our DIN:DIP ratio during the

1 ponding phase suggests an increase in phosphorous limitation with hydrologic residence. The  
2 increase of phosphorous limitation, coupled with an overall increase in Chl-*a* concentrations  
3 suggest the transformation of inorganic nutrients to organic forms.

4         Although we did not observe diel changes in nutrient concentrations, we hypothesize that  
5 nutrient transformations occur rapidly, and once nutrients are taken up they are sequestered via  
6 trophic transfers. In addition, some studies have suggested that within a floodplain there may be  
7 many states of nutrient cycling and primary production (Vegas-Vilarrubia and Herrera, 1993)  
8 which may be a product of the heterogenous nature of floodplain systems. The results from this  
9 study demonstrate that high resolution temporal sampling is important in order to discern short-  
10 term water quality changes, particularly since floodplains are dynamic ecosystems where major  
11 nutrient transformations occur in the span of several hrs. Future work will involve the impact of  
12 varying degrees of hydrologic residence time and habitat heterogeneity on floodplain  
13 biogeochemistry.

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1

2 Table I. Fluxes

	Flood 1 (FP1)		Draining 1 (DR1)	Flood 2 (FP2)		Draining 2 (DR2)	Total		Net
	Flux In	Flux Out	Flux out	Flux In	Flux Out	Flux out	Flux In	Flux Out	Flux
TSS (Mg)	292	101	0.6	968	483	1.0	1260	586	674
VSS (Mg)	46	30	0.4	135	100	0.4	181	131	51
TN (kg)	6559	603	159	21939	18891	124	28499	25206	3293
NO <sub>3</sub> -N (kg)	1487	410	18	7292	8017	27	8779	9471	692
NH <sub>4</sub> <sup>+</sup> -N (kg)	594	534	3	1605	1150	4	2199	1691	509
TP (kg)	956	769	27	2544	2528	15	3501	3340	161
PO <sub>4</sub> -P (kg)	243	279	12	825	797	6	1067	1094	27
DOC (Mg)	25	27	1.3	99	98	1.2	124	128	4
Chl- <i>a</i> (kg)	19	17	0.6	46	44	1	65	62	3

1 **Figure Legends:**

2 Figure 1. The Cosumnes River Preserve floodplain. Black arrows denote generalized surface  
3 water flow paths. Black boxes indicate the 4 levee breaches in the study site: 2 water entry  
4 breaches along the Cosumnes River (NB and SB) and 2 exit breaches from the upper floodplain  
5 to the lower floodplain (WB and EB). Stars denote locations of autosamplers at NB (inlet) and  
6 WB (outlet).

7 Figure 2. (a) Cosumnes River discharge at the Michigan Bar monitoring station during our study  
8 period; and (b) electrical conductivity (EC) of water at the inlet breach (black) and exit breach  
9 (grey).

10 Figure 3. Total suspended solids (TSS) at (a) the inlet breach (black) and outlet breach (grey)  
11 during the entire study period; best fit regressions of TSS at the outlet during (b) draining 1, (c)  
12 draining 2 and (d) ponding.

13 Figure 4. Volatile suspended solids (VSS) at (a) the inlet breach (black) and outlet breach (grey)  
14 during the entire study period; best fit regressions of TSS at the outlet during (b) draining 1, (c)  
15 draining 2 and (d) ponding.

16 Figure 5. Percent volatile suspended solids of the total suspended solids (% VSS) at (a) the inlet  
17 breach (black) and outlet breach (grey) during the entire study period; best fit regressions of TSS  
18 at the outlet during (b) draining 1, (c) draining 2 and (d) ponding.

19 Figure 6. Total nitrogen (TN) at (a) the inlet breach (black) and outlet breach (grey) during the  
20 entire study period; best fit regressions of TSS at the outlet during (b) draining 1, (c) draining 2  
21 and (d) ponding.

1 Figure 7. Nitrate nitrogen ( $\text{NO}_3\text{-N}$ ) at (a) the inlet breach (black) and outlet breach (grey) during  
2 the entire study period; best fit regressions of TSS at the outlet during (b) draining 1, (c) draining  
3 2 and (d) ponding.

4 Figure 8. Ammonium nitrogen ( $\text{NH}_4^+\text{-N}$ ) at (a) the inlet breach (black) and outlet breach (grey)  
5 during the entire study period; best fit regressions of TSS at the outlet during (b) draining 1, (c)  
6 draining 2 and (d) ponding.

7 Figure 9. Total phosphorous (TP) at (a) the inlet breach (black) and outlet breach (grey) during  
8 the entire study period; best fit regressions of TSS at the outlet during (b) draining 1, (c) draining  
9 2 and (d) ponding.

10 Figure 10. Orthophosphate ( $\text{PO}_4\text{-P}$ ) at (a) the inlet breach (black) and outlet breach (grey) during  
11 the entire study period; best fit regressions of TSS at the outlet during (b) draining 1, (c) draining  
12 2 and (d) ponding.

13 Figure 11. Total nitrogen to total phosphorous ratio (TN:TP) at (a) the inlet breach (black) and  
14 outlet breach (grey) during the entire study period; best fit regressions of TSS at the outlet during  
15 (b) draining 1, (c) draining 2 and (d) ponding.

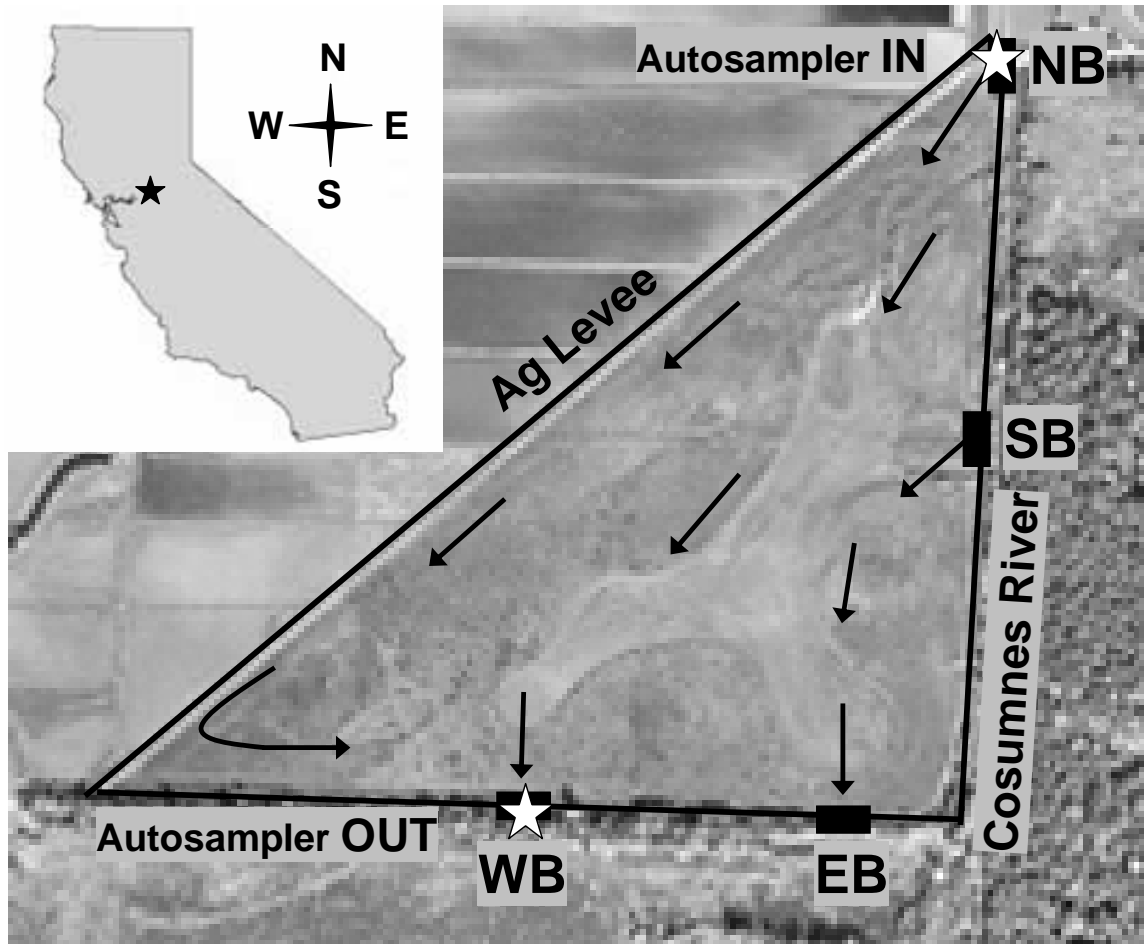
16 Figure 12. Dissolved inorganic nitrogen to dissolved inorganic phosphorous ratio (DIN:DIP) at  
17 (a) the inlet breach (black) and outlet breach (grey) during the entire study period; best fit  
18 regressions of TSS at the outlet during (b) draining 1, (c) draining 2 and (d) ponding.

19 Figure 13. Dissolved organic carbon (DOC) at (a) the inlet breach (black) and outlet breach  
20 (grey) during the entire study period; best fit regressions of TSS at the outlet during (b) draining  
21 1, (c) draining 2 and (d) ponding.

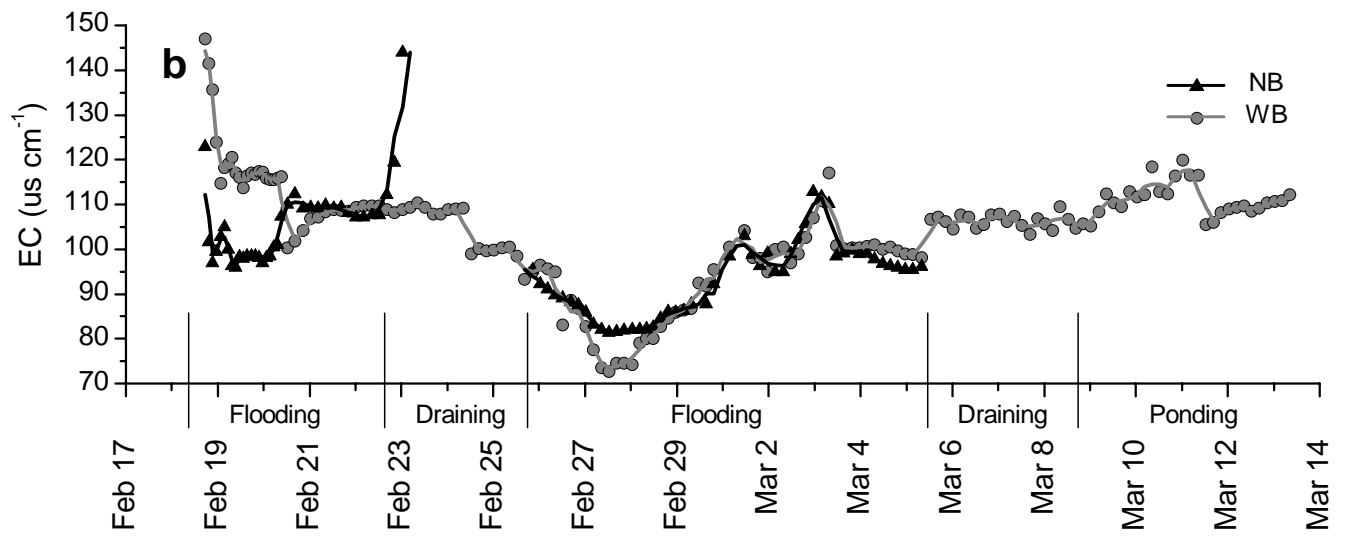
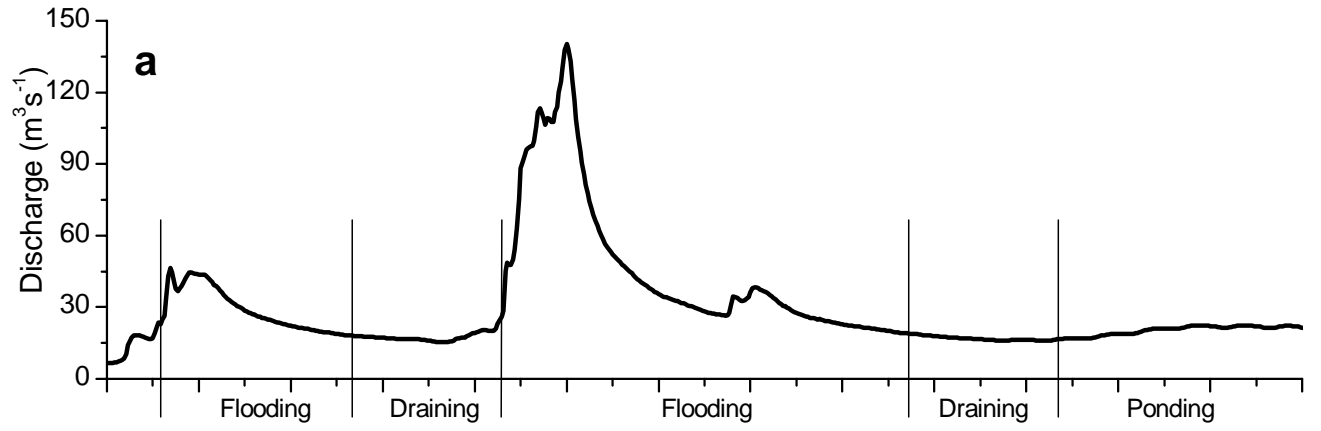


1 Figure 14. Chlorophyll a (Chl-a) at (a) the inlet breach (black) and outlet breach (grey) during  
2 the entire study period; best fit diel regressions of Chl-a at the outlet during (b) draining 1, (c)  
3 draining 2 and (d) ponding.

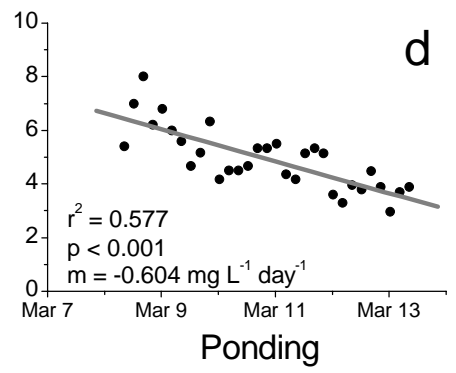
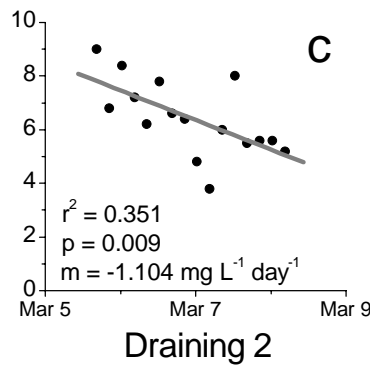
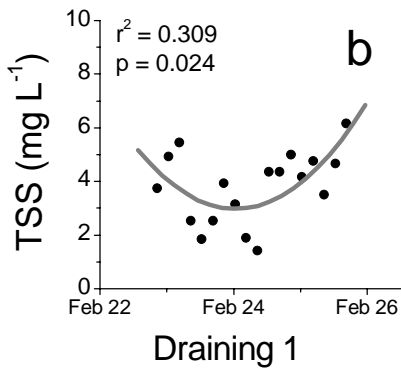
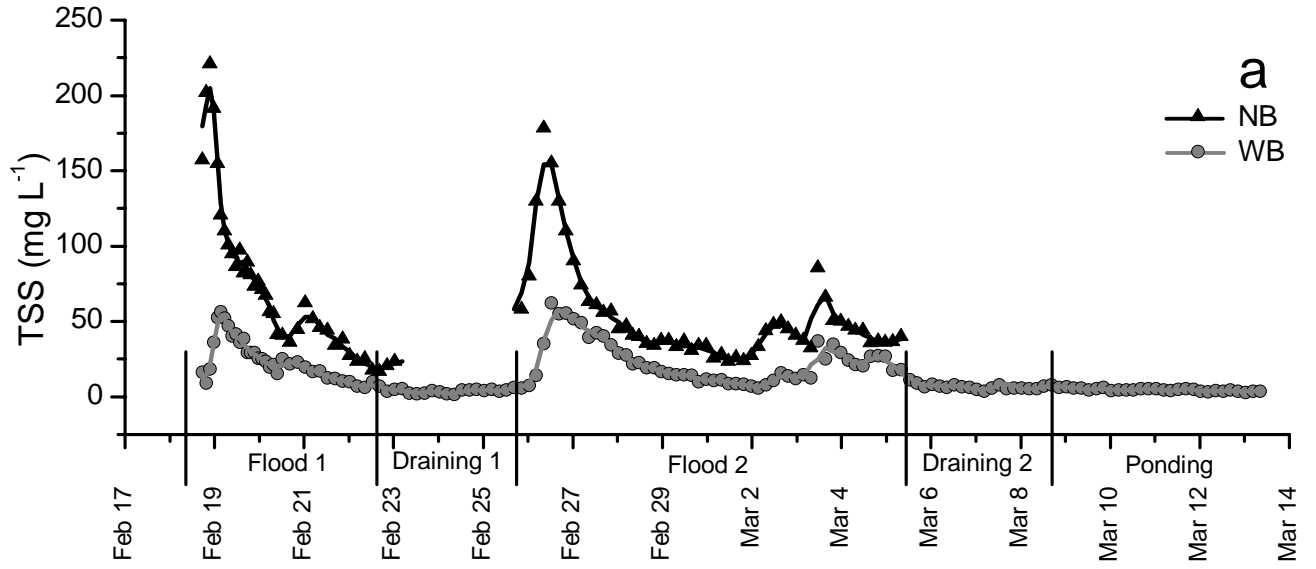
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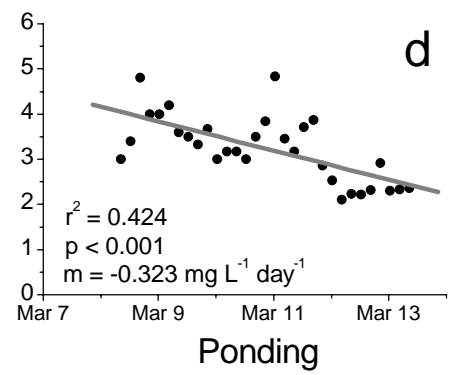
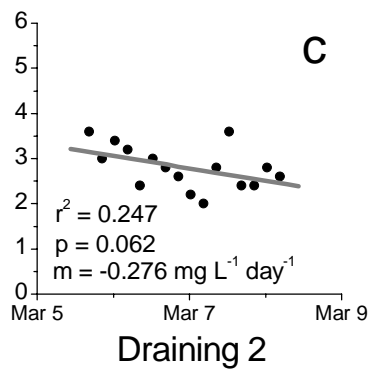
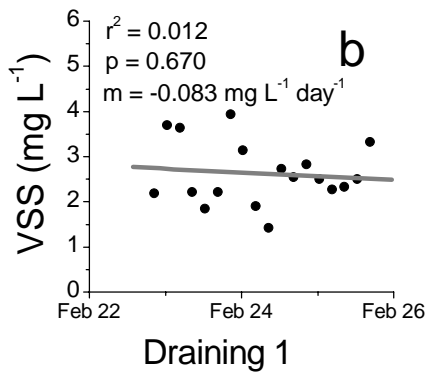
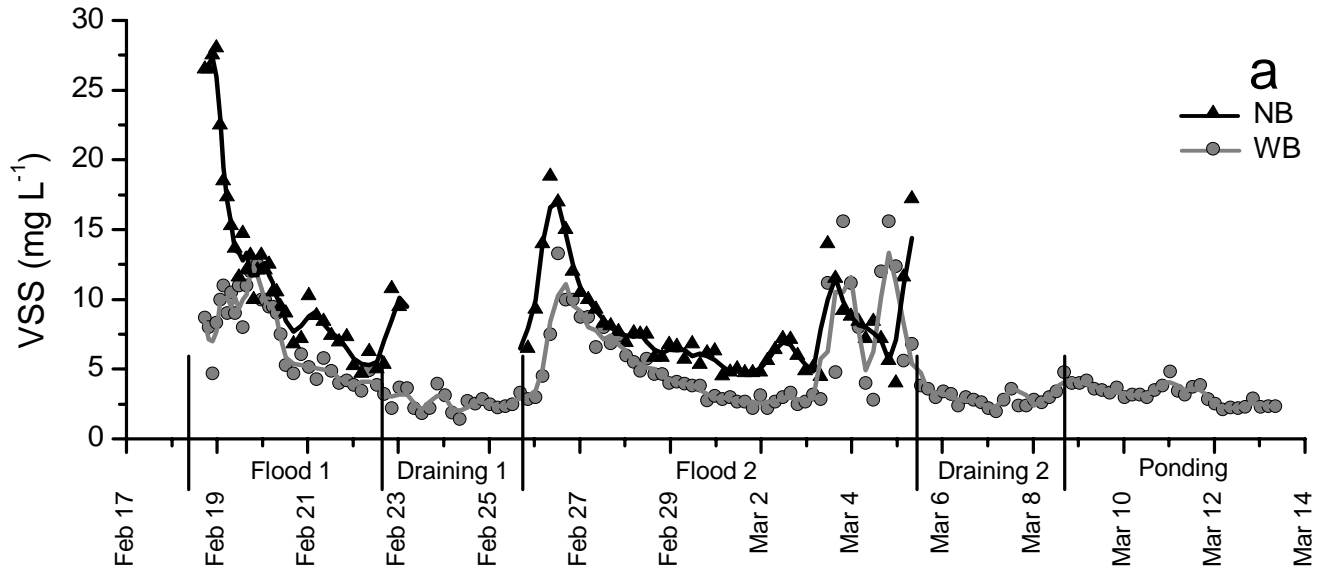
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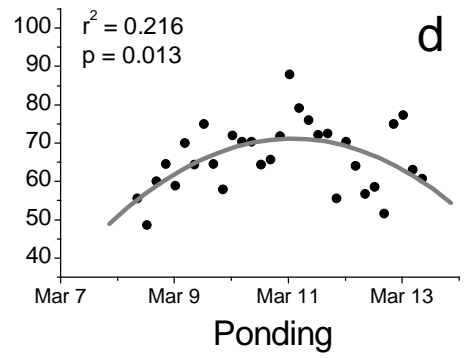
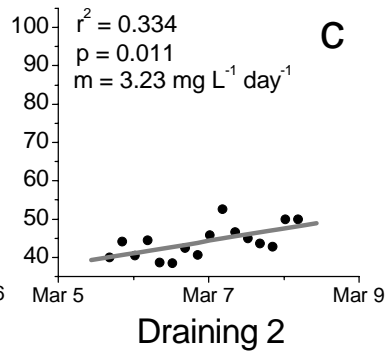
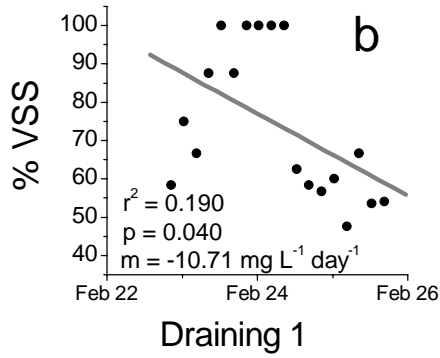
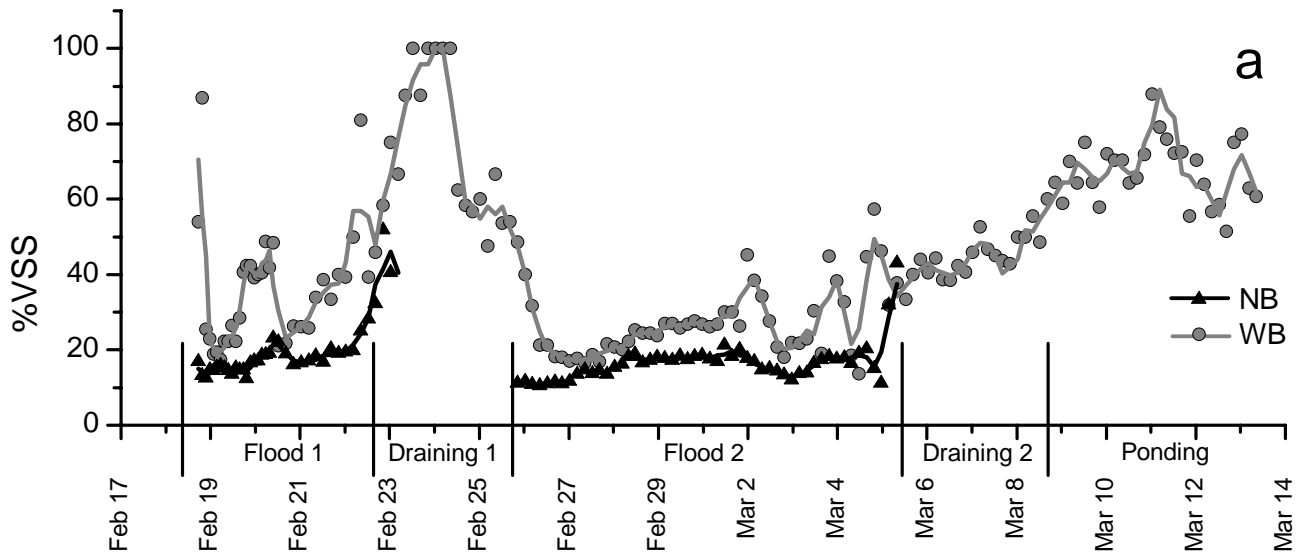
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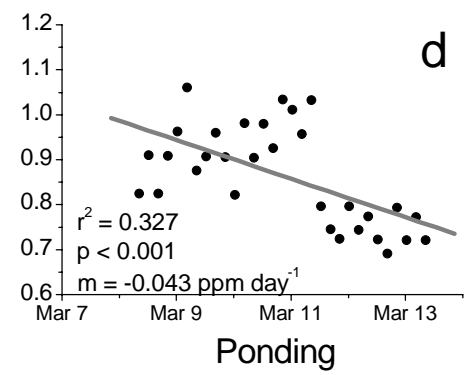
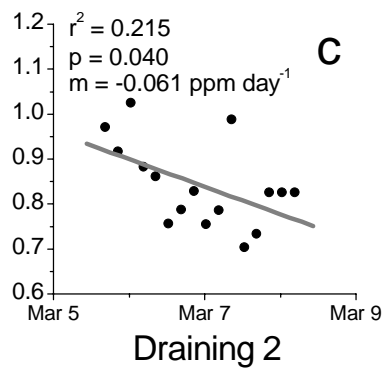
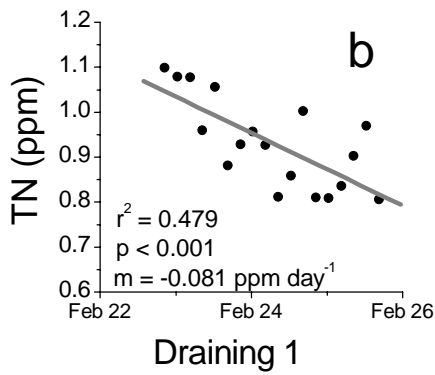
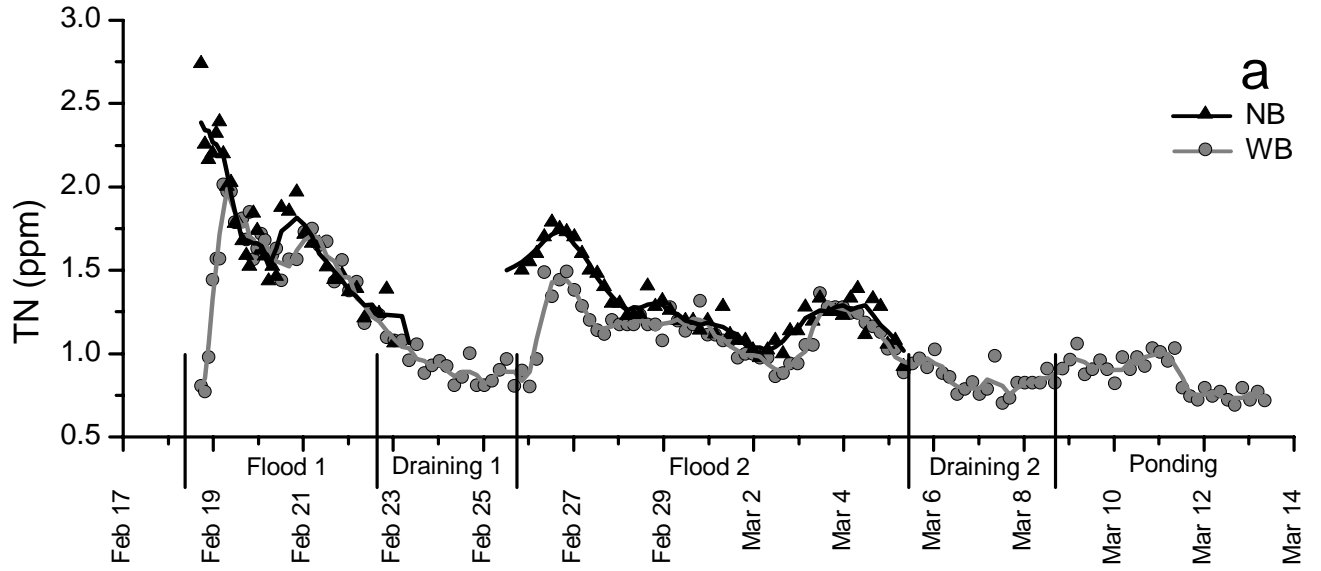
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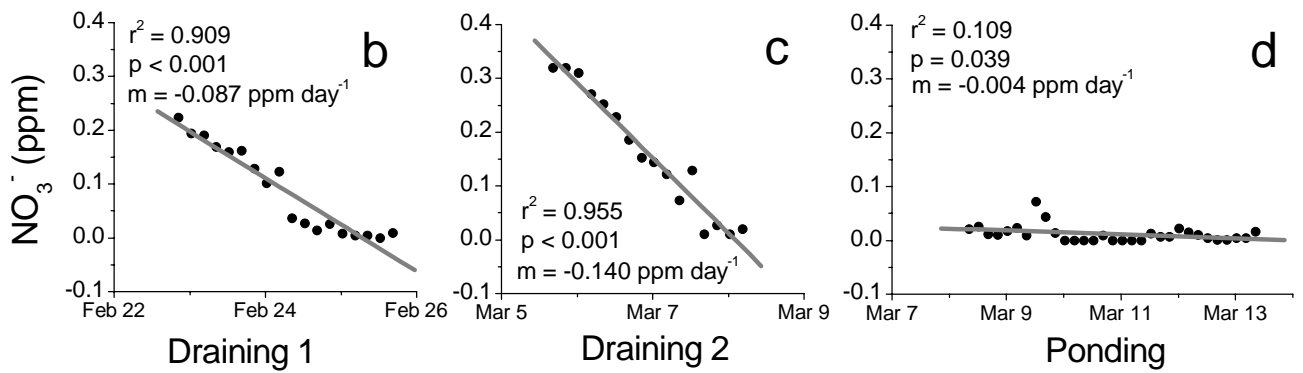
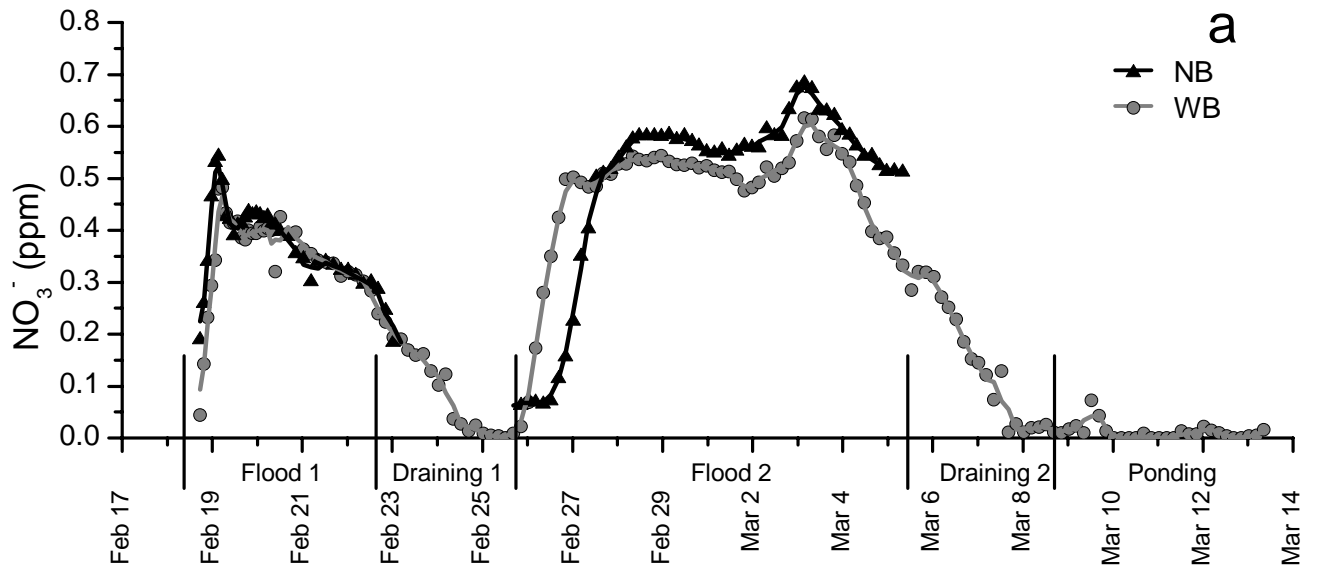
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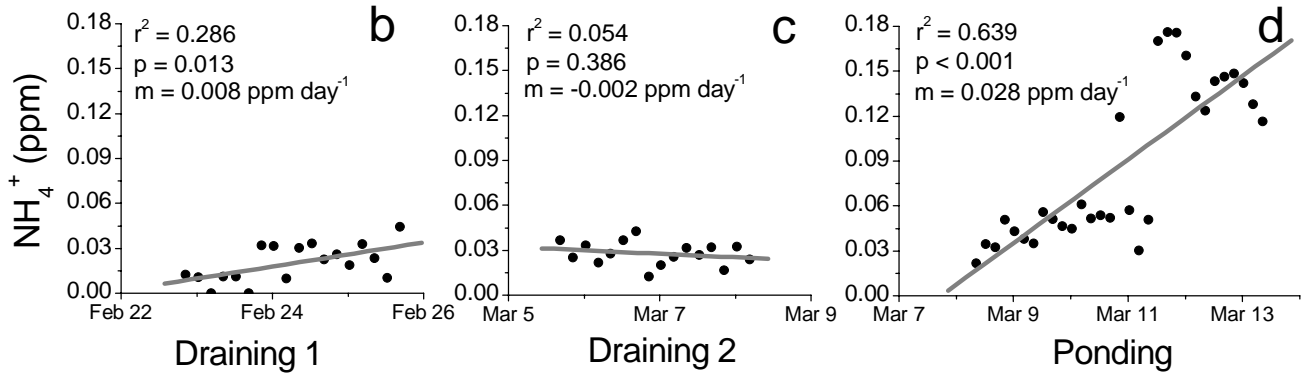
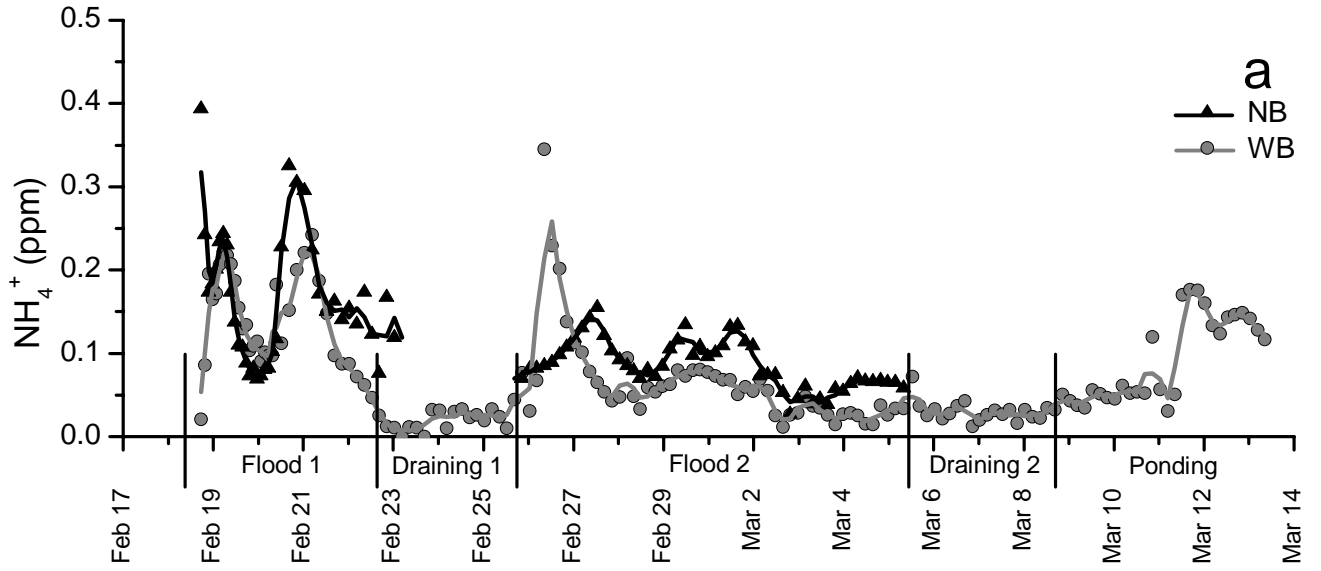
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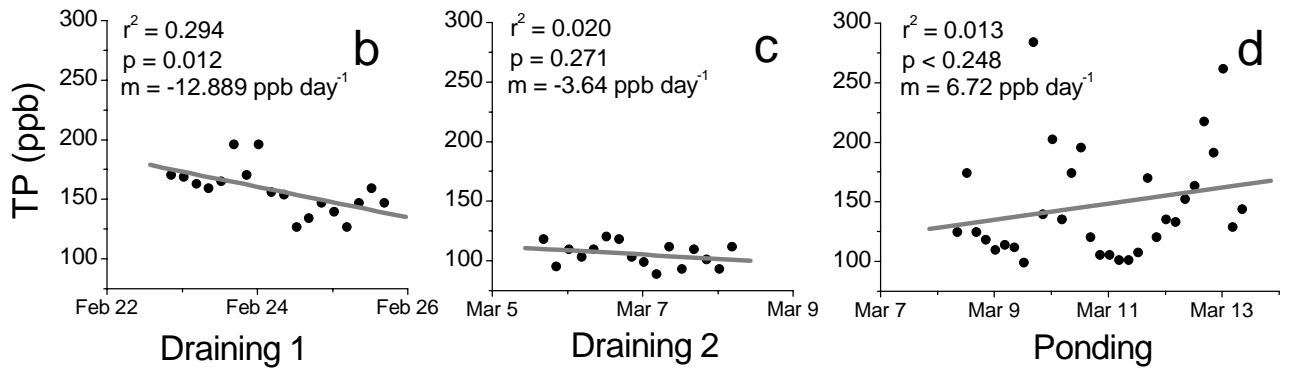
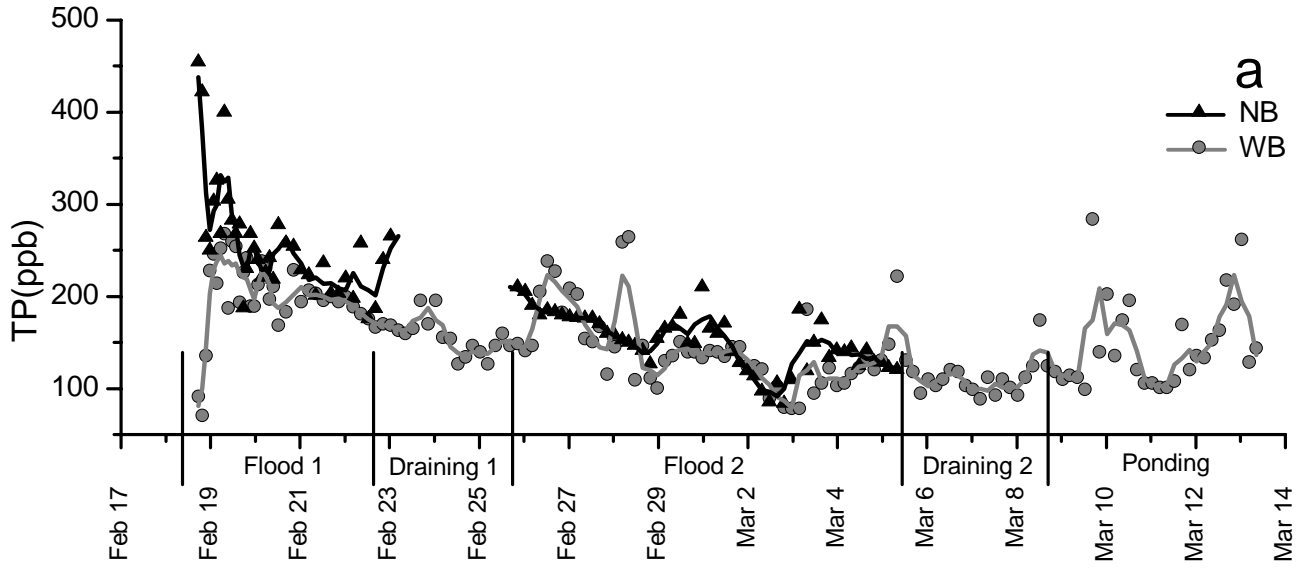


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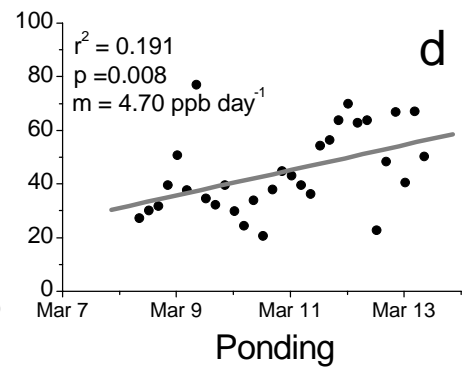
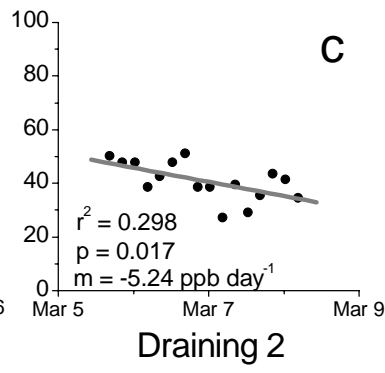
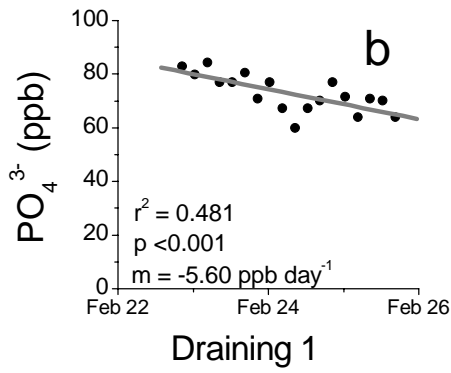
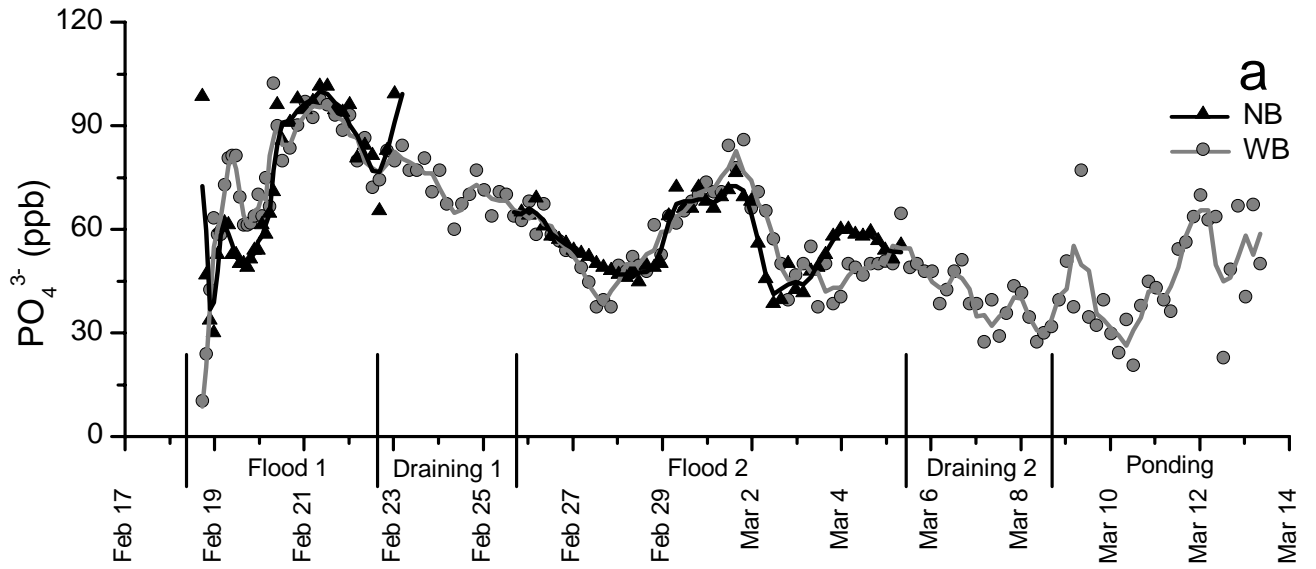


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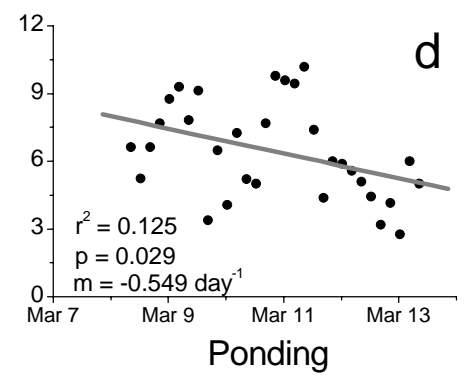
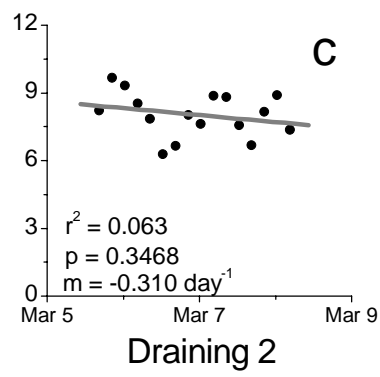
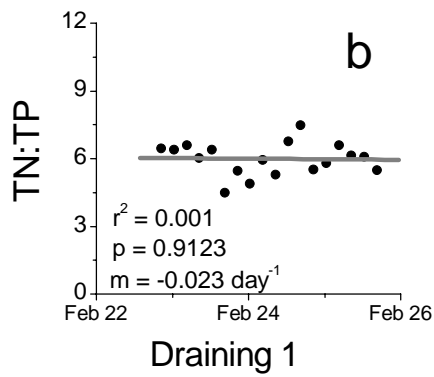
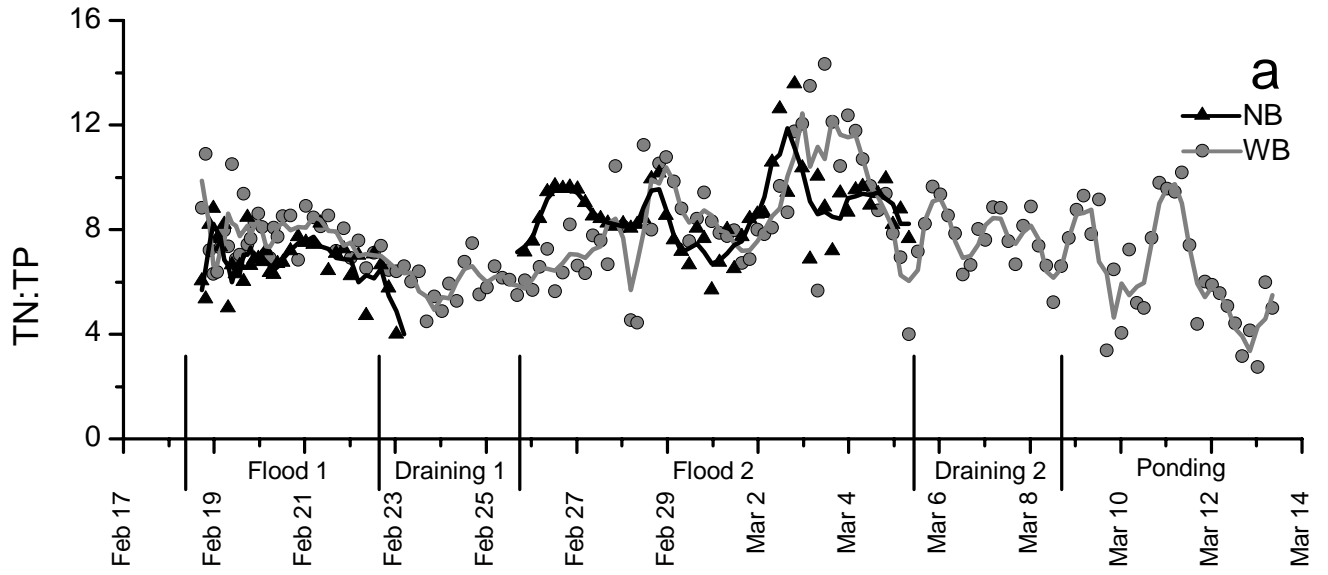




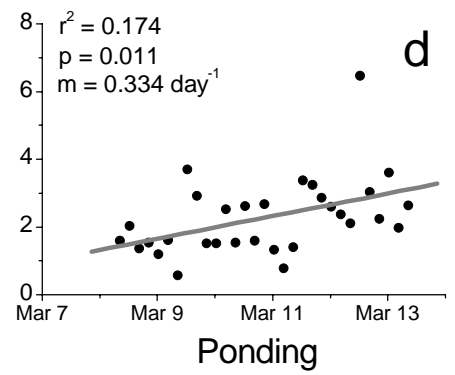
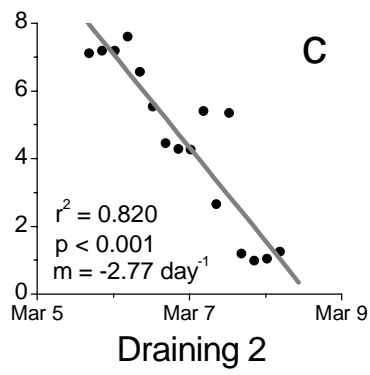
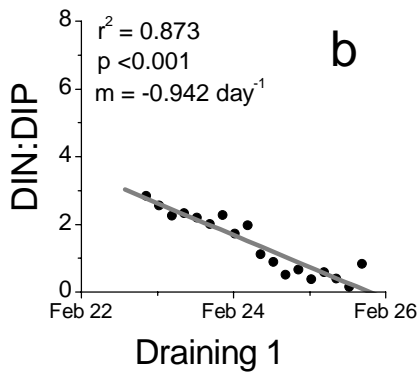
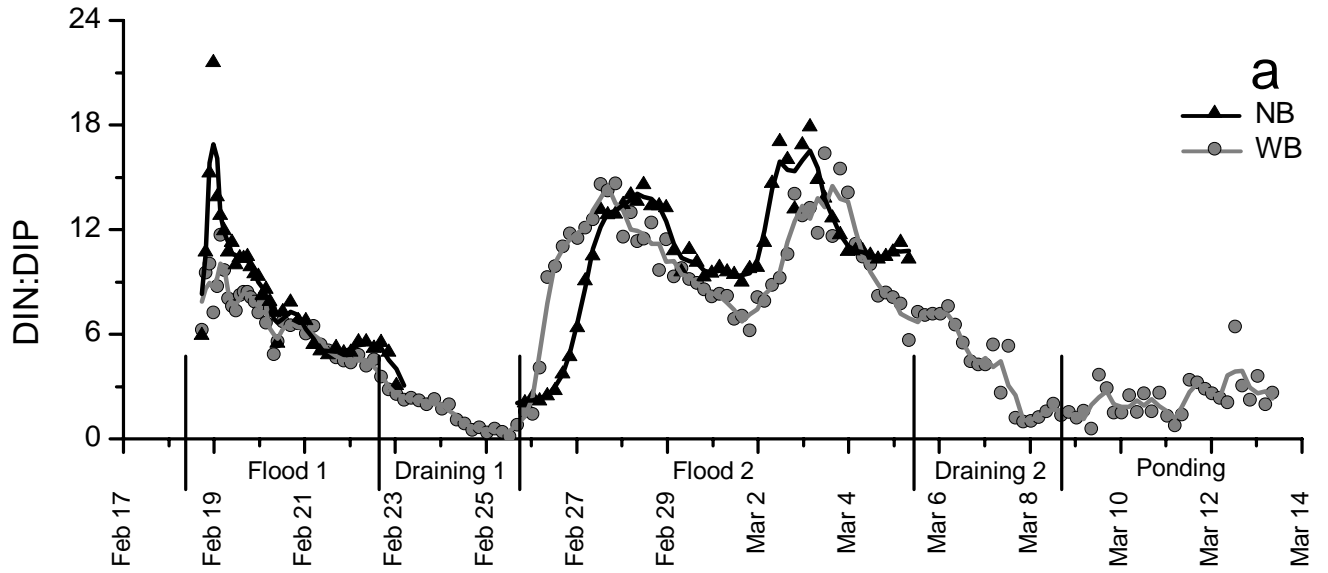
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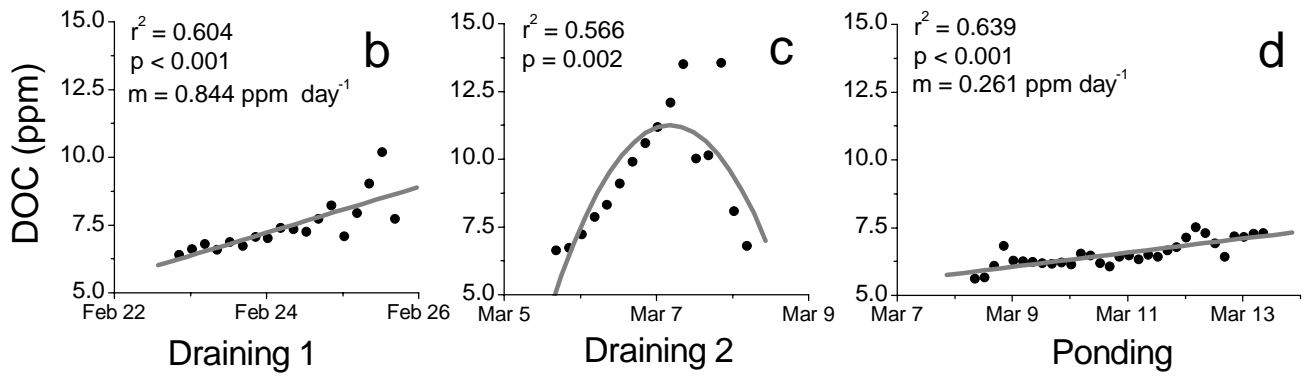
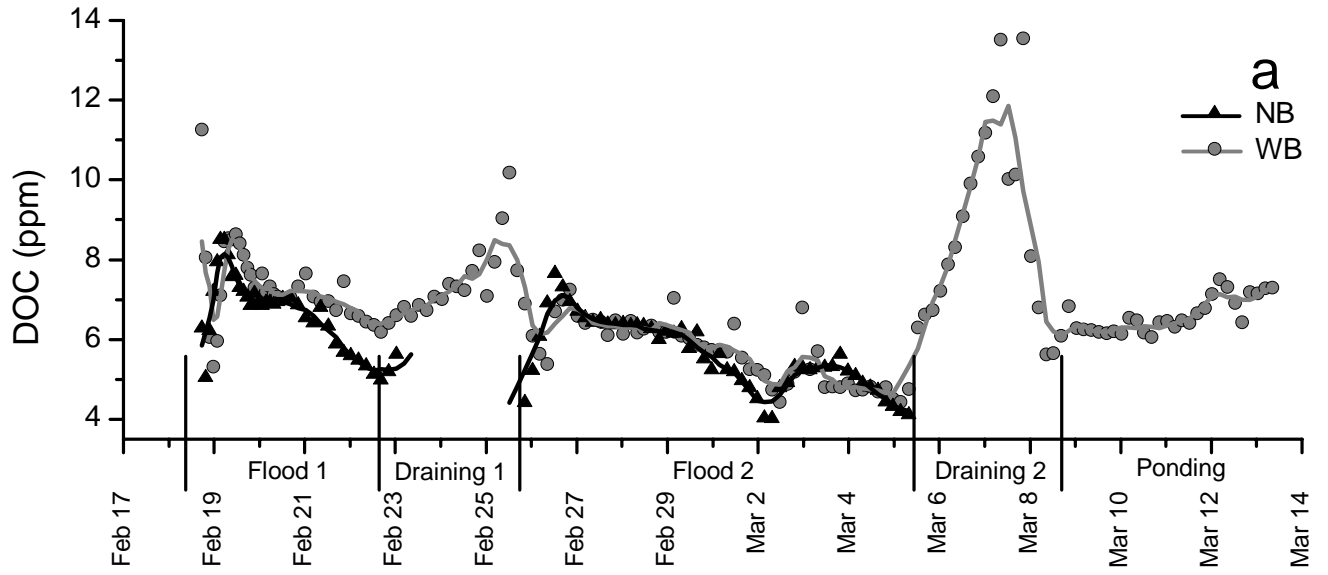
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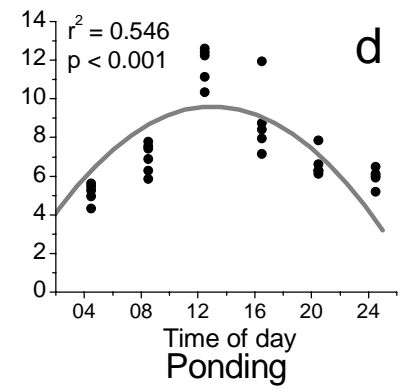
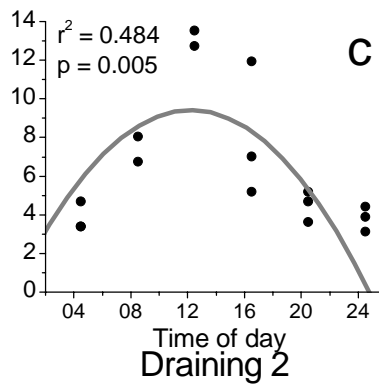
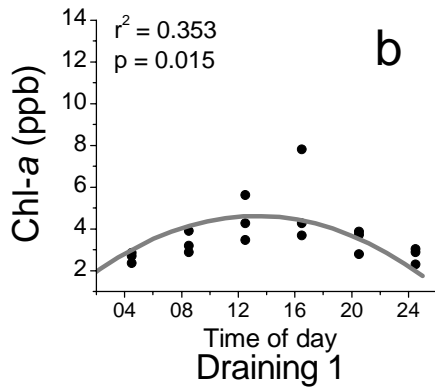
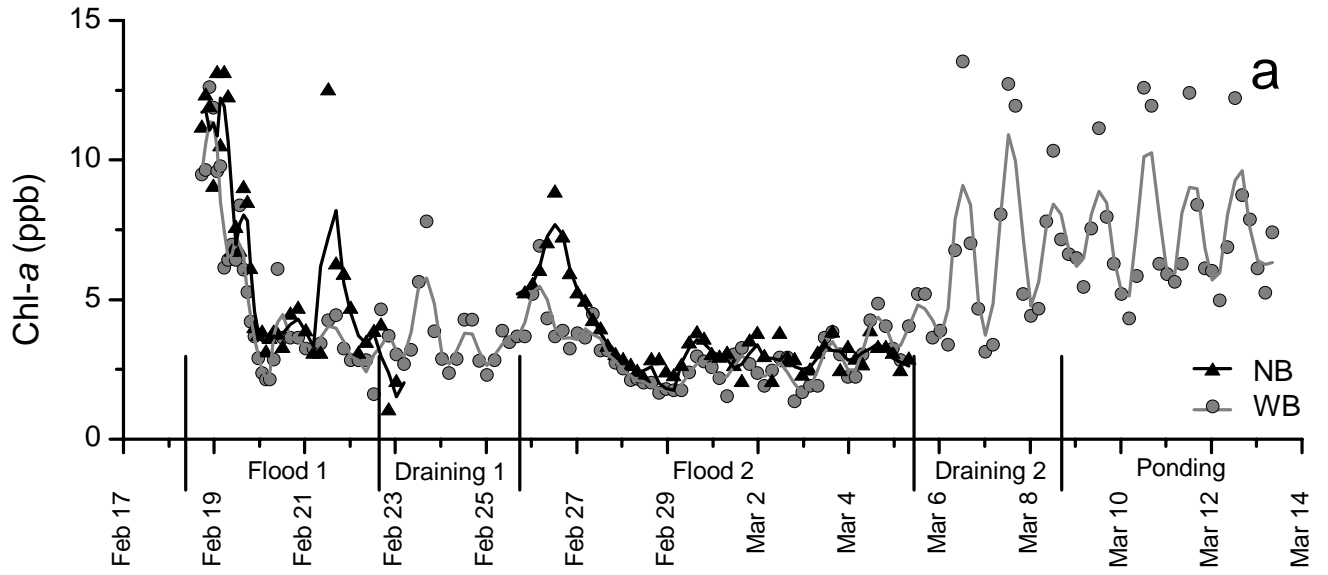
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