

Partitioning the flood pulse: The biogeochemistry of floodwaters in a restored free-flowing river-floodplain system

Dylan S. Ahearn¹, Carson A. Jeffres², Jeffrey F. Mount³, Randy A. Dahlgren¹

¹*Department of Land, Air, and Water, Resources, University of California, Davis, California 95616*

²*Center for Watershed Sciences, University of California, Davis, California 95616*

³*Department of Geology, University of California, Davis, California 95616*

¹Corresponding author. Tel.: 206-441-9080; fax: 206-441-9108
E-mail Addresses: dahearn@herrerainc.com

Submitted for Publication in: *Freshwater Biology*

Running head: Biogeochemistry of flood pulse phases

Keywords: Flood pulse, floodplain, Cosumnes River, flux, residence time, restoration

1 **Abstract**

2 Floodwaters traversing a 36 ha restored floodplain in central California were intensively
3 monitored for sediment, nutrients, dissolved organic carbon (DOC), and chlorophyll-a (Chl-a)
4 from 31 December 2004 to 20 June 2005. The floodplain was an annual sink for all constituents
5 measured: total suspended sediment (TSS) = 372 Mt ha⁻¹ yr⁻¹; volatile suspended sediments
6 (VSS) = 55 Mt ha⁻¹ yr⁻¹; total inorganic nitrogen (TIN) = 0.43 Mt ha⁻¹ yr⁻¹; DOC = 3 Mt ha⁻¹ yr⁻¹;
7 and Chl-a = 0.01 Mt ha⁻¹ yr⁻¹. However, closer analysis revealed that some small flooding events
8 caused net DOC and Chl-a export from the floodplain. Partitioning of the phases of the flood
9 pulse revealed three physically and chemically distinct stages: the flushing phase, transport
10 phase, and draining phase. The flushing phase was a brief period of DOC and Chl-a export on
11 the rising limb of the flood, this phase only occurred after an extended period with no upstream
12 connection. When elevated constituent concentrations ceased floodplain egress the flushing
13 phase ended and the transport phase began. The transport phase dominated the flux balance of
14 the system and was marked by retention of all the measured constituents on the floodplain. The
15 draining phase began when outflow from the floodplain exceeded inflow, this phase was
16 characterized by net export of DOC and Chl-a. The fact that small floods were not dominated by
17 the retentive transport phase helps explain why smaller floods tended to cause net export, rather
18 than retention, of materials on the floodplain. We provide a conceptual model of the flood pulse
19 phases which includes and broadens the model proposed by Tockner et al. (1999). Finally, we
20 propose the notion of “floodplain proportional flooding” for optimizing diverse food resource
21 export from restored floodplain systems, whereby median flood size should not overwhelm
22 floodplain volume. In this way residence time is increased as is the potential for the floodplain

1 to be a source for DOC and phytoplankton, valuable food resources for downstream aquatic
2 ecosystems.

3

4

5

6

7

8

9

10

11

12

13

14

15

16

17

18

19

20

21

22

23

1 **Introduction**

2 Resource exchange across the river-floodplain system is widely recognized as a principal
3 ecosystem driver in low-gradient channels with extensive lateral floodplains (Bayley, 1995;
4 Cuffney, 1988; Junk et al., 1989; Ward and Stanford, 1995). Development of floodplains for
5 agriculture and other purposes has lead to the widespread leveeing and regulation of channels
6 and their waters. It has been estimated that 40 000 km of levees have been constructed in the
7 United States (Johnston Associates, 1989) and that 98% of channel flow is regulated (Vitousek et
8 al., 1997). A ramification of these landscape alterations is the hydraulic disconnection of
9 channels with adjacent riparian areas and the elimination of the flood pulse. With the
10 recognition of the value of connectivity in aquatic-terrestrial systems (Taylor et al., 1993; Ward
11 and Stanford, 1995) came the impetus to restore these habitats and begin the undoing of 100
12 years of ecologically insensitive river engineering (sensu Babbitt, 1995).

13
14 Managers and scientists from myriad backgrounds have conducted floodplain restoration
15 projects. In each instance, a river-floodplain system has been manipulated to serve some set of
16 beneficial ecological and/or societal functions. Many projects have taken a holistic approach –
17 attempting to rehabilitate inundation patterns, resource exchange, lateral migration of organisms,
18 and structural habitat. An example of this approach can be found in Florida where the \$500
19 million dollar Kissimmee River restoration project aims to restore the ecological functioning of
20 11,000 ha of floodplain habitat (Dahm et al., 1995; Whalen et al., 2002). But, other floodplain
21 restorations serve a much more focused purpose. The 24,000 ha Yolo Bypass near Sacramento,
22 California was constructed in the 1930’s solely for flood abatement purposes (Sommer et al.,
23 2001). Today the Yolo Bypass is managed to provide many beneficial services (Sommer et al.,

1 2004), but no single project can be managed to optimize all the benefits a floodplain ecosystem
2 could potentially provide.

3

4 Floodplains serve as biogeochemical transformers of floodwaters. As nutrients move onto the
5 floodplain particulate forms quickly settle out (Mitsch et al., 1995) and dissolved species are
6 biologically assimilated as floodplains tend to have lower velocities, longer exposure times, and
7 are generally more productive than adjacent channels (Mitsch and Gosselink, 2000; Robertson et
8 al., 2001; Sommer et al., 2004; Wetzel, 1992). Meanwhile, high biomass, elevated retention
9 times, large width to depth ratios, and periodic scouring across the floodplain contribute to the
10 accumulation and subsequent export of carbon (in its many forms) back to the channel (Cuffney,
11 1988; Tockner et al., 1999; Valett et al., 2005). In this way the flood pulse progressively extracts
12 nutrients from the channel and replaces these nutrients with labile (Tockner et al., 1999) and/or
13 recalcitrant (Cuffney, 1988) food resources. Most studies which have calculated input/output
14 mass balances for these constituents have done so at a coarse timescale and so it is not altogether
15 clear at which point during the flood pulse the floodplain is acting as a sink or a source. This in
16 turn will have implications for the effect of flood magnitude on input/output dynamics as
17 different size floods will be dominated by different phases of the flood pulse.

18

19 In this study of a restored floodplain in central California, we aim to define the phases of the
20 flood pulse in an effort to better understand source/sink dynamics during floods of varying
21 magnitude. It has been suggested that the restoration of floodplains in this geographical area
22 would serve the purpose of bolstering a waning supply of food resources in the upper San
23 Francisco Bay Estuary (Foe and Knight, 1985; Jassby and Cloern, 2000). With this ecological

1 service in mind we set out to examine which factors control nutrient and carbon export from the
2 floodplain.

3

4 **Study Site**

5 The study site was located 34 km south of Sacramento, CA on the lower Cosumnes River,
6 approximately 5.5 km upstream from the confluence with the Mokelumne River. In 1997, four
7 breaches were cut into the levee bordering the eastern edge of the channel. Two inlet breaches
8 (Tn and Ts) allow river water to enter the 36 ha restored floodplain during floods. Mean flood
9 transit time across the floodplain in 2005 was approximately 1 day; during which time the
10 floodplain held an average of 90 000 m³ of floodwater. After traversing the floodplain, water
11 egresses through two exit breaches (Te and Tw). Mean discharge across the floodplain in 2005
12 was 6.09 m³ s⁻¹, while mean discharge in the main channel during this same period was 37.1 m³
13 s⁻¹ (USGS gage #11335000). Discharge dynamics in the Cosumnes River are driven by the
14 Mediterranean climate of the region, which is characterized by warm wet winters and hot dry
15 summers. Average precipitation in the upper and lower watershed is 804 mm y⁻¹ and 445 mm y⁻¹,
16 respectively, with (~79%) of the rainfall occurring between November and March. Rainfall-
17 induced flooding occurs on the floodplain during this period, after which time flooding is
18 primarily driven by snowmelt in the upper basin (Ahearn et al., 2004). By June the flood season
19 has ended and the floodplain steadily dries until the floodwaters return (usually the following
20 December).

21

22 The floodplain has both deep and shallow water habitats with a pond (average max depth = 3.2
23 m) the dominant feature in the system. The system is still in early successional stages of riparian

1 vegetation establishment, with dominant species of cottonwood (*Populus fremontii*), willow
2 (*Salix* spp.), and oak (*Quercus lobata*) covering approximately 15% of the floodplain (Viers et
3 al. in prep). Without a shading overstory, the floodplain has a very productive community of
4 aquatic macrophytes and epiphytic algae which thrive in shallow areas.

5

6 **Methods and Materials**

7 *Sample collection*

8 Material fluxes through the floodplain were determined using automatic pump samplers (ISCO
9 6700) situated at three of the four breaches (Tn, Te, and Tw) (Fig.1). Breach Ts was not sampled
10 because it was difficult to access, and as it was only 400 meters downstream from Tn (both sites
11 received unidirectional flow from the main channel), chemistry at the two sites was assumed to
12 be identical. The autosamplers were programmed to collect time-weighted composite samples
13 during flooding events. A 2 h sampling frequency (2-sample composite) was used on the rising
14 limb of floods, 4 h (composite) for the peak and 1 day subsequent, 24 h (discrete) on the falling
15 limb, and 48 h (discrete) between events. Sampling began with the first flooding event on 31
16 December 2004 and ended when the floodplain finally disconnected (at the inlet and outlet) from
17 the river on 20 June 2005. During this period there were 7 distinct floods separated by
18 floodplain draining periods lasting from 1 to 20 days (Fig. 2). During the 172 days of flooding,
19 175 samples (169 matched pairs) were collected from each of the three sites.

20

21 *Capturing water flux*

22 One of the most difficult tasks in any analysis of biogeochemical fluxes in aquatic systems is
23 attaining accurate flow data. In order to determine water fluxes we installed pressure transducers

1 at each of the four levee breaches (Durck PDCR 1830). Water stage was collected every 10
2 minutes for the duration of the study. On 11 occasions we measure velocities in the breaches
3 with a Marsh McBirney (Flow-mate 2000) velocity meter at 0.6 depth, in set increments across
4 the breaches. A minimum of 10 velocity measurements were taken at each breach. TN, TW and
5 TE were all measured while a field technician was wading in the breach, while TS was measured
6 from a boat that was attached to a cable moored to the levees. Discharge was subsequently
7 calculated using the methods described by Hauer & Lamberti (1996). Resultant discharge data
8 were regressed against stage, and rating curves were developed for each breach. Analysis of
9 rating curve residuals indicated that there was between 4 and 7% error in our flow estimations.
10 Discharge measurements were taken at flows ranging from 0.1 to $12 \text{ m}^3 \text{ s}^{-1}$. Flows which
11 exceeded $12 \text{ m}^3 \text{ s}^{-1}$ at Tn were estimated by extending the rating curve. Error is, of course,
12 introduced in this process; so as to avoid an additive error we only extended the Tn rating curve
13 and set inflow equal to outflow for flows above $12 \text{ m}^3 \text{ s}^{-1}$ at Tn. We estimated that error
14 introduced by this assumption could be no greater than 20% as the ratio of floodplain area ($3.7 \times$
15 10^5 m^2) to average transport phase volume ($1.28 \times 10^7 \text{ m}^3$) was small (0.029). An error of 20%
16 in our volume calculations when spread across the surface of the floodplain amounts to +/- 6.9
17 m. It is difficult to imagine this much water being lost or gained from a floodplain with no
18 tributaries, clay-rich soils, and cool weather evapotranspiration rates (the major floods occurred
19 between January and April). As such the 20% variation served as a good boundary condition for
20 our sensitivity analysis. The sensitivity analysis indicated that, within the range of uncertainty,
21 the relationship between the large and small storms and among the different flood pulse phases
22 was changed only in magnitude – relative patterns remain the same. A stage gage malfunctioned
23 during flood 7, the last flood of the season (Fig. 2), so this flood was excluded from the flux

1 analyses. Constituent fluxes were calculated by linearly interpolating concentration data
2 between sampling events on an hourly time step and multiplying by average hourly discharge.

3

4 *Sample analysis*

5 One liter samples were retrieved from the autosamplers within 24 h of collection and stored at 3
6 °C through completion of analysis. Prior to splitting the sample total dissolved solids (TDS) was
7 measured using an Accumet AB30 conductivity meter with a conversion coefficient of 0.66. A
8 300 ml split was filtered through a pre-combusted, pre-weighed glass fiber filter; the filter was
9 dried at 60 °C for 24 hours and weighed again to measure total suspended sediment (TSS).
10 Volatile suspended solids (VSS) were then calculated from the same sample after ashing at 550
11 °C for 3 hours. The minimum detection limit (MDL) for TSS and VSS was approximately 0.7
12 mg L⁻¹; values which fell below the MDL were set to 0.1 mg L⁻¹ for flux calculations.
13 Chlorophyll-a (Chl-a) was measured from another 300 ml sub-sample using standard extraction
14 and fluorometry techniques (American Public Health Association, 1998). The remaining sample
15 was filtered through a 0.2 µm polycarbonate membrane (Nuclepore) and used for the remained
16 of the analysis. Nitrate (NO₃⁻) was measured spectrophotometrically (Hitachi U-2000) after
17 reduction with a Vanadium(III) reagent (Doane and Horwath, 2003). Ammonium (NH₄⁺) was
18 also measured colorimetrically, the analysis used the Berthelot reaction to form chloramine,
19 which was coupled with two non-para-substituted phenols to induce coloration (Forster, 1995).
20 The lower limit of detection for the NO₃⁻ method was 7.0 µg L⁻¹, while the ammonium method
21 had a MDL of 20 µg L⁻¹. Phosphate (PO₄⁻³) was measured using the Phosphomolybdate
22 blue/ascorbic acid method with a MDL of 10 µg L⁻¹ (Murphy and Riley, 1962). Total Nitrogen
23 (TN) and Total phosphorus (TP) were digested with a 13.3% persulfate reagent and autoclaved

1 for 1 hour (Yu et al., 1994), the digested sample was then measured using the previously noted
2 methods for nitrate and phosphate, respectively. Finally, dissolved organic carbon (DOC) was
3 measured using a Dohrmann UV-enhanced persulfate TOC analyzer (Phoenix 8000) with a
4 detection limit of 50 $\mu\text{g L}^{-1}$.

5

6 *Statistical Analysis*

7 In order to detect statistically significant differences among constituent concentration data at the
8 three sampling sites (Tn, Te, and Tw) the Friedman test was used. An nonparametric analog to
9 the blocked ANOVA (Helsel and Hirsch, 1992), this test was used because the data did not meet
10 the assumptions (e.g. normality and constant variance) required for a parametric test. A blocked
11 test was applied to remove variance in the data introduced by sampling across a range of flow
12 conditions. When a statistical difference ($\alpha = 0.05$) was detected using the Friedman test, a
13 subsequent nonparametric multiple range test (Zar, 1984) was conducted to determine which
14 specific sites were statistically different from each other.

15

16 **Results**

17 *Annual Source-Sink Dynamics*

18 An initial step in the analysis of water entering and egressing from the study site involved
19 applying a nonparametric Friedman ANOVA test to matched pair samples ($n = 169$) across the
20 entire data set (Table 1). The results indicate that TSS, VSS, TIN, TP and Chl-a concentrations
21 were significantly higher at the inlet (Tn) than at the outlets (Te and Tw) of the floodplain.
22 Conversely, concentration of TDS and DOC were significantly lower at the inlet to the
23 floodplain ($p < 0.05$). With the exception of the peaks of the flood pulse, TN:TP ratios were

1 always below 15-30, indicating phytoplankton N limitation (Geider and La Roche, 2002) on the
2 floodplain. Because phosphorus was not a limiting nutrient and TP patterns tracked closely with
3 TSS, this constituent was not included in further analyses. Additionally, because the focus of
4 this study was on nutrients and food resources, there was no further analysis of TDS (though
5 TDS was used to aid in defining the flushing phase of the flood pulse).

6
7 An analysis of fluxes across the floodplain indicated that the floodplain acted as an annual sink
8 for all measured constituents (Table 2). The floodplain was most effective at removing TSS and
9 VSS with a 68% and 63% removal efficiency (Table 3). On a yield basis this resulted in the
10 retention of 372 and 55 Mt ha⁻¹ yr⁻¹ of TSS and VSS, respectively (Table 4). Removal efficiency
11 was also high for Chl-a (55%) while the floodplain retained proportionally less DOC and TIN
12 (7% and 17%, respectively). Closer analysis of the data indicated that the floodplain acted as a
13 constituent sink during some floods and a source during others (Table 1). The trend indicated
14 that during small floods the floodplain acted as a source of DOC and either released Chl-a or
15 retained very little (Table 1). In contrast, during large floods the floodplain was always a sink.
16 To further investigate why this occurred we analyzed the source/sink dynamics for each phase of
17 the flood pulse.

18 19 *Phases of the flood pulse*

20 In our analysis we identified three distinct phases of the flood pulse. Figure 3 shows an example
21 flood from 2005 (flood 4) with associated flood pulse phases. At the onset of flooding there was
22 a flushing phase. A flushing period has traditionally been described in the literature as the period
23 at the initiation of flooding where solute and sediment export is elevated (Gupta and Saul, 1996;

1 Lee et al., 2002). As such, the boundary conditions for the flushing period are physical as well
2 as chemical. The flushing period began when stage began to rise at the floodplain inlet
3 (physical) and ended when outflow concentrations were not significantly different from inflow
4 (chemical) (Fig. 3). Having a chemical boundary condition meant that not all floods would have
5 a flushing phase. Our data indicate that a flushing phase (defined using flow, Chl-a, and TDS)
6 only occurred when a flood arrived after a period of dry antecedent conditions when floodwaters
7 had ceased to flow onto the floodplain. This occurred before floods 3 and 4, so these were the
8 only floods with flushing phases. The transport phase began either with the onset of flooding or
9 at the end of the flushing phase and ended when outflow from the floodplain exceeds inflow
10 (Fig. 3). When outflow exceeded inflow the floodplain drained and the water exiting the
11 floodplain was derived primarily from floodplain water, this we deem the draining phase (Fig.
12 3).

14 *Flushing*

15 Flushing phases were characterized during the rising limbs of floods 3 and 4 (Figs. 3 and 4).
16 When taken together the flushing phases exported 0.13 and 0.24 Mt ha⁻¹ yr⁻¹ of TSS and VSS
17 from the floodplain (Table 4). As the floodplain tended to retain TIN, the flushing phase only
18 exported 0.01 Mt ha⁻¹ yr⁻¹. Dissolved organic carbon and Chl-a were the two constituents which
19 were exported in the greatest quantities during this phase, with 0.72 and 1.0 Mt ha⁻¹ yr⁻¹,
20 respectively. Though these numbers were substantial, as a percentage of total annual influx the
21 constituent masses yielded during the flushing phase were small (Table 3), a testament to
22 dominance of the transport phase in annual floodplain fluxes.

23

1 It should be noted that constituent retention during the flushing phase was sufficiently small to
2 be within the range of error introduced by the flow estimations (~7%). As such, with this
3 method, we can not say with confidence that the floodplain acted as a source or sink for a given
4 constituent during this phase. Instead, if we assume inflow equaled outflow during this phase (a
5 reasonable assumption given the relatively simple hydraulics of the floodplain and short transit
6 times) we can compare constituent concentrations to assess retentiveness. During the flushing
7 phase concentrations of TSS and TIN were significantly higher at the inlet to the floodplain than
8 at the outlets, conversely concentrations of DOC and Chl-a were higher at the outlets (Table 5).
9 This would indicate that the flushing phase was marked by TSS and TIN retention, while
10 exporting DOC and Chl-a. Lastly, VSS was significantly greater at T_n than T_w but there was no
11 statistical difference between T_n and T_e (Table 5). Flux and concentration differences between
12 sites were greater during subsequent phases so flux differencing (as opposed to statistical
13 concentration comparisons) was used to quantify source/sink dynamics.

14

15 *Transport*

16 During the transport phase mean residence time (MRT) was 1.2 h (range = 0.8 – 8.6 h). As such,
17 there was not much time for biological processing on the floodplain. So while import of
18 sediment and dissolved constituents was high, export of autogenous floodplain constituents (Chl-
19 a, DOC) was low. The result was retention of all measured constituents save DOC during the
20 transport phases of the small floods (Tables 3 and 4). Of the measured constituents, sediment
21 retention was the greatest with an annual average retention of 940 Mt ha⁻¹ yr⁻¹ during the
22 transport phases of the large floods. The transport phases of the large floods dominated the
23 annual flux budget of the floodplain with between 93 and 98% of the annual retention for TSS,

1 VSS, and Chl-a occurring during these periods. During small floods, however, the
2 biogeochemical dominance of the transport phase was less prevalent; in these floods the draining
3 phase accounted for ~25% of the change in DOC and Chl-a fluxes across the floodplain.
4

5 *Draining*

6 In the context of constituent retention the draining phase was most similar to the flushing phase,
7 in that DOC and Chl-a were exported while sediment and nutrients were retained (Table 3 and
8 4). When weighed against annual fluxes the draining phase only accounted for <1% of the flux
9 budget for any given constituent (Table 3). But as previously mentioned, in a given small flood
10 the draining phase could account for ~25% of the Chl-a and DOC flux budget. It follows that the
11 biogeochemistry of large floods will be dominated by the transport phase while small flood
12 fluxes will be driven by a combination of the three phases. The flux vs. time graphs for Chl-a in
13 figure 4a,c,e provide a clear illustration of these dynamics. The net flux response in flood 3
14 (small flood, dry antecedent conditions) is dominated by the export of Chl-a in the flushing and
15 draining stages (Fig. 4a). Flood 5 was a small flood with wet antecedent conditions so there was
16 no flushing phase, as such the Chl-a response is dominated by the draining phase (Fig. 4c).
17 Finally, flood 6 is a large flood and clearly net Chl-a retention is driven by transport phase
18 dynamics (Fig. 4e).

19

20 **Discussion**

21 *Floodplain proportional flooding*

22 It has clearly been shown that residence time plays a vital role in biogeochemical dynamics of
23 large river systems (Reckendorfer et al., 1999) and floodplains (Hein et al., 2004). Hein et al.

1 (2004) found that water age on a Danubian floodplain was related to Chl-a hyperbolically with
2 maximum Chl-a occurring when the water in the floodplain was approximately 10 days old.
3 Similarly, in our study system it was found that Chl-a concentrations did not significantly
4 increase on the floodplain until floodwaters ceased from entering at the inlet breaches (Ahearn et
5 al., (in review)), that is until the draining phase was well under way. Tockner et al. (1999)
6 conducted the only other study that we are aware of which calculated a Chl-a flux balance for a
7 restored floodplain. In their analysis the monitored floodplain was an annual source of Chl-a
8 with a 4.5% increase between input and output fluxes. In our study the floodplain was an annual
9 Chl-a sink with 55% retention of influxed Chl-a. The most likely explanation for this difference
10 is the order of magnitude variation in mean residence time (MRT) between the two sites. The
11 Danubian floodplain had an MRT of 11 days while the MRT during this study was 1 day. So
12 while allochthonous Chl-a was being imported and retained in both systems, autochthonous
13 production and export was more limited in the Cosumnes.

14
15 In our study the importance of residence time can also be seen when comparing TIN and Chl-a
16 dynamics between flooding events. As flood volume increases (i.e. MRT decreases) less TIN
17 was retained and more Chl-a was retained (Fig. 5). Likewise, small floods tended to retain more
18 TIN and less Chl-a. This is likely a causal linkage because N:P ratios on the floodplain averaged
19 7.9, indicating N limitation to algal growth. This would imply that during small floods (high
20 MRT) the floodplain is more efficient at removing TIN and generating Chl-a. Given the need for
21 more high quality food resources in downstream receiving waters (Foe and Knight, 1985;
22 Kimmerer and Orsi, 1996), it would seem that phytoplankton generation from restored
23 floodplains would be optimized if only small floods occurred. In an unregulated system, this is

1 of course, impossible to control. What could be controlled however, is the amount of water
2 entering the floodplain (with a weir), and/or the size of the restored floodplain (with an
3 excavator). Both variables will control the MRT of waters passing through the floodplain. Past
4 research on floodplain fluxes has primarily been conducted in flow-controlled systems
5 (Engelhardt et al., 1999; Faber et al., 1989; Tockner et al., 1999; Valett et al., 2005) and those
6 that have monitored constituents that are affected by MRT have found their floodplains to be
7 biogeochemical sources. We believe the floodplain in our study acted as a sink because the
8 restored floodplain area/volume was not proportional to the magnitude of flooding. In a study by
9 Hamilton et al. (2004) on three undisturbed floodplains in South America they reported a ratio of
10 watershed area to floodplain area ranging between 2.5 and 6.5, in our study that same ratio is
11 5500. If flow onto the floodplain is not to be controlled then it is obvious that floodplain size
12 must be increased if rehabilitation to a more natural hydroperiod and associated biogeochemical
13 benefits are the goals.

14

15 *Partitioning the flood pulse*

16 In a definitive restored floodplain study, Tockner et al. (1999) outlined three hydrological phases
17 to flooding on a Danubian floodplain. Phase I was identified as the disconnection phase, phase II
18 was characterized by seepage flow and backwater connection, and phase III was the transport
19 phase. The characteristics of phase II became the backbone of what was later deemed the “flow
20 pulse” (Tockner et al., 2000), and which is now accepted as an important aspect of floodplain
21 hydrology/ecology. Given the information garnered from this study we believe it would be
22 informative to further divide phase III (transport phase) into the flushing phase, the transport

1 phase, and the draining phase. Each of these phases has independent biogeochemical and
2 physical variation which if grouped together goes unappreciated.
3
4 Figure 6 provides a conceptual model which enumerates the characteristics of all the flooding
5 phases in a temperate river-floodplain system. The disconnection phase is an important phase
6 for intra-floodplain dynamics as residence times, water temperature, and biotic competition for
7 resources are high (Heiler et al., 1995), but there is no surface export to the channel, so out-flux
8 is minimal. The flow pulse phase is highly variable from system to system and is dependent
9 upon subsurface connection between the main channel and the floodplain, the extent of tributary
10 waters, amount of direct rainfall, and degree of backwater inundation (Tockner et al., 2000).
11 This makes the flow pulse difficult to characterize in general terms. For instance, in our study
12 the flow pulse was nonexistent, as there were no tributaries entering the floodplain, the clay-rich
13 soil inhibited subsurface exchange, there was no backwater effect, and there was a small area
14 within which rainfall could collect. In braided systems however, the flow pulse is an easily
15 identifiable and vital stage in the flooding process (see Tockner et al., 2000). The flushing phase
16 is important for intra-floodplain dynamics as it redistributes floodplain resources and forms a
17 complex perirheic front between floodwaters and displaced antecedent waters on the floodplain
18 (Ahearn et al., (in review); Mertes, 1997). This process contributes to floodplain heterogeneity
19 and patch complexity. This phase is short lived but can export high concentrations of Chl-a (Fig.
20 4a,b) and DOC (Table 4). The transport phase will likely determine the floodplain flux balance
21 for a given flooding event. We propose that MRT during the transport phase will be the
22 governing control on the mass balance of the flood pulse. If the floodplain volume and flood
23 magnitude are “proportional” then we may see constituent export during this phase (see DOC

1 export for small floods, Table 3 and 4), otherwise this phase will be characterized by mass
2 retention. The draining phase will, in general, last longer than the transport and flushing phases,
3 and will be defined by the export of waters from the high residence time distal areas of the
4 floodplain. During this phase the floodplain is expected to be an exporter of food resources (Chl-
5 a, DOC) to downstream receiving waters. Because of the relatively long duration of the draining
6 phase and flow pulse phase and due to the trend toward the export of food resources during these
7 phases, these two periods constitute an ecologically vital portion of the flood pulse.

8

9 *Coarse particulate organic matter export*

10 A caveat which necessitates mentioning is that coarse particulate organic matter (CPOM, defined
11 here as particulate organic matter > 1mm) was not measured in this study. Previous studies on
12 the fluxing of materials through floodplains have focused on organic and inorganic sediments
13 (Florsheim and Mount, 2002; Gomez et al., 2003; Walling et al., 1999), phosphorus (Mitsch et
14 al., 1995), nitrogen (Andersen, 2004), or a combination of sediment, nutrients, and seston
15 (Brunet and Astin, 2000; Engelhardt et al., 1999; Valett et al., 2005). Other studies have
16 concentrated on inputs and outputs of CPOM (Cellot et al., 1998; Cuffney, 1988; Jones and
17 Smock, 1991), but rare are the studies that address the fluxing of both particulate and dissolved
18 forms of carbon across floodplains (for two examples see Robertson et al., 1999; Tockner et al.,
19 1999). These latter studies are vital if the export of food resources from floodplains is going to
20 be rigorously addressed.

21

22 It has been shown that attached algae can account for a substantial portion of the biomass in
23 productive shallow waters (Kaldy et al., 2002; Moncreiff et al., 1992) and be the primary

1 foundation for floodplain aquatic food webs (Bunn et al., 2003). During the transport phase,
2 when primary flowpaths shift across the floodplain, a portion of this algal material along with
3 other forms of CPOM on the floodplain may be dislodged and potentially exported. Indeed, the
4 studies of which we are aware that have quantified CPOM budgets for lowland floodplains have
5 all found the floodplains to be CPOM sources (Cellot et al., 1998; Cuffney, 1988; Tockner et al.,
6 1999). Cursory vegetative assays of our study floodplain indicated that epiphytic algae were
7 abundant in all but the deepest ponded areas. It follows that though the floodplain in our study
8 was a sink for all measured constituents, it could well have been a source of nutrient-rich CPOM,
9 a potentially important food source for downstream aquatic environments. Junk et al. (1989)
10 postulated that slow pulsing, or flood pulses with high MRT, would not export as much carbon
11 and nutrients to the channel as fast high-flow pulses. It is true that large storms can export high
12 quantities of particulate organic matter from a floodplain but our data indicate that floodplains
13 will not necessarily be “flushed” of other important constituents (DOC, Chl-a) during these large
14 events. Instead we have seen that export of DOC and Chl-a occur during the slow pulse events.
15 In this way it would seem that both small and large floods are necessary to create a diverse and
16 productive linkage between the channel and its floodplain.

17

18 **Conclusions**

19 Though on an annual basis the studied floodplain was a sink for all measured constituents,
20 analysis of small and large floods reveals a more complex story. We have shown that during
21 large floods the flood pulse is dominated by the transport phase – and because retention times are
22 very low on our floodplain during this stage thereby limiting autochthonous production of DOC
23 and Chl-a – the floodplain acts as a net sink. During small floods however, net flux through the

1 duration of the flood pulse can be substantially influenced by the flushing and draining phases.
2 These phases tend to export food resources from the floodplain, so during small floods the
3 floodplain acted as a net source of DOC and, for one flood, a net source of Chl-a. The
4 partitioning of the flood pulse into these three phases was helpful in explaining the
5 biogeochemical dynamics on the floodplain and we have proposed an amendment to Tockner's
6 (1999) hydrological phases to include our results. The resultant conceptual model is now more
7 rigorous and hopefully will be applicable to other temperate systems. If a primary goal of future
8 floodplain restoration is to create an additional source of food resources for downstream aquatic
9 systems then we recommend a variable hydroperiod which includes "floodplain proportional
10 flooding". A variety of flood intensities would assure the efficient export of both the dissolved
11 and particulate materials which are essential for downstream aquatic ecosystems.

12

13 **Acknowledgments**

14 The authors would like to thank X. Wang and E. Gallo for their help and support in this project.
15 Consultation regarding the statistical analysis approach was provided by J. Lenth of Herrera
16 Environmental Consultants. Aid with GIS analysis was graciously provided by J. Viers. We
17 would also like to thank the Cosumnes River Preserve Partners for access to the floodplain and
18 support of these research efforts. This research was funded by California Bay-Delta Authority
19 Ecological Restoration Program (Award # ERP-01-NO1).

Figures

Fig. 1 – 200 dpi

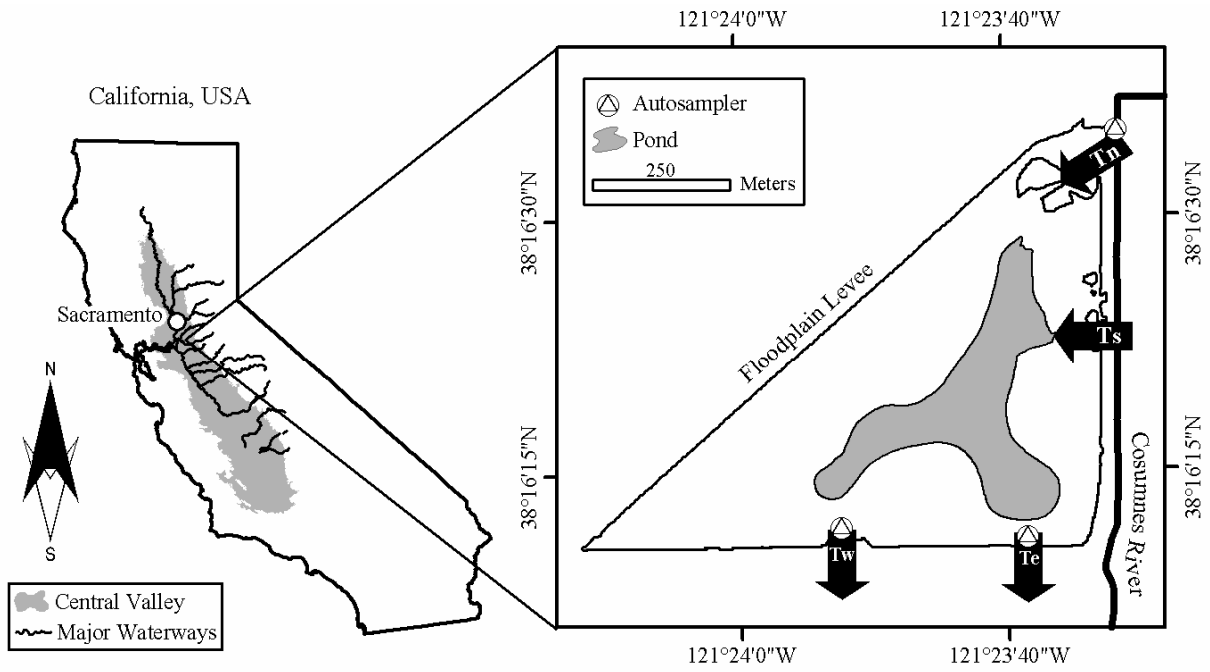


Fig. 2

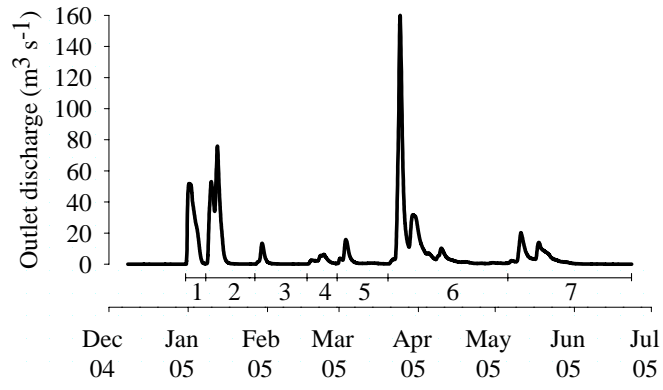


Fig. 3

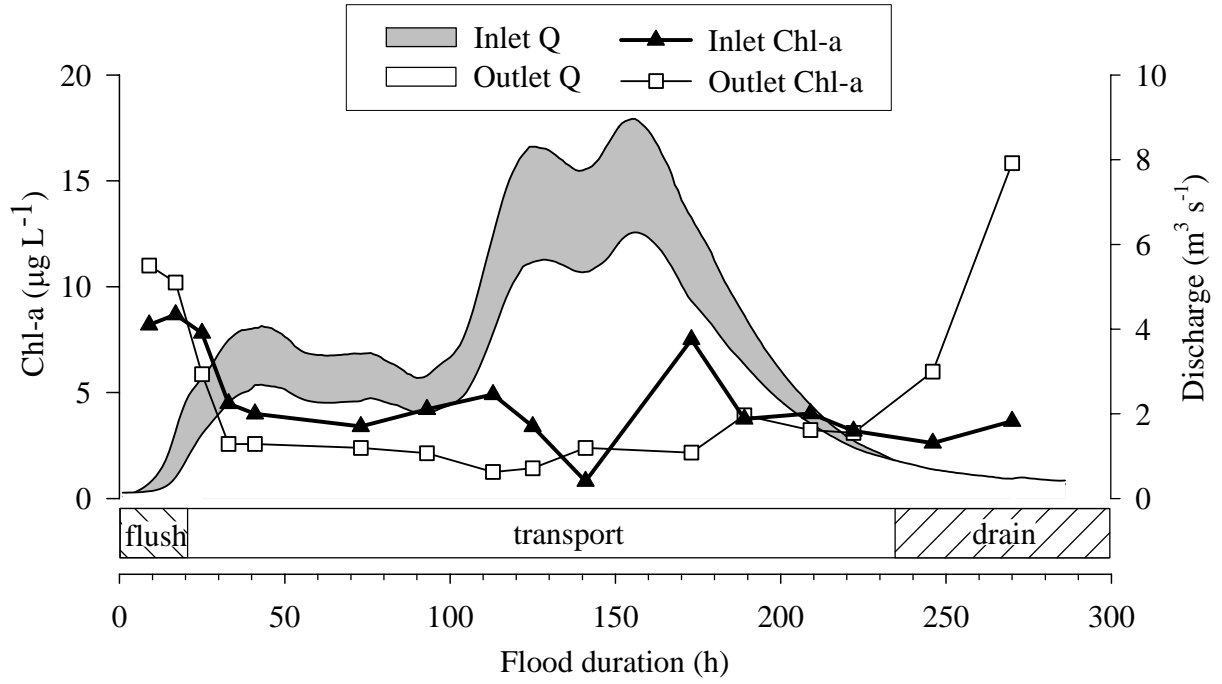


Fig. 4

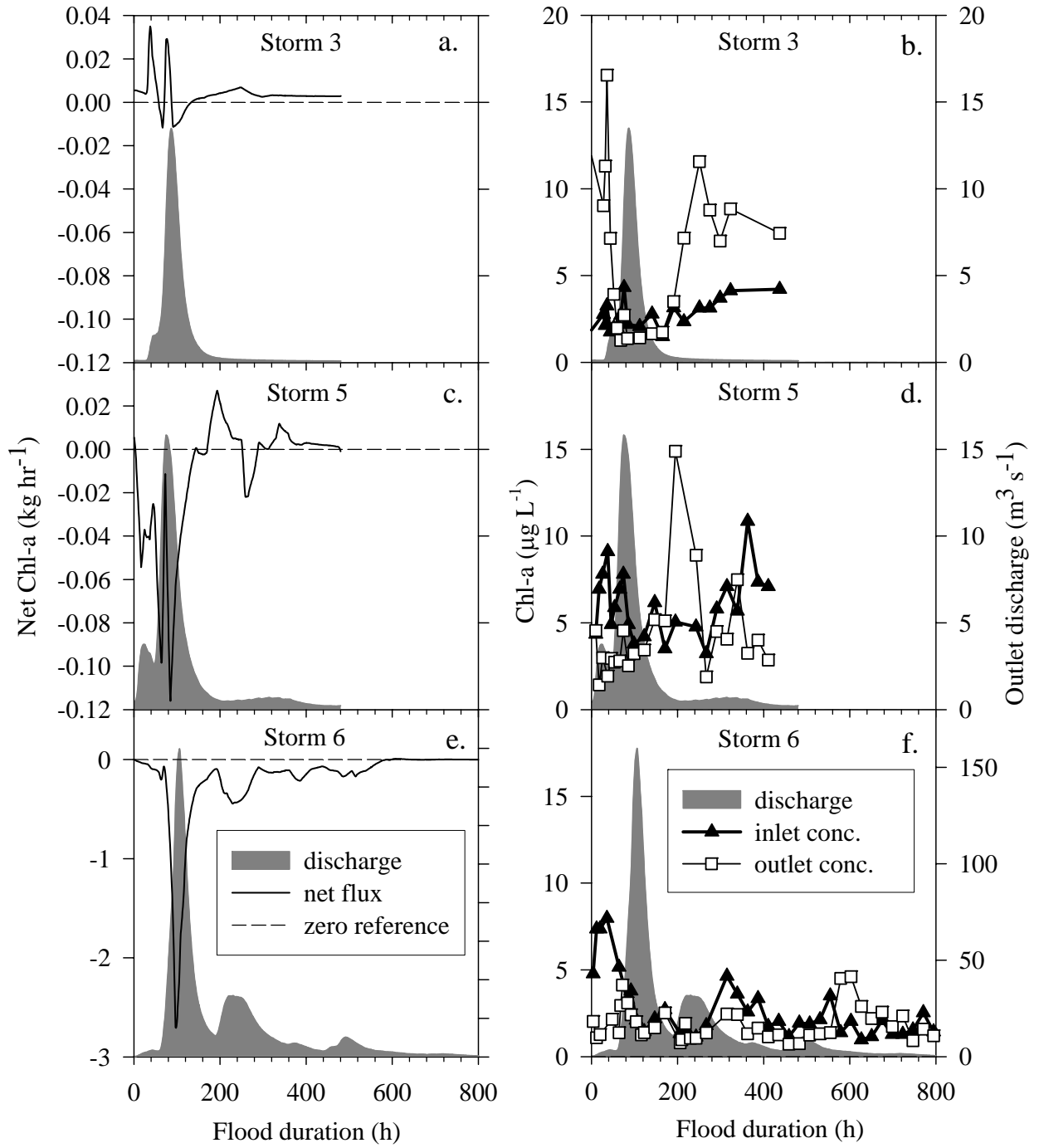


Fig. 5

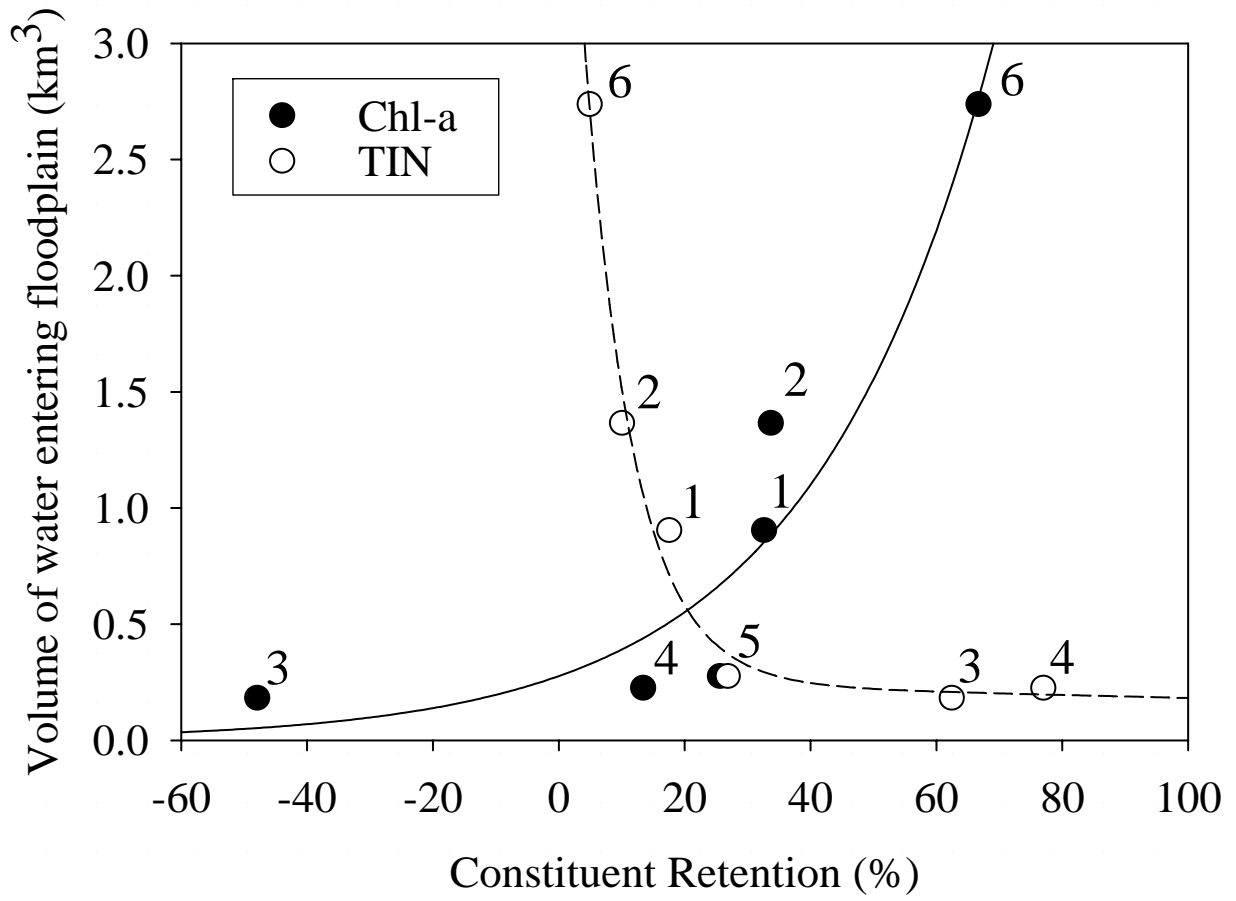
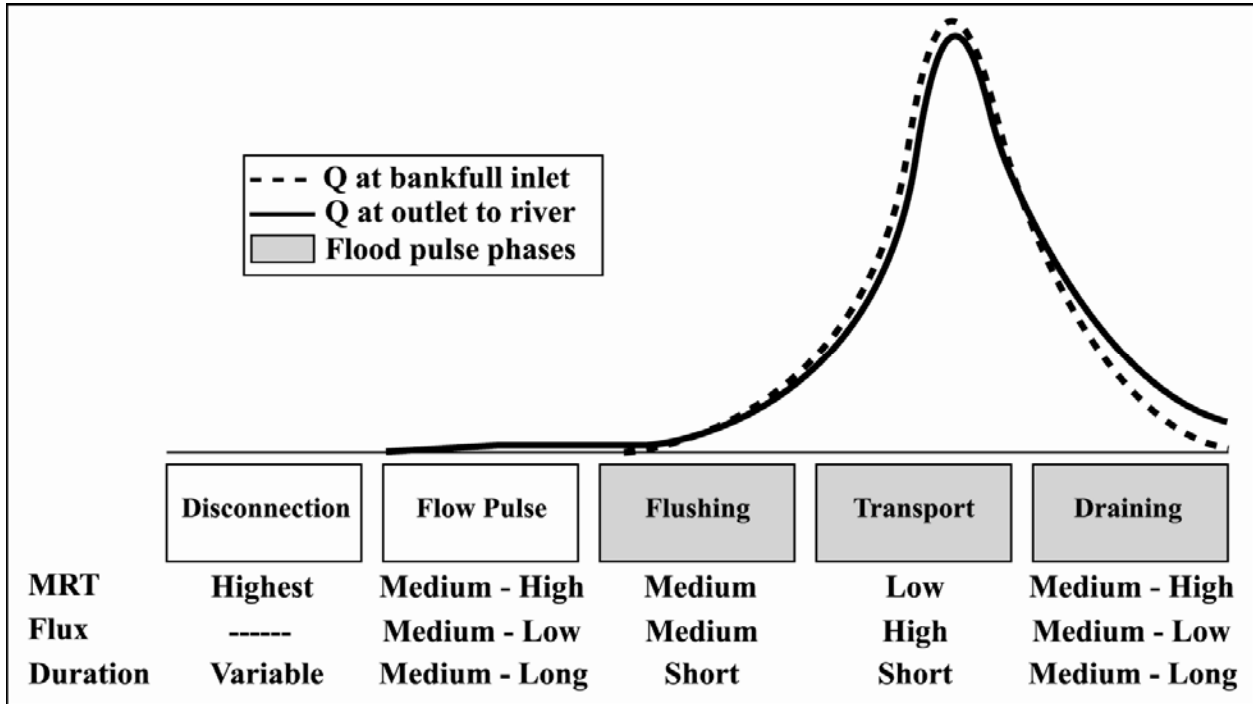


Fig. 6 – 200 dpi



1 **Figure Captions**

2 Fig. 1

3 Location of the restored floodplain in the Cosumnes River Watershed. Direction of flow onto
4 and off the floodplain is indicated at each of the four breaches. Locations of autosamplers for the
5 collection of water quality samples are also marked.

6

7 Fig. 2

8 Combined flood hydrograph from the exit breaches (T_e , T_w). There were seven distinct floods
9 in 2005, in this study flood 7 was excluded due to stage gage equipment failure at the inlet
10 breach (T_n).

11

12 Fig. 3

13 An example hydrograph and chemograph from flood 4 for the purpose of illustrating the stages
14 of the flood pulse. The flushing phase is marked by the increase of Chl-a at the outlets. The
15 transport phase illustrates Chl-a retention in the system as the inlet concentrations and flows are
16 consistently higher than outlet. The draining phase is marked by increased Chl-a concentrations
17 at the outlet and greater outflow than inflow.

18

19 Fig.4

20 Chlorophyll-a fluxes and input/output concentrations for three representative floods during 2005.
21 Flood 3 was a small flood preceded by a dry period so a flushing phase is evident in (a) the flux
22 response and (b) the inlet and outlet concentrations. Flood 5 had no flushing period but the
23 significance of the draining phase is evident in both (c) the flux response and (d) the

1 chemograph. Flood 6 was the largest of the season and imported large amounts of Chl-a while
2 exporting less, the result is the flux response and chemograph seen in (e) and (f).

3

4 Fig. 5

5 Percent Chl-a and TIN retention (as a percentage of flood flux) vs the flood volume reveals an
6 inverse relationship between the two constituents. Each flood is marked with its flood number.

7

8 Fig. 6

9 Conceptual model of the phases of the flood pulse. A model hydrograph serves as an example of
10 potential inflow and outflow dynamics during each phase. The mean residence time (MRT),
11 intensity of constituent fluxing, and duration of each phase is tabulated.

Table 1. Comparison of paired constituent concentrations (n = 169) entering the floodplain at Tn and exiting at Te and Tw using a Freidman test (Helsel and Hirsch, 1992) for significance with a subsequent nonparametric multiple range test (Zar, 1984) for describing relationships between sites.

Parameter	Sampling Site			p-Value ^{\$}
	Tn	Te	Tw	
TDS	1 ^{a*}	2 ^b	3 ^c	<0.001
TSS	3 ^c	2 ^b	1 ^a	<0.001
VSS	3 ^b	2 ^a	1 ^a	<0.001
TIN	3 ^c	2 ^b	1 ^a	<0.001
TP	3 ^c	2 ^b	1 ^a	<0.001
DOC	1 ^a	2 ^b	3 ^c	<0.001
Chl-a	3 ^b	2 ^a	1 ^a	<0.001

*Numbers indicate relative relationship (1= low, 3=high) between Friedman rank sums for each site, while superscript letter indicates if the relationship is significantly different.

\$ Friedman p-Value assessing significant differences among the three stations. Bold values indicate that significant differences exist between the sampling sites ($\alpha = 0.05$).

Table 2. Mass retention of constituents for each of the 6 floods analyzed.

Flood	Relative size	MRT days	TSS Mt	VSS Mt	TIN Mt	DOC Mt	Chl-a kg
1	large	0.3	572	88	2	11	12
2	large	0.4	757	96	1	4	13
3	small	3.5	20	2	1	-5	-2
4	small	1.9	103	13	1	-5	1
5	small	2.3	124	10	0.3	-10	5
6	large	0.5	3024	469	0.4	42	162
all storms	—	1.0	4600	678	5.7	39	191

Table 3. Constituent mass retention as a percentage of annual influx to the floodplain. Retention is partitioned by flood pulse phase and frequency of occurrence (%) is reported for each phase.

Data are tabulated for large flood events as well as for the small floods alone.

		Water	TSS	VSS	TIN	DOC	Chl-a	Frequency
Large floods	Flushing ¹	—	—	—	—	—	—	—
	Transport	1.07	63.49	59.94	9.37	9.00	53.56	37
	Draining	-0.43	0.49	0.31	0.39	-0.34	-0.23	20
Small floods ²	Flushing	-0.02	-0.01	-0.01	-0.01	-0.03	-0.08	2
	Transport	2.99	3.22	2.22	6.81	-1.29	2.22	17
	Draining	-0.34	0.42	0.15	0.28	-0.40	-0.83	24
All floods	Annual total	3.27	67.62	62.61	16.85	6.94	54.64	100

¹No large flood was preceded by a period of high residence time on the floodplain so there was no flushing phase for the large floods.

²Floods 1, 2, and 6 were considered large floods, while floods 3, 4, and 5 were considered small (see Fig. 2).

Table 4. Floodplain yield ($\text{Mt ha}^{-1} \text{ yr}^{-1}$) for measured constituents. Yields are calculated for each flood-pulse phase for both the large and small floods of 2005.

		TSS	VSS	TIN	DOC	Chl-a $\times 10^3$	Duration (d)
Large floods	Flushing ¹	—	—	—	—	—	0
	Transport	-940	-141	-0.64	-11	-41	47
	Draining	-13	-1	-0.05	0.75	0.32	26
Small floods ²	Flushing	0.13	0.24	0.01	0.72	1	3
	Transport	-105	-12	-0.99	3	-4	21
	Draining	-10	-0.54	-0.03	0.76	1	30
All floods	Annual total	-372	-55	-0.43	-3	-0.01	127

¹No large flood was preceded by a period of high residence time on the floodplain so there was no flushing phase for the large floods.

²Floods 1, 2, and 6 were considered large floods, while floods 3, 4, and 5 were considered small (see Table 2).

1 Table 5. Comparison of paired constituent concentrations (n = 9) entering the floodplain during
 2 the flushing phase at Tn and exiting at Te and Tw using a Freidman test (Helsel and Hirsch,
 3 1992) for significance with a subsequent nonparametric multiple range test (Zar, 1984) for
 4 describing relationships between sites.

Parameter	Sampling Site			p-Value ^{\$}
	Tn	Te	Tw	
TSS	3 ^b	2 ^a	1 ^a	<0.001
VSS	3 ^b	2 ^{ab}	1 ^a	0.032
TIN	3 ^b	2 ^a	1 ^a	<0.001
DOC	1 ^a	2 ^b	3 ^b	<0.001
Chl-a	1 ^a	2 ^b	3 ^b	<0.001

5 ^{*}Numbers indicate relative relationship (1= low, 3=high) between Friedman rank sums for each
 6 site, while superscript letter indicates if the relationship is significantly different.

7 ^{\$} Friedman p-Value assessing significant differences among the three stations. Bold values
 8 indicate that significant differences exist between the sampling sites ($\alpha = 0.05$).

9
 10
 11
 12
 13
 14
 15
 16
 17
 18
 19
 20

1 **References**

2

3 Ahearn, D.S., Sheibley, R.W., Dahlgren, R.A. and Keller, K.E., 2004. Temporal dynamics of
4 stream water chemistry in the last free-flowing river draining the western Sierra Nevada,
5 California. *Journal of Hydrology*, 295(1-4): 47-63.

6 Ahearn, D.S., Viers, J.H., Mount, J.F. and Dahlgren, R.A., (in review). Priming the productivity
7 pump: Flood pulse driven trends in suspended algal biomass distribution across a restored
8 floodplain. *Freshwater Biology*.

9 American Public Health Association, 1998. *Standard Methods for the Examination of Water and*
10 *Wastewater*. APHA, AWWA, WEF, Baltimore, MD.

11 Andersen, H.E., 2004. Hydrology and nitrogen balance of a seasonally inundated Danish
12 floodplain wetland. *Hydrological Processes*, 18(3): 415-434.

13 Babbitt, B., 1995. Science - Opening the next chapter of conservation history. *Science*,
14 267(5206): 1954-1955.

15 Bayley, P.B., 1995. Understanding large river floodplain ecosystems. *Bioscience*, 45(3): 153-
16 158.

17 Brunet, R.C. and Astin, K.B., 2000. A 12-month sediment and nutrient budget in a floodplain
18 reach of the River Adour, southwest France. *Regulated Rivers-Research & Management*,
19 16(3): 267-277.

20 Bunn, S.E., Davies, P.M. and Winning, M., 2003. Sources of organic carbon supporting the food
21 web of an arid zone floodplain river. *Freshwater Biology*, 48(4): 619-635.

22 Cellot, B., Mouillot, F. and Henry, C.P., 1998. Flood drift and propagule bank of aquatic
23 macrophytes in a riverine wetland. *Journal of Vegetation Science*, 9(5): 631-640.

- 1 Cuffney, T.F., 1988. Input, movement and exchange of organic-matter within a sub-tropical
2 coastal blackwater river floodplain system. *Freshwater Biology*, 19(3): 305-320.
- 3 Dahm, C.N., Cummins, K.W., Valett, H.M. and Coleman, R.L., 1995. An ecosystem view of the
4 restoration of the Kissimmee River. *Restoration Ecology*, 3(3): 225-238.
- 5 Doane, T.A. and Horwath, W.R., 2003. Spectrophotometric determination of nitrate with a single
6 reagent. *Analytical Letters*, 36(12): 2713-2722.
- 7 Engelhardt, C., Kruger, A., Karrasch, B. and Baborowski, M., 1999. Input-output balances of
8 nutrients and plankton in a flooded area of the lower Odra. *Acta Biochimica et*
9 *Biophysica Hungarica*, 27(5): 325-330.
- 10 Faber, P.A., Keller, E., Sands, A. and Masser, B.M., 1989. The Ecology of Riparian Habitats of
11 the Southern California Coastal Region: A Community Profile. Biological Report
12 85(7.27), U.S. Fish and Wildlife Service, Washington, DC.
- 13 Florsheim, J.L. and Mount, J.F., 2002. Restoration of floodplain topography by sand-splay
14 complex formation in response to intentional levee breaches, Lower Cosumnes River,
15 California. *Geomorphology*, 44(1-2): 67-94.
- 16 Foe, C. and Knight, A., 1985. The effect of phytoplankton and suspended sediment on the
17 growth of *Corbicula fluminea* (Bivalvia). *Hydrobiologia*, 127(2): 105-115.
- 18 Forster, J.C., 1995. Soil nitrogen. In: P. Nannipieri (Editor), *Methods in Applied Soil*
19 *Microbiology and Biochemistry*. Academic Press, San Diego, CA, pp. 79-87.
- 20 Geider, R.J. and La Roche, J., 2002. Redfield revisited: variability of C : N : P in marine
21 microalgae and its biochemical basis.
- 22 Gomez, B. et al., 2003. Production, storage, and output of particulate organic carbon: Waipaoa
23 River basin, New Zealand. *Water Resources Research*, 39(6): 1-8.

1 Gupta, K. and Saul, A.J., 1996. Specific relationships for the first flush load in combined sewer
2 flows. *Water Research*, 30(5): 1244-1252.

3 Hamilton, S.K., Sippel, S.J. and Melack, J.M., 2004. Seasonal inundation patterns in two large
4 savanna floodplains of South America: the Llanos de Moxos (Bolivia) and the Llanos del
5 Orinoco (Venezuela and Colombia). *Hydrological Processes*, 18(11): 2103-2116.

6 Hauer, R.F. and Lamberti, G.A., 1996. *Methods in Stream Ecology*. Academic Press, San Diego,
7 CA.

8 Heiler, G., Hein, T., Schiemer, F. and Bornette, G., 1995. Hydrological connectivity and flood
9 pulses as the central aspects for the integrity of a river-floodplain system.

10 Hein, T., Baranyi, C., Reckendorfer, W. and Schiemer, F., 2004. The impact of surface water
11 exchange on the nutrient and particle dynamics in side-arms along the River Danube,
12 Austria. *Science of the Total Environment*, 328(1-3): 207-218.

13 Helsel, D.R. and Hirsch, R.M., 1992. *Statistical Methods in Water Resources*. Studies in
14 Environmental Science 49. Elsevier Publications, New York, NY, 522 pp.

15 Jassby, A.D. and Cloern, J.E., 2000. Organic matter sources and rehabilitation of the
16 Sacramento-San Joaquin Delta (California, USA). *Aquatic Conservation-Marine and
17 Freshwater Ecosystems*, 10(N5): 323-352.

18 Johnston Associates, 1989. A status report on the nation's floodplain management activity: an
19 interim report prepared for the interagency task force on floodplain management., U.S.
20 Government Printing Office, Washington, D.C.

21 Jones, J.B. and Smock, L.A., 1991. Transport and retention of particulate organic-matter in 2
22 low-gradient headwater streams. *Journal of the North American Benthological Society*,
23 10(2): 115-126.

- 1 Junk, W.J., Bayley, P.B. and Sparks, R.E., 1989. The flood pulse concept in river-floodplain
2 systems. In: D.P. Dodge (Editor), Proceedings of the International Large River
3 Symposium. Canadian Special Publication of Fisheries and Aquatic Sciences, Ottawa,
4 Canada, pp. 110-127.
- 5 Kaldy, J.E., Onuf, C.P., Eldridge, P.M. and Cifuentes, L.A., 2002. Carbon budget for a
6 subtropical seagrass dominated coastal lagoon: How important are seagrasses to total
7 ecosystem net primary production? *Estuaries*, 25(4A): 528-539.
- 8 Kimmerer, W.J. and Orsi, J.J., 1996. Causes of long-term declines in zooplankton in the San
9 Francisco Bay estuary since 1987. In: J.T. Hollibaugh (Editor), *San Francisco Bay: The*
10 *Ecosystem*. AAAS, San Francisco, CA, pp. 403-424.
- 11 Lee, J.H., Bang, K.W., Ketchum, L.H., Choe, J.S. and Yu, M.J., 2002. First flush analysis of
12 urban storm runoff. *Science of the Total Environment*, 293(1-3): 163-175.
- 13 Mertes, L.A.K., 1997. Documentation and significance of the perirheic zone on inundated
14 floodplains. *Water Resources Research*, 33(7): 1749-1762.
- 15 Mitsch, W.J., Cronk, J.K., Wu, X.Y., Nairn, R.W. and Hey, D.L., 1995. Phosphorus retention in
16 constructed fresh-water riparian marshes. *Ecological Applications*, 5(3): 830-845.
- 17 Mitsch, W.J. and Gosselink, J.G., 2000. *Wetlands*. John Wiley & Sons, New York, NY, 920 pp.
- 18 Moncreiff, C.A., Sullivan, M.J. and Daehnick, A.E., 1992. Primary Production Dynamics in
19 Seagrass Beds of Mississippi Sound - the Contributions of Seagrass, Epiphytic Algae,
20 Sand Microflora, and Phytoplankton.
- 21 Murphy, J. and Riley, J.P., 1962. A modified single-solution method for determination of
22 phosphate in natural waters. *Analytica Chimica Acta*, 27: 31-36.

- 1 Reckendorfer, W., Keckeis, H., Winkler, G. and Schiemer, F., 1999. Zooplankton abundance in
2 the River Danube, Austria: the significance of inshore retention. *Freshwater Biology*,
3 41(3): 583-591.
- 4 Robertson, A.I., Bacon, P. and Heagney, G., 2001. The responses of floodplain primary
5 production to flood frequency and timing. *Journal of Applied Ecology*, 38(1): 126-136.
- 6 Robertson, A.I., Bunn, S.E., Boon, P.I. and Walker, K.F., 1999. Sources, sinks and
7 transformations of organic carbon in Australian floodplain rivers. *Marine and Freshwater*
8 *Research*, 50(8): 813-829.
- 9 Sommer, T. et al., 2001. California's Yolo Bypass: Evidence that flood control can be compatible
10 with fisheries, wetlands, wildlife, and agriculture. *Fisheries*, 26(8): 6-16.
- 11 Sommer, T.R., Harrell, W.C., Solger, A.M., Tom, B. and Kimmerer, W., 2004. Effects of flow
12 variation on channel and floodplain biota and habitats of the Sacramento River,
13 California, USA. *Aquatic Conservation-Marine and Freshwater Ecosystems*, 14(3): 247-
14 261.
- 15 Taylor, P.D., Fahrig, L., Henein, K. and Merriam, G., 1993. Connectivity is a vital element of
16 landscape structure. *Oikos*, 68(3): 571-573.
- 17 Tockner, K., Malard, F. and Ward, J.V., 2000. An extension of the flood pulse concept.
18 *Hydrological Processes*, 14(16-17): 2861-2883.
- 19 Tockner, K., Pennetzdorfer, D., Reiner, N., Schiemer, F. and Ward, J.V., 1999. Hydrological
20 connectivity, and the exchange of organic matter and nutrients in a dynamic river-
21 floodplain system (Danube, Austria). *Freshwater Biology*, 41(3): 521-535.
- 22 Valett, H.M. et al., 2005. Biogeochemical and metabolic responses to the flood pulse in a
23 semiarid floodplain. *Ecology*, 86(1): 220-234.

1 Vitousek, P.M., Mooney, H.A., Lubchenco, J. and Melillo, J.M., 1997. Human domination of
2 Earth's ecosystems. *Science*, 277(5325): 494-499.

3 Walling, D.E., Owens, P.N. and Leeks, G.J.L., 1999. Rates of contemporary overbank
4 sedimentation and sediment storage on the floodplains of the main channel systems of the
5 Yorkshire Ouse and River Tweed, UK. *Hydrological Processes*, 13(7): 993-1009.

6 Ward, J.V. and Stanford, J.A., 1995. Ecological connectivity in alluvial river ecosystems and Its
7 disruption by flow regulation. *Regulated Rivers-Research & Management*, 11(1): 105-
8 119.

9 Wetzel, R.G., 1992. Gradient-dominated ecosystems - Sources and regulatory functions of
10 dissolved organic-matter in fresh-water ecosystems. *Hydrobiologia*, 229: 181-198.

11 Whalen, P.J., Toth, L.A., Koebel, J.W. and Strayer, P.K., 2002. Kissimmee River restoration: a
12 case study. *Water Science and Technology*, 45(11): 55-62.

13 Yu, Z.S., Northup, R.R. and Dahlgren, R.A., 1994. Determination of dissolved organic nitrogen
14 using persulfate oxidation and conductimetric quantification of nitrate-nitrogen.
15 *Communications in Soil Science and Plant Analysis*, 25(19-20): 3161-3169.

16 Zar, J.H., 1984. *Biostatistical Analysis*. Prentice Hall, Inc., Englewood Cliffs, NJ, 718 pp.
17