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WATER QUALITY RESPONSE TO A PULSED-FLOW EVENT ON THE MOKELUMNE RIVER, CALIFORNIA

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ABSTRACT

Controlled water releases from reservoirs (i.e. artificial floods) are used as a management technique to remove fine sediments and detrital materials from spawning gravels, mobilize gravel bars and clear encroaching brush from stream banks. The effects of a managed release event on water quality were investigated on the lower Mokelumne River in the western Sierra Nevada, California. The managed release was characterized by an increase in flow over a 4-day period (from 11 to 57 $m^3 s^{-1}$). Automatic pump samplers were used to collect samples for water quality from 0.7, 16.4, 37.4 and 54.4 km below Camanche Dam. These sampling sites provided water quality data for three distinct stream reaches: a gravel and sand-textured substrate reach (0.7–16.4 km), a reach characterized by lentic conditions associated with a small reservoir (16.4–37.4 km), and fine sand and silt-textured substrate reach (37.4–54.4 km). Water samples were analysed for total suspended solids (TSS), total nitrogen, ammonium (NH_4-N), nitrate (NO_3-N), total phosphorus, soluble reactive phosphorus (SRP), dissolved organic carbon (DOC), foecal coliforms and *E. coli*. Chemographs for all constituents exhibited spikes in concentration with each increase in streamflow for the rising limb. Fluxes of TSS, total P and total N released from the 0.7 to 16.4 km reach were 322, 0.32 and 0.70 Mg, respectively. The small reservoir acted as a sink for particulate materials retaining about 50% of TSS, 48% of total P and 43% of total N. However, the reservoir acted as a source of dissolved nutrients (NO_3-N = 0.28 Mg and SRP = 0.055 Mg). The stream reach below the reservoir (37.4 to 54.4 km) was a source of particulate materials, dissolved nutrients and bacteria, possibly due to agricultural and urban inputs. Copyright © 2007 John Wiley & Sons, Ltd.

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INTRODUCTION

River flow regulation by dams/impoundments often results in adverse effects on downstream riverine habitat (Chin *et al*., 2002; Nislow *et al*., 2002; Petts *et al*., 1993). Pulsed flow events (artificial floods) are one management technique that has gained considerable interest as a means to improve ecological conditions by mimicking 'natural flow' regimes (McDonald *et al*., 1982; Poff *et al*., 1997). It is known that impounded rivers display altered geomorphological, chemical and biological patterns on both a temporal and spatial scale as compared to free flowing rivers (Petts, 1980). The paucity of high-flow events facilitates the accumulation of fine sediments and organic material within gravels (Morris and Fan, 1998; Stevens *et al*., 2001) and promotes periphyton, aquatic macrophyte and riparian vegetation growth (Johnson *et al*., 1995). Additionally, impoundments with hypolimnetic release points have been shown to buffer seasonal thermal fluctuations (Webb and Walling, 1996). These alterations impact community trophic structure and disrupt the seasonal chemical and physical signals upon which organisms rely (Ward and Stanford, 1979). Ultimately, these conditions can lead to a reduction in aquatic ecosystem biodiversity and an increase in aggressive non-native species (Moyle, 1995).

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It is hypothesized that pulse flow events can improve downstream fish and macroinvertebrate habitat and discourage non-native species that are not adapted to high flushing flows (Stanford *et al*., 1996). Pulse releases have been shown to successfully remove fine sediments (Kondolf and Wilcock, 1996) and create sediment bars (Beschta *et al*., 1981), as well as facilitate changes in channel and floodplain geomorphology (Beschta *et al*., 1981; Kondolf and Wilcock, 1996; Schmidt *et al*., 2001). In natural flow regimes, bankfull discharges (highest flows without flooding) are most effective at moving sediment, re-ordering substrate, and forming and shaping sand bars (Hill *et al*., 1991). However, determining the optimum magnitude of the pulse release is often dependent on more than just ecological and geomorphological factors; the loss of hydropower, loss of water supply, and the estimated gravel size that will be entrained by the pulse are key considerations when determining the magnitude of the pulse to release (Kondolf and Wilcock, 1996; Wu and Chou, 2004). Of the pulse release studies that have been conducted only a few have emphasized varied flow regimes and their effects on sediment transport and water quality (Petts *et al*., 1985; Robinson *et al*., 2003).

Unlike natural floods, pulse flows are artificial floods caused by dam release whereby there is no direct chemical or sediment contribution from the terrestrial landscape via runoff. River bedload is considered one of the primary contributors of constituents determining water quality during pulse releases (Jakob *et al*., 2003; Petts *et al*., 1985). However, particulate and solute contributions from submerged banks due to stage rise are yet to be quantified and must not be overlooked. Substrate type is an obvious driver of water quality during pulse releases. Substrate structure and consistency determine the amount of entrainable material within the channel and determine the storage capacity for certain water quality constituents, such as phosphorus that is sorbed to sediments.

The export of many water quality constituents (e.g. nutrients, pathogens) during pulse flows is often correlated with the entrainment of sediments. Foulger and Petts (1984) described how suspended solids play a significant role in controlling solute release during pulse flows, while other studies show that in-channel sediment stores may be a potential trap for phosphorus (Evans and Johnes, 2004) and bacteria (McDonald *et al*., 1982). Sediment transport is highly variable and is related to the magnitude of the pulse, the channel morphology, and storage and availability of sediments within the bed material (Foulger and Petts, 1984; Nislow *et al*., 2002; Robinson *et al*., 2004). The response of sediment concentrations to pulse flows often displays an unpredictable hysteresis whereby concentration peaks can occur prior to (Petts *et al*., 1985), coincident with (Beschta *et al*., 1981), or following (Jakob *et al*., 2003) peak flow. These differences in sediment pulse timing reflect the complexity and variation that exists within river channels and make predictions of water quality response to pulse flows difficult.

This study examined pulse flows in the lower Mokelumne River, California that were conducted to enhance the integrity of restored salmon spawning gravels below Camanche Dam. Persistent low flows over a 2-year period led to sedimentation of fines within the spawning gravels and extensive growth of submerged macrophytes, which were thought to decrease salmon hatch survival. Flow was increased to $57\,m^3\,s^{-1}$ in a series of four stepped flow increases to scour sediment and aquatic macrophytes from the river channel. The purpose of this paper is to determine spatial and temporal patterns of dissolved and particulate water quality constituents (sediments, nutrients, bacterial, dissolved organic carbon) resulting from stepped flow water releases of varying magnitudes ($11–57\,m^3\,s^{-1}$). Downstream changes in water quality constituents (concentrations and fluxes) are related to differences in stream reach characteristics. Results of this study provide a basis for design of future controlled water releases in terms of discharge-sediment transport characteristics and meeting water quality concerns.

STUDY SITE

The study was conducted downstream of Camanche Dam in the lower Mokelumne River watershed located in the central Sierra Nevada (watershed area $\approx 1624\,km^2$; Figure 1). Water quality constituents were examined at four sites over a 54.4 km reach (distance from dam/elevation: Site A = 0.7 km/39.3 m; Site B = 16.4 km/17 m; Site C = 37.4 km/9.7 m; Site D = 54.4 km/3 m). Land use grades with decreasing elevation from rural oak woodlands, to farmland and vineyards, to an urban landscape with extensive agriculture. The streambed substrate in the reach between the dam and site A consists of restored salmon gravels. The reach between sites A and B is characterized by a wide shallow channel with a gravel substrate transitioning to sand just above site B. The surrounding environment includes oak woodlands interspersed with vineyards. The reach between sites A and B will be referred to as the

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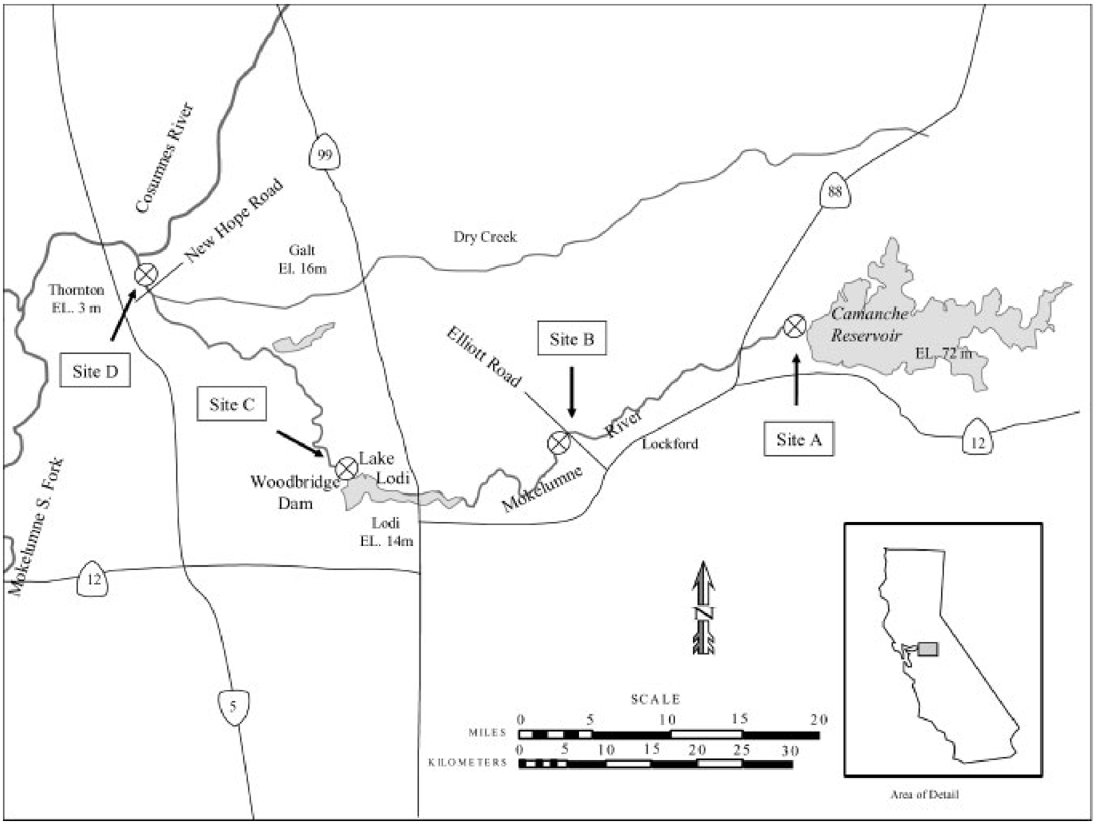

Figure 1. Map of study reach in the lower Mokelumne River. The reach extends from Camanche Dam to just above the confluence with the Cosumnes River

coarse substrate reach. Downstream of site B, the river flows into Lake Lodi, a small irrigation and recreation reservoir. Between sites B and C there is a substrate transition that shifts from sand above Lake Lodi, to silt in the backwaters of the reservoir. The reach between sites B and C will be referred to as the reservoir reach. Land use on the reservoir reach includes vineyards as well as urban impacts from the city of Lodi, which is located just above Lake Lodi. Site C is located 0.2 km below the dam impounding Lake Lodi. The river channel below Lake Lodi, between sites C and D, becomes narrower and incised due to channel leveeing for flood control. The reach has a substrate of fine sands and silts and is tidally influenced in its lower portion. Land use surrounding this reach includes intensive agriculture. The reach between sites C and D will be referred to as the fine substrate reach.

METHODS

The pulse release from Camanche Dam took place over 14 days from 26 May to 10 June 2003. In the 2 years prior to the pulse flow, flows ranged between 8 and 15 $m^3 s^{-1}$. The rising limb of the pulse release consisted of four stepped flow increases over a 4-day period beginning at midnight each day. Base flow at the onset of the release was 11 $m^3 s^{-1}$ and flows were ramped up to 17, 29, 40 and 57 $m^3 s^{-1}$ over 4 days. The descending limb occurred over 10 days to mimic the natural shape of a storm hydrograph. Flows were decreased by between 2 and 8 $m^3 s^{-1}$ per day for 7 days to 17 $m^3 s^{-1}$ where it remained for 2 days before stabilizing at 14 $m^3 s^{-1}$.

ISCO 6700 pump samplers were used to collect one-litre water samples during the 12 days of elevated flow. The intake tubes were staked near mid-channel and were a minimum of 15 cm above the streambed. Sampling frequencies during the rising limb were greater during pulse events to capture rapidly changing water quality

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conditions at greater resolution. Site A was sampled at half-hour intervals during pulse events because of its close proximity to the dam release point. Sites B, C and D were sampled hourly during periods of increasing flows and every 2 h once flows stabilized between pulse releases. On the descending limb greater sampling intervals were used because large water quality fluctuations were not observed (4–12 h sampling intervals).

Water quality parameters that were measured included total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN), dissolved nutrients (NH_4, NO_3 and soluble-reactive phosphorus (SRP)), foecal coliform and *Escherichia coli* (*E.coli)*. Dissolved nutrients were determined after filtration through a 0.2 μm polycarbonate membrane (Millipore). Nitrogen measurements were conducted using a Carlson conductimetric autoanalyser (limit of detection (LOD) = 5 $\mu g\, l^{-1}$) (Carlson, 1978, 1986). Total nitrogen (TN) was measured by the same method following persulphate digestion of an unfiltered sample (LOD = 20 $\mu g\, l^{-1}$) (Yu *et al*., 1994). SRP was quantified using the ammonium molybdate method and a spectrophotometer (LOD = 2 $\mu g\, l^{-1}$) (Hitachi U-2000 spectrophotometer) (Clesceri *et al*., 1998). Total phosphorus (TP) was measured by the same method following persulphate digestion (LOD = 5 $\mu g\, l^{-1}$) (Clesceri *et al*., 1998). A Dohrmann UV-enhanced persulphate TOC analyser (Phoenix 8000) was used in the analysis of dissolved organic carbon (DOC) with a detection limit of 50 $\mu g\, l^{-1}$.

TSS was determined by filtering a sample through a GFC glass fibre filter to collect the suspended solids. Samples were dried at 60°C for 24 h and weighed to obtain TSS. Enumeration of foecal coliforms (colony-forming units per 100 ml; cfu 100 ml^{-1}) was accomplished by direct membrane filtration and culturing the membrane onto mFC agar at 44.5°C for 24 h (Clesceri *et al*., 1998). Enumeration of *E. coli* was performed using direct membrane filtration within 24 h of collection and culturing the membrane onto selective agar at 44.5°C for 24 h (Clesceri *et al*., 1998). Laboratory QA/QC was performed for all analytical analyses and included replicates, spikes, blind samples and reference materials.

Gauging stations located at the outlet of Camanche Dam, Elliott Road, and Woodbridge Dam provided flow for sites A, B and C, respectively (Figure 1). Site D flow was modeled using the DHI MIKE 11 model. The MIKE 11 model was developed by the Danish Hydraulic Institute in 1987 (Danish Hydraulic Institute, 2000). MIKE 11 is an unsteady, one-dimensional modelling package used in this application for the fully dynamic solution of the St. Venant equations of energy and momentum. In addition, the coefficient specifying the implicit-explicit extent of the solution was selected to minimize numerical diffusion. The model has been applied by several investigators to the North Delta area that includes the Mokelumne River (Blake, 2001; Hammersmark, 2003). MIKE 11 has also been generally applied and examined for efficacy to several hydraulic routing investigations similar to this study (Shumuk *et al*., 2000). Flows provided by the gauging stations and by the MIKE 11 model were used to determine constituent fluxes at each site.

RESULTS

Pulse hydrographs

Hydrographs from the four monitoring sites displayed the effect of channel form and complexity as the wave pulse progressed downstream (Figure 2). Average travel times between sites A and B, B and C, and C and D were about 2, 6 and 6 h, respectively. Pulse events at site A, (0.7 km) below the dam, nearly coincided with the release of water from Camanche Reservoir. The hydrograph depicts sharp stepped increases in flow during the initial 4 day rising limb and similar sharp decreases for the 9-day receding limb. Site B (16.4 km) hydrograph was characterized by the same pulse increases in flow however; the hydrograph no longer displayed the sharp steps seen at site A. The steps have become rounded due to attenuation of the wave pulses as they moved downstream and due to lateral storage within the channel.

Site C (37.4 km) is just below Lake Lodi, which has a storage capacity of about $2.5 \times 10^6\, m^3$ and a mean depth of 2 m. The total flow generated by the pulse release was enough to turn the lake over 15 times. Site C shows a unique hydrograph characterized by an increase in flow to a localized peak followed by a small decrease in flow. Due to diversions for agricultural irrigation from Lake Lodi only 78% of the water released during the experiment was recovered below the dam at site C. Modelled flow at site D (54.4 km) depicts several small peaks resulting from tidal

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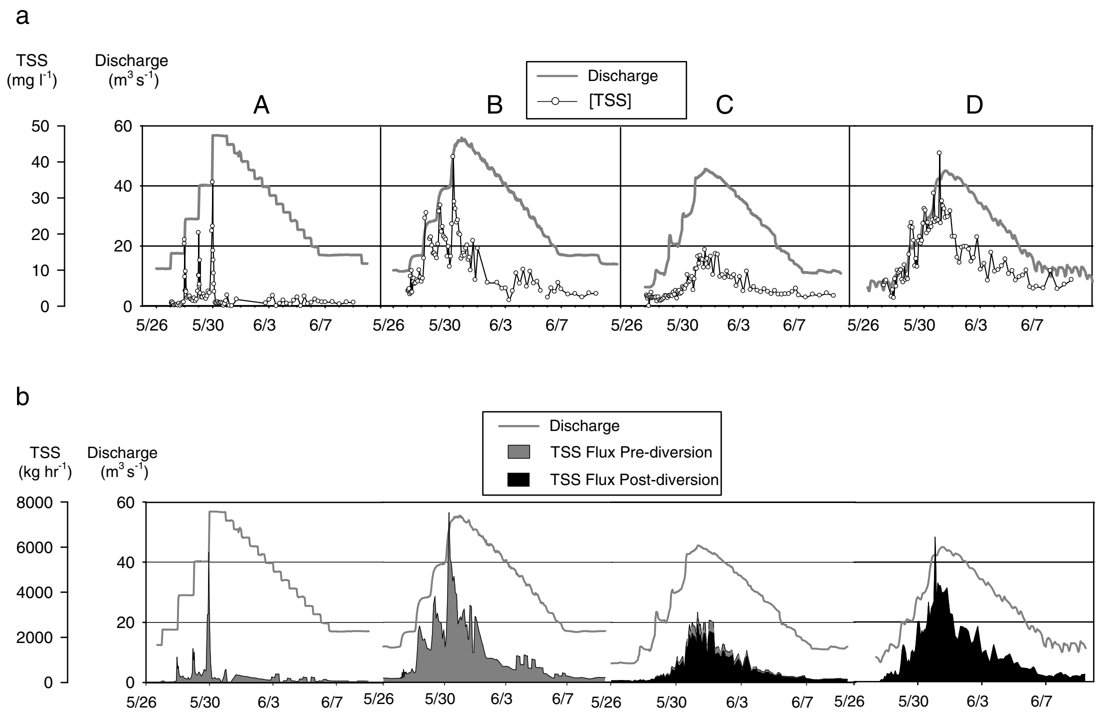

Figure 2. Plots of flow versus time with (a) total suspended solids concentration and (b) TSS flux. The grey plot is the TSS flux that would have occurred without flow diversion from Lake Lodi and is used for comparison to site B, upstream of Lake Lodi. The black plot is the flux that accounts for the 22% flow diversion at Lake Lodi and is used for comparison with site D, downstream of Lake Lodi

influences that affect the lower Mokelumne River. At site D the general hydrograph recovered to some degree to the shape of the site B hydrograph (Figure 2). The result was a unique hydrograph at each of the four sites.

Total suspended solids

Concentrations of total suspended solids (TSS) showed distinctly different patterns among the four sites (Figure 2a). At site A each stepped flow increase with the exception of the initial pulse (from 12 to 18 $m^3 s^{-1}$) resulted in a corresponding TSS spike. TSS spikes at site A were sharp peaks with a maximum value of 34.3 $mg\,l^{-1}$ characterized by elevated concentrations for less than 2 h and a decrease to base concentrations in less than 5 h. Minimum concentrations between stepped pulse events were between 6% and 10% of peak concentrations. The median concentration was 1.7 $mg\,l^{-1}$. The correlation between flow and TSS concentration was very low at site A ($r = 0.28$, n = 89, $p = 0.008$) due to large spikes at the onset of stepped flow increases followed by a rapid return to base concentrations.

Site B (Figure 2a) was characterized by similar TSS spikes to those of site A occurring at the stepped flow increases but the spikes were broader. Peak concentrations at site B reached 41.3 $mg\,l^{-1}$ and the median concentration was 9.9 $mg\,l^{-1}$. Site B peaks were broader and the descending limb of the peaks displayed a shoulder following passage of the TSS peak. Minimum concentrations between stepped pulse events were between 32% and 51% of peak concentrations. The correlation between flow and TSS concentration was $r = 0.57$ ($n = 83$, $p < 0.0001$).

Site C did not display distinctive sediment spikes during pulse events as was observed at sites A and B due to the flow and sediment dynamics within the reservoir. Maximum concentrations for TSS were as high as 15.6 $mg\,l^{-1}$ and the median concentration was 4 $mg\,l^{-1}$ (Figure 2a). The correlation between flow and TSS concentration at site C ($r = 0.88$, $n = 91$, $p < 0.0001$) was considerably stronger than for sites A and B.

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Site D showed a return of the TSS spikes with each stepped flow increase similar to sites A and B. Peak concentrations were as high as 42.4 mg l^{-1} and median concentrations were 12.3 mg l^{-1}. Minimum concentrations between stepped pulse increases were between 47% and 75% of peak concentrations. The correlation between flow and TSS concentration at site D was higher than sites A and B but lower than site C ($r = 0.73$, $n = 83$, $p < 0.0001$).

Sediment fluxes at each site displayed the same general pattern as the concentration data (Figure 2b). The sediment flux pattern indicated that the greatest entrainment occurred during the fourth and highest magnitude stepped flow increase compared to the previous pulses. Flux at site A was clearly dependent on the pulses coming out of the dam with little to no entrainment between pulses and during the descending limb of the hydrograph. Site B showed the greatest entrainment during the onset of stepped flow increases but fluxes remained above 1000 kg h^{-1} between increases indicating that entrainment also occurred after the initiation of the stepped flow increases. Flux at site C was predictably dampened due to sedimentation within Lake Lodi. In general TSS flux increased with increasing flow through Lake Lodi. Site D had much higher TSS fluxes between stepped flow increases compared to the other three sites and had peak fluxes at the onset of each stepped flow release.

Nutrients

Total phosphorus (TP) displayed a similar pattern to that of TSS with respect to stepped pulse increases (Figure 3a). At site A peak concentrations occurred at the onset of each pulse and then concentrations declined. As with TSS concentrations TP peaks were sharp and narrow at site A with peak concentrations lasting less than 2 h before returning to base concentration. The maximum concentration for TP was 127 $\mu g\,l^{-1}$ and a median concentration of 15 $\mu g\,l^{-1}$. TP concentrations were relatively constant near 15 $\mu g\,l^{-1}$ during the falling limb. These concentrations reflect the reservoir outfall chemistry which ranged between 14 and 20 $\mu g\,l^{-1}$ during the months of May and June (data provided by East Bay Municipal Utility District (EBMUD)). There was a strong correlation between TP and TSS ($r = 0.87$, $n = 89$, $p < 0.0001$) at site A.

Site B displayed broader peaks and a slightly weaker correlation between TP and TSS ($r = 0.79$, $n = 83$, $p < 0.0001$). Peak concentrations were not as distinct as those of site A with maximum values as high as 73 $\mu g\,l^{-1}$.

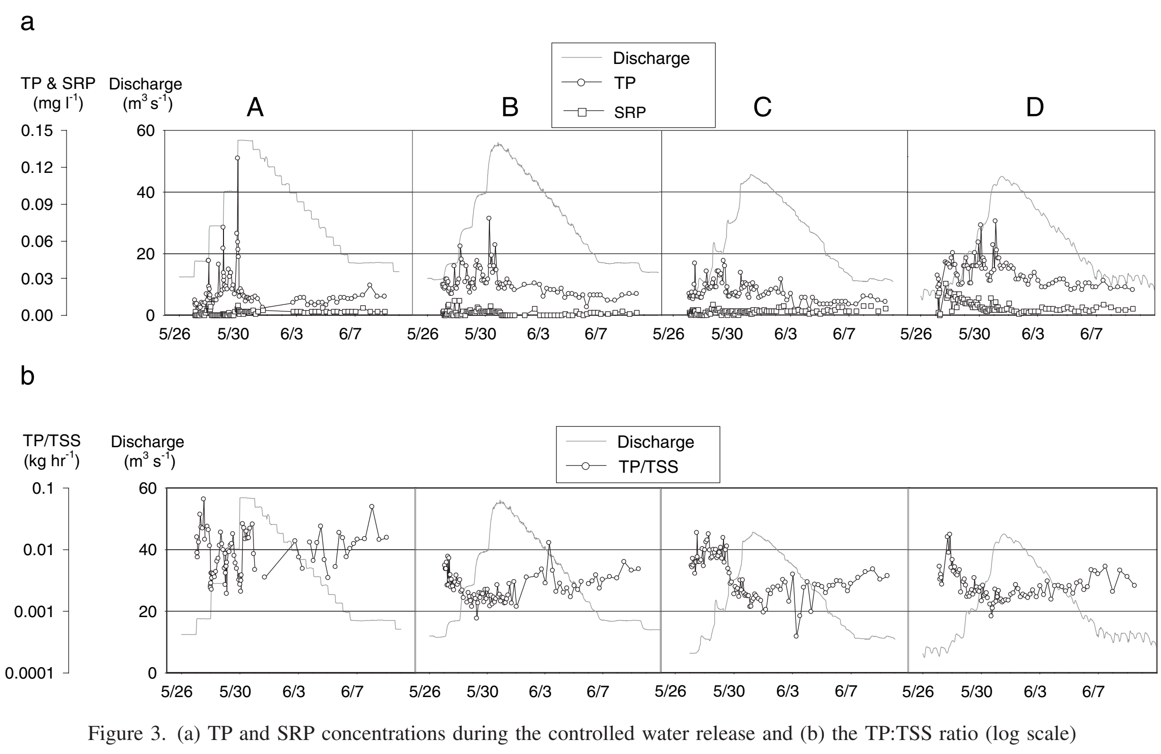

Figure 3. (a) TP and SRP concentrations during the controlled water release and (b) the TP:TSS ratio (log scale)

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Although peak concentrations were higher at site A, median concentrations at site B were 35% greater than site A (23 $\mu g\,l^{-1}$). As flows began to ramp down from peak discharge, TP concentrations decreased with decreasing flow.

Maximum TP concentrations at site C were considerably lower than those of sites A and B. Concentrations never exceeded 40 $\mu g\,l^{-1}$, whereas at sites A and B maximum concentrations were 127 and 73 $\mu g\,l^{-1}$, respectively (Figure 3a). This pattern in TP concentrations among sites was similar to the pattern for TSS concentrations. However, there was no significant correlation between TP and TSS at site C ($r = 0.04$, $n = 83$, $p = 0.73$).

Site D had the highest sustained TP concentrations among sites. The correlation between TP and TSS remained weak ($r = 0.61$, $n = 83$, $p < 0.0001$), however, it was considerably stronger than upstream site C. TP concentration peaks were distinct during the stepped flow increases and concentrations decreased to a relatively steady concentration of about 10 $\mu g\,l^{-1}$ as flow decreased along the falling limb.

Soluble reactive phosphate (SRP) displayed very low concentrations at sites A, B and C (<15 $\mu g\,l^{-1}$; Figure 3a). Phosphate concentrations at site D were elevated (24 $\mu g\,l^{-1}$) for the first 3 days of the study before returning to base concentrations of about 5 $\mu g\,l^{-1}$ through the remainder of the study.

The highest TP:TSS ratios occurred at site A indicating that these sediments have a higher organic matter content and/or adsorbed PO_4 content on fine sediments (Figure 3b). At the onset of increased flow, all sites experienced elevated TP:TSS ratios with a decrease occurring either before or after the second pulse of 29 $m^3\,s^{-1}$. After the initial decrease, TP:TSS ratios generally remained stable except for site A which displayed high variability. The low TSS values at site A (Figure 2a) may contribute to this variability. TSS values were near the detection limit and so introduced considerable noise.

Total nitrogen (TN) concentrations displayed a less distinctive pattern with respect to the flow pulses (Figure 4a). Peaks in TN concentrations occurred during pulses at site A but patterns were noisy and not easily distinguished. As flows began to ramp down, concentrations stabilized at about 0.3 $mg\,l^{-1}$, which may reflect the TN concentration of water released from the reservoir. The outflow TN chemistry was not measured from Camanche Dam. General

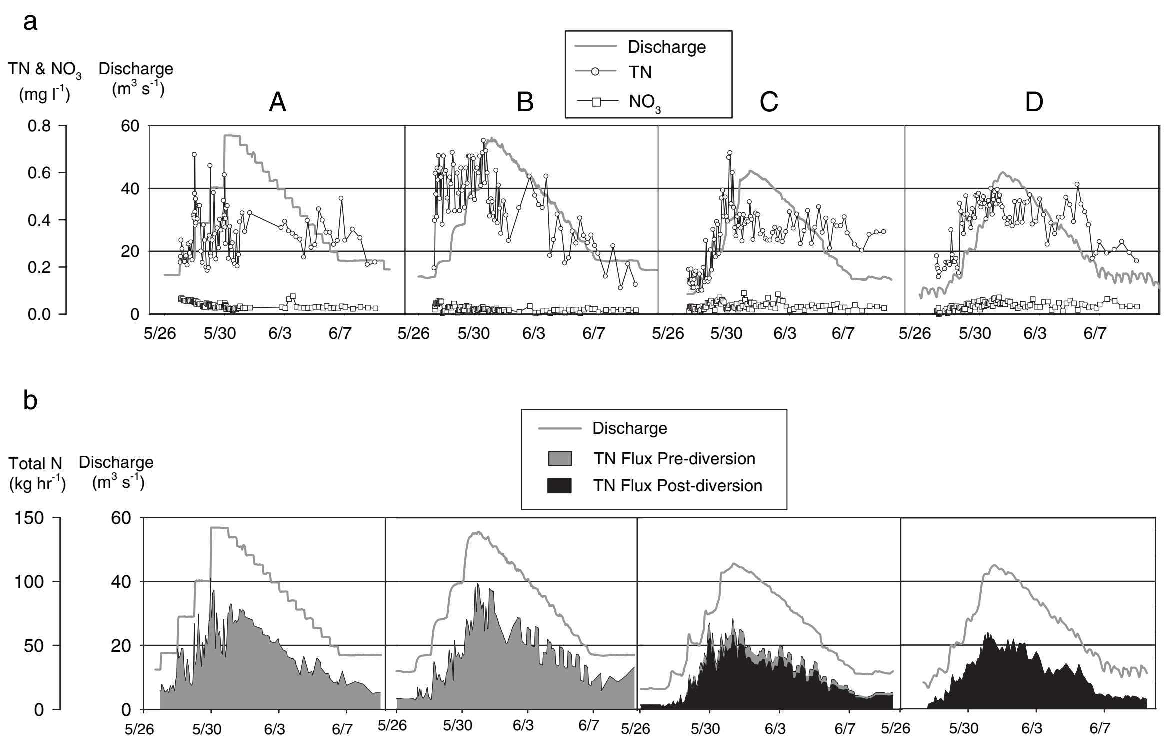

Figure 4. (a) TN and NO_3 concentrations during the controlled water release and (b) TN fluxes. The grey plot is the TSS flux that would have occurred without flow diversion from Lake Lodi and is used for comparison to site B, upstream of Lake Lodi. The black plot is the flux that accounts for the 22% flow diversion at Lake Lodi and is used for comparison with site D, downstream of Lake Lodi

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increases in TN concentrations accompanied increases in flow at sites B, C and D. Sites C and D displayed a positive correlation between flow and TN concentrations during the rising limb, however, peaks were not clearly distinguishable during the pulse events. Total N concentrations at sites C and D remained in a relatively consistent range between about 0.3 to 0.5 mg l^{-1} during the falling limb. Total N fluxes showed increases in N transport with each increase in flow at sites A and B. There was an overall trend of increasing TN flux with increasing flow during the rising limb and decreasing flux throughout the falling limb at all sites (Figure 4b). This pattern was driven primarily by changing water volumes rather than large changes in TN concentrations.

Mineral N concentrations were a very small fraction of total N concentrations (Figure 4a). Concentrations of NH_4-N were generally less than 0.01 mg l^{-1} for all sites throughout the study. Nitrate concentrations showed a small increase during the initial pulse events at sites A and B but then remained low (<0.02 mg N l^{-1}) throughout the remainder of the study. Nitrate concentrations at sites C and D were slightly elevated compared to sites A and B throughout the entire event.

Indicator bacteria

The correlation between foecal coliform and *E. coli* concentrations was strong at sites A and B with *r* values of 0.92 ($n = 42$, $p < 0.0001$) and 0.93 ($n = 50$, $p < 0.0001$), respectively, and weaker at sites C and D with *r* values of 0.78 ($n = 49$, $p < 0.0001$) and 0.58 ($n = 41$, $p < 0.0001$), respectively. Foecal coliform and *E. coli* concentrations displayed spikes at the onset of each pulse release for sites A, B and C, followed by a rapid decrease suggesting exhaustion of bacteria stored in the sediments (Figure 5a,b). Bacteria concentrations were very poorly to moderately correlated with TSS concentrations at these sites during the rising limb with *E. coli* displaying a stronger correlation with *r* values of 0.28 ($n = 42$, $p < 0.01$), 0.63 ($n = 49$, $p < 0.0001$), 0.56 ($n = 50$, $p < 0.001$), and -0.04 ($n = 40$, $p = 0.80$) at sites A through D, respectively. Foecal coliform correlations with sediment at sites A through D included *r* values of 0.03 ($n = 42$, $p = 0.76$), 0.29 ($n = 49$, $p = 0.045$), 0.40 ($n = 49$, $p = 0.0039$), and -0.26 ($n = 41$, $p = 0.1005$), respectively. Concentrations were elevated at site B, C and D compared to site A (Figure 5). Following the initial flushing of bacteria presumably from the streambed sediments at site A, the low bacterial concentrations reflect their low concentrations in the reservoir, which is protected as a recreational

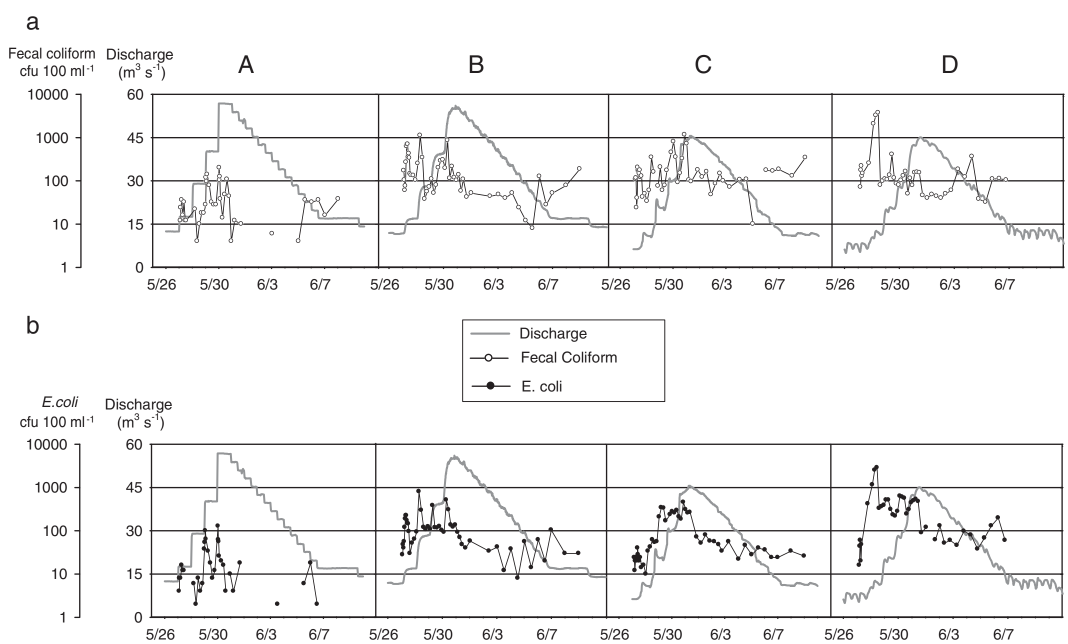

Figure 5. (a) Foecal coliform (federal standard = 400 cfu 100 ml^{-1}) and (b) *E. coli* concentrations (California standard = 126 cfu 100 ml^{-1})

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resource for swimming and boating. Site D displayed a distinct flushing peak at the onset of the first pulse event that was at least a factor of three times greater (3738 cfu 100 ml^{-1}) than the highest concentrations observed at the other three sites. Foecal coliform concentrations exceeded drinking water standards of 200 (California) and 400 (federal) cfu 100 ml^{-1} during pulse events but remained elevated for only a short period of time. *E. coli* concentrations exceeded the California regulation of 126 cfu 100 ml^{-1} consistently during the 2nd through 4th pulse events at sites B, C and D.

DOC

Dissolved organic carbon is a major drinking water concern because it is a precursor of carcinogenic disinfection by-products, such as trihalomethane. DOC concentrations (Figure 6a) displayed an increase during the pulse events at all four sites with concentrations varying from 0.5 to 3.6 mg l^{-1}. During the receding limb of the hydrograph, DOC concentrations generally remained within a tight range between 1.3 and 2.0 mg l^{-1}, concentrations typical of waters released from Camanche Reservoir (data provided by EBMUD).

Chemical flux dynamics

Flow and concentration data were combined to determine constituent fluxes at each sampling site for the entire pulse release. Particulate fluxes of TSS, TN and TP displayed similar patterns at each individual reach (Table 1a). The coarse substrate reach (sites A to B) was characterized by an increase in TSS, TN and TP fluxes by a factor of 5.6, 1.1 and 1.6 times, respectively. The increased fluxes were due to the contribution of upstream sources that were already entrained and the suspension of local sources due to the energy of the wave front traveling downstream. In the reservoir reach (sites B to C), Lake Lodi captured 39, 30 and 18% of TSS, TN and TP loads, respectively. Two load values were calculated for site C, 'C total' and 'C channel' (Table 1a). 'C total' takes into account the total volume of water that enters Lake Lodi and is used to compare site B with site C. 'C channel' takes into account only

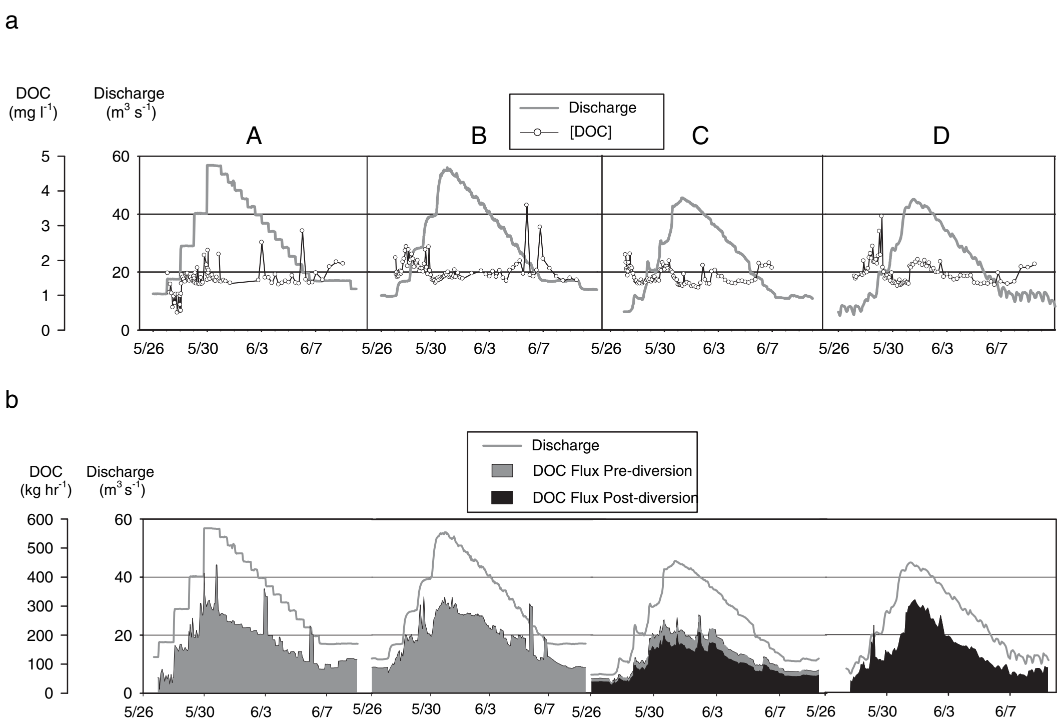

Figure 6. (a) Dissolved organic carbon concentrations and (b) DOC fluxes during the controlled water release. The grey plot is the DOC flux that would have occurred without flow diversion from Lake Lodi and is used for comparison to site B, upstream of Lake Lodi. The black plot is the flux that accounts for the 22% flow diversion at Lake Lodi and is used for comparison with site D, downstream of Lake Lodi

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Table 1. The total flux for each site for all of the constituents measured (a) 'C total' represents the flux at site C without taking into account the 22% diversion at Lake Lodi. 'C channel' represents the flux at site C taking into account the diversion from Lake Lodi. (b) is the reach fluxes of material on a per wetted area basis ($g\,m^{-2}$). 'C total' is compared to site B and 'C channel' is compared to site D. Wetted surface area data provided by Merz and Setka (unpublished)

Part a	TSS (Mg)		TN (Mg)	NO_3-N (kg)	TP (kg)	PO_4-P (kg)
A	70.6		12.8	1167.0	532.5	99.5
B	392.5		13.5	664.4	855.0	51.8
C total*	238.3		9.4	939.6	546.1	106.9
C channel	195.3		7.7	770.2	447.6	87.6
D	413.3		8.4	829.5	832.2	146.6
Part b	Surface area m^2	TSS $g\,m^{-2}$	TN $g\,m^{-2}$	NO_3-N $g\,m^{-2}$	TP $g\,m^{-2}$	PO_4-P $g\,m^{-2}$
B-A	538746	597	1.41	−0.933	0.599	−0.089
D–C channel	533642	408	1.31	0.111	0.721	0.011

*C total accounts for diversion from Lake Lodi.

the volume of water that passes over the spillway and continues downstream to site D. This flux excluded the water and constituent fluxes that were diverted at the spillway for irrigation. 'C channel' loads were used for comparison to site D loads. We assume that the water diverted from Lake Lodi retains the same chemistry as the water that remains in the river channel due to the close proximity of the diversion point and spillway. TSS, TN and TP loads increased by a factor of 2.1, 1.1 and 1.9, respectively, between 'C channel' and site D.

Fluxes of dissolved nutrients (NO_3 and SRP) displayed contrasting patterns compared to particulate constituents. In the coarse substrate reach NO_3 and SRP loads decreased by a factor of 1.8 and 1.9, respectively. In contrast, the reservoir reach acted as a source for nutrients releasing 1.4 and 1.6 times the amount of NO_3 and SRP, respectively, input from upstream. The fine substrate reach was characterized by further increases in NO_3 and SRP by a factor of 1.1 and 1.7, respectively.

Constituent fluxes were also calculated on a wetted surface area basis (per m^2) for the stream reaches between A and B and C and D to normalize for the wetted surface area of the channel (Table 1b). Positive values indicate reaches that acted as sources and negative values are reaches that were sinks. Compared to the fine substrate reach, the coarse substrate reach contributed appreciably greater TSS fluxes and similar TN and TP fluxes on a per m^2 basis. The coarse substrate reach was an appreciable sink for NO_3 and SRP while the fine substrate reach was a source for dissolved nutrients.

DISCUSSION

Boundary condition: site A

It is well supported that channel sediment supply plays a crucial role in the transport of sediment during pulse releases (Foulger and Petts, 1984; Jakob *et al*., 2003). In a pulse release study on the Trinity River in California, Wilcock *et al*. (1996) showed that low discharges selectively transported fine sediments but were not strong enough to loosen the gravel bed structure in order to release sequestered fine sediments. Thus the structure of the substrate as well as the supply of fine sediments both contribute to the TSS concentration signature. The amount and type of sediment that has accumulated within a channel determines how much entrainable sediment is available upon the release of pulse flows. In the 2 years prior to this study, flows ranged between 8 and 15 $m^3\,s^{-1}$ allowing for accumulation of fine sediments within the streambed.

The streambed above site A, located just below Camanche Dam, contained augmented salmon spawning gravels, which had accumulated appreciable levels of fine sediments over several years. By looking at the hysteresis of sediment entrainment we see how sediment supply appears to be controlling the TSS signature. Site A hysteresis (Figure 7a) clearly shows increased sediment concentrations at the onset of each pulse release followed by decreased concentrations to a relative stable level between individual pulses. This type of TSS signature is

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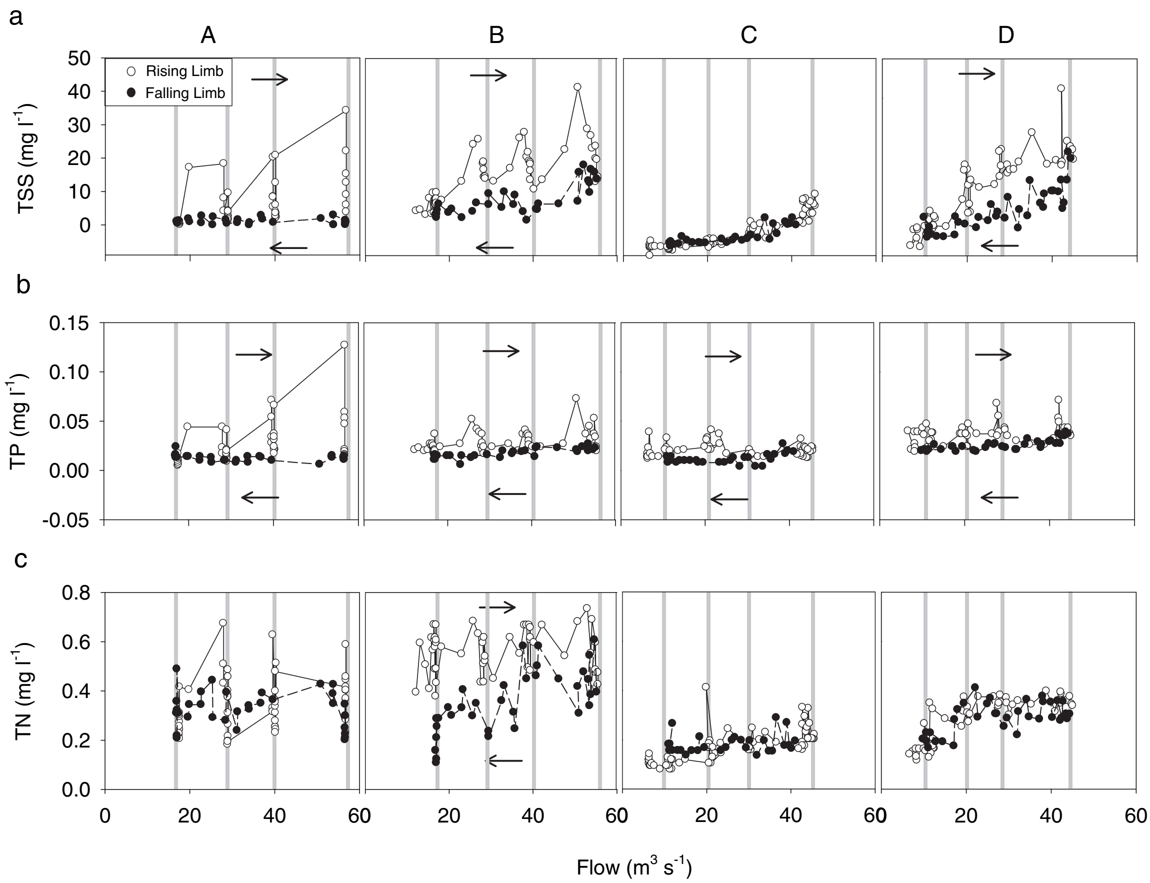

Figure 7. Hysteresis plots of all sites for (a) TSS, (b) TP and (c) TN. Vertical grey lines represent flows where each step in flow stabilized. Arrows represent the direction of the hysteresis loops

characteristic of exhaustion of the available sediment supply (Beschta *et al*., 1981; Eustis and Hillen, 1954; Hudson, 2003). The TSS peak followed by rapid sediment exhaustion with each successive flow increase is likely due to the release of fine sediment by the loosening of the gravel bed structure and/or entrainment of larger particle sizes.

In a pulse release study by Petts *et al*. (1985), it was suggested that the magnitude of the pulse and the size of the flow increase (the change in magnitude) both play roles in controlling the TSS signature. They found that the velocity created along the riverbed by the kinematic wave is dependent not only on the flow but also on the size of the increased flow. As the gravel substrate reorganizes, fine sediments stored within the gravel matrix become available for entrainment and subsequent exhaustion. The majority of the sediment flux was moved during the 4th flow increase that peaked at $57\,m^3\,s^{-1}$ at site A. At site A, 1, 15, 30% and 54% of the total sediment flux was released at the 17, 29, 40 and $57\,m^3\,s^{-1}$ flows, respectively. These fluxes suggest that the amount of entrainable sediment stored in the channel was positively correlated with the magnitude of the pulse and the change in magnitude of the pulse.

Site A hysteresis for TP (Figure 7b) mimics very closely the TSS response to the pulse releases. Further evidence of fine sediment exhaustion from within the gravels was elevated TP:TSS ratios during the initial stepped flow increase. This pattern suggests that P-rich sediment was released at the onset of the experimental releases. Studies have shown that fine sediments are the primary source of P due to the high surface area of fine particulate matter that allows for increased binding sites for phosphorus sorption (Vaze and Chiew, 2004). Thus elevated TP to TSS ratios suggest a smaller particle size and/or detachment of P-rich organic materials (e.g. periphyton, detrital organic

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materials). The data suggest that the particulates released initially were fine particles rich in phosphorus and that particulate phosphorus during higher flows decreased due to the coarsening of the sediments entrained.

Hysteresis of TN was highly variable displaying both clockwise and counter clockwise behaviour (Figure 7c). This pattern reveals that TN is being released before and after peak discharge and that it does not follow the same relationship to flow as does TSS and TP. This mixed hysteresis combined with poor correlations between TN and TSS suggest that nitrogen is not released with the sediment and that it is possibly being stored in the organic fraction. Within the river channel the release of TN from the bedload is much more variable than that of TSS and TP. Flux data (Figure 4b) suggest that while TN does not display the extensive exhaustion observed for TSS some source depletion is occurring after the onset of the pulse releases.

Foecal coliform and *E. coli* concentrations suggest that channel storage of bacteria was exhausted and was linked to the exhaustion of the sediment supply. These results are consistent with current research on foecal coliforms whereby foecal coliforms are found to accumulate in stream sediments (Albinger, 1993; Crabill *et al*., 1999) and are released during high flow events (Boyer and Kuczynska, 2003). McDonald *et al*. (1982) further documented the depletion of foecal coliform within a stream channel during a pulse release. They determined that bacterial concentrations can increase as much as 10-fold due to flow increases and that these increases were likely linked to in-channel sediment stores. TSS and bacterial concentrations appeared to be linked during the sharp spikes that occurred at the onset of each flow increase at site A.

Coarse substrate reach

Pulse releases create energy waves that propagate downstream (Glover and Johnson, 1975). As they move downstream the wave energy decreases and the wave attenuates as the crest of the wave decreases. Contributions to water quality from energy waves such as these come from local sources that are released by the energy wave and by the chemistry of the pulse flow waters moving behind the wave (Foulger and Petts, 1984). At site B the TSS peaks were much broader than those at site A displaying the lengthening of the sediment slug entrained by the pulse wave (Figure 2a). TP to TSS ratios at site B (Figure 3b) were initially elevated and then decreased as flow increased. This suggests that fine sediments and organic materials rich in TP were flushed out of the system by the flow increases and that subsequent stepped flow increases entrained a coarser sediment fraction as seen at site A.

The mass of TSS that moved past site B was 83% greater than the mass that moved past site A. The main differences between the fluxes at these two sites is that site A received little to no sediment inputs from upstream due to the dam that was only 700 m upstream. In addition the gravel substrate at site A contained a limited amount of entrainable sediments so that once the smaller particles had been mobilized the gravels were too big to be transported. Site B received sediment inputs from the 15 km of river channel between sites A and B and has a sandy substrate conducive to trapping fine sediments. Hysteresis at site B (Figure 7a) displays the same clockwise hysteresis to that of site A but base concentrations for both the rising and falling limb are generally higher. Increasing pulse flows allow for entrainment of sediments with higher entrainment thresholds. Entrainment threshold is a function of particle size, packing of the sediments, and the geometry of the sediments (Buffington and Montgomery, 1997). Assuming the geometry of sediments at site B (sand substrate) were uniform, the observed hysteresis could be explained by the coarsening of bed load particle sizes and/or the depletion of loosely packed particles in the bed. However, entrainment continued to occur when flows were held constant. This suggests that sediment depletion is occurring at site B but not to the degree observed at site A.

Site B substrate also appears to play a role in TP entrainment. Hysteresis of TP (Figure 7b) displayed clockwise behaviour with exhaustion of channel TP supplies during the stepped flow increases. Because concentrations continue to decrease with decreasing flow it appears that TP storage is not entirely exhausted at lower flows. Because of the loose substrate, phosphorus continues to be entrained at site B whereas at site A the armoured substrate displays very rapid exhaustion. Because TP peaks during pulse releases and TP to TSS ratios at site A are elevated compared to site B there appears to be a larger fine sediment fraction mobilized at site A. The gravels at site A have a greater potential to trap fine sediments within large interstitial spaces whereas the ability of sands to trap sediment would be reduced. However, due to a much higher volume of sediment at site B there remains a higher TP flux at site B than site A.

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Within the coarse substrate reach we see the potential uptake of dissolved nutrients by microorganisms within the hyporheic zone, as well as uptake by periphyton and aquatic plants (Hall *et al*., 2002). With respect to the loss of dissolved inorganic nitrogen, denitrification may also play a significant role within the hyporheic zone (Bernhardt *et al*., 2002). The net negative flux of SRP may also be the result of sorption to sediments that bind and retain phosphorus within the hyporheic zone halting export (McKnight *et al*., 2004).

Reservoir reach

The marked hydrologic shift from a free flowing river channel to a reservoir creates significant water quality adjustments at the outflow of Lake Lodi. TSS hysteresis (Figure 7a) at site C displays a linear relationship between discharge and TSS concentration whereas sites A and B displayed clockwise hysteresis. Unlike sites A and B, site C does not exhibit exhaustion of sediments but a linear increase in concentration with flow. It is assumed that coarser particles are captured behind the dam while finer particles remain in the water column and are exported from the reservoir. Thus the TSS storage capacity of the reservoir prevents the sediment exhaustion patterns seen at sites A and B following each flow increase. Local sources of fine sediments within the reservoir may be pulled into suspension by the energy of the pulse wave moving through the reservoir and are possibly a contributor to water quality at site C.

We would expect that fine particles may be released throughout the pulse release because the substrate at the bottom of the reservoir is dominated by fine particles. Complementing the flushing of fine sediments are elevated TP:TSS ratios at the onset of the pulse releases suggesting that fine particulates rich in TP are being released during the first two pulse events (Figure 3b). After the first two stepped flow increases, there is a decline in TP concentration which corresponds to a sharp decline in TP:TSS ratios. The decrease in TP:TSS ratios could be due to the coarsening of the particulate matter with a lesser ability to bind phosphorus or a decrease in P-rich organic sediments. Furthermore sediments released from the bottom of reservoirs have often experienced anoxic conditions. Anoxic conditions lead to reduced environments, which can facilitate the release of phosphorus from iron oxides resulting in P-depleted sediments. The initial release of P-rich sediments may be followed by P-depleted sediments leading to lower TP:TSS ratios.

Dissolved constituents SRP and NO_3 were exported from Lake Lodi (Table 1a). This result is opposite to that observed along the river reach between sites A and B. The capture of particulate nitrogen and phosphorus within Lake Lodi and the subsequent processing and nutrient transformation may lead to a consistent source of dissolved nutrients within the sediments of the reservoir (Martinova, 1993). The supply of dissolved nutrients may be high due to the build up of particulate nutrients in Lake Lodi from agricultural inputs of organic nutrients from vineyards above the reservoir. As these sediments are disturbed by the energy of the incoming flows the release of dissolved constituents will be reflected in Lake Lodi outflow (site C). This may explain why Lake Lodi acts as a source of dissolved nutrients.

Foecal coliform and *E. coli* concentrations are the only water quality constituents that displayed distinct peaks during stepped pulse increases at site C. Unlike sites A and B, site C did not exhibit depletion of *E. coli* stores. Extensive buildup of *E. coli* populations within reservoir sediments was documented by An *et al*. (2002). Furthermore An *et al*. (2002) found that water column foecal coliform concentrations were strongly correlated with the resuspension of sediments due to recreational boating. Due to the relatively shallow mean depth of Lake Lodi (2 m) the resuspension of sediments caused by the wave energy may lead to the foecal coliform peaks observed during the stepped flow increases. In addition, bacteria, at intermediate sizes between our dissolved and particulate constituents may be small enough to be entrained by the energy of the pulse wave moving through Lake Lodi, but large enough that it does not mix well and is pulsed over Woodbridge Dam as a slug. After the stepped flow increases peak, flow then slightly decreases (Figure 2). During this period between flow increases, settling of foecal coliform may occur, decreasing the concentration in the outflow from Lake Lodi until the next flow increase causes resuspension.

Fine substrate reach

TSS, bacterial and nutrient data suggest that anthropogenic factors above site D are considerable. The agricultural and urban impacts on the river channel at site D include greater inputs of nutrients from fertilizers and

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urban runoff, as well as high sediment loads from agricultural tail waters. Low flows year round have led to a river reach dominated by a fine-silt particle substrate that is accumulating inorganic nutrients and releasing those nutrients only when subjected to increased flows.

Site D represents how the water quality signature recovers after passing through a small reservoir. Sediment spikes occurred at or near the onset of pulse releases showing the ability of the river channel to readjust back to a similar TSS signal seen at sites A and B. Hysteresis for TSS returns to a clockwise pattern as was seen at sites A and B (Figure 7a). This suggests that sediment depletion is occurring within the channel. However, as flows decrease TSS concentrations gradually decrease with flow to base concentrations. This suggests that an appreciable amount of entrainment is still occurring at flows below peak flow on the falling limb. At site A, TSS concentrations drop to base levels immediately after peak flow, which suggests that sediment exhaustion is occurring to a much greater degree at site A than site D. Site B is characterized by an intermediate degree of sediment exhaustion between sites A and D whereby the decrease in sediment concentration with decreasing flow is more substantial than site D and less than site A. Using substrate type to explain these results it is concluded that as the substrate coarsens the degree of sediment exhaustion increases and the amount of entrainable sediment supply decreases. Because site D has a fine-silt substrate facilitated by low flow and agricultural inputs, it displays the least amount of sediment exhaustion.

Significant flushing of constituents occurred above site D during the rising limb of the hydrograph. In addition to the flushing of TSS, there was a spike in the TP to TSS ratio, and a large spike in foecal coliform and *E. coli*. Site D displayed the highest median concentrations of TSS, TP, SRP and foecal coliforms throughout the pulse release even though it received 22% less flow than the other sites due to diversion from Lake Lodi. The fine substrate reach was a source for dissolved nutrients (SRP and NO_3) whereas the coarse substrate reach was a sink for these constituents. This discrepancy may be due to the addition of nutrients from agricultural and municipal inputs from the surrounding region. These low flow conditions may be conducive to high foecal coliform populations within the sediments above site D.

Anthropogenic impacts on rivers with natural flow regimes often display elevated suspended solid and nutrient concentrations during storm events (Ahearn *et al*., 2004). These impacts are often attributed to landscape contributions to water quality during storms where the contribution of bedload is often difficult to separate from landscape contributions (Markich and Brown, 1998). Because the Mokelumne pulse release did not directly link the landscape to the river channel the impact of agriculture and municipalities on the water quality contribution from the bedload was observed. The build up of nutrients, sediment, and foecal coliforms reflect the anthropogenic inputs of municipal and agricultural tail waters in conjunction with high residence times and the lack of flushing flows.

CONCLUSIONS

Spatial, hydrological and geomorphologic patterns played a central role in the water quality dynamics of this pulse flow release. The substrate texture in the reach between sites A and B was predominantly gravel transitioning into sand. This reach was a source for particulate constituents TSS, TN and TP while acting a sink for dissolved nutrients (SRP and NO_3). The substrate in the reach between sites B and C transitions from sand to a fine-textured substrate. The water quality of this reach was controlled by Lake Lodi, which acted as a sink for particulates and a source for dissolved nutrients. Dissolved constituents remained in solution and were transported through Lake Lodi more effectively than particulate matter. The reach between sites C and D has a channel geomorphology that was dominated by leveed, incised channels with fine-textured substrates. This reach was a source of both particulate and dissolved constituents most likely due to its readily mobilized bed and anthropogenic inputs of sediment and nutrients.

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