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EFFECTS OF RIVER REGULATION ON WATER QUALITY IN THE LOWER MOKELUMNE RIVER, CALIFORNIA

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ABSTRACT

This study examines the effects of flow regulation on water quantity and quality by comparing an impounded system (Mokelumne River) with an adjacent unimpounded system (Cosumnes River). Between 1999 and 2002, the Cosumnes River displayed a strong seasonal cycle for each constituent analysed (total suspended solids, NO_3-N, total nitrogen, PO_4-P, total phosphorus, dissolved silicon, specific conductivity, flow), while reservoirs in the lower Mokelumne buffered and attenuated physical and chemical fluctuations creating a weak seasonal pattern. Dissolved silicon and total suspended solids were the two constituents most efficiently sequestered by the reservoirs. While the reservoirs acted as traps for most constituents, NO_3-N and PO_4-P were produced during the drier years of the study, 2001 and 2002. In contrast, the unimpounded reference reach in the Cosumnes was an annual source for all constituents measured. The Cosumnes delivers its highest NO_3-N concentrations during the winter months (December–April), while peak concentrations in the Mokelumne occur during the snowmelt (May–July) and baseflow (August–November) seasons. Due to downstream N-limitation, this temporal shift in NO_3-N export may be contributing to accelerated algal growth in the reach immediately downstream and eventually to algal biomass loading to the downstream Sacramento–San Joaquin Delta. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: water quality; nutrient dynamics; river regulation; impoundment; Cosumnes River; Mokelumne River

INTRODUCTION

The ubiquity of large dams in the United States and the largely negative impact that these dams have on aquatic ecosystems (Williams and Wolman, 1984), together create the need for the scientific study of impounded river systems. For the past 25 years, research of impounded systems has revealed that streamflow regulation by dams can alter seasonal fluctuations in stream temperature (Fraley, 1979; Ward and Stanford, 1979; Webb and Walling, 1993a, 1996, 1997), solute chemistry (Hannan, 1979; Kelly, 2001), nutrient loading (Hannan, 1979; Puig *et al.*, 1987), and sediment transport (Ibanez *et al.*, 1996; Morris and Fan, 1998; Scheiber and Rausch, 1979). These alterations to streamflow and water quality frequently have deleterious effects on downstream trophic structure and function (Cortes *et al.*, 1998; Petts *et al.*, 1993; Ward and Stanford, 1979; Webb and Walling, 1993b). Downstream impacts, however, can be highly variable as each impounded system is unique.

The location of a dam within a river system, its age, depth and surface area, the hydraulic residence time, the regional climate, operation of the dam, and chemistry of the inflowing waters all influence how impoundment affects downstream water quality (Berkamp *et al.*, 2000; Hannan, 1979; Imevbore, 1970; Petts, 1984; Soltero *et al.*, 1973). In Kelly's (2001) analysis of the inputs and outputs of five major reservoirs on the Rio Grande, Colorado River, and Lower Columbia River, she found that reservoirs in different regions processed nutrients differently. Reservoir passage decreased NO_3-N fluxes in the Rio Grande, increased NO_3-N fluxes in the Lower Columbia, and had little effect on NO_3-N in the Colorado. A 1979 Department of Water Resources (DWR) study on the effect of drought on 17 reservoirs in central California found that all the reservoirs surveyed registered significant nutrient increases with the onset of drought but it was the shallow reservoirs that were the most impacted (Department of Water Resources, 1979). In California, a single integrative study looking at the effect of dam-building associated with

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the Central Valley Project took place in 1980 (United States Water and Power Resources Service and the South Delta Water Agency, 1980). This study was beneficial because it looked at total dissolved solids at the head of the Sacramento–San Joaquin Delta, before (pre-1944) and after (post-1952) the emplacement of numerous upstream dams, thus integrating the variation in chemical processing between individual impoundments. They found that a combination of reduced flow caused by upstream impoundments and increased salt load from downstream development led to an increase in total dissolved solids of between 93 and 116%. Though the report was not able to definitively quantify which portion of the increase was due to impoundment alone, it points to the fact that upstream impoundments can have an impact on the chemistry of downstream environments.

The effect of impoundment on dissolved silicon (DSi) has been given less attention in the literature but the results from those studies which have focused on the topic have been very consistent. Impoundments and lakes from Finland and Yugoslavia all tend to act as significant DSi sinks (Conley *et al.*, 2000; Friedl *et al.*, 2004; Humborg *et al.*, 1997, 2000). The result in many cases seems to be downstream shifts in phytoplankton communities from siliceous to non-siliceous species (Humborg *et al.*, 1997, 2000). The western Sierra Nevada (where this study was conducted) is primarily composed of granites and granodiorites in the headwater reaches, a rich source of DSi, yet nearly all the rivers draining this area pass through multiple impoundments. As such, there is the potential for significant DSi removal from tributaries flowing toward the downstream Sacramento–San Joaquin Delta.

The largest river system in California, the Sacramento–San Joaquin (1.63×10^7 ha), occupies 40% of California's land mass and drains twenty major tributaries (Jassby and Cloern, 2000). Of these twenty tributaries only one remains free-flowing: the Cosumnes River. Presently the Sacramento–San Joaquin Delta is in ecological decline as evidenced by the decrease in fish populations using the Delta as passage and home (Jassby *et al.*, 1995; Moyle *et al.*, 1992). Some endemic fish species have already been extirpated (e.g. Sacramento perch (*Archoplites interruptus*), California roach (*Lavinia symmetricus*)), and others are threatened (e.g. Delta smelt (*Hypomesus transpacificus*), Sacramento winter-run chinook (*Oncorhynchus tschaw.y.tscha*)) (Kohlhorst, 1997; Meng and Moyle, 1995). This trend continues down through the food web with invertebrate populations also showing significant declines (Orsi, 1999; Orsi and Mecum, 1996), and may ultimately be traced to alterations in water quality. With all but one of the Delta's major tributaries dammed, an essential step in the management and rehabilitation of Delta waterways is determining how impoundments in the Sierra Nevada may be affecting downstream water quality.

This study begins to address this issue by examining nutrient, solute, and sediment dynamics in the Cosumnes and Mokelumne Basins, two river systems which drain into the head of the Sacramento–San Joaquin Delta. The Cosumnes River is the last free-flowing waterway in the western Sierra Nevada. Directly south of the Cosumnes is one of the most regulated rivers in California; the Mokelumne river system has ten major dams on its main stem. The proximity of the Cosumnes and Mokelumne drainages provides an excellent opportunity for comparative river system research on the impact of impoundments on river chemistry in the western Sierra Nevada.

THE STUDY AREA

The Cosumnes River catchment area is located southeast of Sacramento, CA, and encompasses 1989 km^2 of terrain including 1306 km of waterways (Figure 1). The Mokelumne River lies directly south of the Cosumnes with a catchment area of 1700 km^2 and 1139 km of waterways (Figure 1). Both river systems originate in uplands underlain by granitic bedrock. A belt of metamorphic rock crosses the middle reaches of both catchment areas, separating upland granites from lowland sedimentary units. Land use and land cover are similar for both catchments with the uplands being dominated by coniferous forests, the middle reaches predominantly oak woodland–annual grass rangeland, and the lowlands used for row crops, viticulture, and grazing. The Mokelumne has a greater population and intensive viticulture in its lower reaches while the Cosumnes has row crops and more suburbanization; apart from these differences the basins are well matched geographically (California Department of Forestry and Fire Protection, 2002a, b). In the lower reaches, the Cosumnes joins the main stem of the Mokelumne which then drains to the Sacramento–San Joaquin Delta.

Three stream flow gauges, one in the Cosumnes at site 1 (USGS 1133500) and two in the Mokelumne catchment at sites 3 and 4 (operated by East Bay Municipal Utilities District, EBMUD) were used for flux calculations (Figure 1). There was no gauge at site 2 so flow for this site was modelled (see Methods). The systems were analysed on a water year (w.y.) basis so an annual cycle lasted from October to September. For the four year period of study

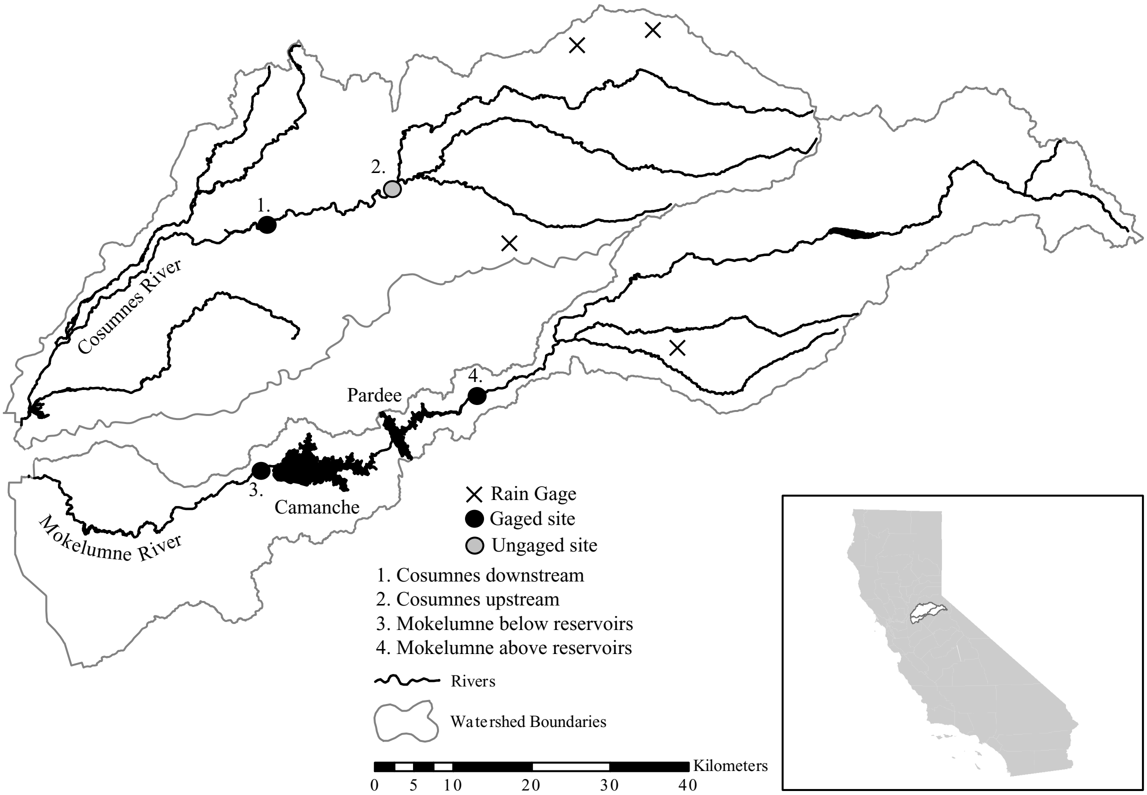

Figure 1. The Cosumnes and Mokelumne catchment areas with sampling points, river gauges, and stream gauges indicated

(1999–2002), the Cosumnes, as gauged at site 1, averaged 0.38 $\text{km}^3\,\text{a}^{-1}$ while the Mokelumne, as gauged at site 3, averaged 0.49 $\text{km}^3\,\text{a}^{-1}$ (Table I). The study period included two wet years (1999, 2000) and two drier years (2001, 2002). During 1999 and 2000 precipitation in the basins was above average by 3% and 23%, respectively; while during 2001 and 2002 precipitation in the basin was below average by 25% and 7%, respectively. During the dry years the Mokelumne released 30% more water than the Cosumnes while during the wet years Cosumnes discharge was 18% lower. The variation in discharge between the basins is due to two factors: (1) the Mokelumne

Table I. Geographic and hydrologic data for the Cosumnes and Mokelumne river systems, 1999–2002

	Annual rainfall total* (mm)	Annual discharge ($\text{km}^3\,\text{a}^{-1}$)	Full natural flow† ($\text{km}^3\,\text{a}^{-1}$)	Area (km^2)	Headwater elevation (m)
Cosumnes				1989	2357
1999	913	0.581	N/A		
2000	1098	0.568	N/A		
2001	663	0.147	N/A		
2002	780	0.238	N/A		
Mokelumne				1700	3151
1999	1018	0.812	1.072		
2000	1212	0.585	0.914		
2001	744	0.288	0.469		
2002	903	0.260	0.716		

*Rainfall totals are calculated from precipitation gauges at the approximate centre of each catchment.
†Full natural flow is calculated by the USGS to equal what the discharge of the river would be without impoundments and diversions.
N/A, not applicable.

Table II. Reservoir characteristics of Pardee and Camanche

Reservoir	Surface area (km^2)	Average volume* (km^3)	Capacity (km^3)	Average depth* (m)	Dam height (m)	Average residence time* (months)
Camanche	31.1	0.35	0.51	11.2	52	12
Pardee	9.1	0.22	0.22	24.6	105	5

*Values averaged over the four year period of the study (w.y. 1999–2002).

has a greater portion of its catchment area in high elevations and so receives more upland precipitation; and (2) the Mokelumne is highly regulated by ten reservoirs so flow from one year may not be representative of precipitation from that year alone.

This study focuses on the two largest reservoirs in the lower Mokelumne, Pardee and Camanche Reservoirs (Table II). The reservoirs are in series with the backwaters of Lake Camanche only 3 km downstream of Pardee Dam (Figure 1). The position of these reservoirs at relatively low elevations (173 m and 72 m) on the mainstem of the river, maximizes their impact on downstream water chemistry (Stanford and Ward, 2001). Pardee Dam, one of the oldest large dams in California, was built in 1929 and serves as the primary water supply for Oakland California. Pardee Reservoir has oligotrophic waters with a Carlson Trophic State Index (TSI) of 30.0 as determined from average summer secchi depths (2000–2004), and a TSI of 31.5 calculated from average summer surface total phosphorus (TP) concentrations (1998–2004) (R. Jung, East Bay Municipal Utilities, personal communication, 2004). Camanche Dam, built in 1963, serves primarily as a recreational lake. Camanche is borderline oligotrophic/mesotrophic with a TSI of 35.6 as determined by secchi depths (1998–2004) and 45.3 as determined by TP (1998–2004) (R. Jung, personal communication, 2004). Both reservoirs release tailwaters primarily from the hypolimnion.

METHODS

Two sites on the Mokelumne and two on the Cosumnes were chosen for the basin comparison. On the Mokelumne, sites above (Mokelumne above reservoirs) and below (Mokelumne below reservoirs) the Pardee–Camanche reservoir system were selected for the analysis (Figure 1). On the Cosumnes, two sites from similar elevations were chosen for comparison: Cosumnes upstream and Cosumnes downstream (Figure 1). Samples from the Cosumnes were collected and analysed in our laboratory while samples from the Mokelumne were collected and analysed by EBMUD. In order to verify agreement between the data sets, we collected and analysed water samples in the Mokelumne concurrent with EBMUD during w.y. 2001 and 2002. The resultant data from each laboratory did not differ by more than 10% for each analyte studied (Table III).

Grab samples from the Cosumnes River were collected biweekly and during storm events from October 1998 to September 2002. Two-litre grab samples were collected from the thalweg of the river and at approximately the mid-depth of the water column. Temperature was measured on-site while specific conductivity (SpC), was measured on unfiltered subsamples in the laboratory. Total suspended solids (TSS) was measured from a 500 ml subsample. The

Table III. Inter-laboratory comparison of methods* and average difference in analysis on samples collected between 21 November 2000 and 22 May 2001

Constituent	EBMUD method	UCD method	Variance (%)	No. of samples
Conductivity	Field meter	Lab meter	0.9	6
Anions	EPA 300.0	EPA 300.0	1.6	5
TN	Persulfate/Latchat	Persulfate/Carlson	8.5	6
TP	SM(18)-4500 P-E	SM(20)-4500P-D	7.3	6
TSS	SM(18)-2540D	SM(20)-2540D	5.2	5
Si	EPA 200.7	EPA 200.7	4.0	6

*EPA refers to Environmental Protection Agency method number. SM refers to the chapter and section of *Standard Methods for the Examination of Water and Wastewater* (Clesceri *et al*., 1998).

Table IV. Percentage error in flux estimates calculated for each constituent at the four sampling sites

Constituent	Site 1	Site 2	Site 3	Site 4
Nitrate*	14.5	17.2	10.0	15.5
Phosphate	13.9	15.4	12.6	11.5
Silicon	5.1	11.2	4.0	4.8
TN	13.3	16.1	7.2	8.9
TP	15.1	18.0	9.0	9.2
TSS	15.5	18.8	15.3	21.4
Flow error†	5.0	11.2	1.0	3.0

*Constituent error includes error propagation from flow error. Analytical error was approximately 4%, but was not included in flux comparison because it varied equally across comparable samples.
†Flow error was determined through personal communication with the operators of the gauges. Site 2 error is due to the inaccuracies inherent in the flow model used; site 3 error is very low because flow is gauged by acoustic Doppler in the Camanche outfall pipe.

TSS split was filtered through a pre-weighed glass fibre filter (Pall type A/E). The filter was dried at 60°C for 24 hours before a final weighing. A separate 125 ml sample was filtered through a 0.2 μm polycarbonate membrane (Nuclepore) and stored at 4°C through completion of analysis. Nitrate and PO_4-P were measured using ion chromatography (Dionex 500x; AS4A). Total phosphorus was analysed from a persulphate-digested split of unfiltered sample (Yu *et al.*, 1994), using the ammonium molybdate method and a Hitachi U-2000 spectrophotometer (Clesceri *et al.*, 1998). Total nitrogen (TN) was measured on a persulphate-digested split of unfiltered sample using a Carlson conductimetric autoanalyser (Carlson, 1978, 1986). Silicon was analysed on a filtered split using an inductively coupled plasma–atomic emission spectrometer (Thermo Elemental—Iris Advantage).

Fluxes were calculated at each site using FLUX Version 5.1, a stream loading model created by the US Army Corps of Engineers (USACE, 1999). When concentrations were below the detection limit of either laboratory, a value of one-half the higher detection limit was used for both UCD and EBMUD data. Standard jackknifing and error propagation techniques were used in the error analysis of the fluxes (Table IV). Error was lowest below Camanche because the hydrograph and chemograph for many constituents were buffered. At other sites error was as high as 21.4% due to constituent hysteresis, flashy flows, and infrequent sampling. In the Cosumnes catchment, site 2 did not have a gauge so flow was modelled using a precipitation runoff modelling system (PRMS) with input from three rain gauges in and around the upper basin (Figure 1). The PRMS model was developed by the United States Geological Survey (Leavesley *et al.*, 1983). It is a conceptual, distributed parameter model capable of continuous simulations. The model was calibrated to the site 1 gauging station with a relative standard error of 11.2%.

The resultant fluxes from all sites were used in a transport coefficient analysis between the two basins. Two sites on the Mokelumne (upstream and downstream of the reservoirs) were chosen in order to illustrate the cumulative influence of the two reservoirs on water quality. Two comparable sites on the Cosumnes were used in the analysis to illustrate differences between a free-flowing reach and an impounded reach. Water years 2001 and 2002 were chosen for this analysis because they represented a dry and average year and also contained the most complete data sets. The flux data were grouped by water quality season (Ahearn *et al.*, 2004) as follows: stormflow season (December–April), meltflow season (May–July), and baseflow season (August–November). In each system the ratio of water output to input flux for each season was plotted against the ratio of constituent output to input flux. Using these ratios we are able to conduct a flow-normalized chemical analysis of the study reaches.

RESULTS

Effect of impoundment on flow

The hydrograph of the Cosumnes differs greatly from that of the Mokelumne (Figure 2). During the storm season, high discharges are intercepted by the seven reservoirs in the upper Mokelumne and only a portion of the flow reaches Pardee Reservoir; the signal from the upper catchment reservoirs can be seen most clearly during the

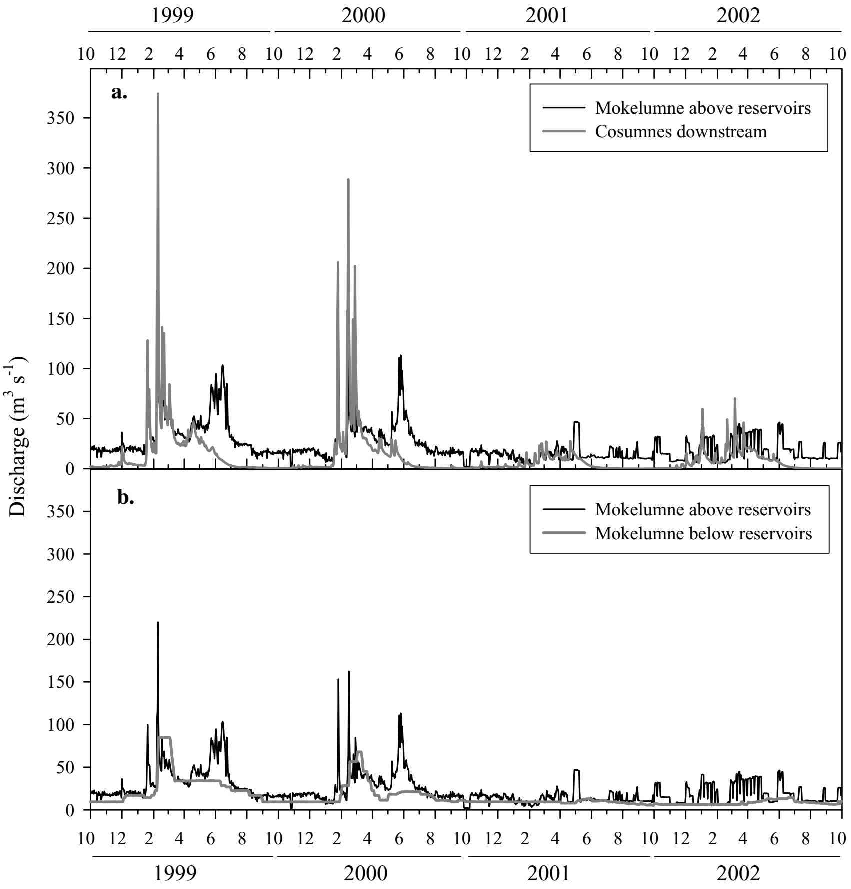

Figure 2. Discharge (w.y. 1999–2002) from two gauges on the Mokelumne River above and below the Pardee–Camanche reservoir system, as well as from the one gauge on the Cosumnes River. The above-reservoir discharge is plotted with the Cosumnes discharge (a) for hydrograph comparison before impoundment by the Pardee-Camanche reservoir system. The above-reservoirs discharge is then plotted with the below-reservoirs flow data (b) for after impoundment comparison. Note that flow above the study reservoirs is impacted by upstream impoundment and diversion, seen most clearly in 2002. Years are in water year format (October to September)

baseflow season of 2002 (Figure 2a). In the Cosumnes, stormflow runs unimpeded into the lowlands creating large peaks in the hydrograph (Figure 2a). Winter storm peaks are also attenuated in the Mokelumne because winter precipitation in the Mokelumne comes as snowfall to a large portion of the upper basin. The resultant snowpack melts in May–July (meltflow season) and creates high flows in the Mokelumne (Figure 2b) which are not seen in the Cosumnes. Meltflows in the Cosumnes instead last from April to June and are less voluminous (Figure 2a). Between January and July (stormflow and meltflow seasons), Pardee and Camanche reservoirs fill to capacity for use over the summer. Camanche reservoir subsequently releases water for the entire summer (baseflow season) elevating baseflow while providing water for downstream irrigation. Meanwhile, Cosumnes discharge at site 1 decreases to between 0.06 and 1.13 m^3 s^{-1} and the lower Cosumnes dries completely in the late summer and early autumn (typically August to November).

Specific conductivity

The Cosumnes River has more dissolved salts in its waters than the Mokelumne and exhibits a stronger seasonal pattern than the Mokelumne (Figure 3). Specific conductivity ranged from a flow-weighted mean value of 69.6 μS cm^{-1} at Cosumnes upstream to 87.5 μS cm^{-1} at Cosumnes downstream. Seasonal variability in SpC at

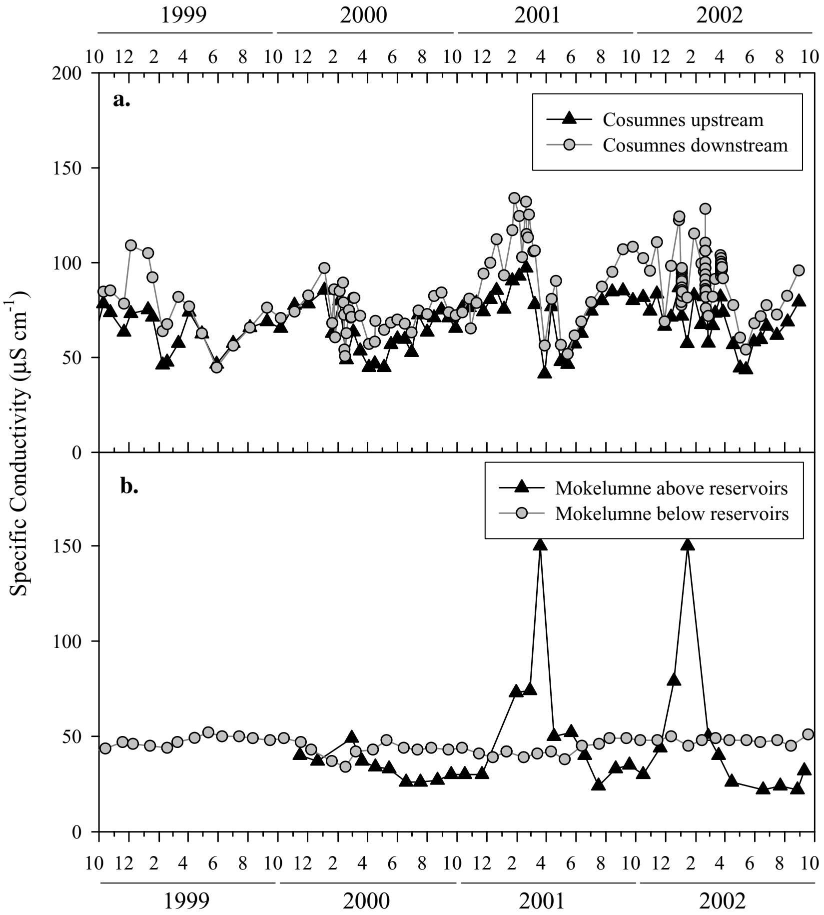

Figure 3. Seasonal variation in specific conductivity in the Cosumnes (a) and Mokelumne (b). Note the significant buffering capacity of the reservoirs in the Mokelumne. Years are in water year format (October to September)

Cosumnes downstream ranged from flushing-flow values as high as 134 μS cm^{-1} and meltflow values as low as 50 μS cm^{-1} (Figure 3a).

Above Pardee Reservoir, SpC varied between 150 μS cm^{-1} during the winter flushing season and 22 μS cm^{-1} during the meltflow season, similar to the trends observed for the Cosumnes. However, this variation was buffered by the Pardee–Camanche reservoir system with outflows of Camanche only varying between 58 and 34 μS cm^{-1} (Figure 3b).

Nutrient transport and processing

The Cosumnes River transports nearly its entire yearly NO_3-N load during the three wettest months of the year (January–March). During the baseflow and meltflow seasons NO_3-N levels are below the detectable limit (<6.0 μg l^{-1} NO_3-N) at both Cosumnes sites (Figure 4a). During the four years of this study the flow-weighted NO_3-N levels averaged 80 μg l^{-1} at Cosumnes upstream and increased to a flow-weighted mean concentration of 120 μg l^{-1} at Cosumnes downstream.

The Mokelumne displayed an attenuated chemograph with much lower NO_3-N concentrations (Figure 4b). Between 1999 and 2002 flow-weighted NO_3-N levels averaged 10 μg l^{-1} above Pardee and were essentially unchanged below the reservoirs with a flow-weighted mean concentration of 20 μg l^{-1}. The Mokelumne site above the reservoirs showed a weak seasonal pattern with elevated NO_3-N concentrations during the storm season, but

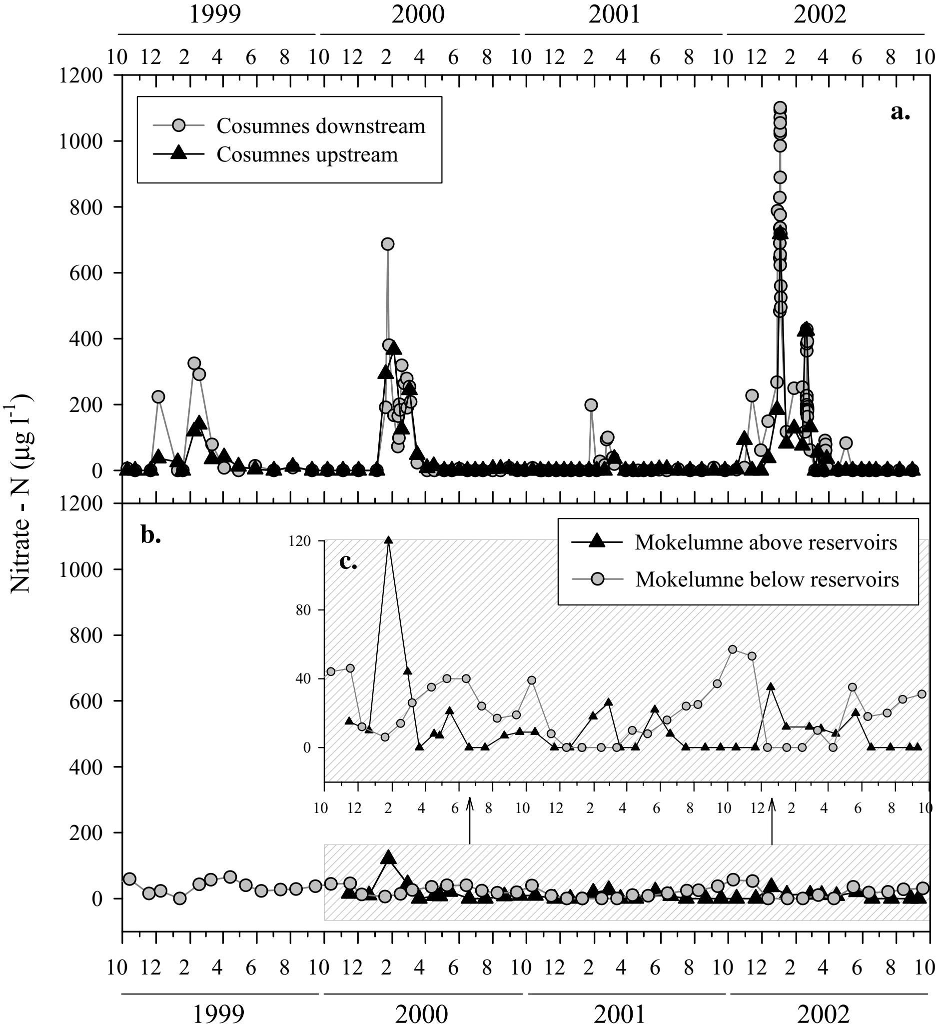

Figure 4. Temporal patterns in NO_3-N concentration in an unimpounded Cosumnes reach (a) and a geographically comparable impounded Mokelumne reach (b). The chemograph for the Mokelumne is scaled up in (c), inset, in order to display the seasonal pattern in NO_3-N. Years are in water year format (October to September)

these elevated levels were not seen below the reservoirs. Instead a different pattern developed below the dams in which NO_3-N concentrations steadily rose from near detection in March to approximately 50 µg l^{-1} in November (Figure 4c). Elevated nutrient levels during the summer months were not observed in the Cosumnes river system.

Total nitrogen (TN) in the Cosumnes was similar at the two sites. There was one annual peak in TN that coincided with the onset of rains in the storm season (Figure 5a). In the Mokelumne, TN concentrations were approximately the same upstream and downstream of the reservoirs, except for a single storm event peak above the reservoirs during the storm season of 2002 (Figure 5b).

Phosphorus species (TP and PO_4-P) were also transported differently in the two rivers. In the Cosumnes PO_4-P is generally below detection (6.0 µg l^{-1}) and was only seen during the largest storms of w.y. 2000 (data not shown), while TP export mimics that of suspended sediment, which is to say, the majority of TP is transported during the largest storms of the year (Figure 6a). Above the reservoirs in the Mokelumne TP followed no discernible pattern except for an increase from 23 to 80 µg l^{-1} during the heavy rains of 2000 (Figure 6b). Below the reservoirs TP is slightly elevated during the meltflow season, but the most distinct increase comes during the early stormflow season when TP spikes to 100 µg l^{-1}, at a time consistent with the annual reservoir thermal destratification and

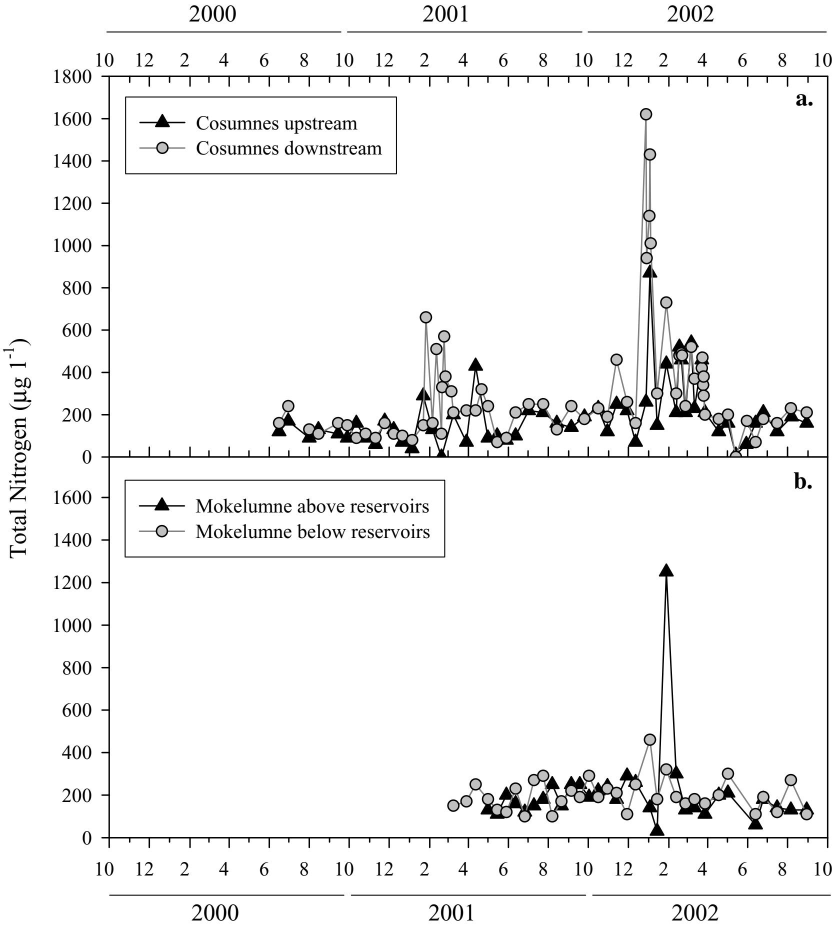

Figure 5. Total nitrogen concentration patterns in the Cosumnes (a) and Mokelumne (b). Data was not available for the Mokelumne until March of 2001. Years are in water year format (October to September)

turn-over. Like the Cosumnes, PO_4-P in the Mokelumne is usually below detection, but unlike the Cosumnes there is no annual pattern to PO_4-P export from the Mokelumne (data not shown).

Ratios of TN to TP show that the Mokelumne is N-limited for the entire year with an average ratio of 6.5—well below the Redfield ratio of 16 (Figure 7b). In the Cosumnes the large N fluxes which come with storms (Figure 5a) create P-limiting conditions during the winter (Figure 7a). During the remainder of the year the two sites on the Cosumnes both have TN:TP ratios at or below 16.

Total suspended sediment

In the Cosumnes river system, downstream sediment fining and agriculture in the lower basin combine to create higher total suspended solids (TSS) concentrations in the lowlands than in the uplands. The four-year flow-weighted mean TSS value at Cosumnes upstream was 12.3 mg l^{-1}, and increased to 16.0 mg l^{-1} at the downstream site. Seasonal variability is strong at each of the sites (Figure 8a), as baseflow carries undetectable levels of sediment (<1.0 mg l^{-1}), and stormflows produce high TSS concentrations (as high as 98.8 mg l^{-1} at Cosumnes downstream).

The Mokelumne has a very different TSS pattern since both the Pardee and Camanche reservoirs act as sediment traps (Figure 8b). A seasonal signal in TSS concentration was only seen above the reservoirs during w.y. 2000 when winter flows carried a maximum concentration of 92 mg l^{-1} (Figure 8b). However, the slight seasonal variation seen above is not seen below the reservoirs where TSS concentrations ranged between 2.0 and 6.7 mg l^{-1} for the duration of the study.

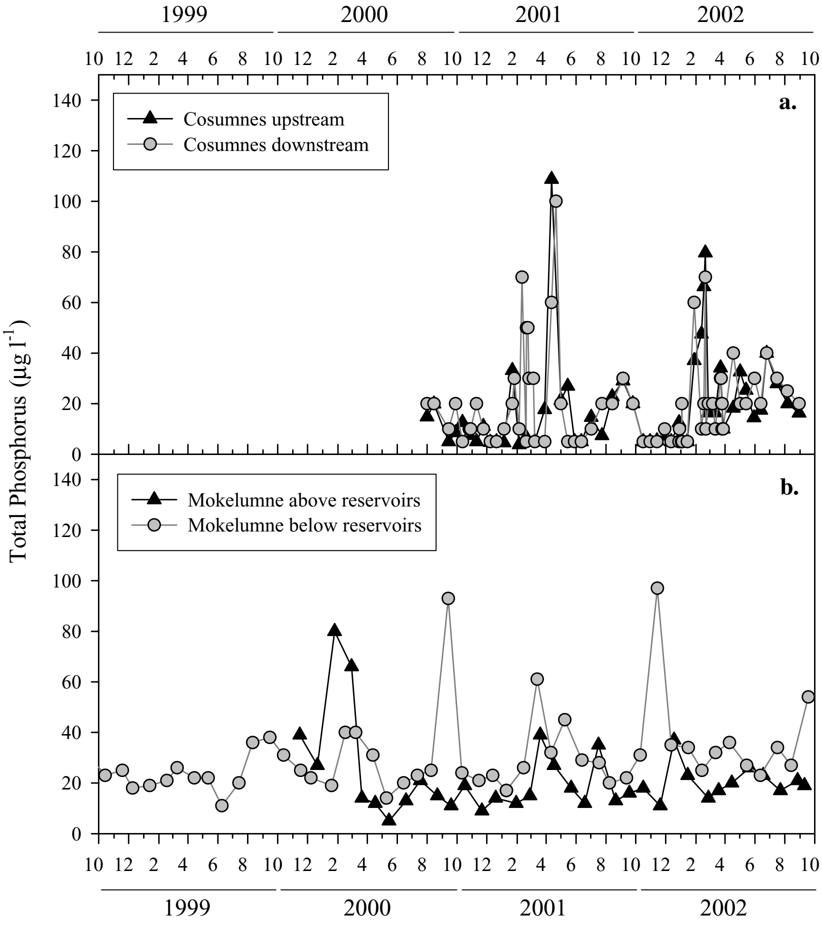

Figure 6. Annual total phosphorus concentration variation in the Cosumnes (a) and Mokelumne (b). Years are in water year format (October to September)

Silicon

In the Cosumnes, DSi showed no clear annual pattern save an increase of 5 mg l^{-1} during the storm season of 2000 (Figure 9a). Mokelumne above reservoirs showed a much clearer pattern as DSi rose to approximately 8 mg l^{-1} during each of the meltflow seasons analysed (Figure 9b). In contrast, the below-reservoir site on the Mokelumne had no annual DSi spike, an indication that the reservoirs act as substantial DSi sinks. Dissolved silicon was always greater than dissolved nitrogen by a factor of 2 or more; the molar ratio of DSI:N necessary for DSi limitation is 1, so DSi limitation is not a factor in these systems.

Transport coefficients

In order to determine whether a reservoir is a source or sink for a constituent, a mass balance is necessary. But because of variable dam operations mass balances are not always representative of the chemical transformations which are occurring in the impounded waters. The use of transport coefficient charts avoids this problem by plotting the ratio of water output to water input for the reservoir against the ratio of constituent output to input flux for the reservoir, thereby normalizing for flow variation (Kelly, 2001). Transport coefficient charts were generated for the Pardee–Camanche Reservoir system and for a comparable unimpounded reach in the Cosumnes River (Figure 10).

Nitrate flux patterns between comparable reaches in the Mokelumne and Cosumnes followed varying trends (Figure 10a,b). In the Cosumnes, the study reach retained a small portion of NO_3-N during the stormflow and

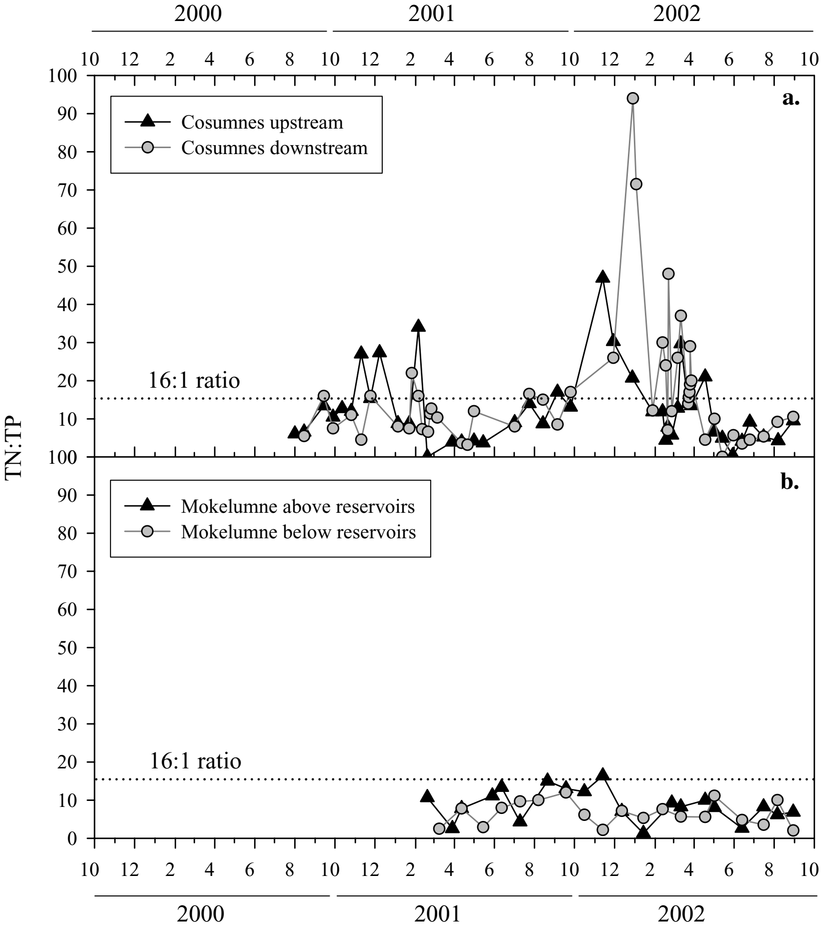

Figure 7. Ratios of total nitrogen to total phosphorus are markedly different between the Cosumnes (a) and Mokelumne (b). The Redfield ratio of 16 to 1 is overlain for reference. Years are in water year format (October to September)

meltflow seasons of 2001 and produced NO_3-N during those same seasons in 2002 (note: stormflow seasons were close to the 1:1 line). In contrast, the Mokelumne reach traversing similar elevations and passing through both Pardee and Camanche reservoirs retained NO_3-N during the storm seasons and substantially increased NO_3-N during the melt and baseflow seasons of both w.y. 2001 and 2002 (Figure 10a).

Though TN was retained in the reservoirs in each of the seasons, TN concentrations were increased during the meltflow seasons, decreased during the stormflow seasons, and remained unchanged during the baseflow seasons of both 2001 and 2002 (Figure 10c). In the Cosumnes there is a very different annual flux pattern as the reference reach increased TN concentration and flux in all the seasons, most markedly during the stormflow seasons (Figure 10d).

Despite retaining TP on a mass basis in many of the seasons analysed, the reservoirs in the Mokelumne increased TP concentrations in each water quality season of 2001 and 2002 (Figure 10e). In the reference reach, TP concentration and flux increased during the stormflow seasons of 2001 and 2002 (Figure 10f); all the other seasons had little to no significant change in TP transport.

Total suspended sediment was generated by the Cosumnes reach during the stormflow seasons of 2001 and 2002. During each other season TSS flux and concentration were reduced (Figure 10h). In the Mokelumne reservoirs TSS dynamics were more complex with no change in TSS concentration during the meltflow seasons, but an increase during each other season (Figure 10g). It is not clear if the suspended solids released by the reservoirs

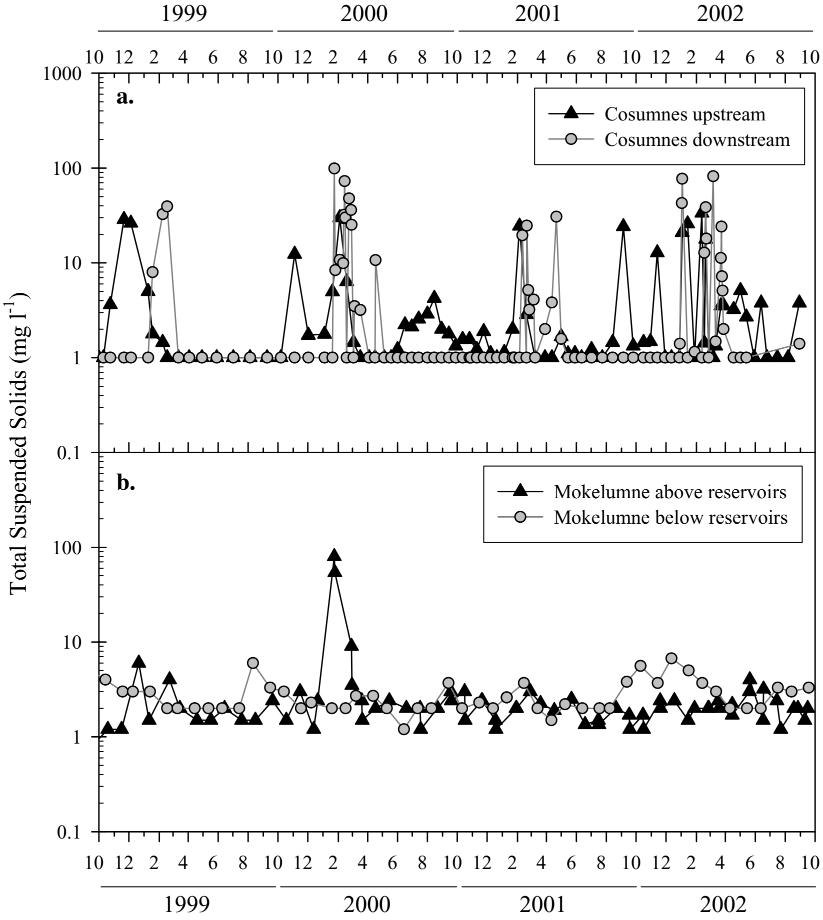

Figure 8. Total suspended sediment variation in the Cosumnes (a) and Mokelumne (b). Note log-scale. Years are in water year format (October to September)

were dominated by organic or inorganic fractions because TSS was not divided into volatile and non-volatile fractions below Camanche Dam.

The Pardee–Camanche system reduced DSi concentrations during the storm and meltflow seasons of 2001 and 2002. The reservoirs slightly increased DSi concentrations during the baseflow seasons (Figure 10i), yet it should be noted that in each season the reservoirs retained DSi on a mass basis. The comparable Cosumnes reach enriched downstream DSi concentrations during the storm and meltflow seasons of 2002. No significant DSi change was seen during the rest of the seasons analysed (Figure 10j).

Watershed fluxes

Transport coefficient charts are useful for demonstrating what time of year reservoirs are retaining or releasing constituents but they do not provide information as to how much of a given constituent is being retained or released. A flux comparison between the Cosumnes and Mokelumne provides the information necessary to comment upon interbasin variability and reservoir impact.

The study reservoirs in the lower Mokelumne served as annual sinks for TP, TSS, and DSi in each of the three years examined (Table V). Between 2000 and 2002 nearly as much DSi (4984 megagrams (Mg)) was retained as TSS (6135 Mg), while only 9.6 Mg of TP was retained (Table V). Annual flux data for TN were only available for 2002 (in 2001 there were incomplete storm season data); during that year 72 Mg were sequestered in the reservoirs.

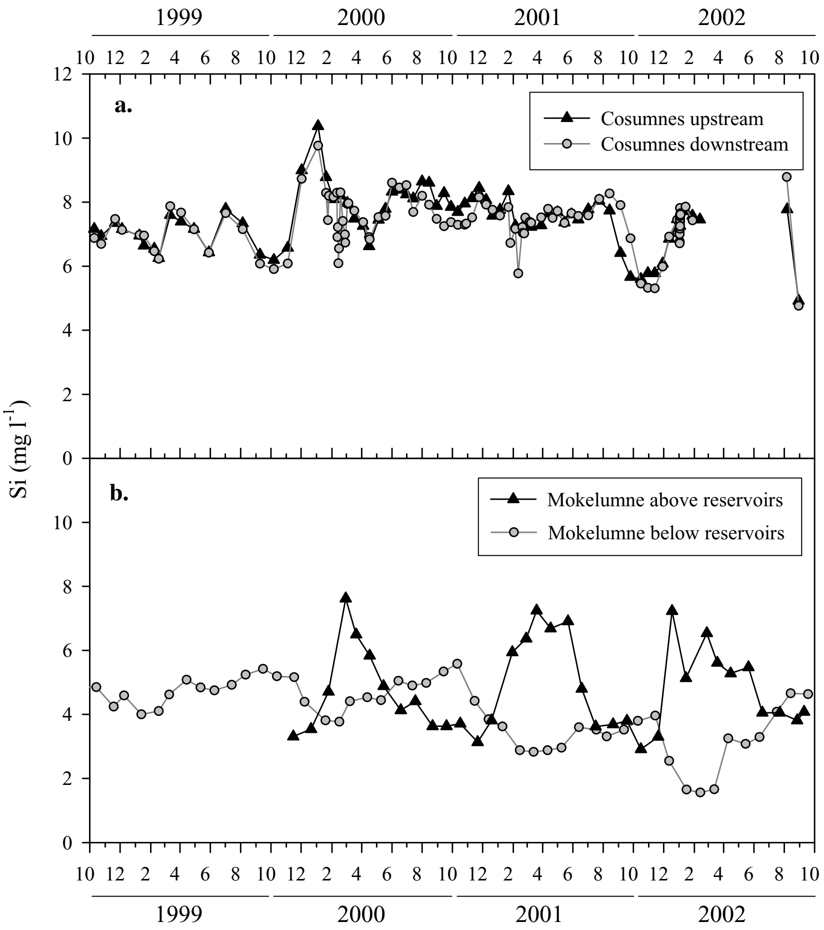

Figure 9. Dissolved silicon is trapped by the Mokelumne reservoirs during the summer and autumn (b), while there is little difference in DSi concentrations between the two free-flowing Cosumnes sites (a). Years are in water year format (October to September)

Following a different pattern was NO_3-N. During 2000 (the wettest year of the study) the reservoir retained 5.65 Mg of NO_3-N but during the next two years, which were considerably drier, 1.04 and 0.47 Mg of NO_3-N were exported by the reservoirs. When compared with the Cosumnes reference reach on a yield basis the Mokelumne export of NO_3-N seems small; Mokelumne yield is less than Cosumnes yield by a factor of 2 and 30 in 2001 and 2002, respectively (Table V). Yet it is the timing of the nutrient release which shows a critical difference between the two reaches. The Cosumnes transports NO_3-N during the stormflow season while the Mokelumne exports NO_3-N during the meltflow and baseflow seasons (Figure 10 a,b). Phosphate followed a similar trend to NO_3-N. In 2000 the reservoirs retained PO_4-P despite a 33.1% increase in concentration. In 2001 there was less water retained and diverted by the reservoirs and a corresponding 74.2% concentration increase in PO_4-P; this resulted in a 0.3 Mg PO_4-P production (Table V). In 2002 PO_4-P was below detection year round both above and below the reservoirs, so the resultant flux reduction is due solely to water retention and diversion.

The Cosumnes reference reach was a source of NO_3-N, TP, TN, TSS, and DSi in each year studied, with only slight DSi concentration decreases in 2000 and 2001. On a yield basis the Cosumnes reach was less of a source of TSS and DSi than the Mokelumne was a sink (Table V), an indication of the reservoirs' removal efficiency for these constituents. Phosphate was the only constituent studied that showed a flux reduction in the Cosumnes reference reach. In 2001, the driest year of the study, there was a 15.3% reduction in PO_4-P concentration through the reach which created a 0.01 Mg retention (Table V).

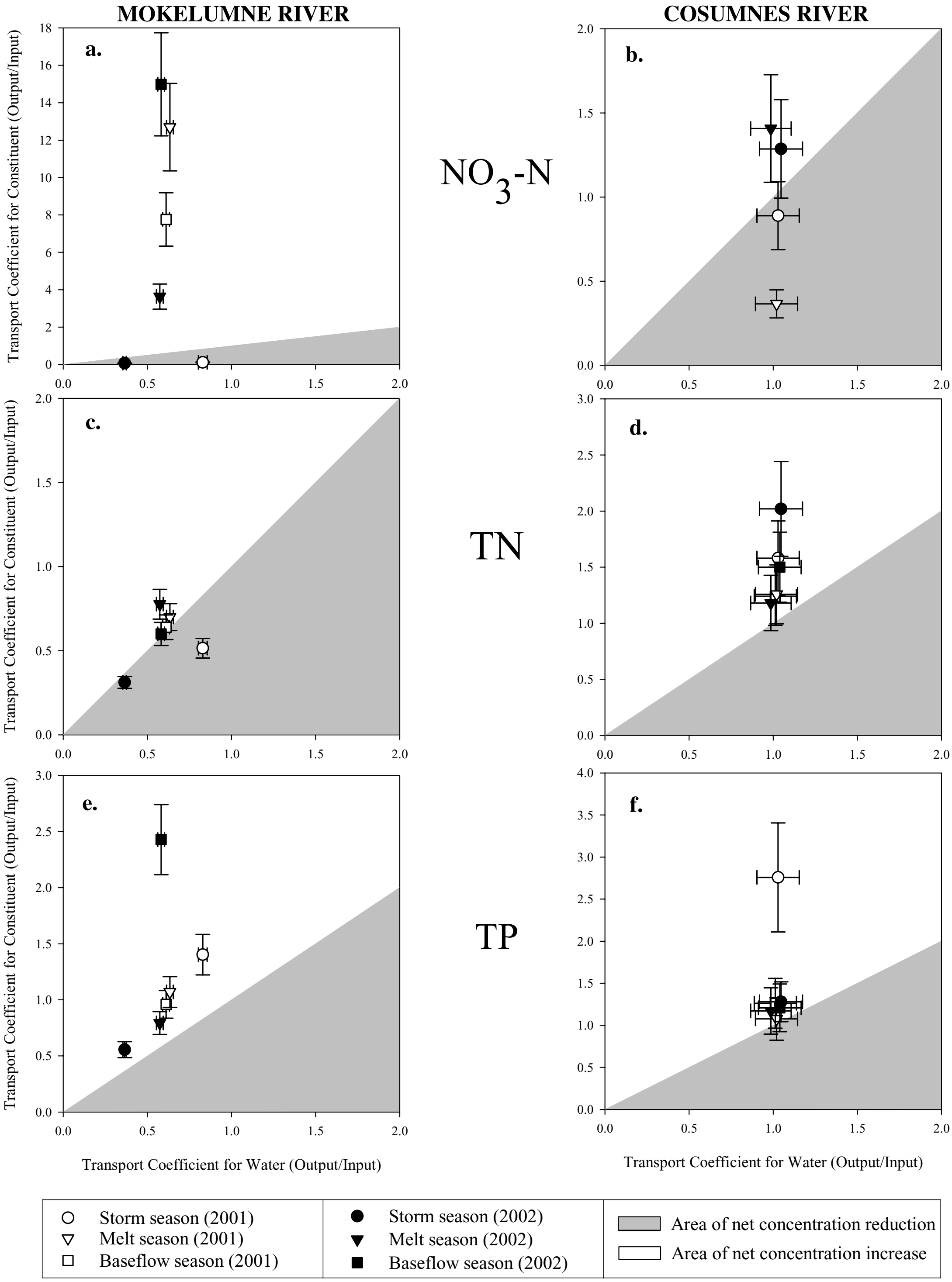

Figure 10. Comparison of transport coefficients for water and selected constituents (NO_3-N, TN, TP, TSS, and Si) above and below the Pardee–Camanche reservoir system as well as in a geographically comparable, but unimpounded, reach in the Cosumnes catchment. Error bars represent error in the flow gauges and flux estimation techniques (see Table IV)

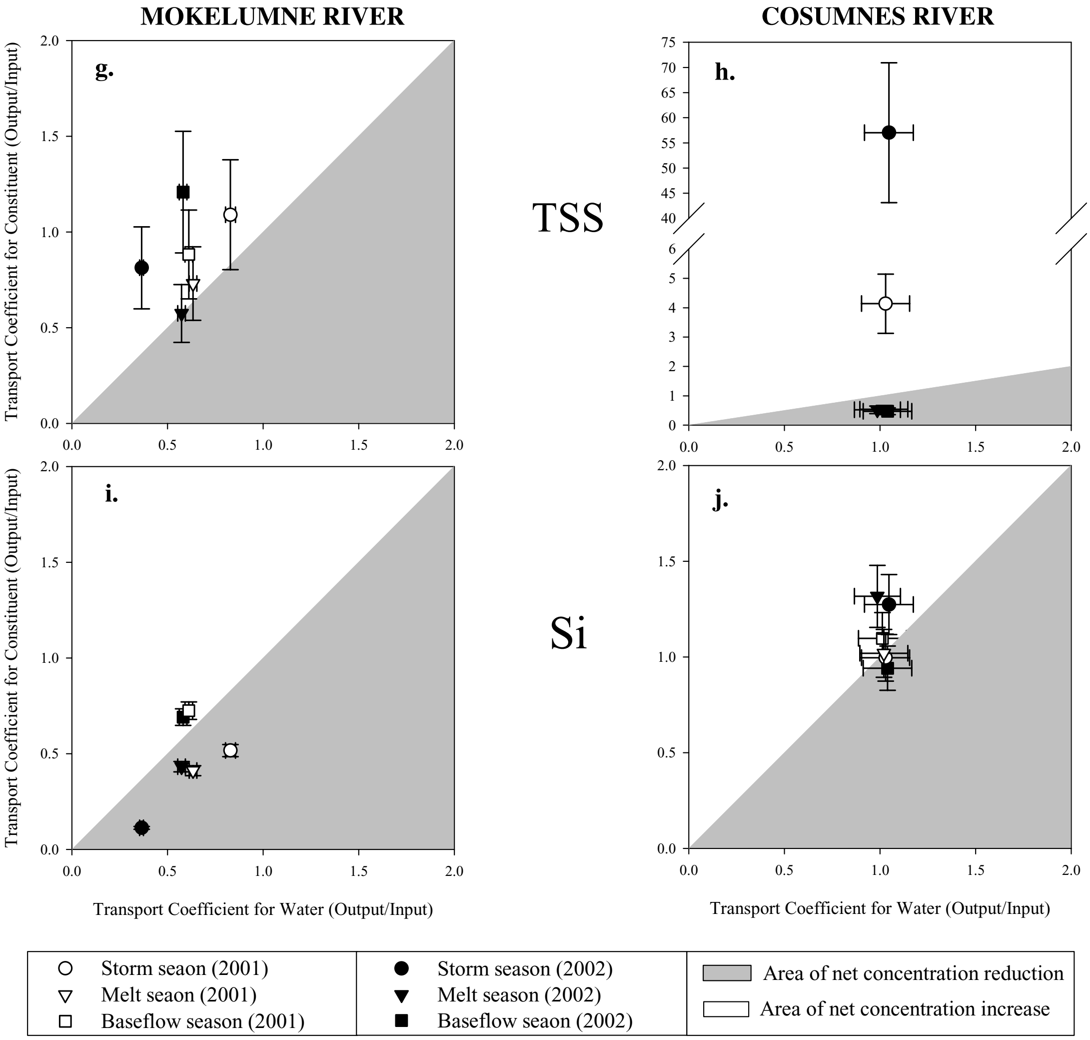

Figure 10. Continued

DISCUSSION

This analysis indicates the significant role that Pardee and Camanche reservoirs play in altering flow dynamics and water quality of the Mokelumne. In most cases the reservoirs act as annual sinks for many inorganic and organic chemicals; this phenomenon has been witnessed in reservoirs of varying size and function in Tennessee (Higgins, 1978), Montana (Soltero *et al.*, 1973), and the arid west (Kelly, 2001), and the same phenomenon is expected in other reservoirs impounding major tributaries draining the western Sierra Nevada. Many constituent fluxes are retained in the reservoirs simply because water is being retained and diverted; this is displayed clearly in Table V when constituents show a positive concentration increase accompanied by a negative net flux.

Dams in California frequently serve a flood control and/or water delivery function, which entails eliminating peak flows and releasing more water during the baseflow season. The change in flow dynamics alone has many ramifications: (1) riverbeds downstream of the dam can become silted in because there are no storm flows to flush them out (Penczak, 1992); (2) due to siltation and bar stabilization, fish spawning habitat downstream of the dam can degrade (Holden, 1979); (3) depending upon dam function and operation, downstream flows can either rapidly fluctuate or be unnaturally stable—both situations can cause a decrease in downstream productivity and biodiversity (Cortes *et al.*, 1998; Poff *et al.*, 1997; Ward and Stanford, 1979).

Table V. Annual flux change and percentage annual flow-weighted mean concentration change based on input and output of the study reservoirs in the Mokelumne and the comparison reach in the Cosumnes

	2000		2001		2002	
	Net flux (yield*)	Conc. change (%)	Net flux (yield)	Conc. change (%)	Net flux (yield)	Conc. change (%)
Cosumnes						
Flow (km^{3}a^{-1})	0.037 (1.60e^{-4})	—	0.005 (0.22e^{-4})	—	0.012 (0.49e^{-4})	—
NO_3-N^2 (Mg a^{-1})	14.49 (0.062)	11.9	2.36 (0.010)	119.4	13.64 (0.059)	25.9
TN (Mg a^{-1})	—	—	23.34 (0.100)	89.2	73.23 (0.314)	69.0
PO_4-P (Mg a^{-1})	1.18 (0.005)	36.3	−0.01 (−0.001)	−15.3	3.86 (0.017)	147.7
TP (Mg a^{-1})	—	—	1.44 (0.006)	38.4	0.89 (0.004)	9.6
TSS (Mg a^{-1})	1463.26 (6.28)	12.1	438.90 (1.88)	65.2	2140.77 (9.18)	152.3
Si (Mg a^{-1})	119.14 (0.511)	−5.1	29.46 (0.126)	−0.7	694.62 (2.980)	24.5
Mokelumne						
Flow (km^3 a^{-1})	−0.29 (−14.2e^{-4})	—	−0.15 (−7.6e^{-4})	—	−0.34 (−16.8e^{-4})	—
NO_3-N (Mg a^{-1})	−5.65 (−0.028)	8.9	1.04 (0.005)	109.5	0.47 (0.002)	151.3
TN (Mg a^{-1})	—	—	—	—	−72.06 (−3.4)	−3.4
PO_4-P (Mg a^{-1})	−0.6 (−0.003)	33.1	0.3 (0.001)	74.2	−2.0 (−0.01)	0
TP (Mg a^{-1})	−6.64† (−0.033)	10.3	−0.19 (−0.001)	49.3	−2.96 (−0.015)	75.1
TSS (Mg a^{-1})	−5541.61 (−27.56)	−71.3	−200.63 (−0.10)	17.9	−392.79 (−1.59)	58.5
Si (Mg a^{-1})	−1743.16 (−8.67)	−10.1	−1168.27 (−5.81)	−28.3	−2072.37 (−10.31)	−33.0

*Units: Mg km^{-2} a^{-1} for constituents; km a^{-1} for flow.

†Value estimated due to lack of concentration data for October and November of w.y. 2000.

Habitat degradation from flow regulation is occurring in the Mokelumne River below Camanche Dam (Smith *et al.*, 2003). With flows not exceeding 14.7 m^3 s^{-1} during 2001 and 2002 (Figure 2b), the minimally disturbed gravels (many of them put into place to enhance spawning habitat) have begun to fill with fine inorganic and organic sediment. To exacerbate the situation the upstream reservoirs are increasing TSS concentrations during drier years (most likely in the form of organic matter) (Figure 8 and Table V), and elevating summer NO_3-N levels (Figure 4b,c) in a N-limited system (Figure 7b). These physical and chemical drivers can promote the growth of periphyton on the downstream spawning gravels and so increase the production of autochthonous organic matter, the same material which is clogging the restored spawning gravels. In order to alleviate this situation EBMUD conducted a controlled release in May 2003. The efficacy of the 56.6 m^3 s^{-1} release is still being examined.

Numerous studies have shown how river impoundment is characterized by downstream solute, thermal, and flow buffering (Hannan, 1979). In the Mokelumne, the solute buffering capacity of the reservoir system was substantial (Figure 3). In Kelly's (2001) analysis of four reservoirs in the desert southwest, reduced solute concentrations in the outfalls of each dam were attributed to dilution from the reservoirs that were filled with water from previous wetter years (low flow years generally create elevated solute levels in local waterways). In the Mokelumne a similar process is at work as the majority of the annual flow is derived from dilute snowmelt. This impounded water is dilute relative to stormflow inputs. When solute-rich, turbid winter flows move into the study reservoirs—this does occur in the Mokelumne despite the fact that there are numerous upstream dams (these dams are located high in the catchment area and so do not have a very large impact on lower catchment chemistry)—the dense water tends to sink and slowly mix with the reservoir body; the result is the solute buffering observed in the outfall. This buffering along with the thermal (data not shown) and flow (Figure 2) buffering combine to create homogeneous conditions immediately downstream which have the potential to reduce aquatic biodiversity.

Our study has shown that dam operations (when and how much water is released), independent of chemical alterations, have a substantial effect on downstream water quality. For instance, mean TSS concentrations decreased in the reservoirs in each of the three years in which fluxes were calculated (Table V). In 2001 and 2002 the reservoirs actually increased TSS concentrations by 17.9 and 58.5%, respectively. Despite the greater concentration increase in 2002 and because there was greater water retention in the same year, the flux reduction was greater in 2002 than 2001. This same pattern of mean concentration enrichment coinciding with mass retention by the reservoirs can be seen, depending upon the year, for many of the nutrients we analysed (Table V). As nutrients and organic particulates are the foundation for aquatic food webs, it becomes apparent how something as simple as water retention by dam operation can impact downstream aquatic ecosystems.

As a primary, and often limiting nutrient (Figure 7), nitrogen plays an especially important role in downstream aquatic ecosystems. In 2000 the reservoirs in the Mokelumne acted as a NO_3-N sink (Table V). But, during the drier years of 2001 and 2002 the reservoir system switched from a NO_3-N sink to a source (Table V). A 1979 study on the effect of drought on 17 Californian reservoirs (Department of Water Resources, 1979) had a similar finding when all the reservoirs in the study became enriched with NO_3-N during the drought. Studies by both Rada and Wright (1979) and Stanford and Ward (1983) have attributed elevated NO_3-N concentrations in effluent waters to the mineralization and subsequent nitrification of organic matter trapped within the impoundment and to nitrogen fixation by phytoplankton. Indeed, analysis of waters behind Camanche Dam (data not shown) reveal that surface waters have virtually no seasonal NO_3-N fluctuation while hypolimnetic waters have a seasonal chemical pattern nearly identical to what is reported at the outflow of the dam (Figure 4c). In the absence of elevated nutrient inputs from upstream (Figure 4c), this would indicate that NO_3-N generation due to mineralization and nitrification in hypolimnetic waters is the cause of the downstream NO_3-N production in the summer. As such, NO_3-N production in the hypolimnion is working to counterbalance the NO_3-N reduction by physical and biogenic sequestration which was most evident in 2000 when NO_3-N imports from upstream exceeded 20 Mg. These results are consistent with those of Martin and Arneson (1978) who studied NO_3-N export variability between a hypolimnetic- and an epilimnetic-release reservoir on the Madison River, Montana. During the summer the epilimnetic-release reservoir was characterized by low NO_3-N levels while the hypolimnetic-release reservoir exported elevated NO_3-N concentrations.

When compared with the Cosumnes, the timing of NO_3-N release to the lowlands of the Mokelumne catchment is offset by approximately 4–8 months (Figure 4). This temporal shift in nutrient export means that lowland aquatic ecosystems are receiving nutrient-enriched waters from the Mokelumne during the warm growing season and from the Cosumnes during the winter when aquatic flora are senesced and cold temperatures are limiting growth. If indeed this alteration is applicable to the other dams impounding the waterways of the Sierra Nevada (since many of the major impoundments release from the hypolimnion we expect this to be the case), then this change has very likely promoted algal production in the tributaries leading into the Sacramento–San Joaquin Delta. The Delta, suffering from heavy sediment and nutrient loads, is light-limited (Jassby and Cloern, 2000). The primary sediment source to the Delta is irrigation tailwaters from the expansive surrounding agriculture. Traditionally, summer dam releases have been used to alleviate downstream water quality problems associated with water diversion and return from agricultural irrigation. Our data suggest that these releases contain elevated NO_3-N levels which can potentially promote algal growth and add more algal biomass to the Delta. Though this source is considerably smaller than what downstream agriculture contributes, it is a source which previously has not been considered.

Dissolved silicon, more than any other constituent, was the most efficiently and consistently removed by the Mokelumne reservoirs. By comparing the study reaches it can be seen that an order of magnitude more DSi was removed from the Mokelumne than was generated by the Cosumnes reference reach, this is most evident in dry years when input sources are reduced (Table V). This removal efficiency has been seen in other impoundment studies in the Baltic and Black Sea tributaries where DSi removal was estimated at 60% (Humborg *et al.*, 1997, 2000). A subsequent study in the Black Sea area estimated the number to be only 4% (Friedl *et al.*, 2004), but this study was only conducted for one year. Retention numbers in the Mokelumne ranged between 10 and 33% depending upon the year (Table V); this equates to a large flux reduction, however, because DSi import from the silicate-rich Sierra Nevada Batholith was large, between 1000 and 5000 Mg a^{-1}. Our results confirm that reservoirs can be substantial DSi sinks but unlike the Baltic and Black Sea the Mokelumne and its basin are not DSi limited, so there is no expected effect on siliceous organisms.

CONCLUSIONS

The Pardee–Camanche reservoir system on the Mokelumne River has altered downstream water quality and quantity. The hydrographs of the Cosumnes and Mokelumne Rivers are dramatically different with winter flows attenuated and summer flows elevated in the Mokelumne. Nitrate fluxes, which if unimpounded would move through the Mokelumne during the storm season, are instead retained and released during the remainder of the year. The release of NO_3-N during the summer coupled with the fact that the downstream reach is N-limited will likely lead to increased algal export in the summer months. The reservoirs acted as net annual sources of NO_3-N and PO_4-P depending upon the internal reservoir conditions and operation in a given year; all other constituents analysed, especially DSi, were retained by the reservoirs on an annual basis. Solute, temperature, and flow buffering was also evident in the impounded Mokelumne. Because comprehensive water quality records do not exist prior to the dam-building era, studies such as this may be the only way to estimate how historical chemical fluxes moved from the Sierra Nevada mountains to the Sacramento–San Joaquin Delta. With this knowledge we can begin to address how the impounding of California's waterways has alerted downstream water quality and aquatic ecosystems.

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