Limnol. Oceanogr., 50(6), 2005, 1752–1762

Sediment and nutrient dynamics following a low-head dam removal at Murphy Creek, California

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Abstract

We studied the impact of the removal of a 3-m dam on sediment and nutrient export. In the year after dam removal, sediment and nitrogen (N) export increased by an order of magnitude over the previous 2-yr mean. Longitudinal surface water samples were collected, sediments were cored, and the channel was surveyed during different seasons to determine the mechanisms driving sediment and nutrient dynamics in the recovering system. The majority of sediment transport occurred in pools and in the lowest 50 m of the 620-m restored reach. Phosphate export occurred primarily during large storms, with the restored reach acting as a phosphate sink during most flow conditions. The majority of surface water N originated from areas within the sediment wedge that had high extractable N concentrations (average NH_4-N = 50 μg g^{-1} and NO_3-N = 38 μg g^{-1}) and dried out on a seasonal basis. Near the former dam site, year-round water saturation apparently inhibited nitrification and export of N as nitrate. This wetland area was the only portion of the restored reach that was an ammonium sink. After dam removal, N leaching from sediments occurred in autumn 2003 and again during the subsequent autumn, suggesting that N leaching from reservoir sediments is largely a seasonal process that may affect downstream aquatic ecosystems for a number of years.

A wealth of research has been conducted on the downstream effects of large impoundments, while surprisingly little attention has been paid to small run-of-river reservoirs (Stanley and Doyle 2002). More than 75,000 major reservoirs (volume: 61,650 m^3) exist within the United States (USACE 1996), and many are impounded by dams that are aging and in disrepair. Removal as a viable alternative to the maintenance of this aging infrastructure has been growing in popularity over the past two decades, during which time more than 500 dams have been removed in the United States (Stanley and Doyle 2003). The dismantling of these dams provides researchers with an opportunity to study both how reservoirs impact river function (Winter 1990) and how rivers respond to dam removal (Doyle et al. 2003*a*).

The removal of dams has been shown to have positive effects on anadromous fish populations. It can open up spawning and rearing habitats in previously inaccessible upper reaches (Kanehl et al. 1997; Smith et al. 2000; Lenhart 2003; Bigford 2004). However, removal of dams has the potential for many other environmental consequences. Reservoir bottom sediments can be mobilized (Shuman 1995; Pizzuto 2002), residence times, flow, and thermal regimes are altered (Poff and Hart 2002), carbon budgets could be drastically changed (Margolis et al. 2001), and lentic nutrient dynamics are shifted to lotic dynamics (Hillbricht-Ilkowska 1999). These changes can, in turn, cause substantial nutrient export to sensitive downstream aquatic ecosystems (Gray and Ward 1982). It is with this knowledge that we seek to better understand how nutrient dynamics are altered after low-head dam removal.

Before removal, the majority of nutrients in an impounded reach are stored in the benthos (Perrin et al. 2000; Stanley and Doyle 2003; Ahearn et al. 2005). With drawdown, the reservoir sediment is exposed and complex biogeochemical reactions begin. When previously reduced sediments are oxidized, metals can be mobilized (Saeki et al. 1993; de Carvalho et al. 1998) with certain species (most notably Fe), binding with and immobilizing phosphate (Degroot and Vanwijck 1993; Kleeberg and Heidenreich 2004). Nitrogen in the sediment may be mineralized, nitrified (Sparling and Ross 1988), and leached (Perrin et al. 2000), denitrified (Kern et al. 1996), or assimilated into riparian vegetation (James et al. 2001). Predicting nutrient export and/or retention after dam removal can thus be complex. Research within restored reservoir reaches is necessary to elucidate the nature of postremoval nutrient dynamics and their impact on downstream aquatic ecosystems.

This study examines sediment and nutrient dynamics in a recently dewatered impoundment in central California. Longitudinal surface water profiles coupled with sediment core analysis and geomorphic surveying were used to identify zones of nutrient leaching and mass wasting within the reservoir sediments. The objectives of the study were to (1) characterize source areas for sediment transport, (2) determine what geomorphic/sediment characteristics lend themselves to either nutrient release or retention, and (3) quantify the impact of dam removal on the downstream export of nutrients and sediment.

Murphy Creek is a second order tributary of the Mokelumne River located southeast of Sacramento, CA (Fig. 1). Its confluence with the Mokelumne River is located just below Camanche Dam in San Joaquin County. The small watershed of 12 km^2 has three impoundments on its mainstem. We focused our efforts on the two lower reservoirs because the uppermost reservoir had little inflow and was inacces-

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Acknowledgments

This research would not have been possible without the assistance of X. Wang, S. Henson, J. Merz, M. Dalal, and S. Diep. The authors thank the Sparrowk family for leading the charge in this restoration project and granting us access to their property. Funding was provided by the CALFED Bay-Delta Project (Grant 99-NO6).

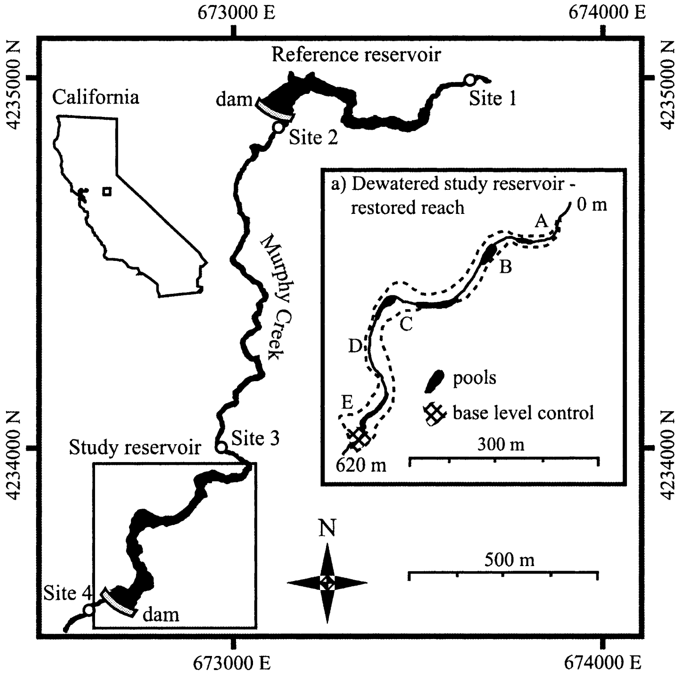

Fig. 1. Study site on Murphy Creek, California. Plan view map shows the study reservoir and the upstream reference reservoir along with the sampling sites used to calculate fluxes (sites 1–4), while (a) shows the restored reach after dam removal. Letters along the channel in (a) mark locations at which soil samples were collected; the gravel base level control is located at 620 m while the top of the restored reach is at the 0 m station.

sible. The two elongate reservoirs were each ~0.013 km^2 and were impounded by overflow dams (~3 m high). The lower dam was removed, whereas the upper dam remained intact. We used the intact upper reservoir as a reference for our study. We refer to the upper reservoir as the ''reference reservoir,'' the lower reservoir as the ''study reservoir,'' and the dewatered lower reservoir as the ''restored reach'' (Fig. 1). Land use in the watershed is predominantly cattle grazing (~80%) and viticulture (~20%), interspersed with a few homes and roads. The sparse oak woodland vegetation leaves waterways unshaded, and macrophyte communities thrive along riparian and littoral zones. The entirety of the watershed is underlain by the Mehrten Formation, a lithified series of lava flows with numerous gravel and cobble laden mudflows.

Both the reference and study reservoirs were eutrophic based on average total phosphorus in outflow water, using a Carlson-type trophic state index (Carlson 1977; Kratzer and Brezonik 1981). Dense stands of cattail (*Typha* sp.) bordered both reservoirs; during the summer, duckweed (*Lemna* sp.) covered the entire surface of the water bodies. Other dominant species included stinging nettle (*Urtica* sp.) and California blackberry (*Rubus* sp.). After removal, cattails, stinging nettle, and saw grass (*Cladium* sp.) quickly colonized the nutrient-rich sediments of the restored reach, creating dense stands in the most saturated soils.

The 3-m-high earthen dam impounding the study reservoir was constructed in the early 1970s to create a stock pond. In 1986, floodwaters breached the dam; the structure was rebuilt the following year, and the impoundment filled to its 15,000-m^3 capacity. As part of an effort to restore as much fish spawning habitat as possible below Camanche Dam, the California Department of Water Resources, East Bay Municipal Utility District, California Bay Delta Authority, and local land owners coordinated to remove the dam in the summer of 2003. After summer inflow ceased, the reservoir was dewatered by pumping the impounded water over the dam, a technique that minimized disturbance of bottom sediments. After dewatering, the earthen dam was excavated, and a gravel control was placed at 0.6 m above the historic channel bed to minimize knickpoint migration in the lower section of the restored reach (Fig. 1). The sediment in the restored reach was left undisturbed and ranged from 2 m deep near the dam to only trace amounts in the upper one third of the former reservoir. After the reservoir was drained, the resultant channel slope was 0.0023.

The Mediterranean climate of California is characterized by hot, dry summers and cool wet winters. The majority of the annual rainfall occurs from December to April, with scarce precipitation during the remainder of the year. In 2002, rainfall was 17% below average, with 490 mm of rain falling on the Murphy Creek Watershed (as gauged at Camp Pardee, ~16 km northeast of the watershed). In 2003, there was 421 mm of precipitation, whereas in 2004 (the year after dam removal), 438 mm of rain fell on the watershed. Although rainfall was comparable among the years, Murphy Creek experienced its highest discharges in 2004, because of large storms arriving later in the winter, moist antecedent conditions, and cool weather.

Materials and methods

Sampling sites were located above and below each reservoir (Fig. 1). Streamwater autosamplers (ISCO 6700) were installed above and below the study reservoir to collect samples during storms. Weekly to biweekly sampling was conducted during base flow at all sites; ~800 samples were collected and analyzed over the 3-yr study. An additional 150 longitudinal surface water samples were collected during the course of nine sampling trips in 2003 and 2004. These samples were collected approximately every 40 m from the top of the restored reach to the old dam site at the bottom. To calculate fluxes of constituents through the reservoirs, pressure transducers (Global Water) installed above and below the restored reach were used to monitor stage. Whenever storm samples were taken, discharge was calculated with the velocity–area technique. These data were subsequently plotted against stage values from the pressure transducers and a rating curve was developed to calculate stream discharge (m^3 s^{-1}).

A reference reservoir served to isolate the effect of dam removal on sediment and nutrients from seasonal effects (Fig. 1). Log-transformed concentration data from above and below the reference and study reservoirs ($n = 33$) were compared both before and after the dam removal using a four-way analysis of variance (ANOVA) model that accounted for repeated measures (Sall et al. 2001). The significance of the three-way interaction term (above/below reservoir; ref-

Table 1. Yearly nutrient and sediment load (difference of out-flux and in-flux) from the study reservoir for 2 yr before dam removal and from the restored reach for 1 yr after removal.

Water year	Annual load (kg)						
	TSS	VSS	TN	NH_4-N	NO_3-N	TP	PO_4-P
2002	1,413	469	224	—	76.6	11.7	−5.0
2003	1,776	666	222	—	70.7	5.1	−15.6
Dam removed							
2004	48,694	5,586	1,738	64.2	689	154	57.7

erence/study reservoir; before/after removal) was tested for each constituent measured to determine if changes in constituent concentrations after the dam removal were caused by seasonal effects or the removal itself. This statistical analysis was weighted toward base flow relationships because there were no autosamplers at the reference reservoir and only 15% of the grab samples were collected during elevated flow conditions.

Grab samples were collected in 125-ml high-density polyethylene (HDPE) bottles for chemical analysis and 500-ml HDPE bottles for suspended sediment analysis. Samples were stored on ice and filtered within 24 h of collection. The 500-ml samples were filtered through preweighed glass fiber filters; the filters were dried at 60°C for 24 h and weighed again to measure total suspended sediment (TSS). Volatile suspended solids (VSS) were calculated from the same sample after ashing at 550°C for 3 h. The minimum detection limit (MDL) for TSS and VSS was $\sim$0.5 mg L^{-1}; values that fell below the MDL were set to 0.1 mg L^{-1} for flux calculations. The 125-ml samples were filtered through a 0.2-μm polycarbonate membrane (Nuclepore) and stored at 3°C through completion of analysis. Nitrate (NO_3^-) and phosphate (PO_4^{-3}) were measured using ion chromatography (Dionex 500x; AS14A column), with a MDL of 6.0 μg L^{-1} (as PO_4-P and NO_3-N). Total phosphorus (TP) was analyzed from a persulfate-digested split of unfiltered sample (Yu et al. 1994); the digested sample was measured with the ammonium molybdate method (Clesceri et al. 1998) using a Hitachi U-2000 spectrophotometer (MDL = 6.0 μg L^{-1}). Total nitrogen (TN) and ammonium (NH_4^+) were measured on a diffusion–conductivity autoanalyzer (Carlson 1986; Carlson et al. 1990); the TN split of unfiltered sample was digested with 13.3% potassium persulfate (Yu et al. 1994), whereas the NH_4^+ sample was filtered and run on the same analyzer. The MDL for both TN and NH_4-N was 6.0 μg L^{-1}.

During the autumn and spring after dam removal, 20 reservoir sediment cores (0.1–1.0 m depth) were collected from five representative sites along the restored reach. At each site, A–E (Fig. 1a), two near channel and two upslope cores were collected. Sediment cores from each site were composited, and the resulting five samples were analyzed for particle size and nutrient content. In autumn 2004, 1 yr after dam removal, cores were again collected from the five sites. On this occasion, the same collection method was used except cores were collected in triplicate, resulting in three sets of four-core composites for each of five sites. All cores were stored in 10-L buckets and kept either on ice or refrigerated through completion of analysis. Sediment cores were analyzed for particle size in November 2003 using a hydrometer (Carter 1993). Extractable NO_3^- and NH_4^+ were determined before and after the major storms of the water year (October–September) 2004 and once more on 9 November 2004 by shaking 20 g equivalent dry mass of sediment with 100 ml of 2 mol L^{-1} KCl for 24 h and analyzing the filtered solution with a Carlson diffusion–conductivity analyzer (Carlson 1986; Carlson et al. 1990).

The topography of the restored reach was surveyed in January 2004 and again in April 2004 at the end of the rainy season. Using a Topcon 802a robotic total station, eight cross-sections and a long profile were mapped in the restored reach. Approximately 3,600 survey points were shot, and sediment depths were measured at nearly 50% of these points. There was minimal sediment accumulation in the upper one-third of the reservoir, so surveying was concentrated in the lower section of the reservoir.

Results

Mass balance—Before dam removal, the study reservoir acted as an annual net source of sediment and nitrogen to the stream (Table 1). Although it was expected that the reservoir would act as a sink for these constituents, an average of 1,595 kg of TSS (36% VSS) and 223 kg of TN were exported in the 2 yrs before dam removal. In contrast, PO_4^{-3} was retained by the reservoir in both 2002 and 2003, whereas TP was exported. Ammonium was not detected in Murphy Creek before dam removal.

Postremoval nutrient and sediment export from the restored reach were an order of magnitude greater than in the 2 yrs before dam removal (Table 1). After the removal of the dam, TSS and TP export increased nearly 30-fold. Organic nitrogen was also exported at higher rates after dam removal, with inorganic-N (NH_4^+ and NO_3^-) accounting for 43% of the 1,738 kg of TN exported (Table 1). Despite the large disturbance to the system, TN : TP mass ratios did not change after removal, remaining between 6 and 8 during all but the largest storms in each of the 3 yrs.

Temporal patterns—Suspended sediment: Before removal, TSS concentrations above and below the study reservoir varied independent of discharge ($r^2 = 0.03$, $p = 0.175$), with the highest concentrations associated with both small and large flow pulses (Fig. 2a). Input and output concentrations were variable with higher concentrations above the reservoir during some storms and higher concentrations below the reservoir during others. After dam removal, significantly higher

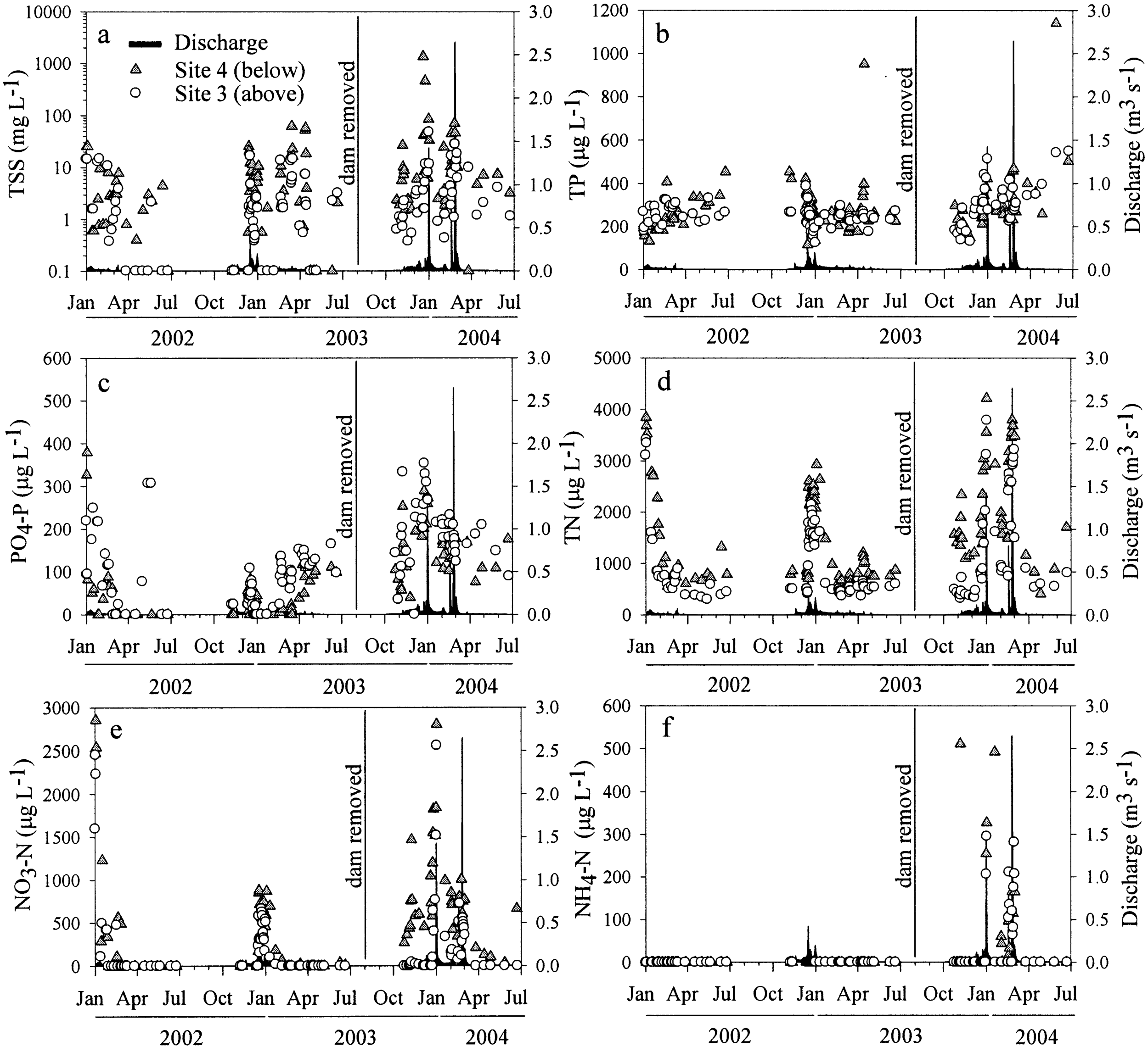

Fig. 2. Temporal patterns of discharge (bars) and (a) TSS, (b) TP, (c) PO_4-P, (d) TN, (e) NO_3-N, and (f) NH_4-N at sampling sites above and below the restored reach. Dividing line in each graph indicates when the dam was removed.

TSS concentrations were measured below the restored reach than above ($p = 0.020$), independent of flow conditions (Fig. 2a). Before removal, 57 mg L^{-1} was the maximum TSS concentration below the restored reach, whereas after dam removal, TSS concentrations as high as 2,000 mg L^{-1} were measured.

Phosphorus: Unlike sediment, TP and PO_4^{-3} temporal patterns did not display a marked change after dam removal (Fig 2b,c). Phosphate concentrations were higher in 2004, but this was not caused by the dam removal because concentrations were elevated both below and above the restored reach (Fig. 2c) and were not significantly different from the reference reservoir (Table 2). During a wide range of flow conditions, PO_4^{-3} was lower below the restored reach, indicating that, during most conditions, the reach was a PO_4^{-3} sink. However, as stated above, when loads were calculated, the reach was a small annual source of PO_4^{-3} after dam removal. A seasonal analysis of PO_4^{-3} loading after dam removal indicated that, during low flows, the reach was a PO_4^{-3} sink, and during high flows, it was a PO_4^{-3} source.

Nitrogen: After removal of the dam, concentrations of all nitrogen species increased below the restored reach. This N increase was not as large as the sediment increase; instead of order of magnitude increases, TN and NO_3^- concentrations were on average two-fold greater after removal (Fig. 2d,e). Ammonium, which was not detectable in the system before removal, was often measurable in 2004 both above and below the restored reach. Ammonium concentrations were similar above and below the reach during large storms, but during occasional small storms, no ammonium was imported, whereas concentrations as high as 500 μg L^{-1} were exported from the restored reach (Fig. 2f). Temporal patterns of TN

Table 2. Significance results from a linear mixed effects model used to compare suspended sediment and nutrient concentrations between the reference reservoir and the study reservoir/restored reach before and after dam removal. Most data analyzed here represent baseflow discharges.

	Constituent Pr > F						
Factor	TSS	VSS	NO_3-N	NH_4-N	PO_4-P	TN	TP
(A) Date	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
(B) Before/after removal	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.02
(C) Above/below reservoirs	0.04	0.04	0.92	0.88	0.26	<0.01	<0.01
(D) Study/reference reservoir	0.71	0.57	0.66	0.47	0.31	<0.01	0.12
(B) × (C)	0.25	0.11	0.66	0.56	0.03	0.10	0.63
(B) × (D)	0.01	0.02	0.53	0.04	0.30	0.21	0.90
(C) × (D)	0.02	0.31	<0.01	0.24	0.06	<0.01	0.03
(B) × (C) × (D)*	0.32†	0.72†	<0.01	0.76	0.32	0.07	0.96

* This three-way interaction isolates seasonal effects from dam removal effects; if signficant, the change in constituent concentration is caused by the dam removal.

† Suspended sediment was not significant because there was minimal storm runoff sampling from the reference reservoir; see Discussion.

and NO_3^- data indicated that, after dam removal, there was a continual leaching of nitrogen from the restored reach independent of flow conditions ($r^2 = 0.04$, $p = 0.218$). Autumn 2003 was characterized by substantially elevated TN and NO_3^- concentrations in water exported from the restored reach, a phenomenon that motivated the exploration of N sources within the area of the dewatered reservoir.

Sediment characteristics and channel morphology—A post dam removal survey of the channel before and after the two largest storms in 2004 (Figs. 3 and 4) indicated that most of the sediment excavation occurred in pools and in the lower section of the reservoir where knickpoint migration carved a 0.5-m-deep channel ~50 m upstream until reaching a bedrock control.

Three months after dam removal, in autumn 2003, there was little indication of reservoir deposits near the upstream end of the restored reach. This upper section, sampled at sites A and B (Fig. 1), was characterized by gravel- and sand-rich sediments (23% and 65%, respectively; Fig. 5). Site A was N poor, with only 5 μg g^{-1} extractable NO_3^--N and 7 μg g^{-1} extractable NH_4-N present during autumn 2003 (Fig. 6a,b). Site B, despite having a similar grain size distribution (Fig. 5), was more N-rich (21 μg g^{-1} extractable NO_3^--N and 14 μg g^{-1} extractable NH_4-N) than site A (Fig. 6a,b). Surface water concentrations of inorganic-N did not increase in the reach between these upper two sites (Fig. 7), so the upper section of the restored reach was deemed a negligible source of streamwater N.

Sites C and D displayed a marked increase in clay and silt content with an accompanying reduction in gravel content (Fig. 5). From site C to the bottom of the reservoir, the sediment profile was dominated by fine-textured reservoir deposits. Between sites C and D, sediment cores collected in autumn 2003 averaged 29 μg g^{-1} sediment-bound NO_3-N and 40 μg g^{-1} sediment-bound NH_4-N (Fig. 6a,b). The area represented by sites C and D seems to be where the greatest release of N to surface water was occurring, as evidenced by surface water longitudinal profiles taken in autumn 2003 and 2004 (Fig. 7a,d).

Site E exhibited the highest clay and silt content of all soil sampling sites (Fig. 5). The area represented by site E is a broad (~25 m width) mud flat with autumn 2003 soil extractable NH_4-N concentrations near 70 μg g^{-1} (Fig. 6b), the highest values found in the restored reach. Site E was unique in that knickpoint migration originating at the old dam site carved a channel through the sediment wedge, but the area never drained because of the downstream gravel base level control. The lack of drainage caused the sediments to remain saturated, keeping oxygen levels low and apparently inhibiting nitrification and/or promoting denitrification as soil extractable NO_3-N levels were low (13 μg L^{-1}; Fig. 6a).

Soil sampling was conducted again in spring and autumn 2004. During the spring, extractable NO_3^- was substantially reduced at each site (Fig. 6a). Soil NH_4^+ followed a similar pattern at all sites except site E, which remained saturated with water through the spring, thereby inhibiting nitrification, a major pathway for N release from the sediment (Fig. 6b). During autumn 2004, soil NO_3^- returned to the levels seen the previous autumn, with an approximate two-fold reduction at site E being the only change from the previous year (Fig. 6a). Ammonium also rebounded from the low values measured in spring 2004, with sites C and D showing the greatest increase.

Longitudinal surface water nitrogen profile—Inorganic nitrogen production (NO_3^-, NH_4^+) by the restored reach was the most conspicuous biogeochemical change after dam removal. To determine the source of N, water samples were collected from a longitudinal transect of the restored reach. In autumn 2003, there was a clear pattern of increasing NO_3^- and NH_4^+ from the middle section of the restored reach (Fig. 7a,d). Nitrate remained near detection limits in the top 180 m of the restored reach. Below 200 m, remnant reservoir sediments became ubiquitous, and an accompanying increase in surface water NO_3^- was measured. There were continual NO_3^- increases in stream waters until 480 m; from 480 m to the old dam site at 690 m, there was no NO_3^- increase in the stream (Fig. 7a).

Ammonium followed a similar pattern until ~400 m, at which point NH_4^+ decreased in the downstream direction. Ammonium was removed from the water column until concentrations near the bottom of the restored reach were sim-

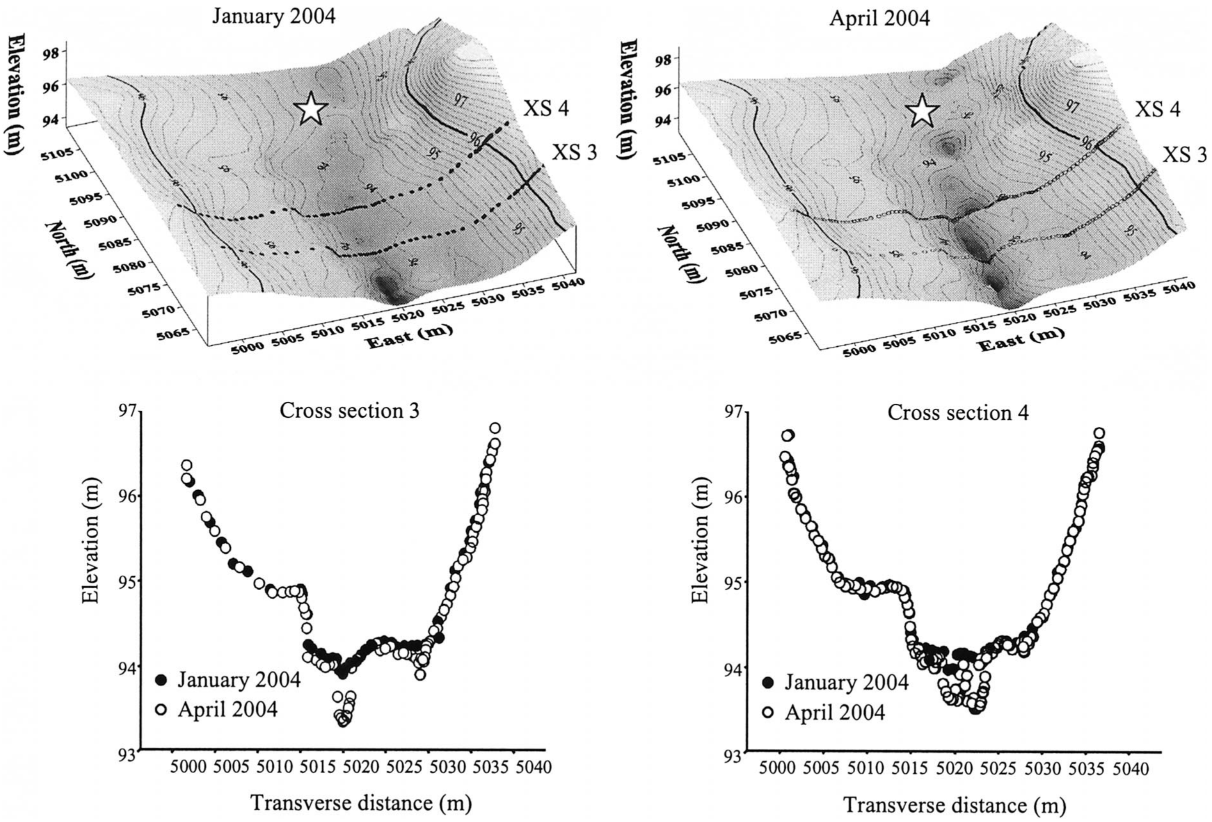

Fig. 3. Surface maps and cross sections from geomorphic surveys of the lower section of the restored reach conducted before and after the majority of the 2004 annual flow in January 2004 and April 2004. The surface maps show elevation above mean sea level, easterly distance, and northerly distance; horizontal distances are relative to a nearby benchmark with coordinates 5,000 E, 5,000 N. The contour interval is 20 cm. The maps show ~50 m of knickpoint migration. The cross sections at XS3 and XS4 indicate an average channel incision depth of 0.75 m and channel width ranging between 2 and 5 m. The presence of large woody debris in the channel accounts for the nonuniform incision seen in cross section 4. In each surface map, the elevation of the old reservoir water surface is indicated at 96 m above mean sea level. The stars on the surface maps indicate the presence of a bedrock control that impeded further knickpoint migration.

ilar to the concentrations that entered the top (~0–180 μg L^{-1}; Fig. 7d). In autumn 2004, 1 yr after dam removal, the same spatial pattern of N leaching from sediments returned (Fig. 7a,d), the only caveat being a slight downstream shift in the zone of maximum NH_4^+ leaching.

During the winter after dam removal, there was very little NO_3 released from the restored reach, whereas import from upstream was elevated to between 900 and 1,420 μg L^{-1} (Fig. 7b). As temperatures warmed in the spring and thick macrophyte stands emerged in the riparian zone of the re-

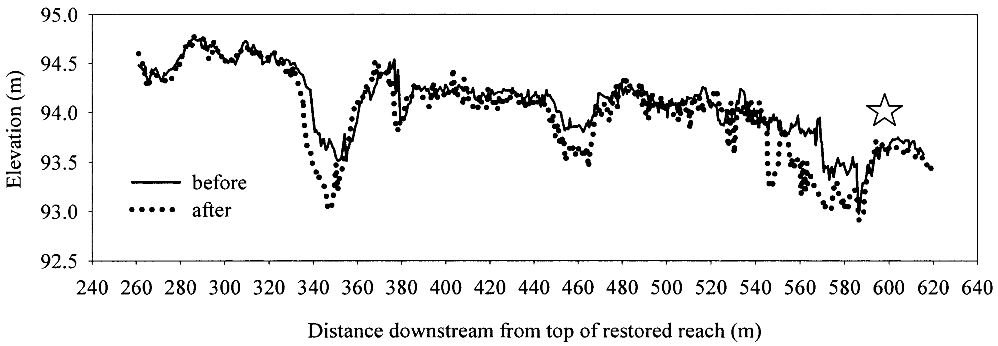

Fig. 4. Longitudinal thalweg profiles surveyed before (January 2004) and after (April 2004) the majority of the annual flow in 2004 (the year after dam removal) indicate that sediment excavation was greatest in deep pools and in the area affected by knickpoint migration. The star marks the location of a bedrock control that impeded further upstream knickpoint migration. Elevation is in meters above mean sea level.

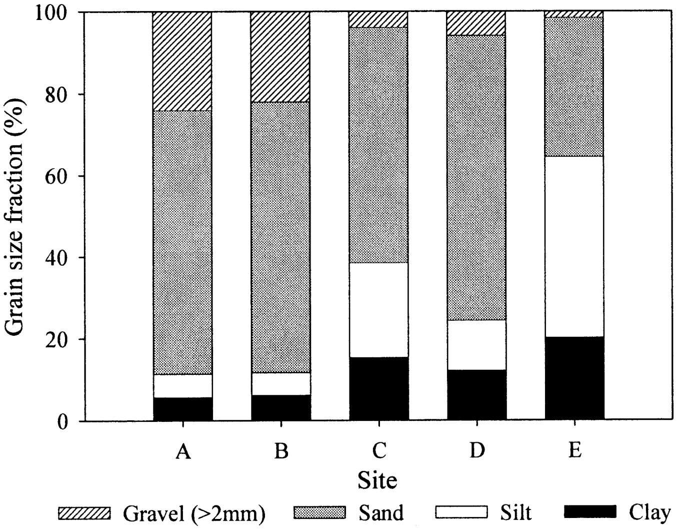

Fig. 5. Sediment particle size distribution at each of the five soil sampling sites. Two near-stream and two upslope cores were collected at each site and composited before analysis. Site A is near the upstream end of the restored reach, whereas site E is near the old dam site.

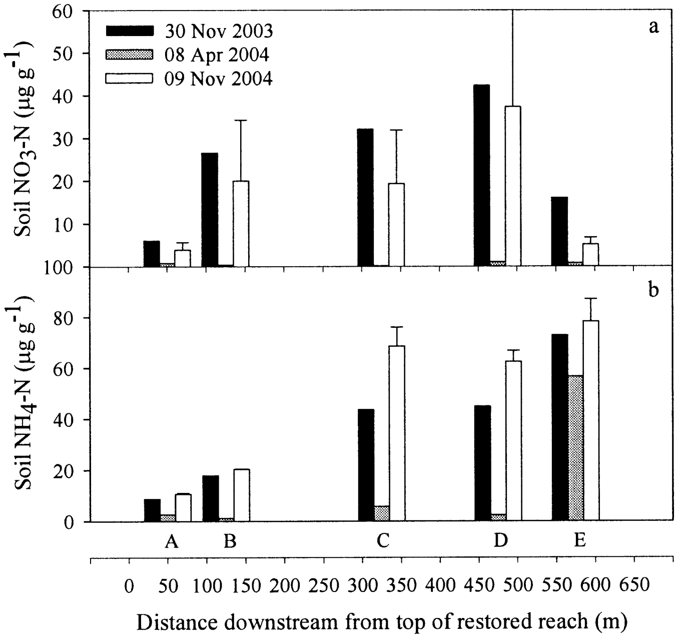

Fig. 6. Soil extractable (a) NO_3-N and (b) NH_4-N in autumn 2003, spring 2003, and autumn 2004. In 2003, the bars represent mean values as measured from composited cores that were collected in quadruplicate from each site and composited before analysis. In autumn 2004, this process was done three times at each site, resulting in three composited samples from each site. Thus, the mean values from 2003 have no associated SD.

stored reach, the NO_3-N release was reduced to near zero, whereas inputs from the upper watershed were between 0 and 200 μg L^{-1} (Fig. 7c). Ammonium release from the restored reach was also greatly reduced in the winter and spring relative to autumn conditions (Fig. 7e,f).

Discussion

Dam removal versus seasonal variation—The primary negative ramifications of dam removal are the potential for downstream transport of sediment (Shuman 1995), nutrients (Stanley and Doyle 2003), and heavy metals (de Carvalho et al. 1998), yet little research has been done to quantify these exports after dam removal (Doyle et al. 2003*a*). The data presented here indicate that there was an order of magnitude increase in sediment and nutrient export after dam removal (Table 1). The study was fortuitous to have a similar reservoir a short distance upstream that could be used as a reference, so interannual effects on sediment and nutrient loading could be separated from the effects of dam removal.

Precipitation patterns in the water year after dam removal created high flows not seen in the previous 2 yrs (Fig. 2). The result was greater fluxes of sediment and nutrients both entering and leaving the restored reservoir reach. Because flows were not comparable before and after dam removal, a portion of the increased sediment and nutrient load from the restored reach may be attributed to increased discharge. It was not feasible to conduct intensive storm sampling at both the study and reference reservoirs, so the comparison between the two systems is weighted toward baseflow differences in constituent concentration ($n = 33$). The resultant under-representation of those constituents that were mobilized from the restored reach primarily during storms contributes to some lack of significance in the four-way ANOVA model (Table 2). For example, the survey and flux data make it clear that, after the dam removal, there was significant TSS export from the restored reach, but because TSS export occurred primarily during large storms, it is not significant in the model (Table 2). In contrast, NO_3^- was generated by the restored reach during all flow conditions; the result is significance in the model. It should be noted that the reference reservoir is not a perfect analog of the study reservoir because the two reservoirs processed sediment and nutrients differently (see Table 2, C × D). As such, the relationship between the two reservoir systems, both before and after removal, is relative.

Channel morphology changes and sediment export—Removal of the Murphy Creek Dam caused excavation of reservoir sediments that changed the characteristics of suspended sediment being exported from the system. Before removal, VSS (i.e., suspended organic material) comprised ~36% of TSS; after removal of the dam, TSS was composed of only 11% organic matter. This change can be attributed to the fact that, before removal, the sediment exported from the reservoir was primarily organic-rich benthic material that was stirred up during storms; once the reservoir was drained and headcutting and mass wasting ensued, more inorganic sediments from deeper in the sediment wedge were entrained.

Sediment excavation began with a knickpoint near the old dam site, which migrated upstream at a rate of 12.5 m/month between January and April 2004, carving near vertical banks. Additionally, sediment excavation as deep as 1.0 m occurred in pools upstream of the knickpoint. Similar

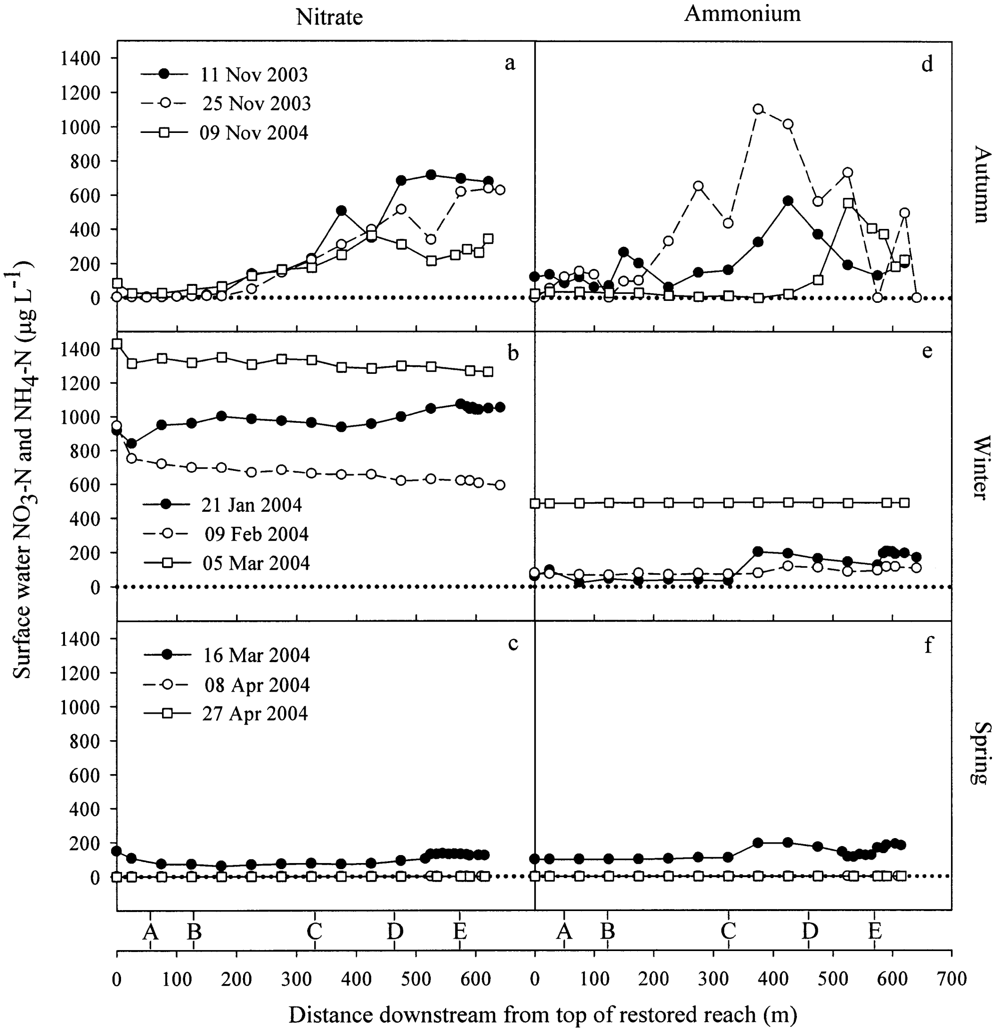

Fig. 7. Surface water NO$_3$-N (a–c) and NH$_4$-N (d–f) concentrations collected along the length of the restored reach. The upstream end of the restored reach is at 0 m, whereas the old dam site is located at 620 m. Surface water transects were collected twice during autumn 2003 (3 months after removal) and again in autumn 2004, three times during winter 2004, and on three occasions during spring 2004. Locations of soil sampling (A–E) sites are included on the *x*-axis for reference.

results were found on the Koshkonong River with the removal of the Rockdale Dam (Doyle et al. 2003*a*). There, possibly because of a steeper grade, knickpoint migration moved at a rate of 40 m/month. Although knickpoint migration was the primary mechanism for sediment removal in both systems, upstream pool scour was not seen in the Rockdale removal.

Phosphorus retention—While the restored reach was a continual source of N, P dynamics were quite different. Figure 2b,c clearly shows that, after dam removal, P concentrations were frequently lower below the restored reach than above. Yet, during this same time, the reach exported 57.7 kg of PO$_4$-P; this increase was largely dictated by two storms, one on 01 January 2004 and the other on 26 February 2004. During both storms, concentrations of PO$_4^{-3}$ were similar above and below the restored reach, but the restored reach gained an average of 0.91 m^3 s^{-1} of water during these storms, so when a PO$_4^{-3}$ flux was calculated, the loading from the reach was higher. This flux analysis indicates that, during low flows, the reach is a P sink (separate experiments involving solute injections conducted during low flows indicated that dilution was minimal), and during high flows, it is a P source. If the primary mechanisms for P removal from the water column are sorption to sediment and binding and precipitation with available Fe (Allan 1995), large amounts of P will be transported during turbid, high flow conditions. Indeed, this is what is seen in Murphy Creek with the first storm and then subsequently the largest storm after dam removal, producing some of the only instances of elevated TP below the restored reach (Fig. 2b). Doyle et al. (2003*b*) showed similar results for the removal of Rockdale Dam, which created a 40% increase in soluble reactive P concentration because of changes in channel morphology, but whereas removal of the dam caused P retention to decline, the reach continued to act as a net sink for P.

Sources of N export—Nitrogen release from sediments was greatest at sites C and D (Fig. 7a,d), which unlike sites A and B, had thick deposits of reservoir sediments. Although site E had high extractable NH_4-N content (average of 76 $\mu g\ g^{-1}$ through the duration of the study) and the thickest deposits of reservoir sediment, the saturated soils released little NO_3^-, and the area apparently acted as an NH_4^+ sink during autumn (Fig. 7d). Although this study did not quantify biotic diversity through the restored reach, cursory vegetation assays indicated that variation in community structure and biomass between sites C and D and site E were not a controlling factor in N dynamics, because the sites had very similar vegetative cover.

The data indicate that the zone of nutrient release within the restored reach is the well-drained area within the sediment wedge, represented by sites C and D. Indeed, studies of sediment N content under oxic and anoxic conditions have shown that soil NH_4^+ increases when desiccated soils become rewet (Qiu and McComb 1996; Baldwin and Mitchell 2000; James et al. 2004). Specifically, James et al. (2004) found that sediment dewatered in a laboratory by 20% and 60% and then rehydrated exhibited a lower exchangeable NH_4^+ concentration and a lower rate of N release than both dry and saturated controls. In contrast, the same sediments dewatered by 95% and rehydrated exhibited a significant increase in exchangeable NH_4^+ and rate of N release. These results explain the observations at Murphy Creek. Site E, which never dried, did not exhibit an increase in extractable NH_4^+ between spring 2003 and 2004 and did not release N, whereas sites C and D, which seasonally dried, showed a marked increase in exchangeable NH_4^+ (Fig. 6b) and contributed up to 700 $\mu g\ L^{-1}$ NO_3-N (Fig. 7a) and 1,100 μg L^{-1} NH_4-N (Fig. 7d) to the channel.

Seasonality of N release—Studies have shown that the period just after dam removal is when the most nutrients are transported downstream (Gray and Ward 1982; Stanley and Doyle 2001). Due primarily to the lack of long-term studies of N transport after dam removal, there is no literature addressing the seasonality of nutrient export after removal. Our results indicate that reservoir sediment N release is strongly dependent on season. During the spring when biotic uptake is at its maximum, there is little sediment-bound inorganic N and negligible release to the channel (Fig. 7b,e), but during the fall when dry soils become wetted, there is a substantial increase in both NH_4^+ and NO_3^-. This increase was quantified in both 2003 and 2004 (Fig. 7a,d), which suggests that each year will bring a new pulse of N from the restored reach. If managers are concerned about N export from a restored reservoir reach, this seasonality must be recognized, and monitoring should continue for a number of years until N export reaches background levels.

Models for hydrogeomorphic controls on N and P dynamics—Predicting how nutrient dynamics will change with an evolving channel subsequent to dam removal is a difficult task. Using the well-defined channel evolution models of Schumm et al. (1984) and Simon and Hupp (1986), Stanley and Doyle (2002) presented a model by which it was assumed that N retention would be a function of sediment water contact, and P dynamics would be controlled by sediment transport. As a newly restored channel evolves, it moves through various stages of incision, migration, and slumping until a quasi-equilibrium is reached. Initial stages before incision are characterized by a large wetted perimeter relative to water volume, meaning high sediment water contact and increased N retention (through uptake and denitrification). Subsequent incision and widening causes significant sediment transport along with high P loading. Once the channel is incised, sediment water contact is reduced and so is N retention.

The P dynamics quantified in Murphy Creek were accurately predicted by this model, as the greatest P export occurred during storms when sediment transport was elevated. However, the model does not predict the N dynamics observed in this study. This is because of the fact that the reservoir sediment was enriched with NH_4^+ that accumulated as N, bound in benthic organic matter, mineralized. Consequently, the sediment is not as much a medium for N uptake and denitrification as it is a significant source of N to the channel. In this system, sediment water contact may only be an ancillary factor driving N dynamics; as previously noted, sediment N content and the degree of annual sediment desiccation seem to be the primary controls on N leaching in Murphy Creek. Given this, the Stanley and Doyle model for N dynamics is not applicable to Murphy Creek, a testament to the fact that the great diversity of impoundments that exist make predictions of the water quality impacts of dam removal difficult (Poff and Hart 2002).

Beyond dam removal—The study of dam removal is a young science, with only a handful of publications addressing the issue. As such, each new study brings to light the relevance of specific ecosystem responses that were previously not considered. It is our hope that in the study of dam removal, the ramifications of the findings are not limited to the restoration of impounded reaches alone, but instead be used to address more general concerns in stream and wetland ecology. The patterns of N release from sediment documented in this study are expected to be seen in any environment where periods of inundation and sedimentation are followed by desiccation and rewetting. In the Mediterranean climate of California, this is a common occurrence with many floodplains, wetlands, stream channels, and reservoir littoral zones that dry on a seasonal basis. Indeed, this same pattern of N leaching has been documented in floodplains (Baldwin and Mitchell 2000), wetlands (Qiu and McComb 1996), rivers (James et al. 2004), and reservoirs (James et al. 2001) in a variety of climates. Realizing the ubiquity of such processes is important for both managers and scientists as we move ahead.

Restoration strategies—The primary reason for removal of the dam on Murphy Creek was to create clear passage for anadromous fishes, yet there was also concern that export of sediment and nutrients would together act to smother downstream spawning gravels and promote periphyton production. The compromise was to create a base level control at the restored dam site. The result was not only the planned sediment retention, but also the creation of a nutrient retentive wetland. The wetland area represented by site E contributed little if any NO_3^- (Fig. 7a–c) to the system and acted as a NH_4^+ sink (Fig. 7d) during the autumn. Although this was an unplanned ramification of the restoration project, it served the goal of nutrient and sediment attenuation. However, the goal of restoring spawning habitat may have been compromised by the base level control, because although there was a channel carved through the lower section of the restored reach (Figs. 3 and 4), the excavation did not reach the old channel bed, and thus, did not create a substrate suitable for spawning.

Results from this study suggest that removal of small run-of-river impoundments can cause an order of magnitude increase in the export of nutrients and sediment in the first year after dam removal. In Murphy Creek, knickpoint migration and pool scour drove the export of sediment from the restored reach, and TSS concentrations as high as 2,000 mg L^{-1} were measured. Accompanying this loss of sediment were substantial increases in N export and lesser increases in P export. Phosphorus loss was driven by sediment export and was seen in only the most turbid high flows, whereas nitrogen loss seemed to be controlled by leaching from sediments rich in inorganic N, primarily in areas of the restored reach that are annually desiccated. Nitrogen release is a seasonal phenomenon, and sediments rich in inorganic N will not be exhausted within the first year after removal; instead, our results indicate that, during subsequent flushing seasons (autumn in California) after dam removal, there will be an increase in the downstream export of N.

It is hoped that the findings of this study will aid in future restoration projects because there are a number of practical applications of the results. (1) If the goal of restoration is to create wetland habitat or attenuate downstream export of nutrients and sediment, a downstream base level control would be efficacious. (2) If export of sediment is of concern and mechanical sediment removal is being considered, dredging efforts should be focused in pools and the lower section of the sediment wedge. (3) If nitrogen export is of concern, it should be recognized that the greatest potential for N leaching is from organic-rich sediments within the sediment wedge that dry out on a seasonal basis; this N leaching may reoccur seasonally for a number of years, so extended monitoring could be necessary.

References

Ahearn, D. S., R. W. Sheibley, and R. A. Dahlgren. 2005. Effects of river regulation on water quality in the lower Mokelumne River, California. River Res. Appl. **21:** 651–670.

Allan, J. D. 1995. Stream ecology: structure and function of running waters, 1st ed. Chapman & Hall.

Baldwin, D. S., and A. M. Mitchell. 2000. The effects of drying and re-flooding on the sediment and soil nutrient dynamics of lowland river-floodplain systems: A synthesis. Regul. Rivers Res. Manage. **16:** 457–467.

Bigford, T. E. 2004. AFS draft study report and policy statement on dam removal. Fisheries **29:** 34–35.

Carlson, R. E. 1977. Trophic state index for lakes. Limnol. Oceanogr. **22:** 361–369.

Carlson, R. M. 1986. Continuous-flow reduction of nitrate to ammonia with antigranulocytes zinc. Anal. Chem. **58:** 1590–1591.

———, R. I. Cabrera, J. L. Paul, J. Quick, and R. Y. Evans. 1990. Rapid direct determination of ammonium and nitrate in soil and plant tissue extracts. Commun. Soil Sci. Plant Anal. **21:** 1519–1529.

Carter, M. R. 1993. Particle-size distribution, p. 363–375. *In* M. R. Carter [ed.], Soil sampling and methods of analysis. Lewis Publishers.

Clesceri, L. S., A. E. Greenberg, and A. D. Eaton. 1998. Standard methods for the examination of water and wastewater. American Public Health Association. Washington, D.C.

de Carvalho, P. S., E. Zanardi, S. V. Buratini, M. C. Lamparelli, and M. C. Martins. 1998. Oxidizing effect on metal remobilization and *Daphnia similis* toxicity from a Brazilian reservoir sediment suspension. Water Res. **32:** 193–199.

Degroot, C. J., and C. Vanwijck. 1993. The impact of desiccation of a fresh-water marsh (Garcines Nord, Camargue, France) on sediment water vegetation interactions. 1. The sediment chemistry. Hydrobiologia **252:** 83–94.

Doyle, M. W., E. H. Stanley, and J. M. Harbor. 2003*a*. Channel adjustments following two dam removals in Wisconsin. Water Resour. Res. **39:** 1–15.

———, ———, and ———. 2003*b*. Hydrogeomorphic controls on phosphorus retention in streams. Water Resour. Res. **39:** 1–17.

Gray, L. J., and A. K. Ward. 1982. Effects of sediment release from a reservoir on stream macroinvertebrates. Hydrobiologia **96:** 177–184.

Hillbricht-Ilkowska, A. 1999. Shallow lakes in lowland river systems: Role in transport and transformations of nutrients and in biological diversity. Hydrobiologia **409:** 349–358.

James, W. F., J. W. Barko, and H. L. Eakin. 2004. Impacts of sediment dewatering and rehydration on sediment nitrogen concentration and macrophyte growth. Can. J. Fish. Aquat. Sci. **61:** 538–546.

———, ———, ———, and D. R. Helsel. 2001. Changes in sediment characteristics following drawdown of Big Muskego Lake, Wisconsin. Arch. Hydrobiol. **151:** 459–474.

Kanehl, P. D., J. Lyons, and J. E. Nelson. 1997. Changes in the habitat and fish community of the Milwaukee River, Wisconsin, following removal of the Woolen Mills Dam. N. Am. J. Fish. Manage. **17:** 387–400.

Kern, J., A. Darwich, K. Furch, and W. J. Junk. 1996. Seasonal denitrification in flooded and exposed sediments from the Amazon floodplain at Lago Camaleao. Microb. Ecol. **32:** 47–57.

Kleeberg, A., and M. Heidenreich. 2004. Release of nitrogen and phosphorus from macrophyte stands of summer dried out sediments of a eutrophic reservoir. Arch. Hydrobiol. **159:** 115–136.

Kratzer, C. R., and P. L. Brezonik. 1981. A Carlson-type trophic state index for nitrogen in Florida lakes. Water Resour. Bull. **17:** 713–715.

Lenhart, C. F. 2003. A preliminary review of NOAA's community-based dam removal and fish passage projects. Coast. Manage. **31:** 79–98.

Margolis, B. E., M. S. Castro, and R. L. Raesly. 2001. The impact of beaver impoundments on the water chemistry of two Appalachian streams. Can. J. Fish. Aquat. Sci. **58:** 2271–2283.

Perrin, C. J., K. I. Ashley, and G. A. Larkin. 2000. Effect of drawdown on ammonium and iron concentrations in a coastal mountain reservoir. Water Qual. Res. J. Can. **35:** 231–244.

Pizzuto, J. 2002. Effects of dam removal on river form and process. Bioscience **52:** 683–691.

Poff, N. L., and D. D. Hart. 2002. How dams vary and why it matters for the emerging science of dam removal. Bioscience **52:** 659–668.

Qiu, S., and A. J. McComb. 1996. Drying-induced stimulation of ammonium release and nitrification in reflooded lake sediment. Mar. Freshwat. Res. **47:** 531–536.

Saeki, K., M. Okazaki, and S. Matsumoto. 1993. The chemical phase changes in heavy metals with drying and oxidation of the lake sediments. Water Res. **27:** 1243–1251.

Sall, J., A. Lehman, and L. Creighton. 2001. JMP start statistics: a guide to statistics and data analysis, 2nd ed. Duxbury.

Schumm, S. A., M. D. Harvey, and C. C. Watson. 1984. Incised channels: Morphology, dynamics, and control, 1st ed. Water Resources Publications.

Shuman, J. R. 1995. Environmental considerations for assessing dam removal alternatives for river restoration. Regul. Rivers: Res. Manage. **11:** 249–261.

Simon, A., and C. R. Hupp. 1986. Channel evolution in modified Tennessee channels. Proceedings of the Fourth Federal Interagency Sedimentation Conference, Las Vegas, NV. U.S. Interagency Advisory Committee on Water Data.

Smith, L. W., E. Dittmer, M. Provost, and D. R. Burt. 2000. Breaching of a small irrigation dam in Oregon: A case history. N. Am. J. Fish. Manage. **20:** 205–219.

Sparling, G. P., and D. J. Ross. 1988. Microbial contributions to the increased nitrogen mineralization after air-drying of soils. Plant Soil **105:** 163–167.

Stanley, E. H., and M. W. Doyle. 2001. Phosphorus transport before and after dam removal from a nutrient-rich creek in southern Wisconsin. Bull. N. Am. Benthol. Soc. **18:** 172.

———, and ———. 2002. A geomorphic perspective on nutrient retention following dam removal. Bioscience **52:** 693–701.

———, and ———. 2003. Trading off: The ecological effects of dam removal. Front. Ecol. Environ. **1:** 15–22.

———, M. A. Luebke, M. W. Doyle, and D. W. Marshall. 2002. Short-term changes in channel form and macroinvertebrate communities following low-head dam removal. J. N. Am. Benthol. Soc. **21:** 172–187.

USACE. 1996. Water control infrastructure: national inventory of dams. Federal Emergency Management Agency. Washington, D.C.

Winter, B. D. 1990. A brief review of dam removal efforts in Washington, Oregon, Idaho, and California. U.S. Dept. of Commerce.

Yu, Z. S., R. R. Northup, and R. A. Dahlgren. 1994. Determination of dissolved organic nitrogen using persulfate oxidation and conductimetric quantification of nitrate-nitrogen. Commun. Soil Sci. Plant Anal. **25:** 3161–3169.

Received: 31 December 2004
Accepted: 10 July 2005
Amended: 6 August 2005