ECOSYSTEM RESPONSES TO LOW-HEAD DAM REMOVAL: ASSESSMENT OF PHYSICAL HABITAT, WATER CHEMISTRY, AND MACROINVERTEBRATES

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Abstract

This two year study focused on understanding the effects of the removal of the low head Nashville dam on the Thornapple River in Barry County, MI. A comparison of data taken before the dam was removed to data taken after the dam was removed indicated changes to the macroinvertebrate community. Isopods abundance per artificial sampler decreased from an average of 744 to 14 from pre- to post-dam removal (2009 to 2010). In addition, there was an approximate 25% increase in the abundance of Ephemeroptera, Trichoptera, and Plecoptera, although a significant increase in EPT was also observed upstream of the former reservoir. Also, in the reach directly below the dam there was an increase in fine sediment that accounted for an average cross-sectional channel aggradation of 26 cm from pre- to post-dam conditions, indicating that some erosion from the reservoir and subsequent downstream deposition is occurring. This was in contrast to the relatively minor changes in the cross-sectional profile observed throughout the other study reaches, both upstream and downstream of the former dam. In addition, there still appears to be a turbidity signature directly below the dam in response to increasing discharge. Specifically, at the site directly downstream of the former reservoir, we observed a 0.5 to 1.0-fold elevation in turbidity during the rising limb of a flood event above that observed at other measurement locations further down and up stream. Finally,

the ratio of molar nitrogen (as nitrate) to total phosphorus (NO_3:TP) indicated that the reaches above the dam were P-limited (mean N:P was 22.3 and 17.3 in 2009 and 2010, respectively) and N-limited below the dam (9.2 and 5.1, respectively). Potential N-limitation increased below the dam from 2009 to 2010 as a result of elevated total P, particularly in the reach furthest downstream. Taken together, these results provide a better understanding of how the removal of a dam affected the ecosystem. Specifically, we observed some improvements in the macroinvertebrate community downstream of the reservoir even though the physical habitat appears to yet be coming into a new dynamic equilibrium with respect to the removed dam.

Introduction

Contemporary ecological theory states that streams and rivers are four-dimensional in that they represent a dynamic, shifting habitat mosaic (*sensu* Stanford 1998) driven by channel migration across the floodplain coupled with the natural flood regime (lateral dimension), interaction with the groundwater (vertical dimension), and longitudinal connection wherein upstream processes influence downstream processes due to the unidirectional flow of water and materials such as nutrients and organic matter (Vannote et al. 1980, Minshall 1988, Ward 1989, Junk et al. 1989, Stanford and Ward 1993, and many others). These three physical dimensions are conceptualized to be continually shifting through time—the fourth dimension (Ward 1989). Thus rivers are perceived to be disturbance-driven stochastic systems, although some degree of predictability is present depending on variables such as flood pulse predictability, duration, frequency and intensity (Stanford et al. 1996, Stanley et al. 2010). Anthropogenic disturbances can be overlaid on top of this conceptual framework resulting in the development of predictions and testable hypotheses. Of these anthropogenic disturbances, perhaps the most wide-spread and pervasive, are the construction and operation of dams and reservoirs.

In the United States the presence of more than 75,000 dams higher than 1.8 m, and countless smaller structures have both positive and negative environmental and social effects (Smith et al. 2002). Dams are constructed for many reasons including flood control, irrigation, urban water supply, and recreation. They also can negatively impact natural stream structure and function by creating physical disconnections, altering the thermal and flow regimes, and can select for invasive species. Past studies have shown that dams have an adverse effect on the rivers and aquatic biota by restricting fish and invertebrate movement, as well as altering water quality and habitat and disrupting nutrient cycling (Santucci et al. 2005). Similarly, dam removal can have positive and negative effects. For example, dam removal can lead to the downstream flux of fine sediments trapped in the reservoir while at the same time allowing for migration of previously constrained species (Poff and Hart 2002). Relatively little research has been conducted to understand how such a dramatic change in habitat brought about by dam removal will affect lower trophic levels, such as aquatic insects, or to assess removal at a functional level using metrics such as ecosystem metabolism (see Cailin et al. 2008 for a review of existing studies). In addition, it is important to study the long-term effect of dam removal because past studies have found that the effects of dam construction have taken at least 2-3 years to emerge (Wu et al. 2008).

Many of these structures, particularly the smaller mill dams, are reaching the end of their life expectancy and the choice must be made to either repair or remove them. In making this choice, it is important to consider all of the possible effects that the removal of a dam may have on the macroinvertebrate populations, physical habitat, water quality and other factors that may affect the ecosystem as a whole.

To understand how the removal of a former mill dam affected the Thornapple River ecosystem, in particular the macroinvertebrate community and the physical habitat, we monitored several parameters that included (i) benthic macroinvertebrate community composition, abundance, and functional feeding group guild structure, (ii) patterns in nutrient concentrations and other water chemistry parameters, and (iii) physical habitat including substrate composition and cross-sectional profile to monitor changes in river bed elevation. Our hypotheses were as follows: (1) Macroinvertebrate metrics (richness, diversity, dominance, functional feeding groups) should improve directly below the dam. The alternative is that fine sediment from the reservoir will have degraded the physical habitat directly below the dam and we will see an even bigger increase in dominance by sediment tolerant taxa, such as the Isopods. 2. Substrate composition and cross-sectional profile data will improve below the dam via increased course substrate. This is based on the prediction that spring floods will move fine sediment from the reservoir further downstream and out of the sampled reaches. This depends on the reservoir substrate remaining relatively stable, which we predicted should be the case based on the very slow rate of drawdown conducted last summer and rapid rates of vegetative re-growth observed this summer (personal communication, Joanne Barnard, Barry County Conservation District).

Methods and Materials

The methods described below generally follow the guidelines outlined in Collins et al. (2007) and Orr et al. (2008). Since this is the final year of sampling in a two-year study, the same methods and materials, as well as study sites, were used. The following sections contain the methods, materials and procedures used during the first year (Caldwell and Snyder 2009).

Study Sites: The Thornapple River is a 4th order river, located in Nashville, Michigan. This river is a major tributary to the Grand River. Land use is dominated by mixed agriculture. In the Thornapple River, three experimental or treatment reaches (located in shallow, riffle habitat) were located below where the dam previously was located (TD1 through 3) and were contrasted with three control reaches upstream of the former reservoir (TU1 through 3) (Figure 1).

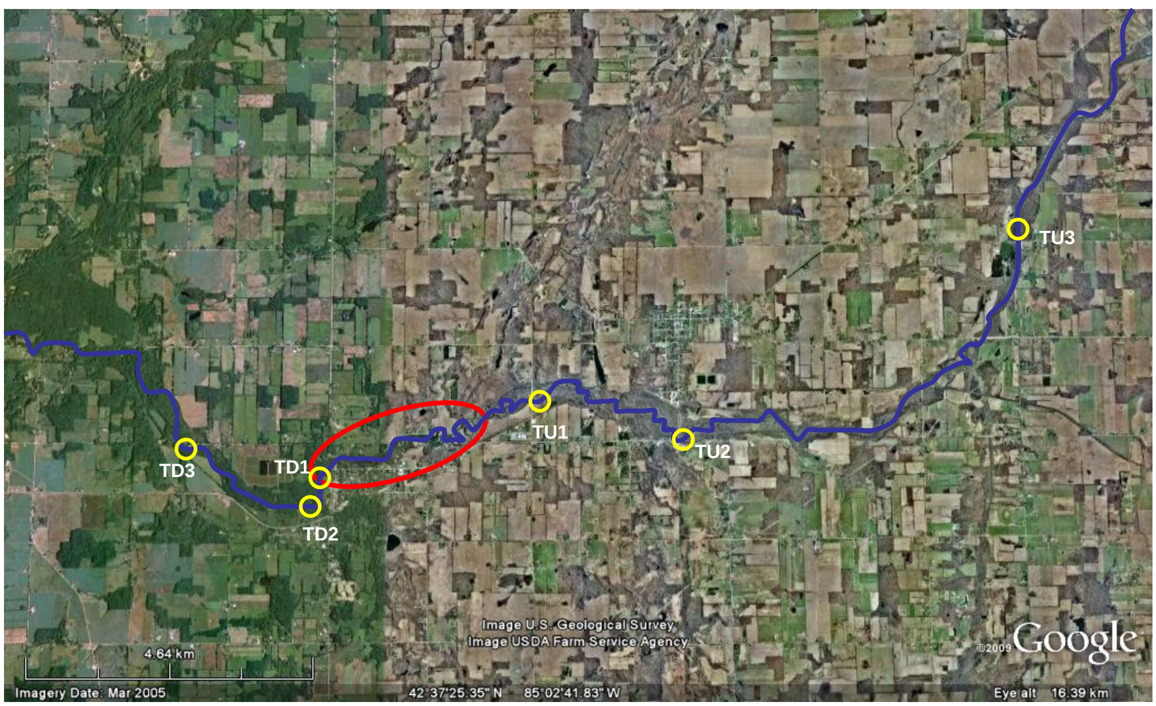


Figure 1. Thornapple River upstream and downstream sites. Red circle indicates dam and reservoir. Locations for up and downstream sites are included in Table 1. Image obtained from Google map.

The three treatment sites were located 0.15 km to 3.93 km below the Nashville dam (coordinates in Table 1). The site most immediately downstream was TD1, followed by TD2, and furthest downstream was TD3 (Figure 1, Table 1). Reference sites on the Thornapple River were located at least 4.45 km upstream from the dam, where direct hydrological influence from the reservoir would be minimal or nonexistent. These were TU3 (15.08 km upstream from the dam), followed by TU2, and TU1, which was closest to the dam (4.45 km upstream) (Figure 1, Table 1).

Water Chemistry

Water chemistry was determined several times throughout each summer (see Figure 2 for specific dates). Dissolved oxygen (D.O., mg/l) and specific conductivity (SC, µS/cm) were measured with a YSI 600 QS multiparameter sonde in mid-stream at each location. Turbidity was measured by taking an integrated depth sample from mid-channel, and analyzed with a portable HACH 2100 P Turbidimeter. Turbidity samples were measured the day that they were taken. Soluble nutrients were collected on August 3rd, 2010, and August 17th, 2009, by taking an integrated depth grab sample from the thalweg in pre-washed nalgene bottles. Samples for NO_3, SRP, SO_4 were either filtered immediately (TU3 and TU2) or were frozen and then thawed and filtered within 4 weeks of collection (TU1 and all downstream transects). Total phosphorus samples were acidified immediately. Nitrate, sulfate, and chloride were run by Ion Chromatography Method 4100C, SRP was automated ascorbic acid Method 4500-P F, and total phosphate was persulfate digestion/automated ascorbic acid Methods 4500-P B and F (APHA 2998).

Molar N:P calculations were done according to Chicharo et al. (2009) wherein the molar contents (mmol/l) of nitrate and phosphate are calculated as follows:

● Phosphate content (mg/l) / molar weight of phosphate (94,972 mg/mmol);

● Nitrate content (mg/l) / molar weight of nitrate (62.005 mg/mmol).

Thus the molar contents of nitrate and phosphate are equal to the molar contents of nitrogen and phosphorus, respectively. The molar content of nitrogen is divided by the molar content of phosphorus.

Physical Habitat

Cross-sectional profiles were conducted to determine relative elevation, substrate composition, fine sediment depth, velocity, and water depth. Using the permanent pin that was installed at each of the sites the previous year, a stadia rod, and a surveying level, we assessed changes in physical habitat (Table 1). Fine sediment depth measurements were taken by pushing a sediment rod into the ground and measuring the depth.

Macroinvertebrates

Macroinvertebrates were sampled with 3 Hester-Dendy (HD) samplers at each site. These sampling devices (representing 0.10 m^2 area each) provided an artificial substrate for the organisms and were stratified along one bank at each site. HD's were retrieved every 3 weeks, during which time invertebrates were removed by spraying and physical removal with forceps, collected in a 250 µm sieve, and immediately preserved with 70% ethanol. HD's were then placed back into the river. A qualitative kick sample was also collected to assess macroinvertebrates from the full suite of available in-stream habitats.

Table 1. Physical/chemical characteristics at each study site in the Thornapple River. At TU-2, substrate, velocity, and fine sediment depth were not measured due to unwadeable conditions.

Site	Latitude and Longitude	Prominent Substrate Composition	Average Velocity (m/s)†	Average Fine Sediment Depth (cm)	Average Temper-ature (°C)*	Average pH*	Average DO (mg/L)*
TD-1	N 42.60553, W 085.09530	59% Sand 41% Gravel 9% Silt 4% Macrophytes	0.87	19.5	18.62	8.25	7.67
TD-2	N 42.60342, W 085.09695	83% Sand 65% Gravel 35% Woody Debris 17% Silt	0.64	19.9	18.6	8.25	8.23
TD-3	N 42.61048, W 085.12094	87% Gravel 78% Silt 30% Sand 13% Woody Debris	0.84	23.8	18.1	8.26	7.84
TU-1	N 42.61693, W 085.05434	77% Sand 31% Silt 23% Woody Debris	0.64	54.8	17.94	8.24	7.61
TU-2	N 42.61126, W 085.02443	N/A	N/A	N/A	17.75	8.19	7.21
TU-3	N 42.64078, W 084.95960	100% Sand 40% Silt 33% Gravel 6% Woody Debris	0.52	20.4	17.74	8.13	7.69

*average of 5 sampling events (dates = 5/11, 5/26, 7/1, 7/14, and 8/3). All samples taken between 9:00 am and 2:30 pm.

†based on a minimum of 10 measurements taken across the channel at six tenths depth.

In the lab, macroinvertebrates were sorted using a dissecting microscope, and then identified to order. The Trichoptera, Ephemeroptera, and Plecoptera, were further identified to family (Merritt and Cummins, 2008). After identification and enumeration, taxa richness, Shannon's diversity (H), and family biotic index (FBI) were calculated (Hauer and Lamberti, 2007). Shannon's diversity typically ranges from 0 to 3, although the actual potential maximum value is dependent on taxa richness. Higher values represent a more evenly distributed community and therefore a 'healthier' community better able to withstand disturbances or impacts. FBI ranges from 1-10, where 10 represent high organic pollution tolerance and thus poor stream health.

Statistical Analyses

All statistical analyses were conducted using SAS® 9.2 wherein the independent variables included sampling date and location and dependent variables included all macroinvertebrate metrics described above. For location, we opted to pool the upstream sites and downstream sites, respectively. However, for clarity, we have presented site-specific data for the macroinvertebrate figures. Thus the statistical model took the form of a before-after, control-impact (or BACI) experimental design wherein the downstream reaches represented an experimental treatment vs. the upstream control reaches. The dam was removed in the Fall of 2009, and all sampling in that year occurred prior to removal, but during the phased draw-down; whereas 2010 sampling was all post-removal. In particular, we were interested in the interaction between date (n=4; 2 in 2009, 2 in 2010) and location (n=2; above vs. below the reservoir) as this would indicate a significant response to dam removal specifically. Assumptions for normality were met in all cases without having to transform data.

Results

Water Chemistry

Chemical measurements for specific conductivity, temperature, dissolved oxygen, and pH were conducted at multiple times during the course of the field season in 2009 and 2010, while nutrient analyses were conducted two times in August of both years. Results from these chemical measurements are presented below.

Specific conductivity ranged between 570- 806 µS/cm. In 2009, there was a relatively large difference between TU1 and TD1 (Figure 2). In 2010, with the dam removed, there were minimal differences in conductivity between these same two sites, with the exception of the July 1st sample. In both years there was a pattern for conductivity to decline in a downstream direction.

It has been found in past studies that the ideal nutrient ratio for plankton is 106 C: 16 N: 1 P (i.e. the Redfield Ratio). Any stream that deviates greatly from this ratio is assumed to be limiting in nitrogen or phosphorus, or could be co-limited (Stelzer and Lamberti 2001). These ratios can be compared between years to understand if there has been a change in the nitrogen composition of the stream. If nitrogen or phosphorus is found to be limiting, it may have an impact on the macroinvertebrate communities.

In 2009, the downstream sites appear to be nitrogen limited and the upstream sites appear to be phosphorus limiting. In 2010, the downstream sites are still nitrogen limited and the upstream sites are still phosphorus limited, but the ratios are different from the year before. This could be due to the removal of the reservoir causing elevated phosphorus levels directly below the dam (Table 2).

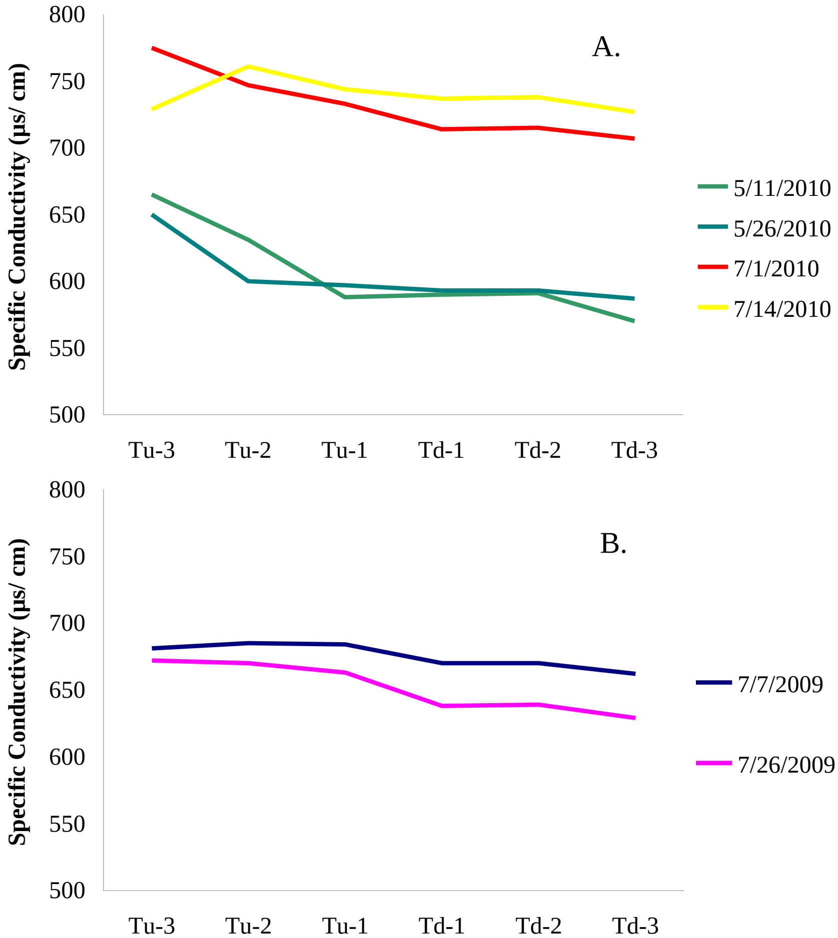


Figure 2: Conductivity measurements collected several times throughout the summer in 2010 (A) and 2009 (B).

Table 2. Comparison of nutrients and molar N:P ratios in the Thornapple River, before (2009) and after (2010) low-head dam removal.

Site	Cl mg/L	SO_4 mg/L	NH_3-N mg/L	SRP-P mg/L	NO_3-N mg/L	TP-P mg/L	N/P Ratio
2009							
TU-3	38	60	0.05	0.006	0.79	0.05	24.2
TU-2	32	53	0.06	<0.005	0.86	0.06	21.9
TU-1	37	51	0.08	0.009	0.82	0.06	20.9
TD-1	35	43	0.11	0.012	0.46	0.08	8.8
TD-2	---	---	---	---	---	---	---
TD-3	36	40	0.09	0.016	0.50	0.08	9.6
2010							
TU-3	28	49	---	0.010	0.62	0.05	18.9
TU-2	34	58	---	0.011	1.00	0.06	25.5
TU-1	21	34	---	<0.005	0.49	0.10	7.5
TD-1	9	14	---	<0.005	0.18	0.06	4.6
TD-2	30	46	---	<0.005	0.54	0.14	5.9
TD-3	31	50	---	<0.005	0.70	0.22	4.9

Turbidity measurements for 2010 ranged from 2-19 NTU. Turbidity data collected on August 3, 2010, is not shown due to mechanical malfunction of the turbidity meter. When compared to discharge, it appears that there is an increase in turbidity directly after an increase in discharge (Figure 3). This increase is greater below the dam. In 2009, the turbidity measurements were found to be in the same range, and were also found to be positively correlated to increasing discharge (Caldwell and Snyder 2009).

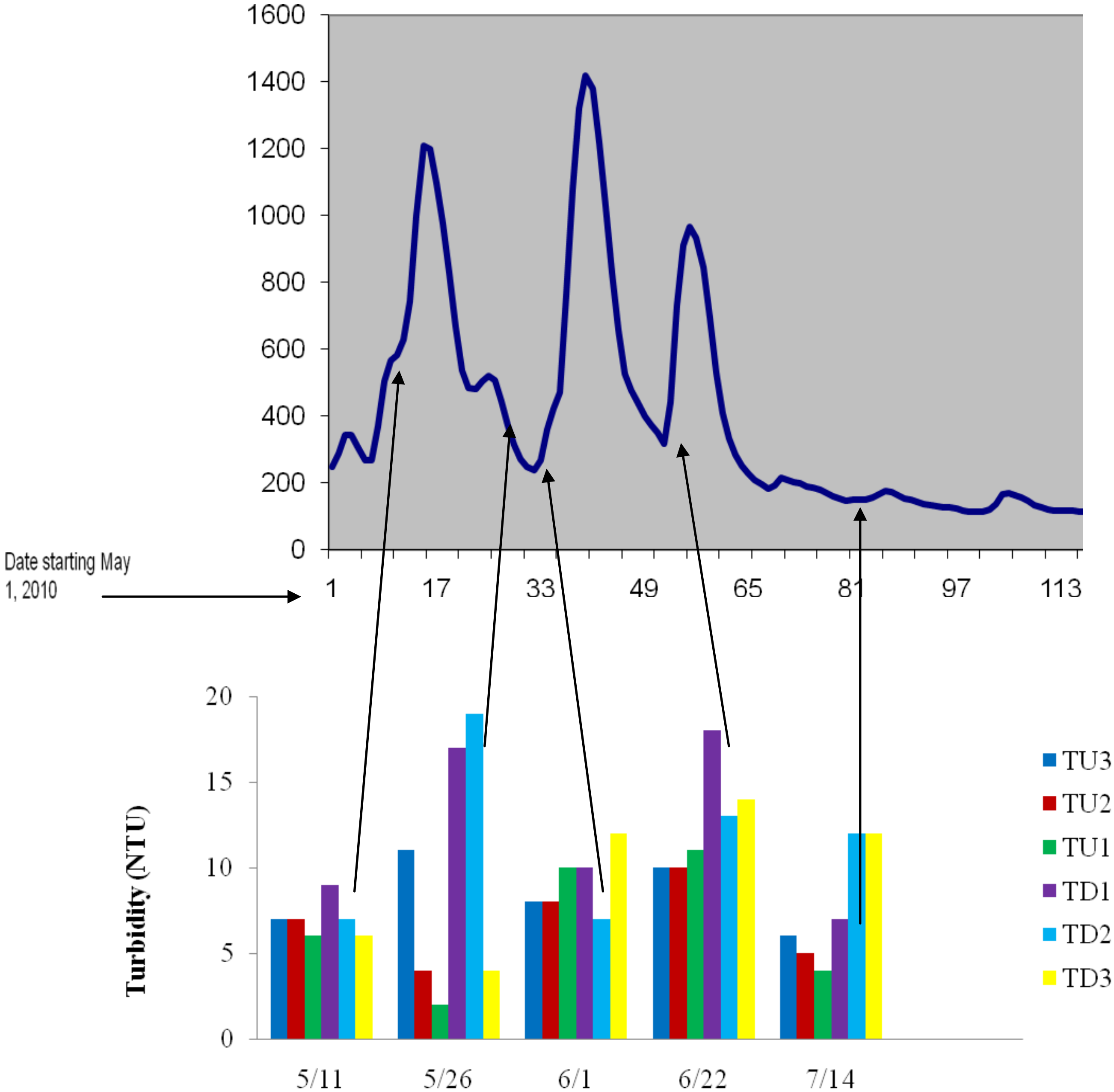


Figure 3: Turbidity measurements and discharge throughout a 4 month period in 2010.

Physical Habitat

Cross-sectional profiling was done to understand if the removal of the dam had caused significant changes in the physical habitat of the stream. Erosion and sediment redeposition are normal processes for rivers and streams, but the dam removal resulted in larger changes directly below the dam (Figure 4) than observed in other monitoring locations.

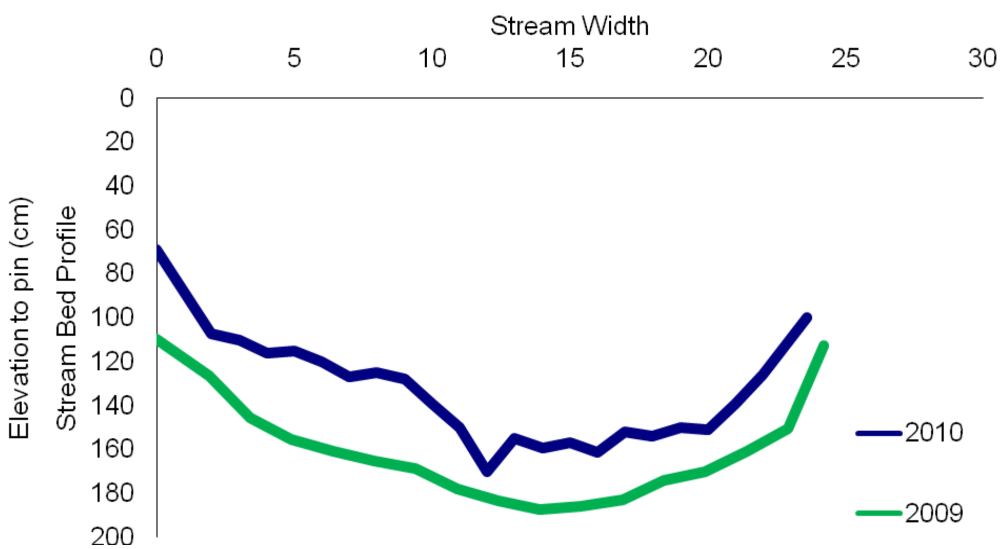


Figure 4: Stream bottom profile of TD1, 2009 compared to 2010. This is the site directly below the dam site, and shows an increased amount of sediment deposit since 2009 when the dam was removed.

At TD1, there was an increase in sediment between 2009 and 2010 (Figure 5). The increase is roughly 26 cm on average, and was not present when the spillway was opened beginning on May 21, 2009. The dam was breached on September 10th, 2009.

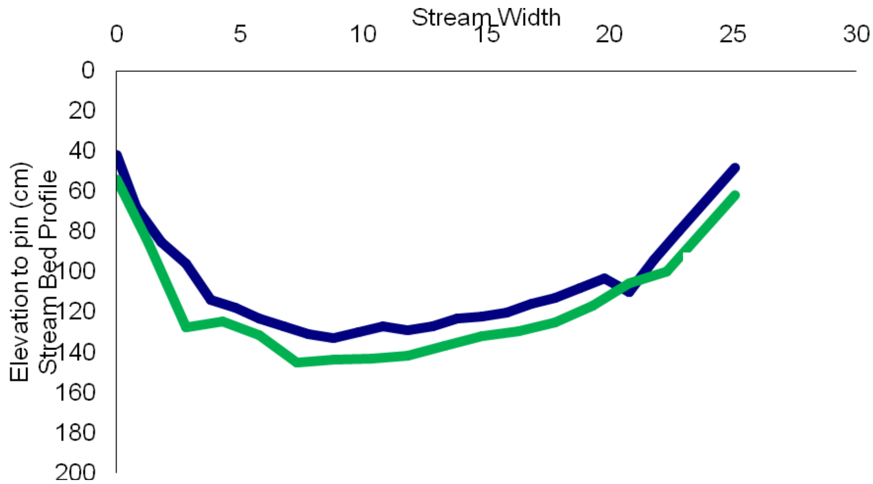


Figure 5: Stream bottom profile of TD2, 2009 compared to 2010.
This site showed very little sediment deposit.

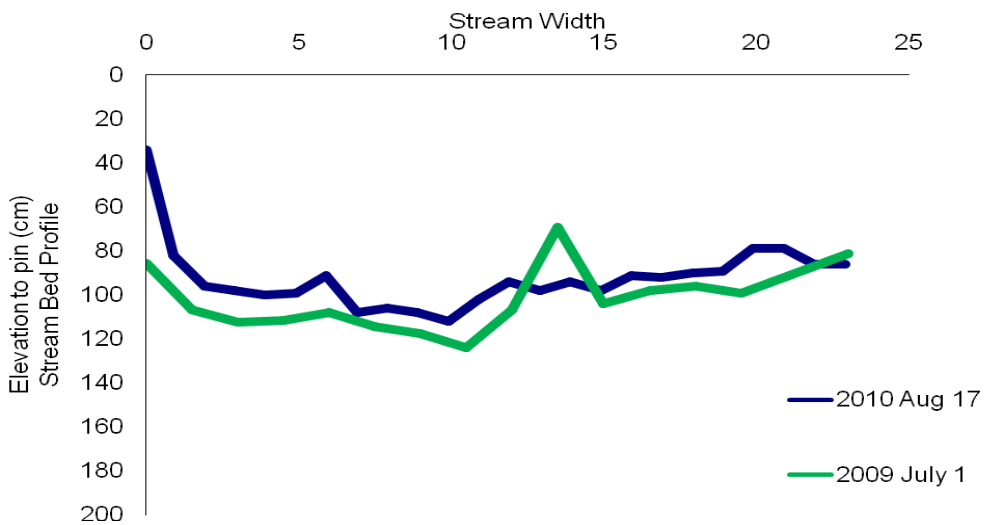


Figure 6: Stream bottom profile of TD3, 2009 compared to 2010. This site showed very little sediment deposit.

When comparing the TD2 and TD3 stream bottom profile data from 2009 to 2010, there is little difference (Figures 5 & 6). The minor fluctuations that are present can be due to the normal erosion and deposition normal in streams. For example, in 2009, the difference between cross sectional profiling measurements fluctuated as much as 12.7 cm throughout the summer.

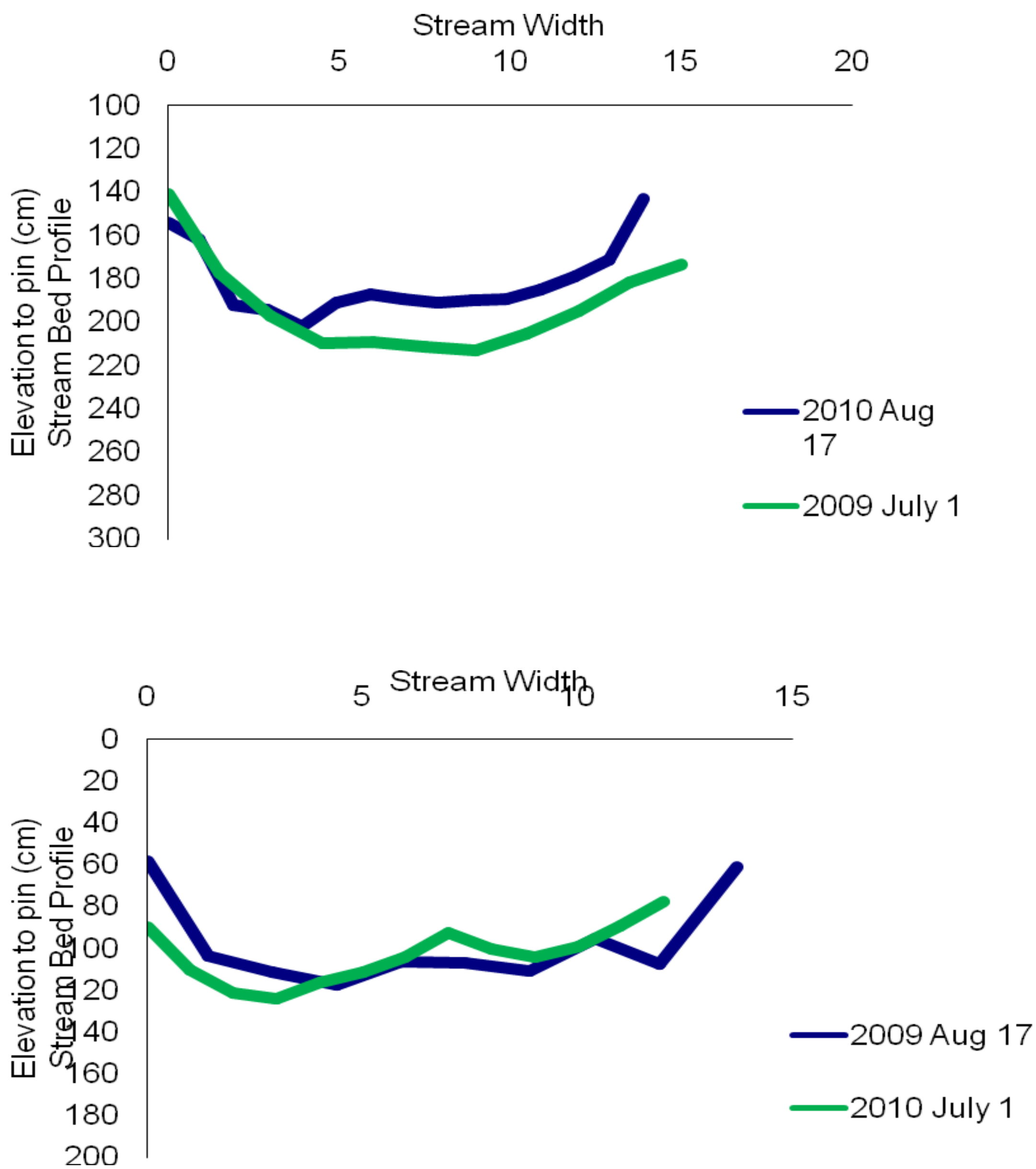
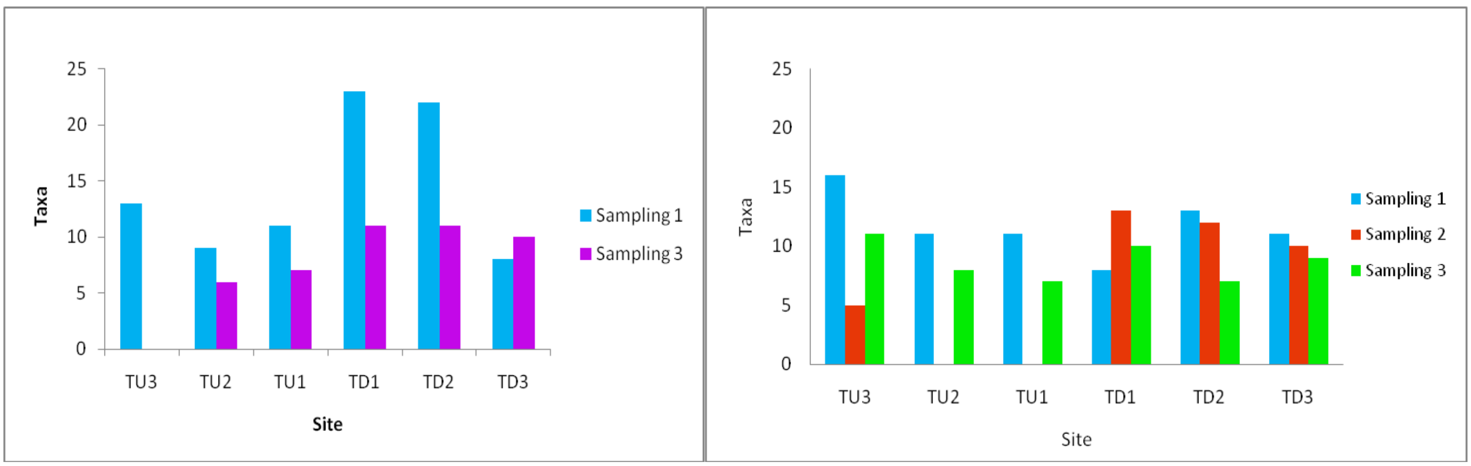


Figure 7: Stream bed profiles from TU1 (above) and TU3 (below). These sites show relatively little change between the two years.

Macroinvertebrates

Raw data from the artificial samplers and kick samples from 2010 are presented in the Appendix. Comparison of the two years yielded the following results. In 2009, there was a large increase in taxa richness below the reservoir. This same pattern was not seen in 2010 (Figure 8). In addition, family richness tended to decline through time from early to late summer in both years.



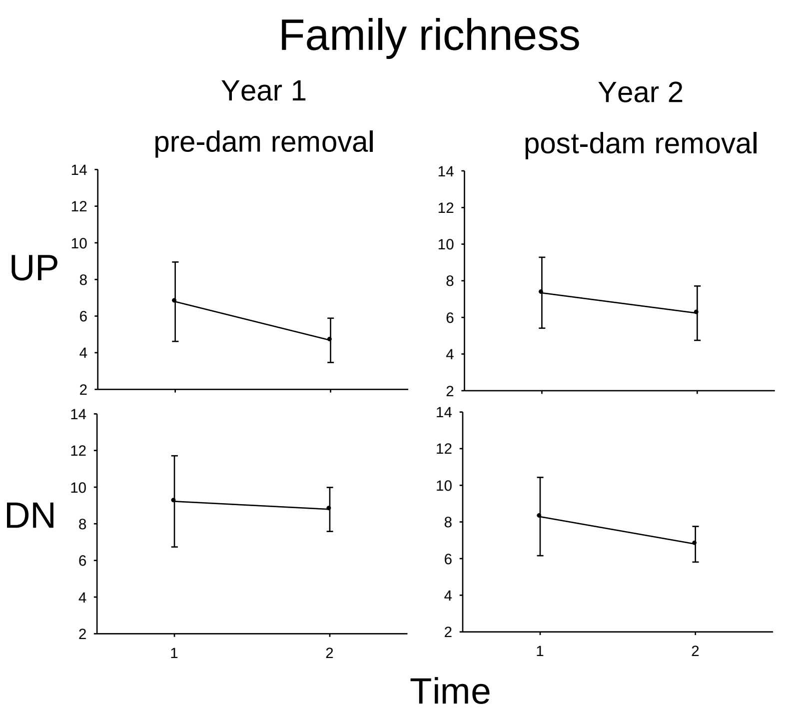


Figure 8: Comparison of taxa richness in 2009 (left plot above) vs. 2010 (right plot above). 2009 sampling dates included 6/17 and 7/27. 2010 sampling dates included 6/22, 7/13, and 8/3. July histograms (red) are missing due to low discharge and inability to collect samples (artificial samplers were above the water level.) In these upper two plots, data from each site is presented. In the plot to the left, up and down stream sites are pooled, respectively.

Statistical comparisons are summarized in the figure to the left (mean, +/- 1 SD). Time 1 and 2 correspond to the 1st and 3rd sampling dates above. In particular, we were looking for a different pattern in the lower right figure as this would indicate an ecological response to the dam removal.

Main effects were significant for time but not for up vs. dn, while interaction between time and up vs. dn was significant for all sites and times. This suggests that the effect of location (up vs. dn) on mean family richness depends on time.

Table 3. Statistical summary of macroinvertebrate richness based on BACI analysis. To demonstrate a significant response to dam removal, we were looking for significance in the grey shaded boxes in particular. In this case, we observed significant differences in family richness both for time (2 years, 2 months each), and the interaction between site and time (time*up/dn).

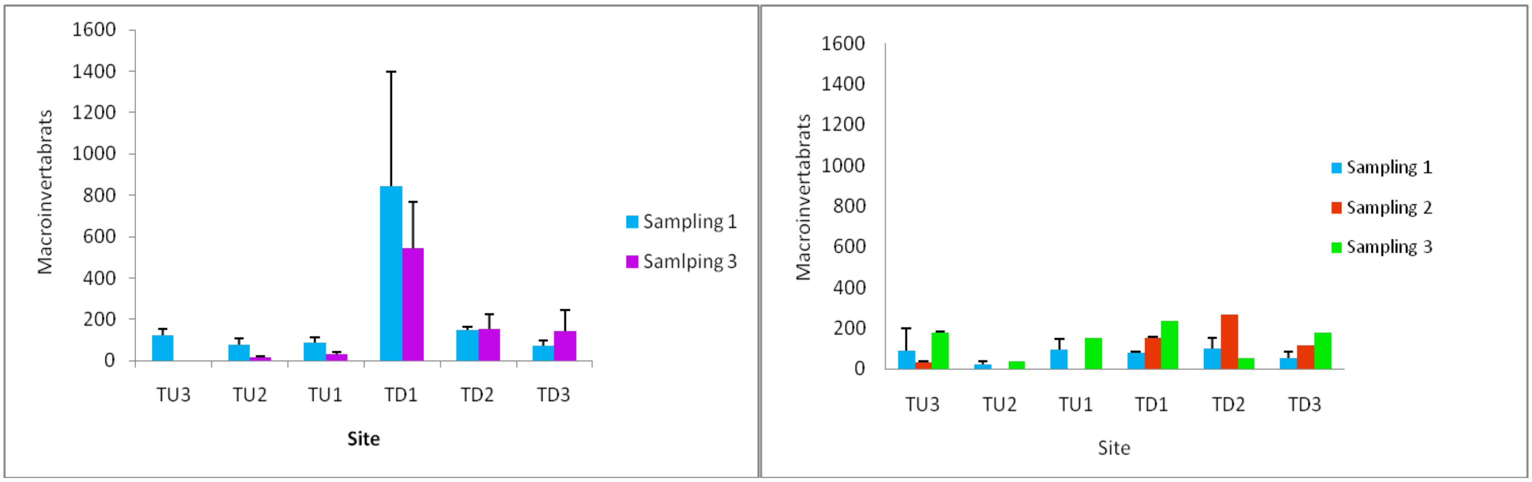
Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	p-value
up vs. dn	1	4	4.79	0.09
time	3	55	3.2	0.03
time*up/dn	3	55	2.8	0.05

Least Squares Means

Effect	Date	Location	Estimate (mean)	Standard Error	DF	t Value	p-value
time*up/dn	Early Summer 09	Down Stream	9.2222	0.7578	55	12.17	<.0001
time*up/dn	Early Summer 09	Up Stream	6.7778	0.7578	55	8.94	<.0001
time*up/dn	Early Summer 10	Down Stream	8.2584	0.8127	55	10.16	<.0001
time*up/dn	Early Summer 10	Up Stream	7.3333	0.7578	55	9.68	<.0001
time*up/dn	Late Summer 09	Down Stream	8.7778	0.7578	55	11.58	<.0001
time*up/dn	Late Summer 09	Up Stream	5.2441	0.87	55	6.03	<.0001
time*up/dn	Late Summer 10	Down Stream	6.7778	0.7578	55	8.94	<.0001
time*up/dn	Late Summer 10	Up Stream	6.2222	0.7578	55	8.21	<.0001

In 2009, abundance of macroinvertebrates (per artificial sampler) jumped from ca. 100 to ca. 700 at the TD1, the site immediately below the dam. This increase was caused almost exclusively by a large abundance of isopoda (spp.) (Caldwell & Snyder 2009). This pattern was non-existent in 2010 indicating significant ($p<0.05$) improvement in the benthic macroinvertebrate community post-dam removal (Figure 9, Table 4) given that the majority of the abundance in 2009 was due to Isopods. In year 1, there was a trend for abundance to decline from early to late summer, while in year 2, the opposite pattern was observed (n.s.). In summary, the effect of location (up vs. dn) on mean abundance depends on time.



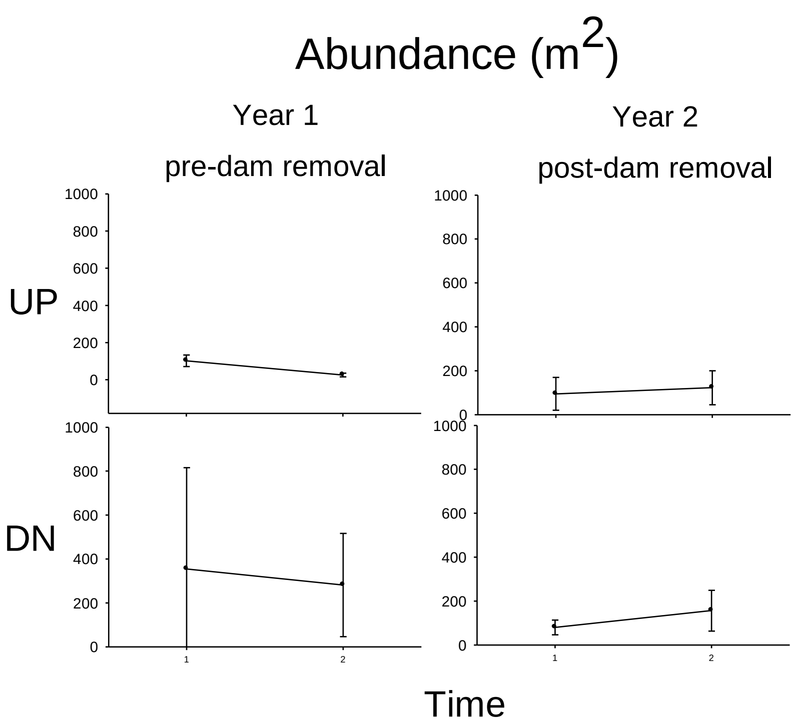


Figure 9: Abundance (+/- 1 SD) per Hester Dendy 2009 (left plot above) vs. 2010 (right plot above). Sampling dates for both 2009 and 2010 correspond to those in Figure 8. Hester Dendy area = 0.1 m^2.

Statistical comparisons are summarized in the figure to the left (means, +/- 1 SD). Time 1 and 2 correspond to the 1st and 3rd sampling dates above.

Table 4. Statistical summary of macroinvertebrate abundance (m^2) based on BACI analysis. To demonstrate a significant response to dam removal, we were looking for significance in the grey shaded boxes in particular. In this case, the only main effect that was significant was between site and time (time*up/dn). For site-specific tests, the increased abundance below the reservoir in 2009 was significant. The lack o f significance at the downstream sites in 2010 is evidence of improvement.

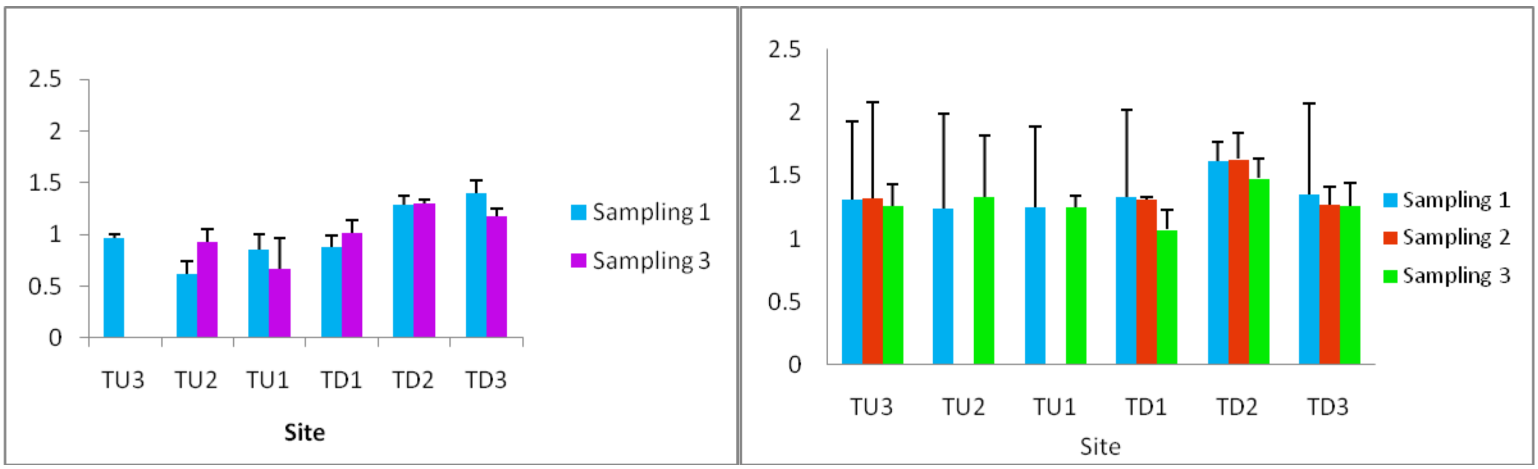
Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	p-value
up vs. dn	1	4	1.24	0.33
time	3	55	2.05	0.12
time*up/dn	3	55	2.75	0.05

Least Squares Means

Effect	Date	Location	Estimate (mean)	Standard Error	DF	t Value	p-value
time*up/dn	**Early Summer 09**	**Down Stream**	354.22	94.1389	55	3.76	**0.0004**
time*up/dn	**Early Summer 09**	**Up Stream**	102.33	94.1389	55	1.09	0.2818
time*up/dn	**Early Summer 10**	**Down Stream**	93.3338	98.5532	55	0.95	0.3478
time*up/dn	**Early Summer 10**	**Up Stream**	94.6667	94.1389	55	1.01	0.319
time*up/dn	**Late Summer 09**	**Down Stream**	280.89	94.1389	55	2.98	**0.0042**
time*up/dn	**Late Summer 09**	**Up Stream**	46.4491	103.52	55	0.45	0.6554
time*up/dn	**Late Summer 10**	**Down Stream**	156	94.1389	55	1.66	0.1032
time*up/dn	**Late Summer 10**	**Up Stream**	122.78	94.1389	55	1.3	0.1976

For 2009, the diversity in the upstream sites was relatively even, and increased at sites TD2 and 3 below the dam. Snyder and Caldwell (2009) concluded that the benthic macroinvertebrate community showed significant improvement or perhaps lack of impact from the dam at these points. A similar pattern was observed in 2010, although the difference between up- and down-stream sites was less. Also, there was an overall increase in diversity at all sites from 2009 to 2010—likely representing a difference between years (Figure 10, Table 5). Statistical analyses indicated that the main effect of location (e.g. up vs. dn) was not significant, whereas sampling time and the interaction of time and location were significant. Diversity in the upstream sites remained relatively stable throughout the experiment, while prior to dam removal there was a decline in diversity from early to late summer. Post-removal, the opposite pattern emerged. We are uncertain why this was the case and recommend additional monitoring. In summary, the effect of stream direction on mean diversity depends on time. Dominance appeared to improve (n.s.) from 2009 to 2010. In 2010, the site with the best (i.e. lowest) dominance index was TD2, indicating that the macroinvertebrate community was most evenly balanced at this site (Figure 11).



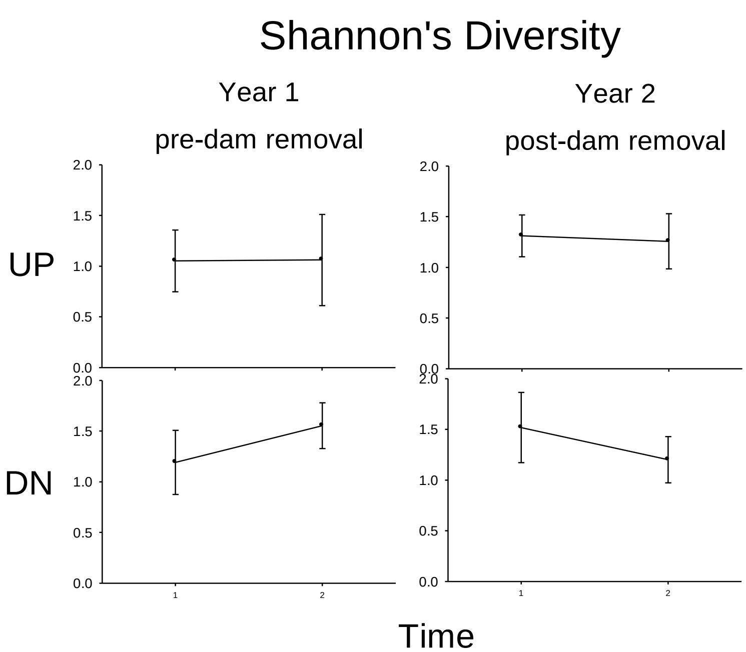


Figure 10: Shannon's Diversity Index (+/- 1 SD) in 2009 (left plot above) vs. 2010 (right plot above). Sampling dates for both 2009 and 2010 correspond to those in Figure 8.

Statistical comparisons are summarized in the figure to the left (means, +/- 1 SD). Time 1 and 2 correspond to the 1st and 3rd sampling dates above.

Table 5. Statistical summary of macroinvertebrate diversity (Shannon's index) based on BACI analysis. To demonstrate a significant response to dam removal, we were looking for significance in the grey shaded boxes in particular. In this case, the main effects that were significant included time and the interaction between site and time (time*up/dn).

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	p-value
up vs. dn	1	4	1.9	0.24
time	3	55	3.5	0.02
time*up/dn	3	55	2.71	0.05

Least Squares Means

Effect	Date	Location	Estimate (mean)	Standard Error	DF	t Value	p-value
time*up/dn	Early Summer 09	Down Stream	1.1902	0.1215	55	9.8	<.0001
time*up/dn	Early Summer 09	Up Stream	1.0521	0.1215	55	8.66	<.0001
time*up/dn	Early Summer 10	Down Stream	1.4969	0.1305	55	11.47	<.0001
time*up/dn	Early Summer 10	Up Stream	1.3105	0.1215	55	10.79	<.0001
time*up/dn	Late Summer 09	Down Stream	1.5526	0.1215	55	12.78	<.0001
time*up/dn	Late Summer 09	Up Stream	1.0728	0.1398	55	7.67	<.0001
time*up/dn	Late Summer 10	Down Stream	1.2001	0.1215	55	9.88	<.0001
time*up/dn	Late Summer 10	Up Stream	1.2559	0.1215	55	10.34	<.0001

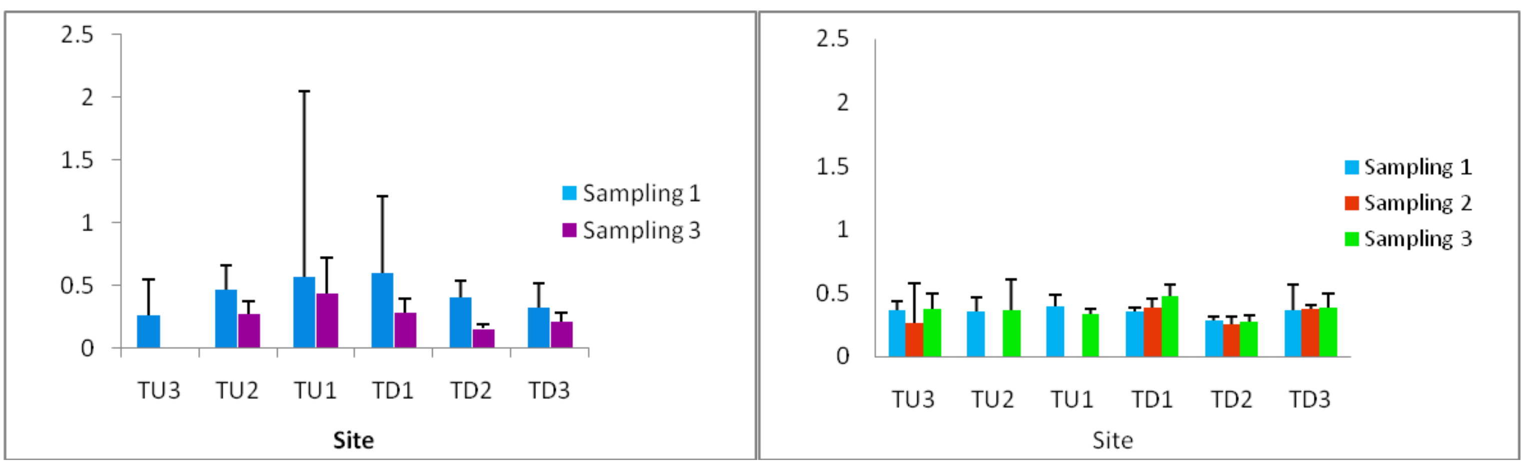
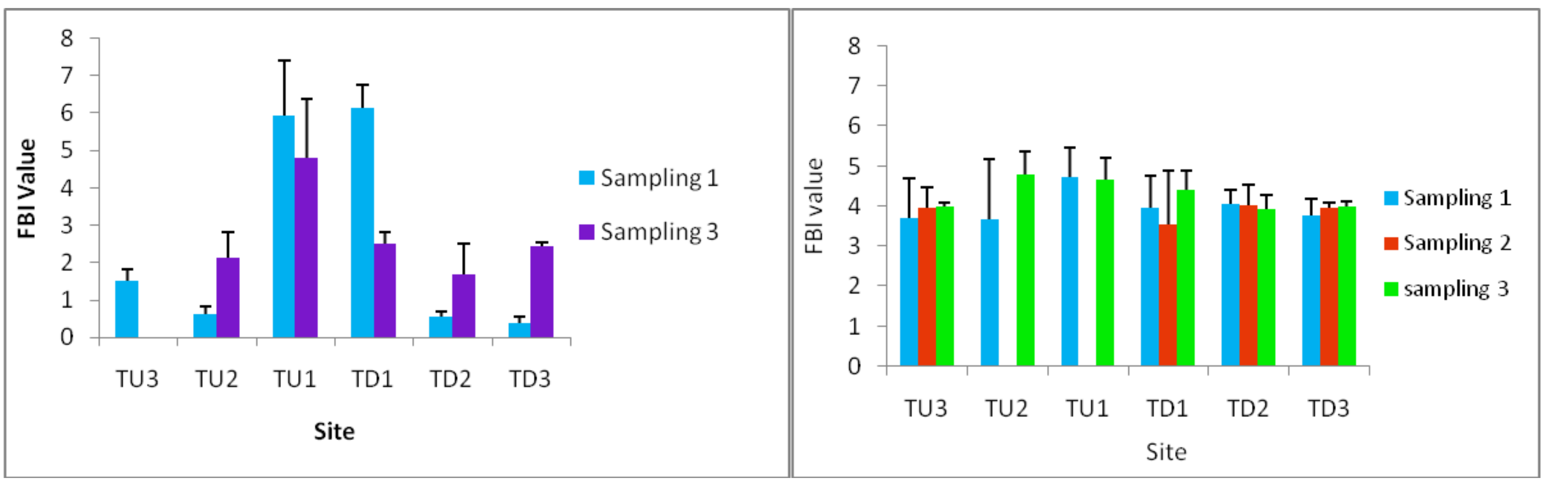


Figure 11: Simpson's Dominance Index 2009 vs. 2010. Sampling dates for both 2009 and 2010 correspond to figure 8. Statistical analyses indicated no significant main effects or interactions.

The Family Biotic Index (FBI) provides a measure of the macroinvertebrate community sensitivity to organic pollution with lower numbers indicating a healthier system (Table 7) (Hilsenhoff 1988). In 2009, the two sites closest to the reservoir (TU1 and TD1) had high values (i.e. less healthy) (Figure 12). In 2010 all FBI values increased (range ca. 3.5-5 vs. ca. 0.5-6) with the exception of the two sites closest to the reservoir (TU1 and TD1), which declined. The only significant main effect was time (Table 6) and there was no significant interaction between time and location.



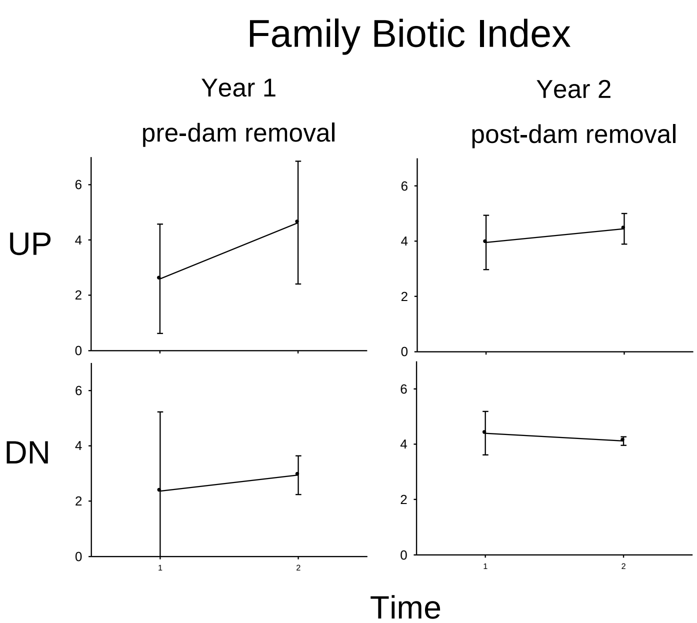


Figure 12: Family Biotic Index (+/- 1 SD) in 2009 (left plot above) vs. 2010 (right plot above). Sampling dates for both 2009 and 2010 correspond to those in figure 8. For FBI, the lower the number the higher the stream quality.

Statistical comparisons are summarized in the figure to the left (means, +/- 1 SD). Time 1 and 2 correspond to the 1st and 3rd sampling dates above.

Table 6. Statistical summary of macroinvertebrate Family Biotic Index, a measure of the impact of organic pollution, based on BACI analysis. To demonstrate a significant response to dam removal, we were looking for significance in the grey shaded boxes in particular. In this case, the only main effect that was significant was time.

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	p-value
up vs. dn	1	4	0.19	0.68
time	3	55	8.24	0.00
time*up/dn	3	55	1.85	0.15

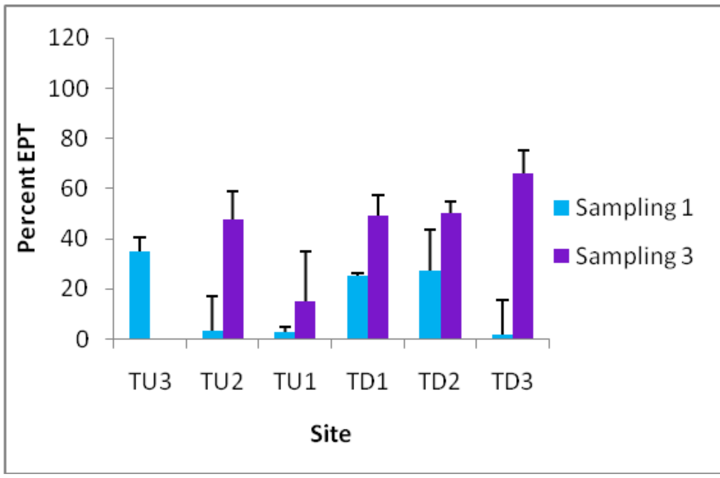
Least Squares Means

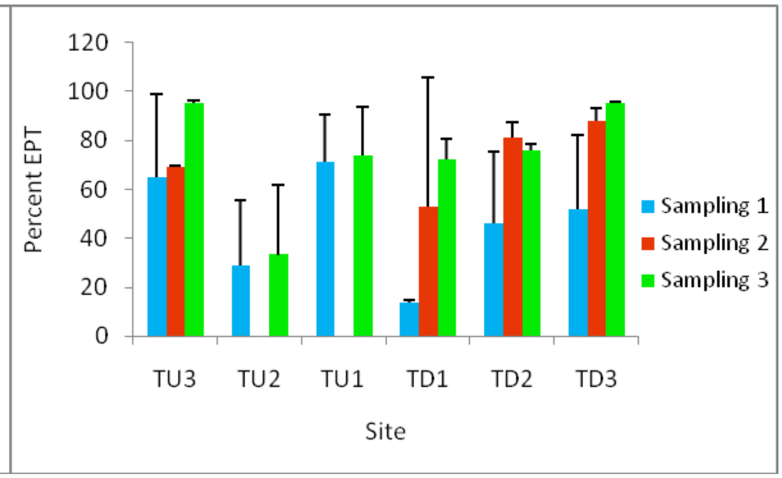
Effect	Time	Location	Estimate (mean)	Standard Error	DF	t Value	p-value
time*up/dn	Early Summer 09	Down Stream	2.3588	0.7332	55	3.22	0.0022
time*up/dn	Early Summer 09	Up Stream	2.5913	0.7332	55	3.53	0.0008
time*up/dn	Early Summer 10	Down Stream	4.4919	0.7661	55	5.86	<.0001
time*up/dn	Early Summer 10	Up Stream	3.9495	0.7332	55	5.39	<.0001
time*up/dn	Late Summer 09	Down Stream	2.9389	0.7332	55	4.01	0.0002
time*up/dn	Late Summer 09	Up Stream	4.5209	0.8033	55	5.63	<.0001
time*up/dn	Late Summer 10	Down Stream	4.1142	0.7332	55	5.61	<.0001
time*up/dn	Late Summer 10	Up Stream	4.4437	0.7332	55	6.06	<.0001

Table 7. Interpretation of FBI data (from Hilsenhoff 1988).

Family Biotic Index	Water Quality	Degree of Organic Pollution
0.00-3.75	Excellent	Organic pollution unlikely
3.76-4.25	Very good	Possible slight organic pollution
4.26-5.00	Good	Some organic pollution probable
5.01-5.75	Fair	Fairly substantial organic pollution likely
5.76-6.50	Fairly poor	Substantial organic pollution likely
6.51-7.25	Poor	Very substantial organic pollution likely
7.26-10.00	Very poor	Severe organic pollution likely

There was a significant increase in % Ephemeroptera, Plecoptera, and Trichoptera (EPT) from early to late summer, as well as a significant improvement from year 1 (pre-dam removal) to year 2 (post-dam removal) in the reaches above and below the impoundment. Results are equivocal given the improvement in year 2 above and below the former reservoir. We recommend additional sampling to better understand the natural range of variation.





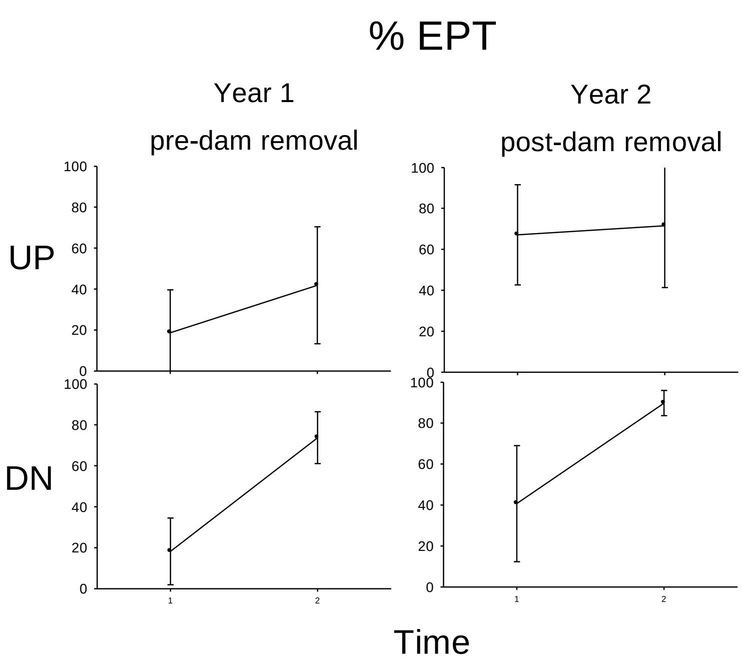


Figure 13: % Ephemeroptera, Plecoptera, and Trichoptera (EPT) in 2009 (upper left plot) vs. 2010 (upper right plot). Sampling dates for both 2009 and 2010 correspond to those in figure 9.

Statistical comparisons are summarized in the figure to the left (means, +/- 1 SD). Time 1 and 2 correspond to the 1st and 3rd sampling dates above.

Table 8. Statistical summary of % EPT, which are indicators of good water quality. To demonstrate a significant response to dam removal, we were looking for significance in the grey shaded boxes in particular. In this case, significant main effects included time and the interaction of time and location (up vs. dn).

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	p-value
up vs. dn	1	4	0.07	0.81
time	3	55	36.7	<.0001
time*up/dn	3	55	5.9	0.00

Least Squares Means

Effect	Time	Location	Estimate (mean)	Standard Error	DF	t Value	p-value
time*up/dn	Early Summer 09	Down Stream	18.1629	10.5068	55	1.73	0.0895
time*up/dn	Early Summer 09	Up Stream	18.6778	10.5068	55	1.78	0.081
time*up/dn	Early Summer 10	Down Stream	40.2922	11.0121	55	3.66	0.0006
time*up/dn	Early Summer 10	Up Stream	67.0464	10.5068	55	6.38	<.0001
time*up/dn	Late Summer 09	Down Stream	73.7318	10.5068	55	7.02	<.0001
time*up/dn	Late Summer 09	Up Stream	51.3435	11.5793	55	4.43	<.0001
time*up/dn	Late Summer 10	Down Stream	89.8014	10.5068	55	8.55	<.0001
time*up/dn	Late Summer 10	Up Stream	71.4646	10.5068	55	6.8	<.0001

Discussion

Water Chemistry

Turbidity was found to be directly correlated with an increase in discharge, particularly in the reach directly below the former reservoir. Several other studies have shown similar findings, and it is hypothesized that there are accumulated fine particles on the stream bed and riparian zone that become suspended during these events (Edwards 1973). Similar patterns were observed in 2009. Caldwell and Snyder (2009) hypothesized that the increase in turbidity below the reservoir during higher discharge was related to the re-suspension and downstream distribution of fine sediments trapped behind the reservoir. This pattern only emerged after the spillway was opened and reservoir drawdown had commenced mid-summer 2009. Similar patterns were observed in 2010 as well, suggesting that the former reservoir is still contributing some fine sediment during higher discharge events. In addition, this makes some sense given the large flux of fine sediment that has moved into the reach just below the reservoir (TD1) (Figure 4). Dams have the potential to act like a sink for fine sediments (Ward and Standford, 1983), so it is likely that sediment that built up behind the dam is still slowly being washed downstream. Over time, the amount of bedload originating from the former reservoir should decline, and be dispersed downstream. It can be expected that in a few years when the sediment has settled and been washed downstream, we will no longer see as much of an increase in turbidity during spates below the former reservoir simply because the substrate therein should be better sorted and stabilized.

Specific conductivity measurements this year were very stable compared to last year. Last year, the measurements indicated a decrease below the dam by roughly 21.5 µS/cm. This year that pattern was not observed. It was hypothesized last year that that trend was occurring because biotic and abiotic components at the impoundment site were absorbing the solutes (Caldwell and Snyder, 2009). Since the impoundment is no longer there, it would make sense that the conductivity measurements are more uniform throughout the river.

Nutrient concentrations suggested that TP increased below the reservoir in 2010, particularly at TD3—the site furthest downstream. We are uncertain as to why this pattern emerged and recommend that additional nutrient sampling be conducted. Molar N:P ratios indicated that the upstream sites were likely P-limited, while downstream sites were N-limited. Interestingly, the degree or extent of N-limitation was stronger in year two, after the dam was removed. This pattern is driven mainly by the increase in TP described above and it is certainly possible that the downstream movement of sediment from the reservoir has increased the phosphorus load downstream. Many studies have noted elevated P-concentrations in fine sediment of reservoirs (for a review, see Kennedy and Walker, 1990). We also recommend that future studies include artificial nutrient diffusing substrata to better understand the role of limiting nutrients in this section of the Thornapple River.

Physical Habitat

There was a noticeable change in the stream bed profiles, particularly TD1--the site immediately below the former reservoir. The sites further downstream, TD2 and 3, did not change as much from 2009 to 2010. It is likely that with the removal of the dam the upstream sediment was washed downstream. There is an abundance of literature that indicates that an increase in fine sediment will negatively impact macroinvertebrate communities (for a good review, see Wood and Armitage 1997). Interestingly, our data suggest that even though there was an increase in fine sediment below the reservoir, the macroinvertebrate community improved, particularly via a reduction in the formerly superabundant isopod taxa. Thus diversity, dominance and FBI all showed improvements below the reservoir (Figures 9, 10, and 11). However, it is also important to note that taxa richness declined significantly. This pattern requires additional analyses to more fully understand. Another pattern that emerged was for there to be a general improvement at all sites from 2009 to 2010. At this point we are uncertain as to why this improvement was observed, although it is possibly related to flow and thermal regimes, land-use changes from one year to the next, or simply natural stochasticity.

Macroinvertebrates

In 2010, Family richness ranged from 5-15, and was even through all of the sites. These values are on the low side when compared to other sites throughout the lower peninsula of Michigan. For example, in a survey of 9 rivers impacted by impoundements, Lessard and Hayes (2003) found that macroinvertebrate family richness averaged 22.6 and 20.5 above and below reservoirs, respectively. In this study samples were collected with Hess nets and thus focused on riffle or run habitat with larger substrata. In our study, substrate was generally dominated by fine sediment (see Table 1) where Hess sampling would have been ineffective. Therefore we chose to use artificial samplers and the lower family richness values observed may have been due to this, and/or to the fact that the habitat was dominated by fine, shifting substrate. We propose that the latter is more likely, but this would require additional testing to prove unequivocally.

When looking at the values from 2009 for Shannon's diversity, the upstream sites were all consistent and equal, while the downstream sites steadily increased from the site immediately below the reservoir downstream. In 2010, similar patterns were observed although overall values were higher than in 2009, suggesting improvement. Diversity at TD1 did not show as much of an improvement in 2010, perhaps indicating that the macroinvertebrate community was negatively impacted by the sediment flux into that reach. However, diversity values at this site were still higher than in 2009. Simpson's dominance index was similar between all sites, though TD2 was lower than all of the other sites indicating a healthier insect community.

Family Biotic Index (FBI) for 2010 was very even though all of the sites. In 2009 the average value for all the sites combined was 2.42, while in 2010 the average value was 4.12. Both of these values are on the lower end for FBI, indicating a healthy stream (Table 2). FBI values in 2009 were quite variable but were highest in the reaches closest to the then-present reservoir, suggesting that the reservoir was acting as a collector of organic material being washed downstream. In 2010 this pattern was not observed. Although benthic organic matter content was not measured, we believe the improvement in FBI scores indicates a reduction in organic material in and around the reservoir and therefore provides a potential mechanistic explanation for the improvement in the macroinvertebrate community in the reaches surrounding the reservoir. This being said, there was a trend for average FBI values across all reaches to be higher in 2010 vs. 2009. At this point we are unsure why this pattern was observed. It is possibly due to differences in year related to sediment loading, thermal and flow regimes, or sample bias. Patterns of percent EPT, or Ephemeroptera, Plecoptera, and

Trichoptera, from 2009 compared to 2010 look similar. However, the percent of EPT for 2010 were higher than from 2009, indicating a healthier stream both above and below the former reservoir. Results from the analysis of macroinvertebrates is mixed. The strongest evidence for improvement was seen in the reduction in abundance driven almost exclusively by the absence of Isopods after the dam was removed.

Conclusions

The removal of the Nashville Dam has affected the physical habitat, water chemistry, and macroinvertebrate populations of that area. But have the consequences been for the better or for the worse? It appears that the physical habitat has experienced some negative consequences, while the response of the macroinvertebrate populations are mixed. An increase in sediment is usually an indicator of poor stream quality, but there was an increase in the EPT families, which are indictors of good water quality, and also a decrease in Isopods, which are indictors of poor water quality. Since river systems promote the flow of sediment downstream, it is possible that the physical habitat will continue to be changed, so future studies that would include both physical habitat and macroinvertebrate community data would be needed to fully understand if the long-term effects of the removal of the dam. Based on the two years of data collected thus far, we conclude that the Thornapple River near Hastings is in the process of coming into a new dynamic equilibrium with respect to sediment movement, bed load, and substrate composition. However, the macroinvertebrate community response appears to yet be in flux with some metrics indicating improvement, while other metrics are equivocal. We believe that more time is needed to determine the ecological response trajectories of the macroinvertebrate community.

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Appendix:

Macroinvertebrate metadata from 2010.

Thornapple River 6/22/2010

Species	TU3					TU2					TU1					TD1					TD2					TD3				
	HD1	HD2	HD3	Kick net	Total Kick	HD1	HD2	HD3	Kick net	Total Kick	HD1	HD2	HD3	Kick net	Total Kick	HD1	HD2	HD3	Kick net	Total Kick	HD1	HD2	HD3	Kick net	Total Kick	HD1	HD2	HD3	Kick net	Total Kick
Amphipoda	3			5	3	7	10	13	4	30						73	16		5	89	37	25	11	19	73	22	10		11	32
Anisoptera			1		1																									
Betidae		4			4							3			3				3			1	2	6	3	1			1	2
Baetiscidae																														
Brachycentridae		2	1	1	3							9	1	7	10							2	7		9		12		4	12
Caenidae																														
Carabidae													1		1															
Chironomidae	54	17	12	4	83		2	8	3	10	11	8	7	30	26	9			2	9	7	25	3		35		4			4
Corydalidae		2			2			1		1																				
Decapoda																	2			2	1	1			2	1				1
Diptera case								1		1																				
Elmdae											1				1						1		1	2	2		3			3
Ephemerellidae		4			4																									
Glossosoatide																														
Hemiptera		1			1																									
Heptagenidae	65	21	10		96	3	2	5		10	10	12	9	2	31	1	2			3	4	8	7		19	3	6		1	9
Hirudinea							1			1																				
Hydrachnidia	1				1																									
Hydrochidae																														
Hydrophilidae																														
Hydropsychiae	121	98	54	1	273	4				4	61	49	70	59	180	11			1	11	16		51	1	67		24			24
Hydroptilidae			1		1																	1			1					
isonychidae																														
isopoda	1		2		3						16	7	5	59	28	11	24		5	35	1	9	5	1	15		2		1	2
leptophlelebiidae								3		3																				
limnephilidae								1		1																				
Megaloptera																														
Perlidae	4	3	2	1	9			1		1	1				1	5	2			7	14	11	11	2	36	2	1		2	3
Platyhelminthes																														
Polycentropodidae	5		1		6											2					2		15		17	4	8			12
Potamanthidae																														
Philopotamidae	2				2	5	1	2		8		2	6		8				1		1		14		15					
Sialidae				2										1		2				2										
Zygoptera												1			1															

Thornapple River 7/13/2010

Species	TU1			TD1				TD2					TD3				
	HD1	Kick net	Total Kick	HD1	HD2	Kick net	Total Kick	HD1	HD2	HD3	Kick net	Total Kick	HD1	HD2	HD3	Kick net	Total Kick
Amphipoda	2	2	2		74		74	2	1	3	18	6				8	
Anisoptera																	
Betidae		3		6	4		10	7	2	13		22	10	7	7		24
Baetiscidae						2											
Brachycentridae		1		4			4	16	87	20	4	123	8	2	2	1	12
Caenidae																	
Carabidae																	
Chironomidae	7	2	7	10	48		58	23	17	4	3	44	1	2	11		14
Corydalidae		1				1								1			1
Decapoda				1			1										
Diptera case																	
Elmdae		3				1		1			1	1	4				4
Ephemerellidae																	
Glossosoatide																	
Hemiptera																	
Heptagenidae	20	10	20	15			15	53	57	48	2	158	24	34	11	3	69
Hirudinea				1			1										
Hydrachnidia																	
Hydrochidae						1											
Hydrophilidae						7		1				1					
Hydropsychiae		39		110	1		111	76	198	87	16	361	83	71	52	10	206
Hydroptilidae																	
isonychidae																	
isopoda	1	1	1	13		2	13	2	1		8	3					
leptophlelebiidae																	
limnephilidae					1		1										
Megaloptera																	
Perlidae													1				1
Platyhelminthes	2	8	2		7		7	7		13	3	20					
Polycentropodidae		1		4	8		12	10	20	33	21	63	7	1	2	6	10
Potamanthidae															2		2
Philopotamidae																	
Sialidae					2		2		1			1					
Zygoptera																	

Thornapple River 8/3/2010

Species	TU3					TU2					TU1					TD1					TD2					TD3				
	HD1	HD2	HD3	Kick net	Total Kick	HD1	HD2	HD3	Kick net	Total Kick	HD1	HD2	HD3	Kick net	Total Kick	HD1	HD2	HD3	Kick net	Total Kick	HD1	HD2	HD3	Kick net	Total Kick	HD1	HD2	HD3	Kick net	Total Kick
Amphipoda	1			1	1	1	3	8	6	12			1	5	1	1			6	1		3	2	4	5	1			1	1
Anisoptera																														
Betidae	45	23	13	5	81	1		10		11	6	18	26		50	31	30	14	9	75	8				8	45	23	13	5	91
Baetiscidae																														
Brachycentridae			1	1	1											2	4	1		7	1	3		2	4			1	1	1
Caenidae																														
Carabidae																														
Chironomidae	6	4	7		17	11	27	6	17	44	1	25	91	2	117	26	14	38	23	78	14	2	2	3	18	6	4	7		17
Corydalidae	1		1		2																					1		1		2
Decapoda																														
Diptera case						2				2																				
Elmdae		1			1		1	1	1	2	1				1	1			2	1							1			1
Ephemerellidae																														
Glossosoatide																														
Hemiptera																														
Heptagenidae	27	25	7		59	7	2	12	3	21	47	30	22	19	99	11	7	6		24	17	8	12		27	27	25	7		59
Hirudinea																														
Hydrachnidia																														
Hydrochidae																														
Hydrophilidae																														
Hydropsychiae	119	74	129	6	322				1		40	57	91	6	181	256	130	115	2	501	47	14	6	1	74	119	74	129	6	322
Hydroptilidae																														
isonychidae																														
isopoda			1		1									11														1		1
leptophlelebiidae																														
limnephilidae																														
Megaloptera																														
Perlidae																1				1										
Platyhelminthes																														
Polycentropodidae	19	15	18	4	52	6	1	5		12	4				4		10	1	1	11	2	7	16	4	25	19	15	18	4	
Potamanthidae																														
Philopotamidae		1			1	2				2							1	2		3							1			
Sialidae									2															2						
Zygoptera																														

Macroinvertebrate metadata from 2009

Thornapple River 6/17/2009

Species	TU3				TU2				TU1				TD1				TD2				TD3			
	HD1	HD2	HD3	Kick	HD1	HD2	HD3	Kick	HD1	HD2	HD3	Kick	HD1	HD2	HD3	Kick	HD1	HD2	HD3	Kick	HD1	HD2	HD3	Kick
Aeshnidae																								
Ameletidae																				1				1
Amphipoda																								
Anisoptera				1		9	15	2			1	3	15	203	67	108	3	3	3	211			1	6
Betidae																								
Belostomatidae	1		1								1										2		1	1
Brachycentridae								2																
Caenidae	1						1						4	4	6	7	13	51	56	50	11	6	15	4
Calopterygidae							1						1		1	2	3			6				
Cambaridae	1																							
Ceratopogonidae														1										
Chironomidae																		1		3				
Chironomidae Pupa	30	74	36	5	54	43	73		29	31	19		66	36	33	25	93	87	58	51	8	25	13	10
Collembola	1	3	2	1	1		2	1	2	1								1	2	1				
Coenagrionidae																								
Corydalidae								2						3	2	6	3		1	12				
Curculionidae	1																							
Decapoda																								
Diptera			1					1				1												
Dryopidae				1											1									1
Dytiscidae larvae																2		1						
Elmdae	2			1												1				5				1
Elmidae Larvae													1			4				4				
Empididae Pupa	1	1																						
Gerridae												1												
Gomphidae																								
Gyrinidae																		1						
Haliplidae								1								1								
Heptageniidae	58	47	36		2	2			3	3	5			1					2		4	4	3	
Hirudinea																								
Hydracarnia																1								
Hydrachnidia																								
Hydroptilidae													2	9	8	3				1				
Hydrophilidae																								
Hydropsychiae																								
Hydropsychiidae	35	7	2	4					24	4	3		16	13	16	7	7	6	7	5	15	64	26	5
Hygrobiidae																								
isopoda				1	2	4	14	4	34	94	67	29	229	1164	601	212	7	6	9	117				
Leptoceridae				1															1	1				
Libellulidae														1										
Limnephilidae																								
Naucoridae																				2				
Notonectidae								3				3												
Perlidae				1									1		1	1	1			2	4	3	2	2
Philopotamidae																								
Phryganeidae															4	1				1				
Platyhelminthes																								
Pleidae																1				25				
Polycentropodidae	1	12	11		1	1	3		4	1					1						1		1	
Potamanthidae																								
Psychomyiidae																								
Sialidae																								
Simuliidae	1														1									
Tipulidae							1																	
Turbellaria													13		14		4	6	4	6				
Veliidae								1																

Thornapple River 8/17/2009

Species	TU2				TU1				TD1				TD2				TD3			
	HD1	HD2	HD3	Kick	HD1	HD2	HD3	Kick	HD1	HD2	HD3	Kick	HD1	HD2	HD3	Kick	HD1	HD2	HD3	Kick
Aeshnidae																				
Ameletidae																				
Amphipoda	1	2	2	18			1	24	6	1		3	17	16	21	57	14	1	1	124
Anisoptera																				1
Betidae					1			8		1					1		7	8	20	49
Belostomatidae																				
Brachycentridae								3	3	1	13	5	4	29	86	30	13			53
Caenidae																				2
Calopterygidae																				
Cambaridae																				
Ceratopogonidae																				
Chironomidae	4	8	2		4		3	10	28	17	37		6	48	36	8	41	4	3	21
Chironomidae Pupa																				
Collembola				6																
Coenagrionidae																				
Corydalidae																				1
Curculionidae				1																
Decapoda																				
Diptera				14									1							1
Dryopidae																				
Dytiscidae larvae																				
Elmdae								1		1			1		1	3	2			9
Elmidae Larvae																				
Empididae Pupa																				
Gerridae																				
Gomphidae																				
Gyrinidae				1																
Haliplidae				1																
Heptageniidae	11	4	10		5	2	2	2	7	6	2		12	10	6	6	14	20	40	16
Hirudinea																				
Hydracarnia																				
Hydrachnidia																				
Hydroptilidae																				
Hydrophilidae																				
Hydropsychiae			2	1	2			86	179	266	463		14	34	40	5	149	23	27	34
Hydropsychiidae																				
Hygrobiidae				4																
isopoda					8	36	30	320	68	30	53	5	1		1	53				1
Leptoceridae																				
Libellulidae																				
Limnephilidae																				
Naucoridae																				
Notonectidae																				
Perlidae			1															1	1	
Philopotamidae									57	13	35			6	1	1	15	4	5	
Phryganeidae																				
Platyhelminthes									77	52	195					4				1
Pleidae																				
Polycentropodidae	1	4	3		1	2	1		11	8	3		21	29	18	4	5	8	9	
Potamanthidae																				
Psychomyiidae																				
Sialidae																1				
Simuliidae																				
Tipulidae																				
Turbellaria																				
Veliidae																				