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THE EFFECTS OF LAMPRICIDE TREATMENTS ON
STREAM pH

presented by

REBECCA N. GANNON

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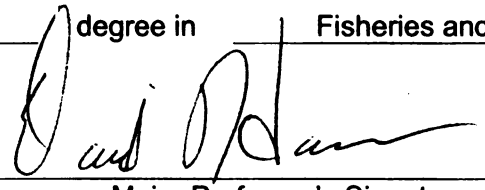

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THE EFFECTS OF LAMPRICIDE TREATMENTS ON STREAM pH

By

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ABSTRACT

THE EFFECTS OF LAMPRICIDE TREATMENTS ON STREAM pH

By

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Addition of lampricide 3-trifluoromethyl-4-nitrophenol (TFM) during sea lamprey control treatments has been hypothesized to cause significant suppression of pH levels in certain river systems negatively impacting fish populations. The goal of this research was to evaluate possible mechanisms of pH suppression in order to adjust chemical control treatment processes to allow for maximum killing effect on sea lamprey (*Petromyzon marinus*) while protecting non-target resident fish species. The cause of the noted pH suppression has been hypothesized to be related to the magnitude of plant production within streams treated and the timing of chemical treatments. In order to assess changes in plant production levels during a treatment, I measured diel variation in dissolved oxygen, pH, temperature, and flow rates before, during and after TFM treatments. TFM additions in streams evaluated in 2005 and 2006 did not impact river pH levels. This finding suggests that TFM applications in rivers with high plant biomass do not or rarely show the pH suppression earlier noted. Suppression appears to be the result of spatial and temporal pH variation among treated rivers.

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Sea lamprey (*Petromyzon marinus*) are parasitic predators that entered the Great Lakes through the New York Finger Lakes (Crowe 1978). After the Welland Canal was completed in 1829, sea lamprey were able to bypass Niagara Falls which had been a natural barrier (Crowe 1978). By the 1940's sea lamprey were present in all five Great Lakes. Sea lamprey have wreaked havoc on the Great Lakes fisheries since the 1930's, contributing to reductions in the number of lake trout to the brink of extinction (Crowe 1978). In the late 1940's, efforts by the American and Canadian governments were initiated to control sea lamprey populations. The first step was to understand this species life cycle, and then to find a method that would kill the lamprey with minimal harm to other aquatic life. It was determined that the best control method was to attack the lamprey when they are most concentrated in stream tributaries as spawning adults or as juveniles (Crowe 1978). Chemical control was researched for several years with over 6000 chemicals tested. Between 1957 and 1958, several promising chemicals were tested in the field, two of which proved to be very effective, 3-trifluoromethyl-4-nitrophenol (TFM) and 5-dichloro-4-nitrosalicylanilide (B73) (Crowe 1978).

Since 1958, TFM has been used to control the populations of sea lamprey in selected tributary rivers of the Great Lakes (Crowe 1978). The liquid chemical is pumped directly into a stream at concentrations pre-determined to be lethal to sea lamprey. The minimum lethal concentration (MLC) is determined by the pH and alkalinity of the river, and is maintained for 9-12 hours continuously at each application site to ensure an effective treatment. Each block of chemical moves down the river based on the velocity of the river. In some cases, it can take 3 to 4 days to treat a river and all of its tributaries. As the block of chemical moves downstream, the concentration of the

TFM decreases because of the additional ground and surface water inputs from tributaries joining the main river. To maintain a lethal concentration, additional chemical is added at "boost" sites, in a leap frog manner along the river. Prior to treating a river for sea lamprey, the water chemistry of the river is determined by measuring several variables including; pH, dissolved oxygen, alkalinity, and temperature. These variables are sampled at numerous sites approximately every four hours for four to five days prior to treatment. Of all the variables measured, pH by far has the most significant impact on the toxicity of TFM (Dawson 1975).

In the early stages of sea lamprey control, a treatment was not considered successful unless teleost fish and sea lamprey were killed. However, for the past 25 years, non-target kills have become a cause for greater concern. For Example, fish kills that occur while working in Michigan must be reported to the Michigan Department of Environment Quality and the Michigan Department of Natural Resources. Under certain conditions, fish kills can occur, even when the levels applied are thought to be within operating range. The suspected cause of unexpected toxicity is thought to be due to pH suppression due to the addition of TFM (Boogaard et al. 2005). Past fish kills have been most prevalent in productive rivers, particularly rivers with high abundance of aquatic macrophytes. It is believed that the addition of lampricide into a river system affects the natural processes of photosynthesis (Dawson 1975) and respiration of macrophytes (Maki 1975), thereby altering pH.

In 1975, Dawson found that the toxicity of TFM in a river system is inversely related with the pH of a river system (Figure 1). As pH decreases, the toxicity of TFM increases (Dawson 1975). The toxicity of TFM is 5 times greater at a pH of 7.00 than at

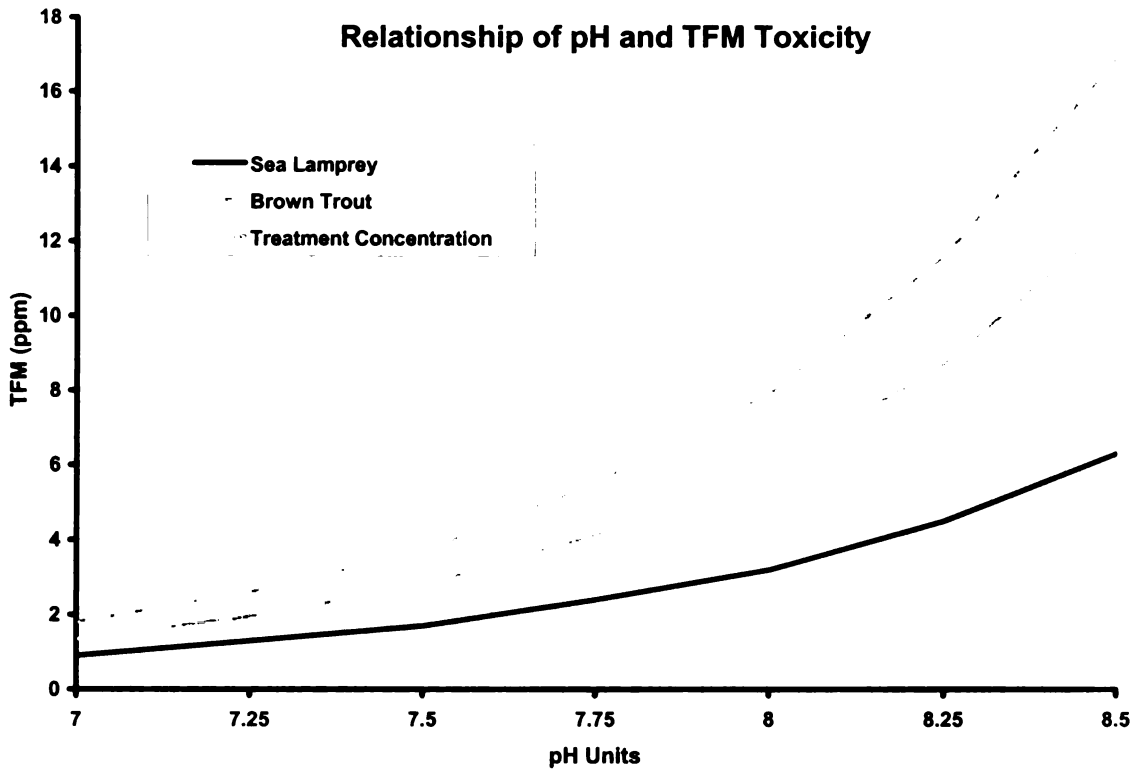

Figure 1. Realtionship of pH and TFM (USFWS SLC Operating Manual). Sea lamprey concentration is the minimum lethal concentration at which lamprey will die. Brown trout concentration is a concentration at which TFM becomes toxic to sensitive species such as brown trout. Treatment concentration is typically run at 75-85 % of the "brown trout" concentration.

a pH of 8.00 (McDonald 2006). In 1993, a prediction chart was created by the United States Fish and Wildlife Service (USFWS) to determine the MLC for a treatment based on the pH and alkalinity of a river (Scholefield et al. 1999). In highly productive rivers, USFWS employees that TFM leads to an apparent suppression of the pH. Bill et. al. (1988) found that a reduction in pH by as little as 0.5 could cause TFM to become toxic to fish during a lampricide treatment when this level would normally not produce non-target mortality. Prior instances of suspected pH suppression have generally occurred in limited stream reaches (i.e., less than five miles) and suppression occurs rapidly (i.e., within hours). As the pH of the river drops, a reduction in the amount of TFM being applied is necessary. If the TFM concentration is not reduced, the level of chemical will

exceed the maximum lethal concentrations for that particular river. If TFM concentration remains above the maximum level for more than a few hours, a fish kill may result.

From 1980-2006, Canada and the United States conducted approximately 1502 TFM treatments during this time period (Table 1). Of those treatments, there were a total of 88 reportable fish kills, representing only 6% of the treatments. A reportable fish kill is any treatment in which 50 individual fish of any one species are killed. Each fish kill is classified to be a kill of sensitive species or non-sensitive species and the cause of the kill is also recorded (e.g., pH suppression or spawning). A sensitive species is a species that is known to be affected by TFM applications. Fish kills of sensitive species accounted for only 5 %. A non-sensitive species is one that does not generally show any adverse affects from TFM addition. Fish kills of non-sensitive species were only 1% of the reportable fish kills. In many cases, sensitive species are native lamprey that are unavoidably killed as a result of the TFM application. This is a very low percentage considering the number of treatments conducted. Although it is a low percentage any fish kill is considered problematic and should be avoided at all cost.

	USA	Canada
Number of treatments	972	530
Number of reportable kills	28	60
Number with a kill of sensitive species	23	52
Number with a kill of non-sensitive species	5	8

Table 1. The approximate number of TFM treatments (1980-2006) and fish kills that have occurred in the United States (1994-2006) and in Canada (1991-2006). A reportable kill is any treatment where more than 50 of any species have been killed by TFM application. A sensitive species is a species that is known to be sensitive to TFM applications (e.g. other native lamprey, log perch, and mud puppies). A non-sensitive species is a species that is not affected by normal TFM levels (e.g., Chinook salmon and walleye).

An additional concern is that TFM treatments that occur on rivers with a large diurnal shift in pH and dissolved oxygen may result in fish kills. Thus one possible mechanism for pH suppression is if TFM inhibits the production of oxygen or decreases the level of pH or dissolved oxygen below their normal levels (Scholefield et al. 1999).

Photosynthesis is the process by which plants take in CO_2 and water, and use sunlight to produce O_2 and glucose. When organisms respire O_2 and glucose are used, and CO_2, water, and energy are released. Photosynthesis and respiration rates affect the concentration of CO_2 which then affects the pH balance. Photosynthesis uses dissolved carbon dioxide, temporarily reducing the concentration of carbonic acid (H_2CO_3), leading to higher pH. As CO_2 is released and dissolved into the river during respiration, the pH is lowered. Thus, if TFM directly or indirectly influences the balance between respiration and photosynthesis, it has the potential to shift river pH. One more complexity is that the rate at which photosynthesis is the greatest is in the middle of the day, before noon, and decreases after noon (Meyer 1939). In 1970, Hynes found that as macrophytes photosynthesize during the day there is an increase in river pH. In the evening, when respiration predominates, the pH of a river decreases. This change in macrophyte processes causes the pH of a river to oscillate throughout a 24 hour period. Maki (1975) and Maki and Johnson, (1976) found that TFM not only affects O_2 production but also plant growth and metabolism which may lower stream pH and dissolved oxygen.

Since lampricide treatments occur during the day and night, light availability may also play a role in suppressing pH levels. It is unknown whether TFM affects macrophyte physiology, or if the color of TFM (yellowish when mixed with water) attenuates the wavelengths of sunlight needed to perform photosynthesis.

Photosynthetic activity varies continuously in river systems due to the natural variation in light intensity (Meyer 1939). Light attenuation is also influenced by the amount of dissolved organic matter and inorganic matter naturally in the river (Krause-Jensen 1998). This background attenuation will influence the fraction of light that is available to the plants and in some cases can act as an inhibitor (Krause-Jensen 1998). Macrophytes tend to photosynthesis best at wavelengths of solar radiation between 400 – 700 nm (Hauer 1996). If TFM is inhibiting photosynthesis by blocking these wavelengths, then the rate of photosynthesis may be reduced.

Being able to predict the cause(s) of pH suppression will help reduce the threat of fish kills. The particular mechanism responsible (e.g., inhibition of photosynthesis or an increase in respiration rates) is not of primary concern, but being able to determine the conditions where pH suppression is likely is the first goal of this research. If we can understand the situations where pH suppression is likely, we may then be able to create a prediction table or some other tool that will allow managers to adjust treatment levels to avoid major fish kills. The goal of this project is to better understand the causes of pH suppression in order to predict its occurrence and minimize its effects on non-target species.

There are three main objectives in this study. The first objective is to determine the degree of pH suppression during applications of TFM. This will be done by collecting water chemistry data and looking at the statistics before, during, and after TFM application. The second objective is to determine if macrophyte abundance is related to pH suppression during lampricide treatments. Plant samples will be collected in order to estimate macrophyte abundance within each river. Not only will plant samples be

collected, but a lab experiment will also be conducted. This will allow me to determine in, a controlled environment, if the addition of TFM affects normal plant functions. The final objective is to document the occurrence of any fish kills that occurred on the study streams.

METHODS

River Selection

Rivers are typically treated for sea lamprey every three to five years, depending on stream productivity. For this study, I selected all three rivers that had a history of suspected pH suppression that were treated in Michigan and northern Indiana during 2005 and 2006. In addition, I sampled six rivers that did not have a prior history of pH suppression. Study rivers were chosen based on two criteria: the treatment schedule and past history of pH suppression. Treatment schedules are released in February. Once the list was released, I coordinated with treatment supervisors to determine which rivers fit my criteria of having a prior suspected pH suppression event and being treated during the field season. A total of nine rivers were sampled for this study (Figure 2). Not all of the rivers sampled had a history of pH suppression. The Chippewa River, Bear Creek, and the Muskegon Rivers have all had potential pH suppression events. The remainders of the rivers chosen were considered control rivers. I felt that the natural river approach would allow for a better view into what is actually occurring during a suppression event. A lab experiment was also conducted but will not be focused on.

Sampling occurred over two field seasons (2005-2006). All rivers sampled were in Michigan except for Trail Creek which is in northeast Indiana near the Michigan border (Figure 2). The length of treated stretches of river ranged from 11.5 miles to 165

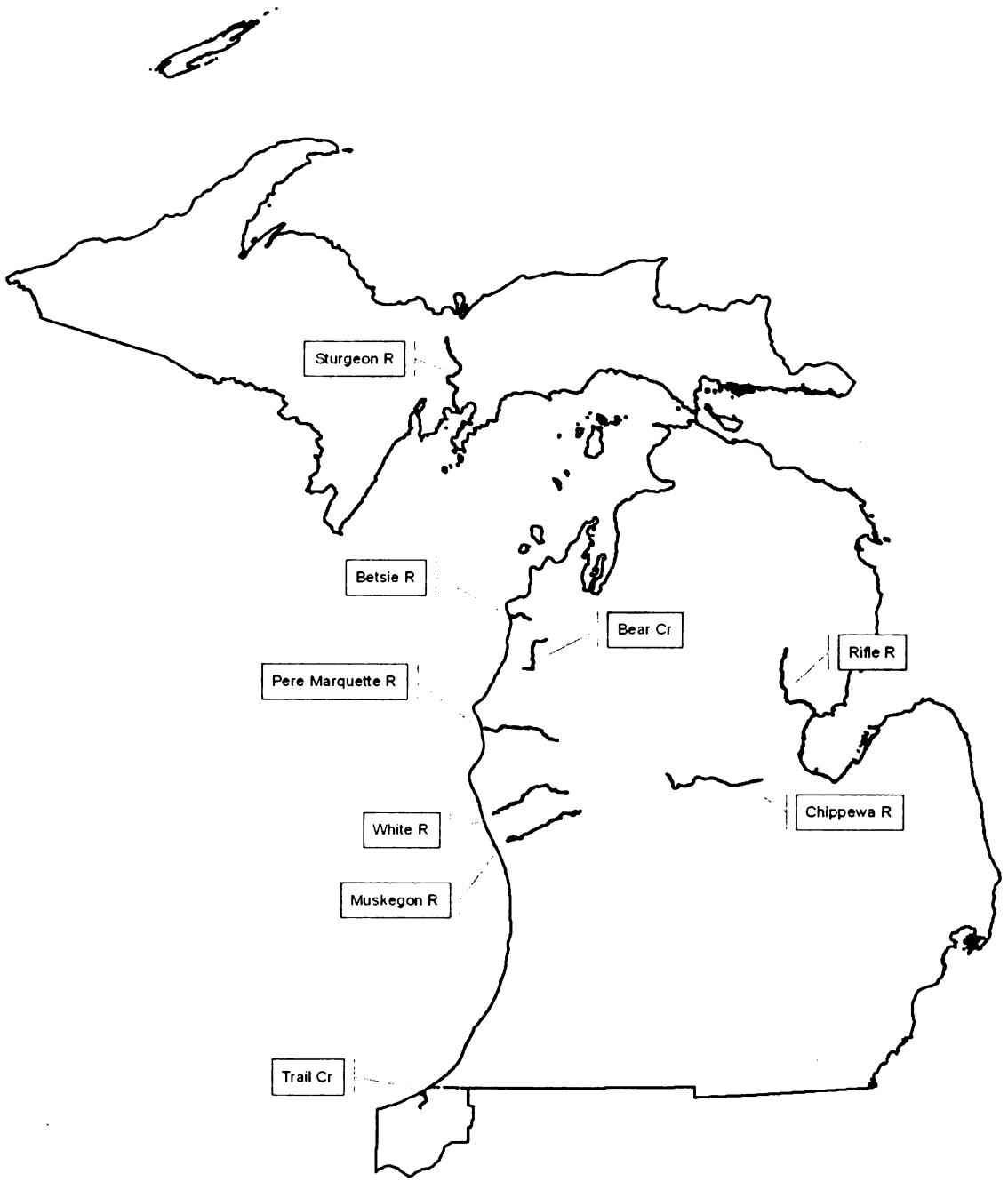

Figure 2. Map of Michigan showing location of study rivers.

miles. Average pH levels ranged from 7.46-8.27 and dissolved oxygen from 5.92-9.83 (Table 2). The alkalinity was relatively high throughout all rivers sampled with an average of 148.

River	Date Sampled	pH	DO	Temp	Alk	CFS	TDS	Miles
Trail Creek	7/26/06-8/03/06	7.46	5.92	21.6	196	24.3	0.3	16.5
Sturgeon River	7/12/06-7/20/06	7.76	7.80	22.7	103	42.1	0.1	68.0
Bear Creek	8/22/06-8/30/06	8.05	8.18	15.7	139	80.0	0.2	47.0
Pere Marquette River	8/08/06-8/17/06	8.19	8.36	18.9	136	320.7	0.2	165.0
Betsie River	9/04/06-9/11/06	8.22	9.28	15.6	171	136.6	0.2	11.5
Muskegon River	8/25/05-8/30/05	8.24	8.47	21.6	148	1233.8	0.2	88.0
Rifle River	9/19/06-9/28/06	8.24	9.83	13.21	191	123.7	0.3	110.0
White River	8/09/05-8/17/05	8.24	8.41	20.1	162	154.5	0.3	70.0
Chippewa River	7/13/05-7/21/05	8.27	7.95	25.7	185	132.2	0.3	73.0

Table 2. Summary of study river attributes. Mean pH, dissolved oxygen (DO, mg/l), temperature (C°), alkalinity (total alkalinity), discharge (cfs), total dissolved solids (TDS, g/l) and miles of river treated with TFM. Rivers are arranged by ascending pH levels.

The alkalinity ranged from 103 to 196 and fluctuated little on a daily basis within any river. The total dissolved solids average was 0.23 g/l and did not vary substantially among rivers. The general size of each river varied widely with discharges ranging from 24 to 1234 CFS with an average of 485 CFS. Land use varied by location consisting of rural, urban, industrial, and agricultural areas.

Data Logger Information

In most cases, four data loggers were placed throughout the river to be treated. One logger, was placed above the TFM application point. This logger never came into contact with TFM during the treatment, and was used as the control logger on each river.

The second logger, treatment 1, was placed downstream of the control. The remaining loggers, treatment 2 and 3, were placed sequentially down the remainder of the river. Locations for logger placement were determined based on the advice of chemical control supervisors and access. Many of the rivers studied had little to no access other than road crossings. Of the nine rivers sampled, four rivers (Muskegon River, Rifle River, Betsie River, and the White River) had dams of various sizes. Treatment application points were located above the dam on the Muskegon, Rifle, and the Betsie River. To maintain a true control logger at dam locations, the logger was placed above the application point which was typically in the pond area formed by the dam.

Hydrolab Datasonde data loggers were used to collect continuous water chemistry data. Each data logger measured pH, dissolved oxygen, temperature, total dissolved solids, and conductivity every fifteen minutes. The data loggers were calibrated before each use and calibration was checked every two days while loggers were deployed. If the logger was not reading accurately, the unit was recalibrated. I found that it was necessary to clean the loggers every two days with a tooth brush to remove buildup on the sensors to maintain accuracy. Once the loggers were retrieved, each logger was cleaned with a mild detergent. Data were collected prior to each treatment, during the treatment, and post treatment. This allowed me to have reference data at every site as well as a logger that was placed above the treatment.

Each data logger was calibrated at the beginning of each sampling period. Each meter took approximately 45 minutes to calibrate. If recalibration was necessary, I found it was generally only the pH probe that required recalibrating. The first calibration was of the pH probe. Using pH 7 and 10 standards, each storage container (a plastic screw

cap cup which holds storage solutions to protect the probes) was filled with a standard and allowed to sit for at least 10 minutes. After 10 minutes if the meter read within an acceptable range (depended on the temperature of the solution and the correction factor listed by the manufacturer) the probe was calibrated. Between each solution, the probe and storage cup were rinsed with de-ionized water. The next step was to calibrate the conductivity meter. The storage cup was filled with conductivity standard 1432, and allowed to sit for 10 minutes before the probe was calibrated. There is no calibration for the total dissolved solids probe.

The final step was to calibrate the luminescent dissolved oxygen (LDO) meter. This was the most difficult meter to calibrate. To calibrate the probe it was necessary to completely dry the LDO probe and the remaining probes. It was then necessary to stabilize the meter so that the probes were facing down. I used a titration stand that was modified to hold the probe. Once the meter was stabilized, the storage cup was filled with tap water to just below the probe, but not touching the probe. The probe was allowed to sit until the meter had reached as close to 100% saturation as possible. This was then checked against the Hydras3LT program provided with the data logger. Once the LDO meter was standardized, the last step was to program the meter for data collection.

Several problems occurred with instrumentation while in the field. On the Chippewa River, the control and the treatment logger #3 both failed. Even though the control logger failed, there were data collected by each treatment logger prior to the TFM treatment thus providing control data for evaluating the effects of TFM. Due to major flooding on Trail Creek, the control and treatment #3 loggers failed to collect data. Both

loggers were submerged in sediment for four days prior to being found and retrieved. The Rifle River also had one logger malfunction, treatment logger #3. Bear Creek also flooded, and the control and treatment #2 loggers were both buried in sediment. These loggers were not retrievable for four days. Due to the flooding, the treatment of Bear Creek with TFM was cancelled. Data were collected, but were not used to determine the impact of TFM on stream water chemistry.

Hand Sampled Water Chemistries

Although the Hydrolab Dataloggers measured pH, dissolved oxygen, and temperature, I coordinated with the chemical control crew from the USFWS Ludington Biological Station to collect hand sampled data. These data were used to check the accuracy of the data loggers. River pH, dissolved oxygen, temperature, and alkalinity were measured every four hours on average, and hourly during treatments.

All hand samples were measured using USFWS Instrument Operating Procedures (IOP). Temperature and pH readings were taken using a handheld Beckman pHI 240 meter (IOP: 007.3A & IOP: 007.1B). Dissolved oxygen was measured in mg/L using an YSI model 55 dissolved oxygen meter (IOP: 008.1). Alkalinity was determined using the sulfuric acid titration method as described in the USFWS Technical Operating Procedure (TOP) (TOP: 005.1).

Non-Target Surveys

A non-target species is any organism that is not a sea lamprey as they are the target of TFM. After TFM treatments occur, staff from the U.S. Fish and Wildlife

Service search along the river to collect, identify, and determine the cause of death of any organism found dead along the river. This is typically done at road crossings because of access limitations on some rivers. Two crew members are sent to each site, one searching upstream 100 yards and the other downstream for 100 yards. In the case of larger rivers, canoes are used.

Plant Biomass

Plant density and abundance were estimated using a quantitative sampling approach. Prior to each collection, ten sites were randomly selected from sites that were easily accessible or had road crossings. Once the ten sites were selected, each site was then brought into ArcGIS and a random transect was generated. Each transect was within 100 yards upstream or downstream of the access point. Transect locations were uploaded into a GPS unit for accurate identification. At each transect, the river width was measured, and the total width was divided by ten to provide sample locations for each of the 10 plots along the transect. Each plot was surveyed using a $1m^2$ aluminum square. The depth of each plot was measured (in meters) and dominant substrate was visually determined. If the depth was over 0.5 meters, plant material was not collected, but the species and density in percent were visually estimated. All plant material was collected within each plot that was under 0.5 m in depth. The plant material was placed in a plastic Ziploc bag, and labeled as to the location within each transect. The plant material was identified, or if I could not identify the plant, pictures and voucher samples were taken. Once identified, the plant material was patted dry and a wet weight was measured in grams. All plant material was then dried for 6 hours in a food dehydrator

until completely dry. Once the plant material was dry, a dry weight was measured, and the sample was discarded.

Laboratory Plant Experiment

A laboratory experiment was set up to determine the effects of lampricide on plant photosynthesis in a controlled environment. The test was run in a bioassay trailer owned by the USFWS. The trailer is set up to run serial dilution toxicity tests, but was modified for our purposes. The bioassay trailer is set up as a flow through system and is set up stream side. I chose to use the Pere Marquette River, Mason County, MI, as the site of my experiment. This site was close to the USFWS station and was the easiest to access. A total of 4 tanks were used: 3 treatment tanks and 1 control.

Plants were collected from the Lincoln River, Mason County, MI, because of the low abundance of plant material in the Pere Marquette River. Plant specimens were collected using a shovel. A 6 inch x 6 inch square, 1 inch deep section was harvested and placed in a cooler with water for transport. Plants were then placed in each tank with a cover of approximately 80%. A grid was drawn at the bottom of each tank and 80 % of the squares were covered with plant material. The plants were left in the tanks for 12 hours in order to allow them to acclimate to the river water. After the 12 hour period, each tank was equipped with a data logger.

All four data loggers were calibrated and programmed to take pH, dissolved oxygen, temperature, conductivity, and total dissolved solids readings every 15 minutes. Plant growth lights were used to simulate natural light. Using electric timers, the lights were turned on at 0630 and shut off at 1930.

The day prior to TFM application, I collected stream chemistry data from 0900 to 1630 and was able to determine a natural shift in pH. The pH ranged from 8.10 to 8.22 with an alkalinity of 150. Based on this information, the calculated minimum lethal concentration (MLC) of TFM was 3.5 ppm. I used a rate of 4.0 ppm which would be typical during a treatment as we usually treat above the MLC. Each logger was set to run 12 hours prior to the addition of TFM. TFM application began at 0900 and was shut off at 2100 that night. Each treatment tank measured at or near 4.0 ppm the entire test. Once the chemical was stopped, the concentration of TFM in the treatment tanks began to decline immediately and was gone within an hour.

The loggers continued to sample for 12 hours after the first study was conducted. After the 12 hours, 60% of the original 80% of plant material was removed leaving approximately 20%. This allowed me to look at the effects of high and low densities. The tanks were again allowed to acclimate for 12 hours. The second application of TFM was executed identically to the first.

Light Attenuation

Light measurement readings were taken using a Li-Cor 189 quantum radiometer photometer with a Li-Cor L1-192SA underwater quantum sensor at a set of selected sites on tributaries to Bear Creek. The sensor was set to measure light intensity (umol/m^2/sec) of photosynthetically active radiation, between the wavelengths of 400-700nm. Five control transects and five treatment transects were measured. The control transects were clear water 3 meters upstream of each treatment site application point. Each treatment transect was 5 meters downstream of the TFM application point. This allowed for the

TFM to be completely mixed within the water column. Within each transect, ten plots were established using the same method as was used for the plant biomass plots. Each light reading was taken 0.5 meters from the water surface. The average depth of each plot was 0.58m.

Analysis

Using SAS, logger information was sorted and summarized. A general linear model (GLM) analysis was used to evaluate differences between sites and diel variation within sites. I also looked at the averages of the three main variables (pH, dissolved oxygen, and temperature) before, during, and after a chemical treatment. The mean diel amplitude of pH, dissolved oxygen, and temperature were also calculated at each logger site. Averages were calculated for the entire sampling period by river and site.

RESULTS

General Trends

Several water chemistry parameters (alkalinity, total dissolved solids (TDS), and conductivity) varied little within each river, but pH, dissolved oxygen (DO), and temperature varied substantially among sites within individual rivers, and on a diel basis. Because alkalinity, TDS, and conductivity varied little within a river, these parameters are simply reported as a mean across all sampling (Table 2). Although pH, DO and temperature varied among sites, most of the rivers studied showed parallel behavior among sites with strong diel patterns evident in these parameters. In most rivers, there was substantial site-to-site variation in pH, DO, and temperature. Site-to-site variation in pH was particularly evident in the White River, Sturgeon River, and Pere Marquette

River (Table 3). Site-to-site variation in dissolved oxygen was highest in the Chippewa River, and was also very high in the Pere Marquette River. Site-to-site variation in temperature was generally less than pH or DO, but was highest in the Sturgeon River.

Within day variation in pH, DO, and temperature was substantial on several rivers (Table 3). The average diel amplitude was 0.35 pH units, 2.48 mg/l DO, and 3.19° C. The Chippewa River showed the largest diel fluctuations in both pH and DO, with pH varying up to 0.76 units per day, and DO varying up to 10.56 mg/l per day. The Muskegon River also showed higher than average diel fluctuations in pH and DO, with mean amplitudes ranging up to 0.55 pH units, and 4.21 mg/l per day.

Graphs of pH and DO over the entire study period for each river, provided in individual river summaries, indicate that the presence of TFM did not result in noticeable reductions in pH or DO. Table 4 shows the summary of results from the GLM analysis on the differences between pre-, during, and after TFM data collected. The averages over all river differences varied very little during the study periods. Temperature had the biggest difference from a TFM treatment with an average difference of 0.48 degree difference after TFM treatment occurred. As was stated before, temperature has no direct effect on the toxicity of TFM but does affect the ability of water to hold oxygen. The GLM analysis showed statistically significant differences in pH before, during, and after treatment, but the magnitude of these differences were not of biological significance. Relative departure of pH from the grand mean was -0.02 units before treatment, during was 0.04 units and after having a average difference of -0.05 units. Dissolved oxygen was consistent during the TFM treatment.

River	Logger	pH	pH Amp	DO	DO Amp	Temp	Temp Amp
Betsie River	Control	8.22	0.43	9.36	2.97	15.25	2.91
	Treatment 1	8.18	0.37	9.48	1.31	15.48	2.98
	Treatment 2	8.23	0.30	9.46	1.42	15.64	2.90
	Treatment 3	8.25	0.24	8.82	2.27	16.18	2.64
Chippewa River	Control				Failed		
	Treatment 1	8.17	0.25	7.14	2.94	25.21	2.90
	Treatment 2	8.31	0.56	7.43	4.38	25.71	3.46
	Treatment 3	8.33	0.76	9.27	10.56	26.30	5.07
Muskegon River	Control	8.39	0.48	8.91	3.46	21.86	2.11
	Treatment 1	8.10	0.55	8.29	4.21	21.26	3.94
	Treatment 2	8.17	0.47	8.23	2.64	21.35	2.93
	Treatment 3	8.30	0.17	8.44	1.32	21.82	2.54
White River	Control	8.41	0.39	8.69	1.56	20.54	3.50
	Treatment 1	8.26	0.39	8.48	2.32	20.85	2.73
	Treatment 2	8.12	0.18	8.17	1.10	19.57	2.29
	Treatment 3	8.19	0.22	8.34	1.53	19.59	2.46
Sturgeon River	Control	7.53	0.34	7.43	2.51	20.75	7.44
	Treatment 1	7.75	0.40	7.73	1.48	23.58	6.62
	Treatment 2	7.83	0.39	8.24	1.64	23.14	3.32
	Treatment 3	7.92	0.33	7.81	2.64	23.17	3.51
Pere Marquette River	Control	7.93	0.20	7.87	1.47	19.29	2.51
	Treatment 1	8.27	0.22	8.16	1.69	18.55	2.27
	Treatment 2	8.21	0.46	9.03	2.89	18.78	3.02
	Treatment 3	8.37	0.19	8.47	1.39	19.17	2.36
Rifle River	Control	8.31	0.20	10.03	0.97	14.50	1.88
	Treatment 1	8.10	0.29	9.91	1.63	12.46	1.94
	Treatment 2	8.35	0.33	9.56	2.11	12.73	2.62
	Treatment 3				Failed		
Overall Average		8.16	0.35	8.57	2.48	19.72	3.19

Table 3. Mean and diel amplitude of pH, dissolved oxygen, and temperature at each site sampled. Averages are computed over entire sample period for each river. Diel amplitude is computed as the mean difference in the daily minimum and maximum.

	Temperature					pH					Dissolved Oxygen				
River Site	B	D	A	P	R^2	B	D	A	P	R^2	B	D	A	P	R^2
Betsie S1	-0.28	0.03	-0.22	<0.001	0.027	0.07	0.11	0.01	<0.001	0.158	-0.08	0.07	-0.18	0.032	0.010
Betsie S2	-0.46	-0.22	-0.34	0.005	0.015	-0.03	0.06	0.00	<0.001	0.049	-0.07	0.22	-0.19	<0.001	0.032
Betsie S3	-1.13	-0.88	-0.73	<0.001	0.136	-0.03	0.11	-0.05	<0.001	0.167	0.51	1.15	0.49	<0.001	0.246
Musk. S1	0.53	0.55	1.05	<0.001	0.039	0.26	0.32	0.42	<0.001	0.072	0.58	0.27	1.24	0.001	0.030
Musk. S2	0.51	0.43	0.64	0.287	0.005	0.18	0.25	0.42	<0.001	0.151	0.60	0.46	1.50	<0.001	0.051
Musk. S3	-0.03	-0.30	0.62	<0.001	0.153	0.07	0.08	0.23	<0.001	0.150	0.45	-0.01	0.90	<0.001	0.039
White S1	-0.43	0.46	-0.28	<0.001	0.057	0.07	0.22	0.27	<0.001	0.083	0.16	0.03	0.33	<0.001	0.053
White S2	0.81	1.52	1.68	<0.001	0.066	0.29	0.49	0.18	<0.001	0.057	0.51	0.70	0.40	<0.001	0.058
White S3	0.80	1.34	2.53	<0.001	0.159	0.23	0.30	-0.07	<0.001	0.078	0.35	0.63	-0.07	<0.001	0.315
Sturg. S1	-2.66	-3.74	-2.45	<0.001	0.055	-0.22	-0.15	-0.19	<0.001	0.085	-0.36	-0.09	-0.32	<0.001	0.022
Sturg. S2	-2.81	-4.72	0.80	<0.001	0.284	-0.29	-0.11	-0.35	<0.001	0.178	-0.84	0.03	-1.10	<0.001	0.260
Sturg. S3	-2.98	-3.18	2.08	<0.001	0.381	-0.35	-0.29	-0.58	<0.001	0.452	-0.40	0.08	-0.68	<0.001	0.115
P.M. S1	0.72	0.60	0.71	0.194	0.004	-0.25	-0.26	-0.50	<0.001	0.625	-0.23	-0.18	-0.36	<0.001	0.066
P. M. S2	0.51	0.16	0.50	<0.001	0.029	-0.20	-0.21	-0.44	<0.001	0.474	-1.07	-0.78	-1.26	<0.001	0.032
P. M. S3	0.09	0.48	0.00	<0.001	0.094	-0.37	-0.40	-0.64	<0.001	0.597	-0.62	-0.54	-0.56	0.001	0.019
Rifle S1	2.09	2.02	1.58	<0.001	0.036	0.14	0.42	0.40	<0.001	0.320	0.35			<0.001	
Rifle S2	1.87	1.23	1.40	<0.001	0.050	-0.03	-0.09	-0.12	<0.001	0.049	0.57	0.12	0.21	<0.001	0.054
Rifle S3	Logger Failed														
Chippewa	No Control														
Averages	-0.14	-0.21	0.48	0.025	0.079	-0.02	0.04	-0.05	0.001	0.187	0.02	0.03	0.05	0.001	0.014

Table 4. Summary of results obtained from General Linear Model (GLM) analysis of differences in temperature, pH, and dissolved oxygen, comparing least square means before (B), during (D), and after (A) TFM exposure at each site.

Before the treatment the average difference was 0.02 mg/l, during was 0.03 mg/l and after the TFM block an average of 0.05 mg/l difference. Statistical comparison of the difference between pre, during, and post TFM time periods suggest the reduction in pH was no greater than 0.10 units, and the reduction in DO was no greater than 0.02 mg/l. Given the magnitude of diel fluctuations and site-to-site variation, I view this as a minor impact on pH and DO.

Among the rivers studied, a fish kill was observed only on the Betsie River. As is evident if Table 4, the pattern in pH and DO within the Betsie River do not appear to have been influenced by the addition of TFM. More details concerning the fish kill and water chemistry on the Betsie River are provided in the river summary.

Analysis

The differences between the pre-, during, and post-TFM treatment readings showed that there were significant changes in pH, dissolved oxygen and temperature readings. Although the results were significant, the high number of samples that were analyzed could account for the detection of minor differences. Table 5 shows the number of miles of river treated with TFM and the number of samples collected with the data loggers.

River	Miles of River Treated	Sample Size
Betsie	11.5	684
Sturgeon	68	737
White	70	742
Chippewa	73	750
Muskegon	88	476
Rifle	110	813
Pere Marquette	165	821

Table 5. Average river miles treated with TFM within the last 25 years. The sample size is the number of water chemistry samples taken by the data loggers deployed on each river.

Individual River Summaries

Betsie River

The Betsie River was the only river studied in which a fish kill occurred during TFM treatment. The TFM treatment on the Betsie River was set up at Homestead Dam. The fish kill occurred below Homestead Dam and continued to Grace Road which is approximately 2 miles downstream. There were 438 salmon were collected from the river and taken to the local trash dump. The treatment had begun at midnight and the fish kill was not noted until the daylight hours. Once the fish kill was determined, the remainder of the treatments were shutdown and the treatment was stopped.

Strong daily shifts in pH were seen during the sampling period (Figure 3). Trends in pH were parallel among all sites and within day, except treatment logger 3 had a unique double daily peak in pH. Logger 3 was located approximately 12 river miles from the control logger at Homestead Dam. Logger 3 had lower daily amplitude shifts in pH (0.24 units), than the control logger, 0.43 pH units, but did not go higher than the control logger pH. A natural drop in pH was detected on day five, lasting two days.

Dissolved oxygen was also nearly parallel, especially between treatment loggers 1 and 2. Dissolved oxygen was higher than average at the dam and lower than average at

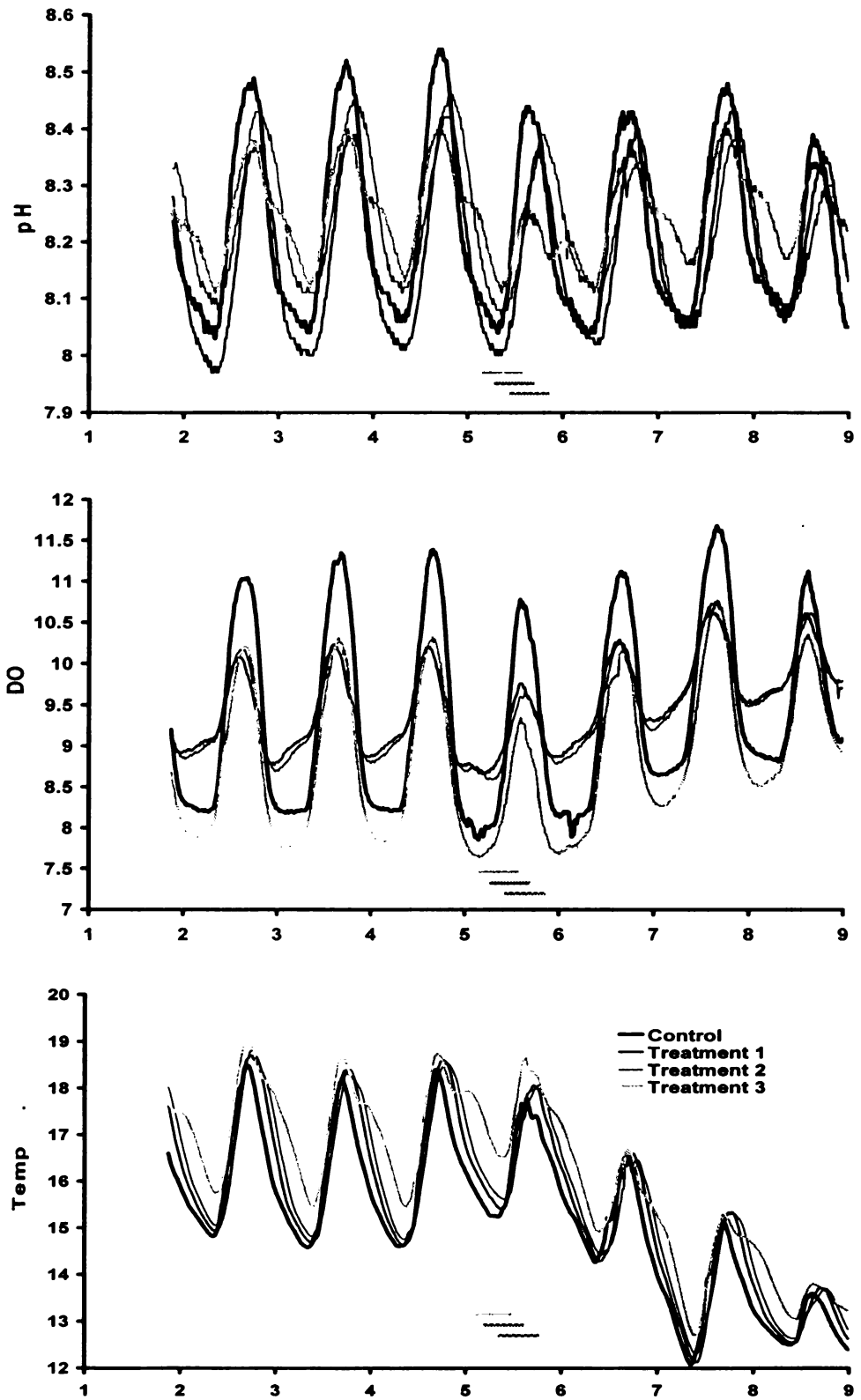

Figure 3. Betsie River graphs of water pH, dissolved oxygen (mg/l) and temperature (C). Bars indicate when TFM chemical block passed through the treatment logger locations.

treatment logger 3. A drop in dissolved oxygen levels was also noted on the fifth and sixth days coinciding with the drop in pH. The average oxygen concentration ranged from 8.82 to 9.48 mg/l across the four sites sampled. Temperature trends were nearly parallel across all sites. A large drop in temperature occurred on day six and continued to decline for the remainder of the sampling period.

Although a fish kill occurred, the addition of TFM did not cause a noticeable suppression of pH (Figure 3). The pH levels on the fourth day had reached a maximum pH of 8.54. After the natural decline on the fifth day, pH never went above 8.44 units.

Sturgeon River

The Sturgeon River showed diel patterns representative of that observed in other rivers (Figure 4). Diel patterns in pH were largely parallel, but there was a high degree of variation among sites in the daily amplitudes of pH. The control data logger had a lower overall pH during the sampling period, averaging 7.53 units. Trends in dissolved oxygen were also nearly parallel among sites. The daily amplitude of DO variation was small when compared to other rivers sampled, with an average amplitude shift of 2.07 mg/l. Temperature was also parallel among the three treatment data loggers. The control logger had a lower temperature overall, but a larger daily amplitude shift than the other three loggers. The treatment loggers had a very large diel fluctuation in temperature, averaging 3.32 to 6.62° C per day.

Pere Marquette River

Water pH differed substantially between sites, with averages ranging between 7.93 and 8.37 units (Figure 5). The pH at the control site was lower than the remaining

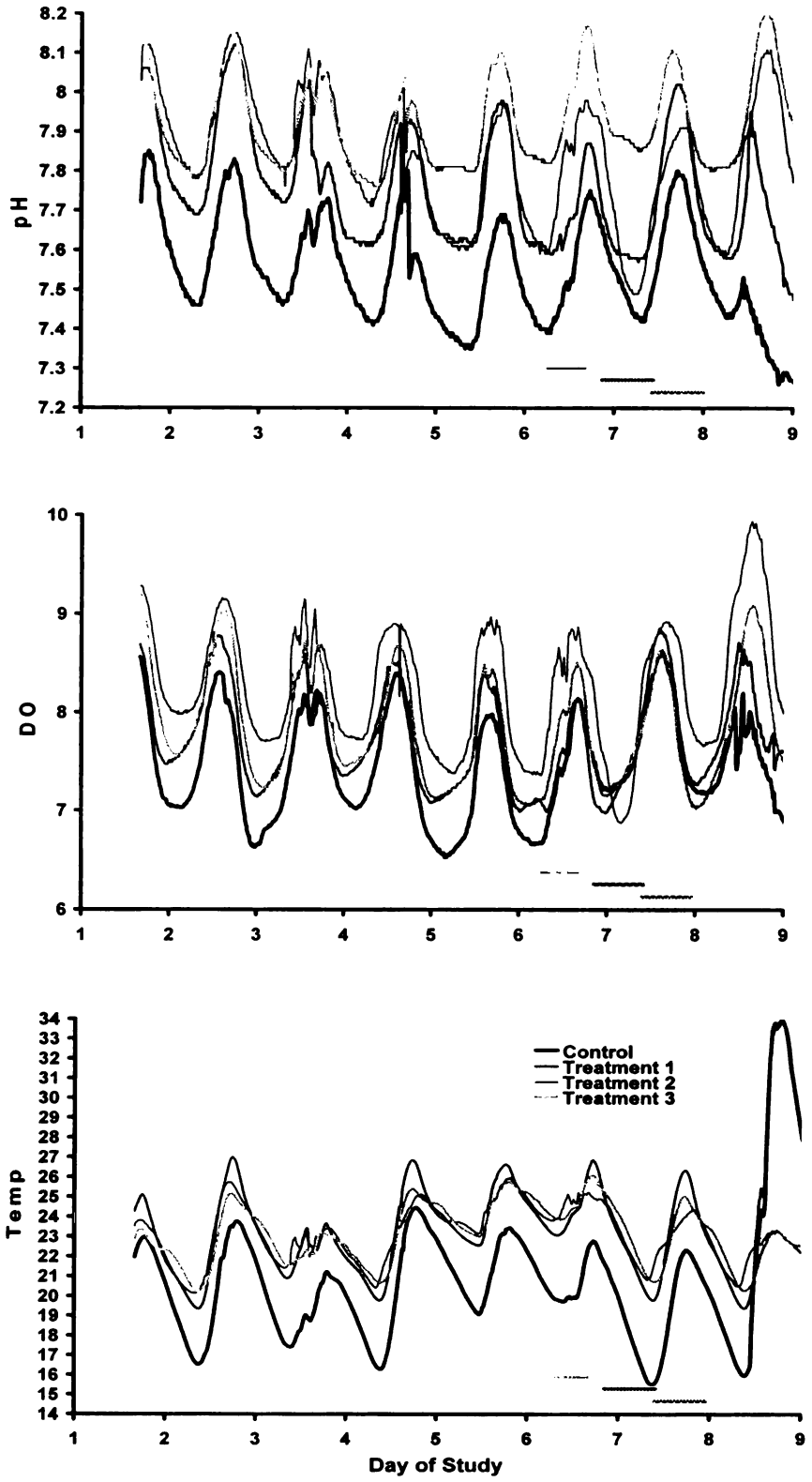

Figure 4. Sturgeon River graphs of water pH, dissolved oxygen (mg/l) and temperature (C). Bars indicate when TFM chemical block passed through the treatment logger locations.

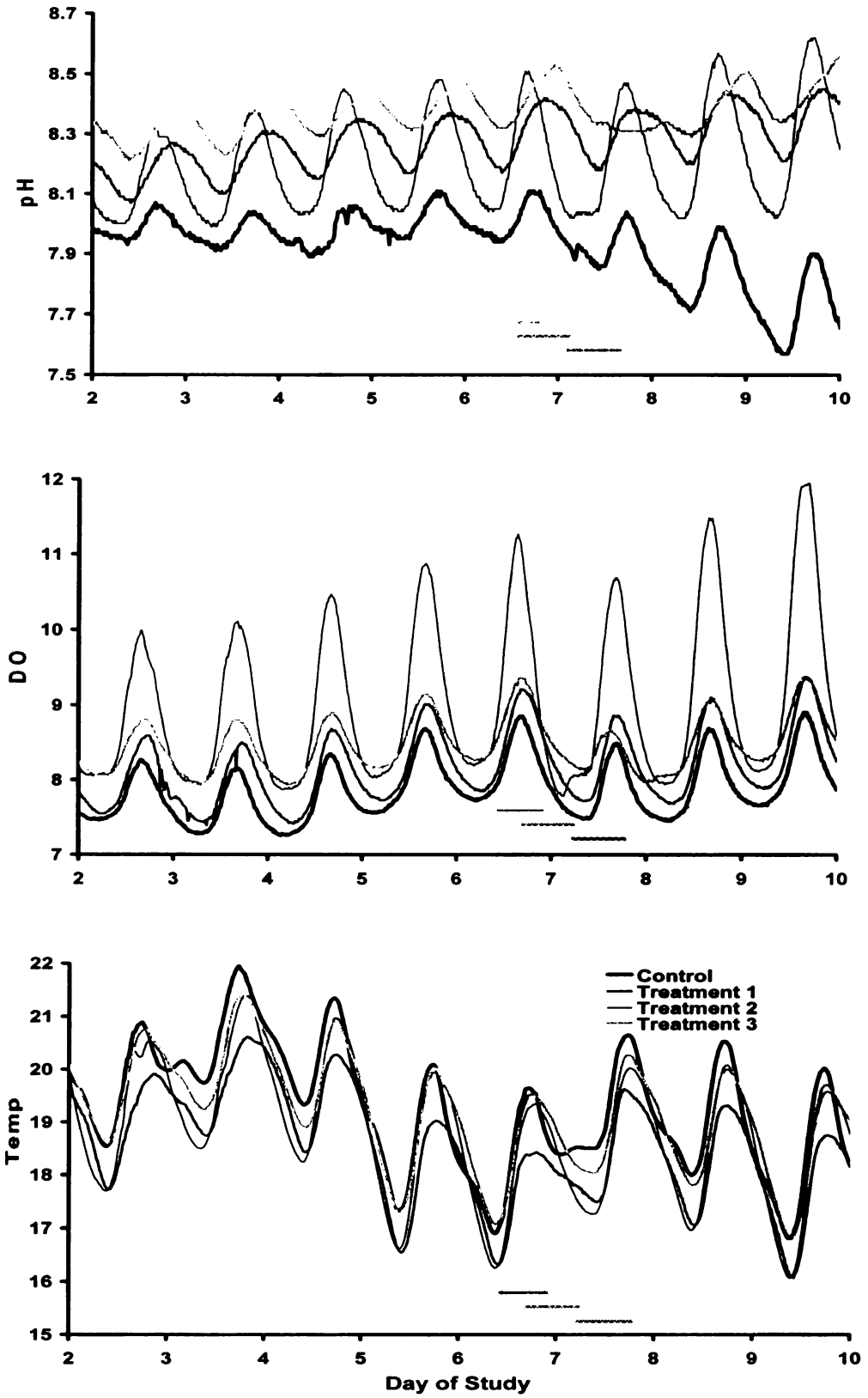

Figure 5. Pere Marquette River graphs of water pH, dissolved oxygen (mg/l) and temperature (C). Bars indicate when TFM chemical block passed through the treatment logger locations

loggers during the entire sampling period, but showed similar diel variation to the other sites. The daily amplitude in DO was similar among sites, only varying by 1.16 mg/l. Treatment logger 2 had the highest within site variation ranging from 7.99-8.62 pH units. Dissolved oxygen levels were comparable across sites. Treatment logger 2 had the highest variation, with a daily amplitude shift averaging 2.89 mg/l. The remaining three loggers had very little variation and were parallel. Temperature was parallel between sites, and a drop in temperature was noted on days 5 and 6 across all sites.

Muskegon River

Water chemistry patterns in the Muskegon River were strongly affected by Croton Dam, located at the upstream boundary of the TFM treatment (Figure 6). The control logger was placed above Croton Dam as the treatment occurred at the dam. The water that was being sampled by the logger was lake water from Croton Pond.

Treatment logger 1 and 2 both had relatively large amplitude diel shifts in pH of 0.55 and 0.47 pH units. Trends over time were similar between these two loggers, but were less parallel than in the other rivers discussed so far. Logger 3 had very little change in pH levels throughout the day and night with an average diel shift of only 0.17 pH units. Treatment logger 3 was in an area that was on average deeper than the other sites and highly turbid.

Loggers 1 and 2 also showed parallel dissolved oxygen trends. Once again, low amplitude diel shifts were recorded at treatment logger 3 with an average shift of 1.32 mg/l while logger 1 was 4.21 mg/l. Temperature readings also showed strong diel patterns among all sites. The three treatment loggers were relatively parallel although

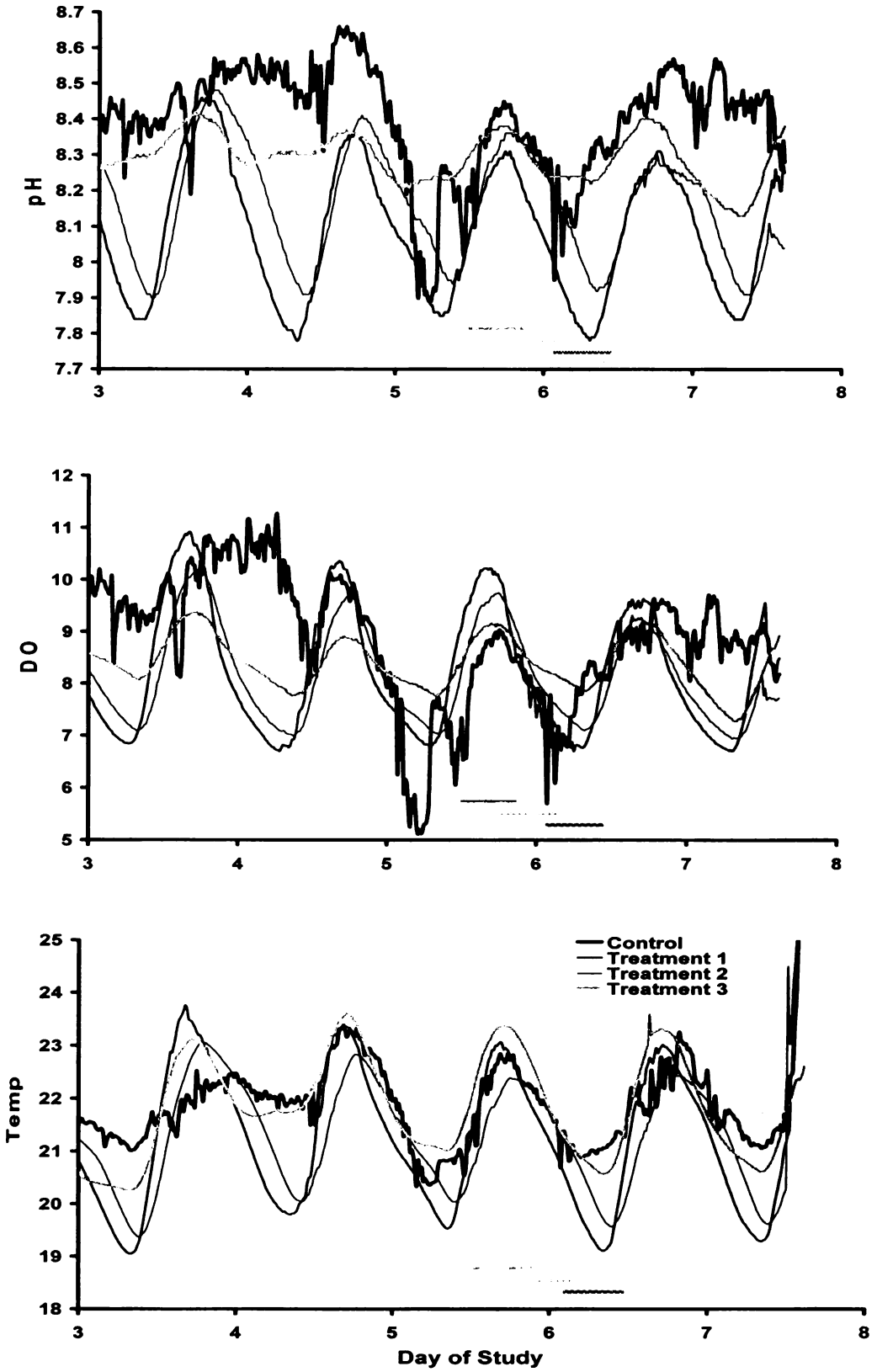

Figure 6. Muskegon River graphs of water pH, dissolved oxygen (mg/l) and temperature (C). Bars indicate when TFM chemical block passed through the treatment logger locations.

logger 3 had a lower amplitude shift of 2.54 degrees than the other two loggers at 3.94 and 2.93 degrees.

Rifle River

Treatment logger 3 on the Rifle River malfunctioned during sampling, and based on trends over time, I suspect treatment logger 2 may have malfunctioned for part of the time. (Figure 7) The control logger was above the dam on the West Branch of the Rifle. There is a moderately large pond above the dam that the logger was sampling from as can been seen in Figure 7. Water pH levels for logger 1 and 2 showed a diel pattern at first and after day six a pattern returned at logger 2 but was not as strong as before. The average amplitude shifts for logger 1 and 2 are 0.29 and 0.33 pH units.

Dissolved oxygen levels were nearly parallel, although the control logger showed the effects of the dam on DO levels. The diel amplitude swing in DO was relatively small, only varying by 1.63 mg/l at logger 1 and 2.11 mg/l at logger 2. Temperature was moderately parallel among the two treatment sites. There was a large increase in temperature on day five and then the temperature returns to original levels after two days.

White River

The diel pattern of pH levels in the White River was very pronounced, as is visible in figure 8. The diel pattern is strong but there is a very low amplitude shift ranging on average from 0.00 units to 0.06 units. As was seen on the Betsie River, double diel pH peaks occurred at the control logger, which was located approximately 100 yards below the Hesperia Dam on the White River. Above the cement dam there is a

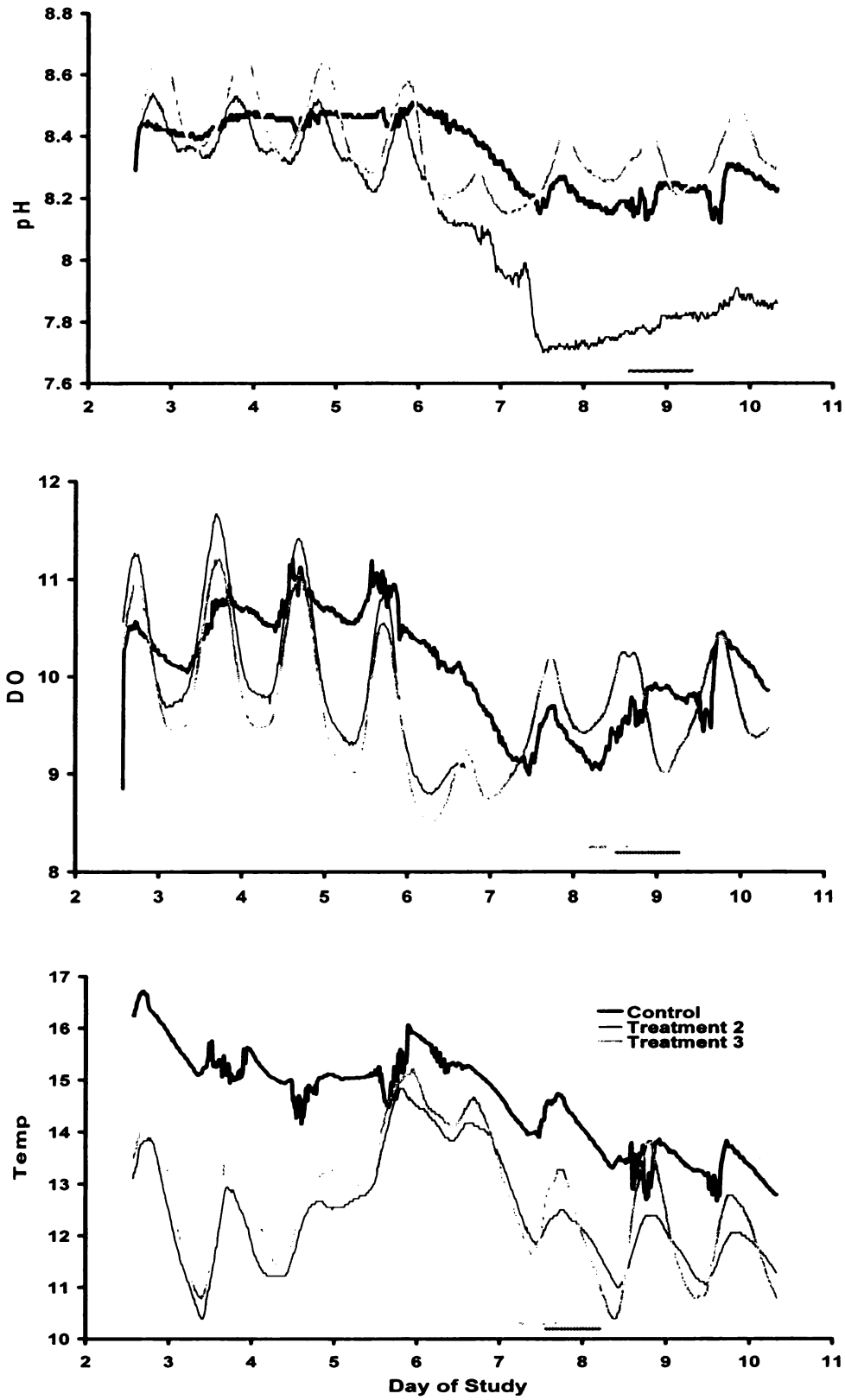

Figure 7. Rifle River graphs of water pH, dissolved oxygen (mg/l) and temperature (C). Bars indicate when TFM chemical block passed through the treatment logger locations.

16.25 hectare pond. Overall, pH was comparatively parallel among the treatment sites with very little site variation with the average variation in diel amplitude being only 0.30 pH units. Oxygen levels were similar among all sites, ranging from 8.17 to 8.69 mg/l. Temperature readings were a little more sporadic. Although there was still a noticeable diel pattern, the parallel nature seen in the levels of pH and DO were not as visible. Temperature at treatment logger 3 fluctuated substantially ranging on average of 2.02 degrees, without an apparent pattern.

Bear Creek

Bear Creek endured heavy flooding during the study period, with the main flooding event occurring on the fourth day of sampling. The control and treatment one loggers were buried in sediment for several days before they could be retrieved. Due to the heavy flooding, this river was not treated for sea lamprey. Thus, data collected were not statistically analyzed. Prior to flooding, pH showed a diel pattern at first but then flood events caused the pH to become erratic and there were no real patterns reestablished until the eigth day of the study (Figure 9).

Dissolved oxygen diel patterns began the same as pH levels, but quickly were affected by the rain. Only the treatment 4 logger was able to capture a reestablished oxygen trend. Temperature was not affected to the extent that pH and dissolved oxygen were interrupted. There was a noticeable diel cycle throughout the sampling period; however, the rain affected the temperature during the fifth day of the study. The control logger temperature dropped dramatically from an average of 14.25 degrees to an

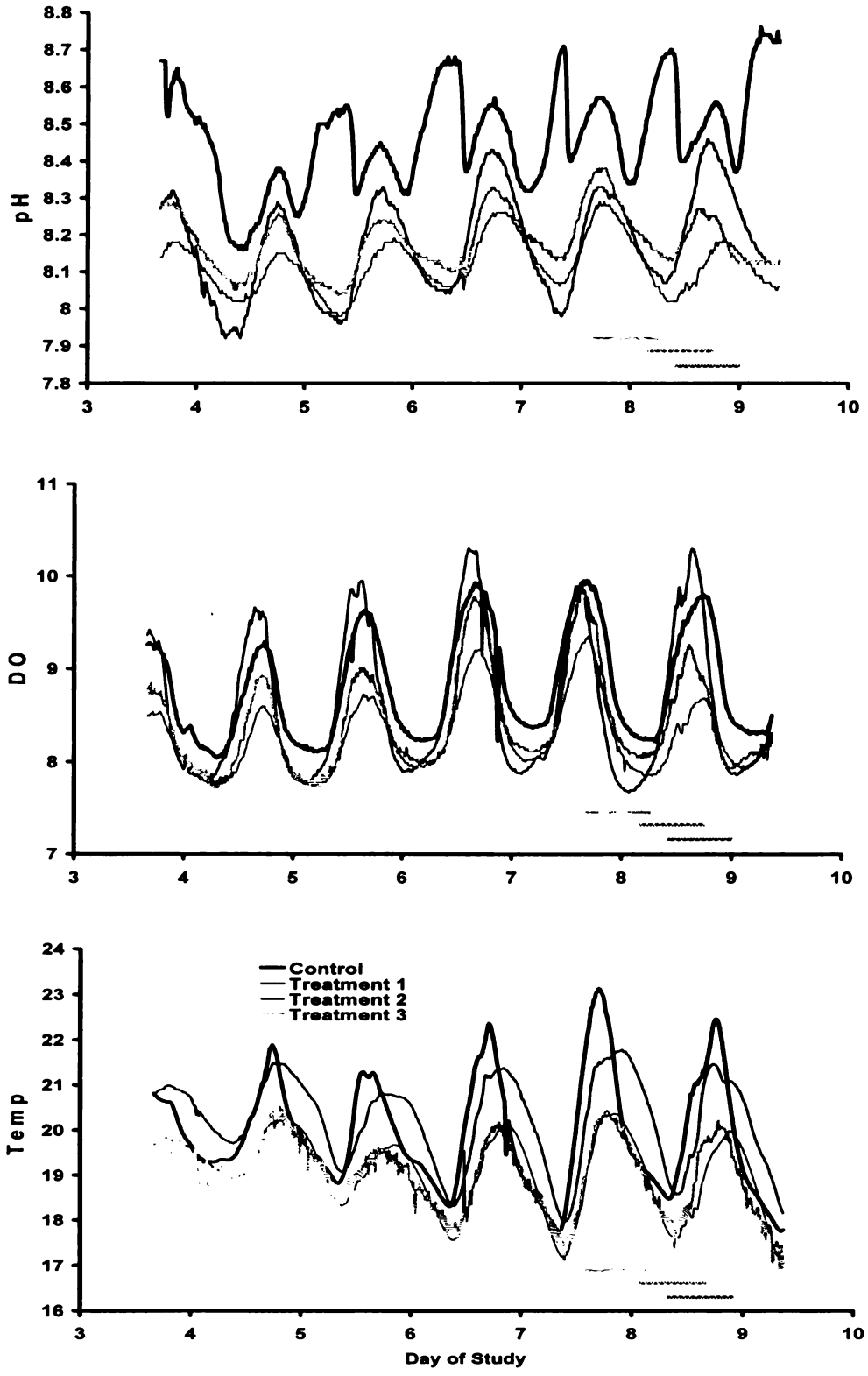

Figure 8. White River graphs of water pH, dissolved oxygen (mg/l) and temperature (C). Bars indicate when TFM chemical block passed through the treatment logger locations.

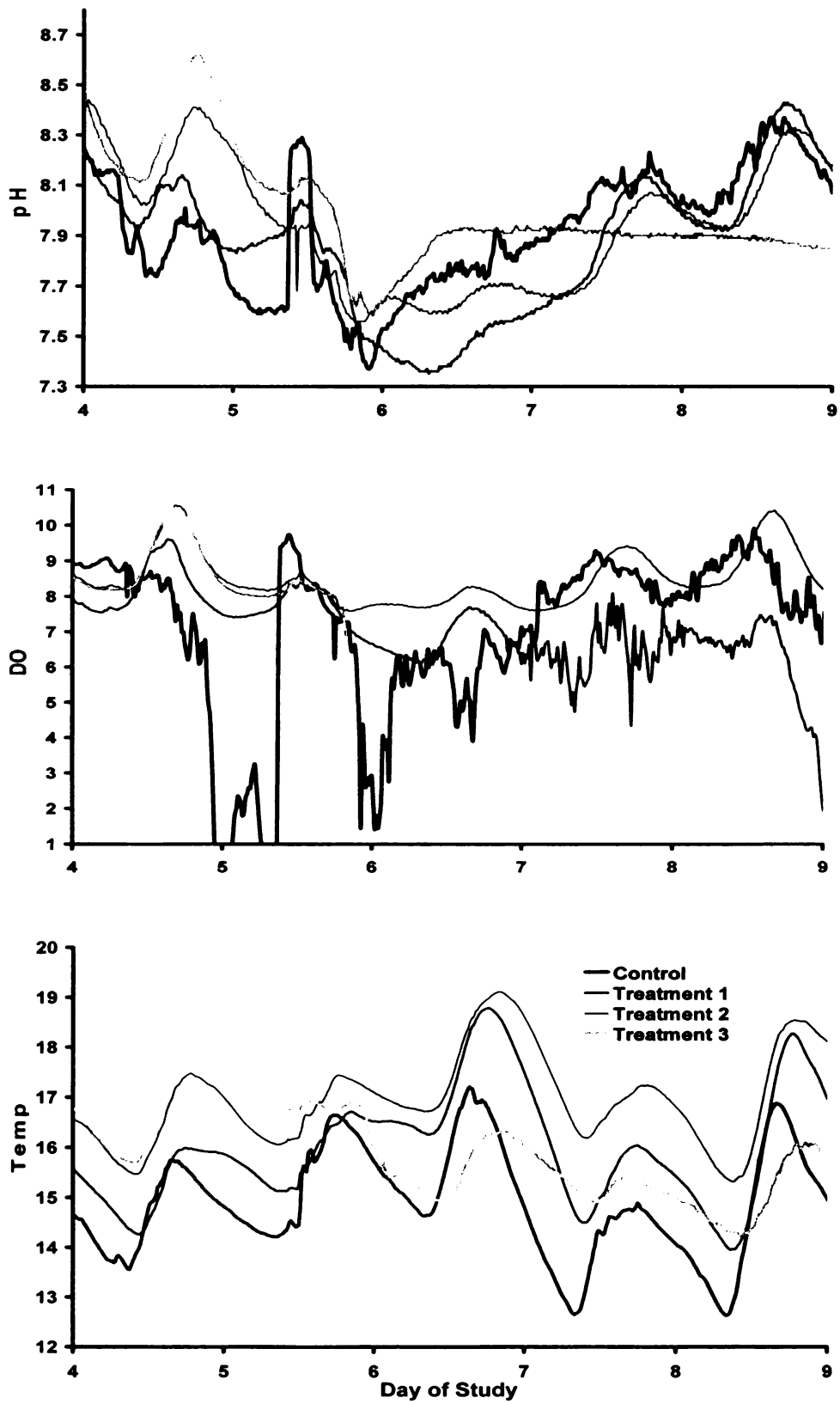

Figure 9. Bear River graphs of water pH, dissolved oxygen (mg/l) and temperature (C). Bars indicate when TFM chemical block passed through the treatment logger locations.

average low of 12.69 degrees but began to return to normal temperature levels towards the end of the sample period.

Trail Creek

Although data were collected, flooding events during the sampling period caused the loggers to malfunction and the data were not representative of typical water chemistry levels. Treatment logger 3 and 4 were both buried in sediment for several days. Figure 10 shows the data that was collected by the loggers but this data was not analyzed statistically. Measurement of pH and DO were very sporadic and no real pattern could be determined. Temperature readings, however, show a strong diel pattern. Between the control logger and the treatment 1 logger, a largely consistent pattern can be seen, although the amplitude was rather minimal. The decrease in temperature between day 5 and 6 can be explained by the heavy rain event that occurred.

Chippewa River

The Chippewa River also had logger malfunctions (Figure 11). The control and treatment 3 loggers malfunctioned. Logger 3 collected a couple days worth of data before the malfunction occurred. During the first three days, logger 3 showed large shifts in daily pH levels with an average amplitude shift of 0.76 pH units. Treatment 1 logger did not have a pattern that was distinguishable throughout the entire sampling period. The average amplitude shift was 0.56 pH units (Table 3).

It was unfortunate that logger 3 failed because it showed dissolved oxygen diel shifts over the first two days that averaged 10.56 mg/l. Smaller amplitude shifts were seen at treatment loggers 1 and 2 but they were still nearly parallel. The average shift in

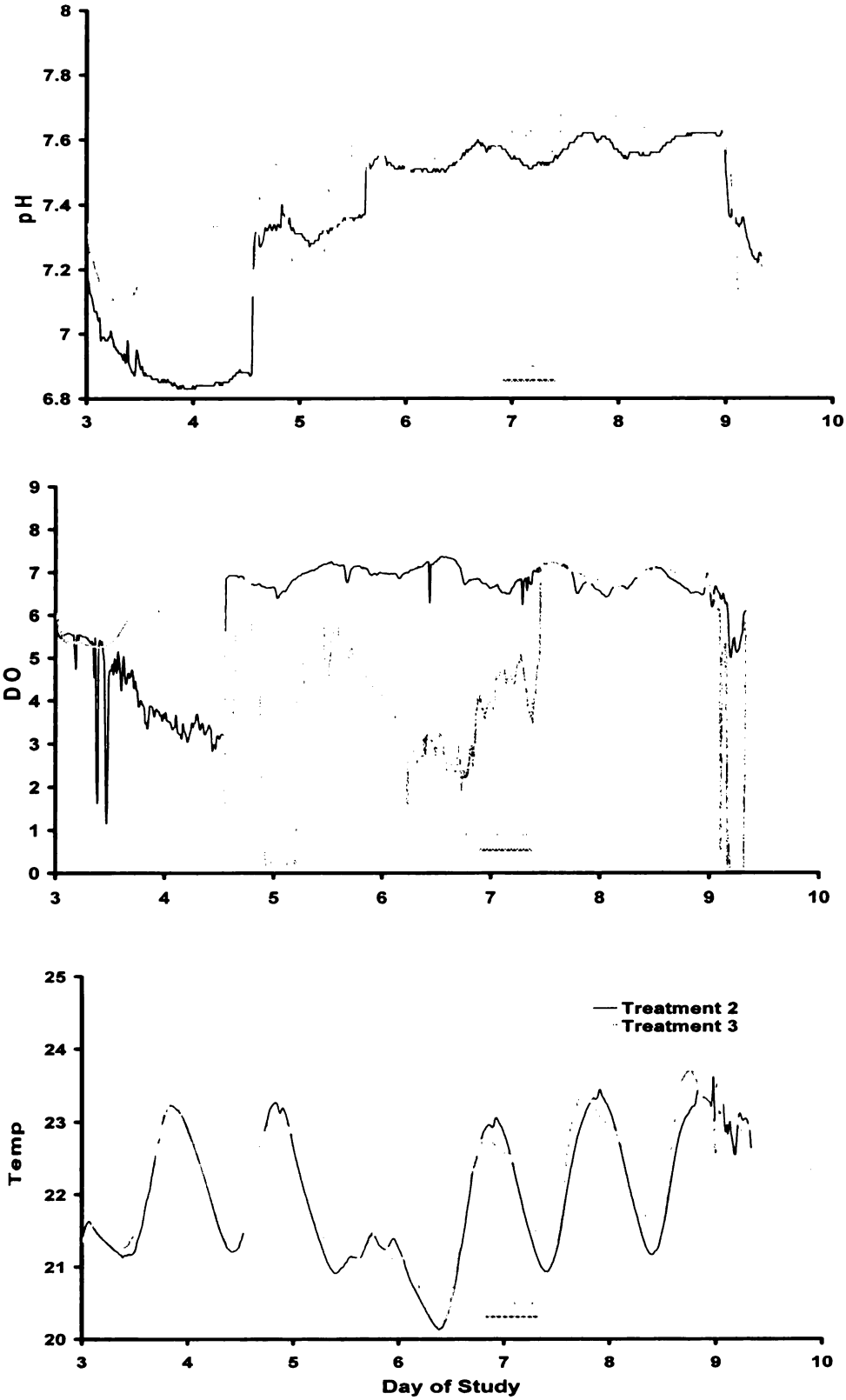

Figure 10. Trail Creek graphs of water pH, dissolved oxygen (mg/l) and temperature (C). Bars indicate when TFM chemical block passed through the treatment logger locations.

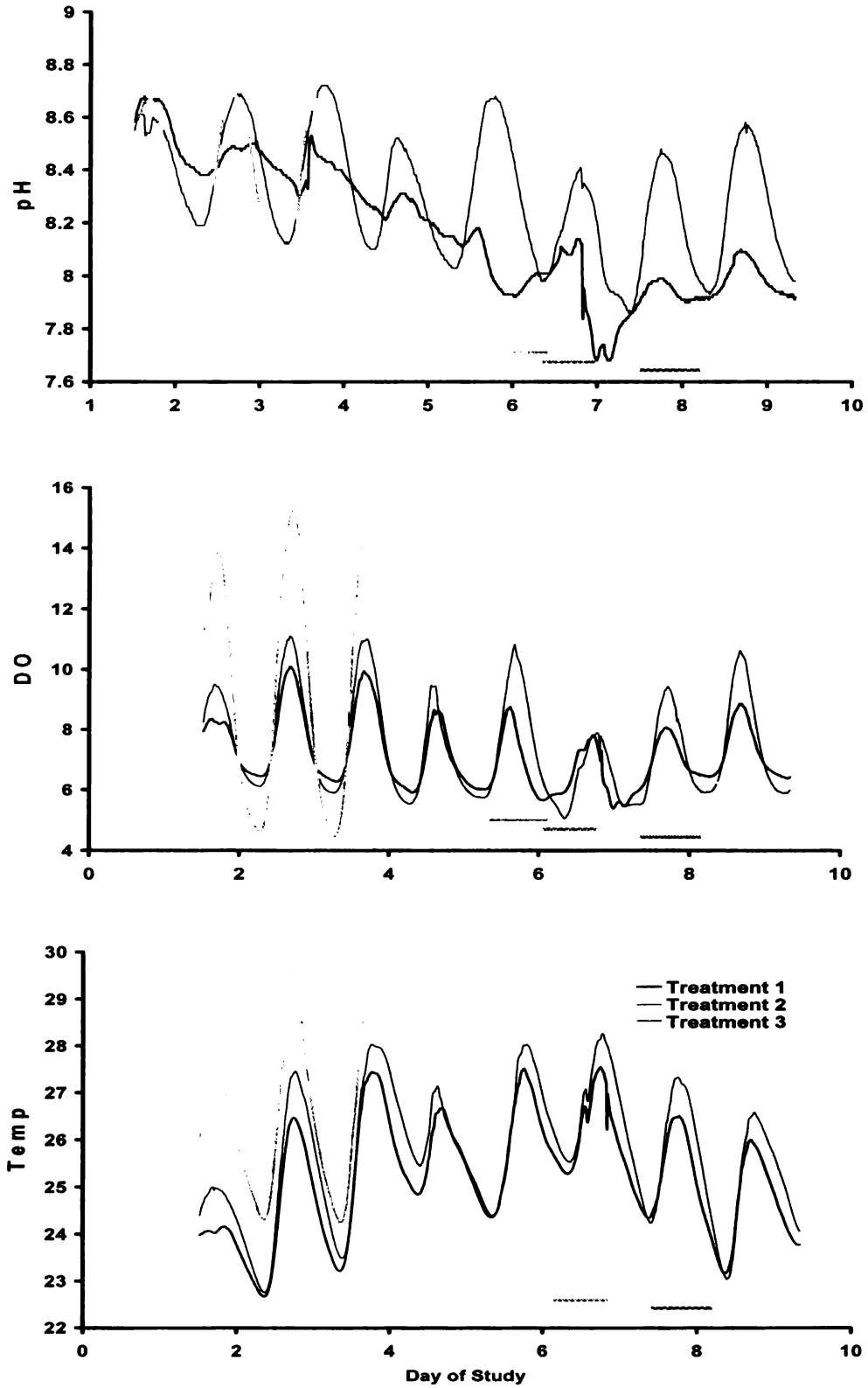

Figure 11. Chippewa River graphs of water pH, dissolved oxygen (mg/l) and temperature (C). Bars indicate when TFM chemical block passed through the treatment logger locations.

dissolved oxygen at logger 1 was 2.94 mg/l while logger 2 was 4.38 mg/l amplitude shift. Temperature, however, was very parallel at loggers 1 and 2. The average temperature shift at logger 1 was 2.90 and 3.46 degrees at logger 2. Logger 3 again had high diel shift amplitude with an average of 5.07 degrees.

Plant Collections

I sampled plants on all nine rivers sampled for water chemistry (Table 6). A total of 680 plots were surveyed. I could not sample all transects within each river due to accessibility and/or depth constraints. The mean depth was 0.51m and ranged from 0.42 to 0.71m while the mean width was 22.6m ranging from 11.7-57.9m (Table 6). No plants were collected on the Pere Marquette River or the Rifle River within the random transects. Although no plants were within the random transects, there were plants within the river systems. The mean plant biomass varied substantially among rivers. Bear Creek had the highest mean dry weight with 2.56g/ m^2 while the Pere Marquette and Rifle Rivers contained no plants within transects. The dominant substrate was sand with 8 rivers being sandy and 1 river being primarily gravel (Muskegon River).

River	Width (m)	Depth (m)	Mean Plant Weight (g/m^2)	Dominant Substrate	N
Rifle	16.8	0.44	0.00	Sand	70
Betsie	17.2	0.46	0.55	Sand	100
Sturgeon	14.1	0.43	0.25	Sand	60
Chippewa	25.9	0.52	1.41	Sand	80
White	21.7	0.50	0.04	Sand	90
Muskegon	57.9	0.71	0.38	Gravel	80
Pere Marquette	15.8	0.59	0.00	Sand	100
Bear	11.7	0.42	2.56	Sand	100

Table 6. Average width, average depth, mean dry plant weight, dominate substrate, and number of plots surveyed during plant biomass collection.

Laboratory Experiment

The controlled plant experiment yielded no significant evidence of pH suppression. After running both the 80% and the 20% plant biomass tanks, no visible sign of pH suppression was found. Throughout the experiment all tanks remained within 0.2 ppm of TFM for the entire 12 hour run. Table 7 shows the results of both experiments. Mean water pH in the two treatment and control tank remained within 0.06 units throughout the entire experiment. Before and during the treatment period, pH's remained virtually the same, all being within 0.03 units. After the TFM application was shut off, the pH of the 80% plant trial was lower than the other two treatments by 0.06 units; however this was not a biologically significant amount.

Dissolved oxygen varied throughout all experiments and in the control tank. Average oxygen levels prior to TFM addition (8.57 mg/l in 20%) were lower than during the treatment (8.68 mg/l in 20%). This could be accounted for because the treatment period ran during the day when photosynthesis would be highest. After TFM was stopped, both the 20% and the control loggers showed decreases in average dissolved oxygen levels. The 80% treatment tank had an increase of 0.12 mg/l in average dissolved oxygen. Temperature readings did not seem to be affected by the addition of TFM. The only noticeable difference was within the 80% logger. The average temperature dropped from 19.12 to 17.97 during TFM application and then increased to 18.42 after TFM was shut off.

Looking at the data it does not appear that TFM had a significant affect on pH, dissolved oxygen or temperature. Most of the variation can be explained by the fact that

photosynthesis is occurring during the TFM addition. This test was also run in a flow through system which takes water from the adjacent river, could explain the subtle differences seen during this experiment.

	pH					
	Before		During		After	
Treatment	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
20%	7.97	0.06	7.95	0.07	8.04	0.06
80%	7.96	0.12	7.92	0.05	7.98	0.05
Control	7.98	0.06	7.95	0.04	8.03	0.04

	Dissolved Oxygen					
	Before		During		After	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
20%	8.57	0.43	8.68	0.20	8.50	0.21
80%	8.34	0.27	8.46	0.14	8.58	0.12
Control	8.27	0.15	8.45	0.17	8.25	1.00

	Temperature					
	Before		During		After	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
20%	17.46	0.41	18.41	1.03	19.31	0.65
80%	19.12	0.43	17.97	0.26	18.42	0.18
Control	18.62	0.91	18.24	0.80	19.00	0.69

Table 7. Laboratory plant experiment results. Mean and standard deviation for three replications of each experiment (20% and 80% plant abundance) as well as the control tank values are represented. Measurements were taken before, during and after TFM was added to each experimental tank.

Light Attenuation

Light measurements were collected on treated tributaries of Bear Creek (Table 8). Although Bear Creek itself was not treated, due to flooding, the tributaries were treated. A total of ten sites were sampled, five control stretches and five treated stretches. The

results show that TFM does have an affect on the intensity of light that reaches 0.5m below the waters surface.

Light intensity in the control stretches ranged from 542 to 678 umols/m^2/sec, averaging 609.8 umols/m^2/sec. Light intensity in the TFM treated stretches ranged from 123 to 189 umols/m^2/sec, with a mean of 152.8 umols/m^2/sec, resulting in a difference of 457 umols/m^2/sec between the control stretch and the TFM treated reach. This is evidence that the addition of TFM does have an effect on the intensity of light available for plants to complete photosynthesis.

Location	Control Average	TFM Treated Average
Big Beaver Creek	542	123
Lemon Creek	678	189
Little Bear Creek	652	176
Little Cedar Cr. Up	581	134
Little Cedar Cr. Down	596	142

Table 8. Average light attenuation measurements taken on Bear Creek.

DISCUSSION

Overall, the data loggers worked well collecting the data needed for this study. The only thing that would have helped would be to have an anti-fouling device attached to the logger. This would reduce the amount of maintenance that was necessary to maintain the accuracy of the loggers.

As was seen in the multiple river graphs, diel patterns resulting from photosynthesis and respiration were visible on all rivers. Within each river, there were large diel amplitude shifts, but there was also a lot of variation between sites along the rivers. Many of the rivers sampled were rather large, the Muskegon with 88 miles treated

and the Chippewa with 73 miles and the Pere Marquette River with 165 miles treated. The lower reaches in these rivers had turbid water and was typically warmer. This may explain some of the site to site variation along a river.

None of the seven rivers that had a TFM treatment and that had functioning loggers experienced pH suppression coinciding with TFM passage. Although pH, dissolved oxygen, and temperature were variable, the effects of TFM were not significant. Although a fish kill occurred during my sampling period, pH suppression does not appear to be the cause. Prior to treatment there appears to have been a natural drop in pH levels. The treatment began around 12 midnight, started while the pH cycle was at its lowest point. Unfortunately, it was not realized that a kill occurred until day break when the carcasses were visible.

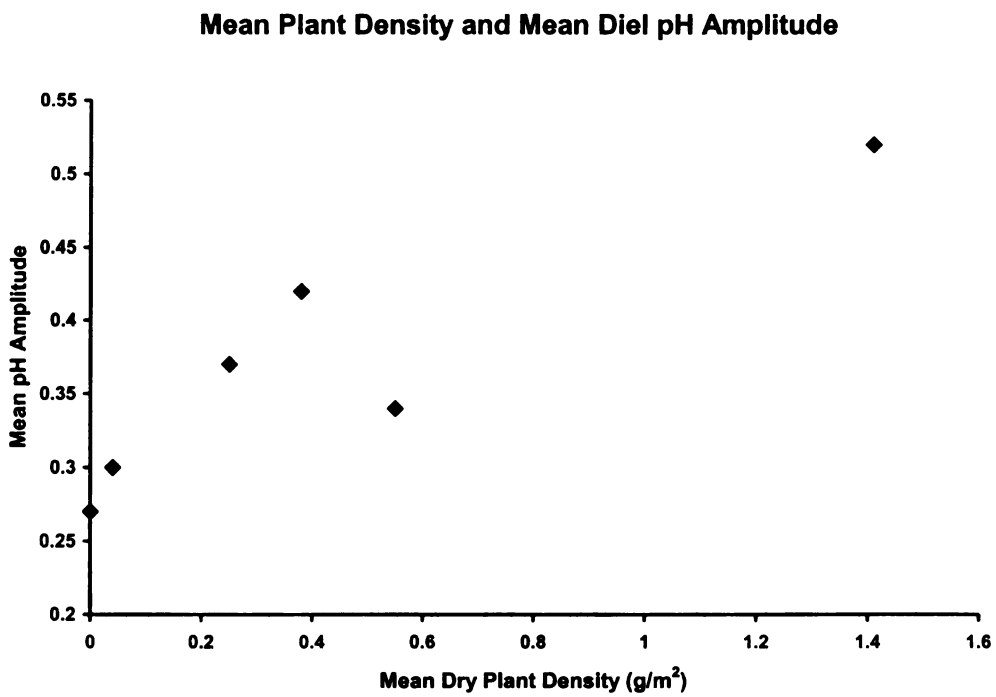

Figure 12. Relationship of mean dry plant density (g/m^2) and mean diel pH amplitude.

Once this was discovered the treatment was cut short and the remainder of the river was not treated at lethal levels of TFM. The Chinook salmon that did perish were in spawning or post-spawning condition which is a stressful period in the fish's life cycle.

The abundance of aquatic macrophytes collected was relatively low in all rivers sampled. No plants were collected on the Rifle or Pere Marquette River, although there were plants within the river, just not in the random transects. Figure 12 shows the relationship between mean pH amplitude and mean dry plant density. There is a clear relationship between plant abundance and pH levels, with mean pH amplitude increasing with density of plants. As would be expected, there is also a relationship between mean dissolved oxygen amplitude and mean plant density (Figure 13). The rise in mean plant density has a positive effect on the mean DO amplitude as this is a byproduct of photosynthesis. This was most evident in the Chippewa River where production and plant biomass were very high compared to the other rivers sampled.

Across all rivers, I observed a positive relationship between mean dissolved oxygen diel amplitude and mean pH diel amplitude (Figure 14). The relationship appears to be non-linear, but the number of data points for high amplitude pH and DO variation is limited and the apparent nonlinearity was driven by the Chippewa River.

Spatial and temporal variation in pH can be caused by many factors such as springs, run-off, plant production, river substrate, industrial effluent, and geology to name a few (Kalff 2002). Because sea lamprey treatments occur in a wide variety of settings and areas, this may occasionally create unique localized conditions. Michigan, Ohio, Pennsylvania, New York, Wisconsin, and Canada all have very different geological make up.

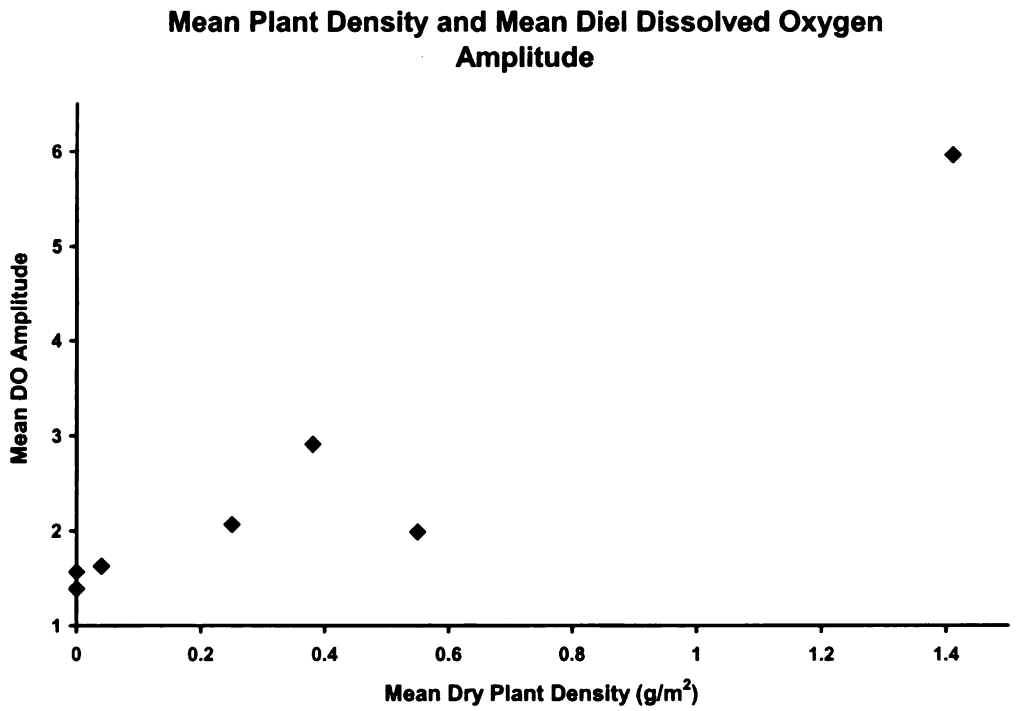

Figure 13. Relationship of mean dry plant density (g/m^2) and mean diel DO amplitude.

This may account for the spatial differences in some areas based on the alkalinity of the water. Where the geology is more calcareous, the alkalinity will tend to be higher (Kalff 2002) which will tend to moderate natural fluctuations in pH. This can also be the case for ground water additions as they pass through the surrounding bedrock and substrate.

The effects of impoundments were also visible from data on rivers with dams. The Muskegon and Rifle Rivers most clearly showed this disturbance. Control loggers were placed in the ponds above both of these dams because TFM treatments occurred at the dam. The White and Betsie Rivers also had dams but did not show the same effect. The White River dam in Hesperia is a smaller dam than that of the Muskegon or Rifle Rivers, and treatment of the White River began below the dam.

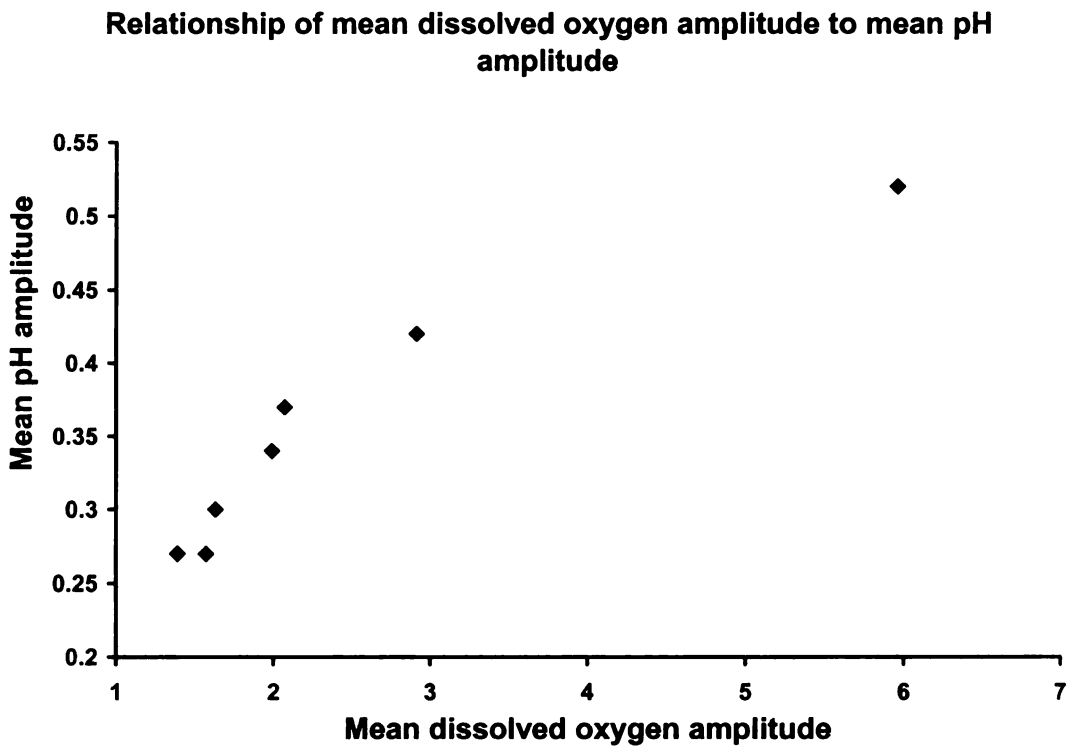

Figure 14. Relationship between mean diel dissolved oxygen amplitude and mean diel pH amplitude.

The control logger was placed below the dam which comes off a pond. The control logger on the Betsie River was placed above a low-head barrier dam, and this river reach flows more like a river as the pond that feeds that area is farther upstream. On both the White and Betsie Rivers a dual pH peak was seen on a daily basis. Both rivers at one point come off of a pond, so there may be a cycle occurring that has yet to be explained.

Fish kills have historically occurred in short random stretches of river that are not easily predicted. This more than likely has occurred due to natural spatial and temporal pH fluctuations. It is possible that localized pockets of pH suppression due to TFM occur, but most likely TFM additions are exacerbating pre-existing variability in pH. In all previous cases, pH suppression occurred in less than 5 miles of river. This may not be

as detrimental in a river like the Pere Marquette where 165 miles of river were treated. But in a river like the Betsie in which only 11.5 miles were treated, 5 miles of suppression can be devastating. Of the 1,502 treatments that occurred over the last 15 years only 6% have had a reportable fish kill. In the grand scheme of things this is a relatively rare occurrence, and should be considered a great success compared to early TFM treatments, which were not considered effective unless teleost fish were killed. Although this is a very small percentage it is still desirable to minimize major fish kills. Although the primary cause of pH suppression was not due to plant abundance, it maybe useful to explore alternative causes of fish kills to avoid future problems. There are several rivers (Cedar River, Upper Peninsula, MI and the Little Salmon River, New York) which have been reported to experience pH suppression in nearly the same place every time the river is treated for sea lamprey. It would be valuable to perform an analysis of the affected area during the next treatment of these rivers, as the primary findings of this study suggest that natural spatial and temporal pH variation may be the primary cause of fish kills.

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