Research Technical Completion Report

POWERBOAT ENGINE DISCHARGES AS A NUTRIENT SOURCE IN HIGH-USE LAKES

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The research on which this report is based was financed in part by the United States Department of the Interior as authorized by the Water Research and Development Act of 1978 (P.L. 95-467).

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14-08-000-G1222-06

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Submitted to
U.S. Geological Survey
United States Department of the Interior
Washington, D.C. 20242

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ABSTRACT

Modern internal combustion engines burn fuels containing various nitrogen and phosphorus compounds as additives (eg: alkyl phosphate, amine phosphate, etc.). Nitrogen oxides are also formed from atmospheric gases during the combustion process. In the case of marine engines, exhaust gases and incompletely burned fuel and oil are discharged directly into the water. *In-situ* enclosure experiments were conducted to quantify nitrogen and phosphorus additions and the biological response from two- and four-cycle outboard engines. The modern two-cycle outboard engine produced 300 mg total nitrogen and 1.0 mg total phosphorus per liter fuel consumed. The 1970 untuned two-cycle outboard produced 180 mg N and 0.9 mg P and the new four-cycle outboard produced 91 mg N and 0.0 mg P per liter fuel consumed. The untuned two-cycle outboard consumed about three times as much fuel as the other two engines. The biological response was moderate considering the concentrated nature of the tests. A motorboat census was conducted on Twin Lakes, Kootenai County, Idaho throughout the 1986 boating season and annual fuel consumption was estimated. Phosphorus and nitrogen loading to Twin Lakes from motorboat engine discharges were calculated and are low when compared to loading from other sources.

INTRODUCTION

Recreational boating is a potential source of water quality problems, if only because of the quantity of boats involved. In 1983 there were 9.2 X 10^6 boats registered in the United States (Commandant of the Coast Guard 1984) and a conservative estimate of gasoline consumption by outboard motors was 4.02 X 10^9 liters (Hanchey and Holcomb 1985). In Idaho, annual boat and accessory purchases exceed $16 million (American League of Anglers and Boaters 1986).

Most motorboats are powered by relatively inefficient two-cycle engines. Two-cycle outboard engines built prior to 1972 drained the crankcase directly into the water resulting in wastage of 10-40% of the fuel (Muratori 1968). Since 1972, two-cycle outboards have had devices installed to recycle the oil/gas mixture which collects in the crankcase (Jackivicz and Kuzminski 1973). Nevertheless, outboard engines discharge exhaust gases containing hydrocarbons, carbon monoxide, carbon dioxide, nitrous oxides, sulfur oxides, aldehydes, lead, and other compounds directly into the water (Hare and Springer, 1973).

A number of studies have addressed various effects of motorboats on aquatic systems. Yousef (1974) and Yousef et al. (1980) found that a 50 horsepower outboard has an effective mixing depth of 4.5 m and that agitation and mixing by motorboats can destratify a lake and increase turbidity. Water phosphorus concentration increased 55% (at least temporarily) in one test lake as a result of entrained sediments and associated phosphorus. English et al. (1963) measured oil, lead, and phenol as a function of outboard use and related outboard wastes to domestic use of water, fish toxicity, and tainting of fish flesh. Shuster (1974) measured fuel wastage and examined microbial growth rates in engine exhaust products. The Boating Industry Association (1975) examined lake response to motorboat use over an 18-month period. While the investigators did not find a significant change in most of the chemical and biological parameters measured (including nitrogen and phosphorus) they measured whole lake effects where a relatively subtle and short-term change in nutrient loading may not be immediately detectable.

One study directly measured exhaust products of outboard engines (Hare and Springer 1973). Although the objective of that study was to measure the atmospheric contributions of outboard engine exhausts, the experimental design allowed the calculation of the fraction of exhaust constituents retained after bubbling through water in a separate system. Hare and Springer estimated that 600,000 kg of nitrogen oxides from outboard engine exhausts were retained in US waters in 1971; they did not measure phosphorus or organic nitrogen.

We have found no studies that address outboard engines as direct nutrient sources to lakes, yet motorboat discharges are potentially significant sources of phosphorus and especially nitrogen to a lake's nutrient budget. Although crude oil contains less than 0.1% nitrogen (Lochte and Littman 1955) and some of this is removed during refining, both nitrogen and phosphorus compounds (such as alkyl phosphate, amine phosphate, alkyl ammonium dialkyl phosphate, etc.) are added to gasoline as detergents, anti-icing and anti-rust agents, and deposit modifiers (Camin 1971). Phosphorus concentrations in gasoline may be as high as 12.6 mg/l (Bartsch 1972). In addition to being found in gasoline additives, nitrogen oxides are formed from atmospheric gases during the combustion process (Owen 1984). Because most marine exhaust gases are bubbled through the water, some enhancement of nitrogen and phosphorus concentrations in lakes receiving heavy motorboat use is possible.

The goal of this study was to determine the importance of powerboat engine discharges as nutrient sources. Specific objectives were as follows: 1) to determine chemical (nutrient) response of lake water to powerboat exhaust; 2) to partition nutrient loading to Twin Lakes, Idaho as to source; and 3) to consider potential implications of powerboat exhaust impacts to lake management.

METHODS

Enclosure Experiments

Powerboat engine experiments were conducted in triplicate in four closed-bottom enclosures made of six-mil clear polyethylene plastic formed into 2.13m long x 0.91m wide x 0.81m deep bags (each enclosing 1,570 liters). The enclosures were fastened to a floating dock on Twin Lakes, Kootenai County, Idaho and rinsed and filled with lake water prior to each trial. One enclosure served as a control, the following outboards were run in the remaining three enclosures: 1) a 9.5 horsepower, two-cycle, 1970 Johnson; 2) a 9.8 horsepower, two-cycle, 1977 Mercury; and 3) a 9.9 horsepower, four-cycle, 1985 Honda. Regular gasoline was used in all engines, but mixed 50:1 with two-cycle motor oil for the two-cycle outboards.

The three trials were conducted during August, 1986. During each trial the outboards were run for an eight-hour period at low speed (approximately 10% throttle) with the propellers removed. Water in the enclosures was stirred prior to collecting samples. Samples were collected from each of the four enclosures as well as from the lake adjacent to the enclosures. Two sets of samples were collected every two hours in acid-washed polyethylene bottles. One set was immediately analyzed for CO_2, alkalinity, pH (Corning Model 7 meter with glass electrode), conductivity and temperature (YSI meter), and oxygen (YSI meter). The second set of samples was frozen for later analysis of total phosphorus and total soluble phosphorus (stannous-chloride method with persulfate digestion; soluble phosphorus was run on filtrate after filtration through a 0.45 u filter), kjeldahl-nitrogen (micro-kjeldahl), nitrate-nitrogen (ultra-violet spectrophotometric screening method), and total organic carbon (combustion-titration method). During one trial, in addition to the above, water samples were collected prior to the test run and after four, eight, and twelve days for analysis of chlorophyll *a*, phytoplankton biomass, zooplankton numbers and composition (modified 10-liter Schindler trap), and phytoplankton numbers and composition (inverted microscope method (Lund et al. 1958)). Except where noted otherwise, all analyses were conducted according to APHA (1985). Total fuel consumption for each outboard was determined after each eight-hour trial. Parameter change per liter fuel consumed was determined using plots of response versus time. Linear regression was used to determine the slope.

Motorboat Use Rates

Motorboat use on Twin Lakes was determined by census techniques similar to those used for fisheries creel surveys. Five volunteer homeowners conducted "instantaneous" counts of motorboats on the lake several times each week during the 1986 boating season. Approximate engine size (large = >45hp, or small = <45hp) and whether the boat was underway was recorded. These data were stratified by weekend/weekday and analyzed separately for large and small motors and Upper and Lower Twin Lakes. Total annual boat-hours on Twin Lakes were calculated according to Scheaffer et al. (1979). Average rated horsepower of the large and small engine categories weighted by estimated hours underway was determined from returns of a survey mailed to all lake residents. Annual fuel consumption on Twin Lakes was calculated for large and small motors using estimated gasoline consumption rates (liters gasoline per brake horsepower-hour) and composite load factors (to convert rated horsepower to brake horsepower) from Hare and Springer (1973).

Nutrient Loading

Twin Lakes are located in northern Idaho, 27 km northwest of Coeur d' Alene. The upper and lower basins are 196 and 158 ha lakes connected by a short channel but will be considered as a single lake for the purposes of this report. About 20% of the 450 homes around the lake are occupied year-round. However, total annual use by lake residents and guests equates to about 420 full-time residents. Twin Lakes is an important recreation area for the Spokane metropolitan area (Falter and Hallock 1987).

Motorboats

Annual nutrient loading from powerboats was determined by multiplying the quantity of nutrients added per liter fuel consumed by the estimated annual fuel consumption on Twin Lakes. Results from the Mercury enclosure were used in nutrient loading calculations because the Mercury outboard was considered to be most representative of outboards currently used on Twin Lakes.

Other Nutrient Sources

Nutrient loading from tributaries in 1986 was determined from the hydrology of surface inflows and nutrient analyses of tributary water. The inflow hydrograph was divided into sections with each section containing a nutrient concentration datum. Total nutrient loading was determined as the sum of (flows x concentrations). Samples were collected in acid-washed polyethylene bottles and frozen for later analysis for total phosphorus (stannous chloride method with persulfate digestion), nitrate nitrogen (spectrophotometric screening method), and total kjeldahl nitrogen (micro-kjeldahl technique) according to APHA

(1985). Some smaller tributaries were not sampled as often as Fish Creek because of access difficulties. In these cases, a missing concentration datum was approximated by the mean of samples collected before and after the missing sample.

The direct nutrient load from cattle was calculated by multiplying the effects of one animal by the total number of animals and by a scaling factor to account for that portion of nutrients entering the lake. Each adult cow was assumed to contribute 0.022 kg TP and 0.136 kg TN daily (Viets 1971).

Precipitation was monitored throughout WY 1986. Precipitation plus dryfall was collected from a site about 1 km south of, and at the same elevation as Twin Lakes in a 34.4 cm x 43.2 cm acid-washed plastic pan mounted 1.5 m above the ground. Samples were usually collected after each major precipitation event or series of events and then frozen for later nutrient analyses.

Nutrient loading from wastewater systems was calculated by multiplying per-capita loading rates (Cantor and Knox 1986) by percent transported to the lake, conservatively estimated (for Twin Lakes) at 15% for phosphorus and 25% for nitrogen, times per-capita use as determined from a homeowner's survey (Falter and Hallock 1987) and from a shoreline survey (Panhandle Health District 1 1977).

Internal phosphorus loading was determined separately for anaerobic and aerobic conditions. Anaerobic phosphorus loading was determined by measuring the increase in hypolimnetic phosphorus concentration during the period of summer stratification in Lower Twin Lake (the upper lake did not stratify). Aerobic loading was approximated from sediment phosphorus release rates determined for nearby Liberty Lake by Mawson et al. (1983).

The determination of nutrient loading to Twin Lakes was funded in part by the Twin Lakes Improvement Association. The methods used and results are presented in more detail in Falter and Hallock (1987).

RESULTS

Enclosure Experiments

<u>Physical/Chemical</u>

During the three eight-hour tests, the Honda, Mercury, and Johnson outboards consumed an average of 5.30, 6.48, and 17.03 liters of fuel, respectively. Appearance of the Honda enclosure changed little throughout the test; the Mercury and Johnson enclosures were both milky with floating oily globules (brown in the Mercury enclosure and black in the Johnson) by the first sample period (2 hrs) (Figure 1). Both two-cycle enclosures smelled strongly of gasoline and oil.

Total organic carbon and carbon dioxide concentrations increased dramatically during the test (Figure 2). The four-cycle Honda caused the largest increase in CO_2 (from an ambient concentration of 4.3 mg/l to 54.0 mg/l after eight hours); the Johnson caused the smallest change (4.3 to 16.8 mg/l). The rate of change decreased as the concentration in the containers increased. Four days after running the engines, CO_2 concentrations in all enclosures had decreased sharply but not quite to ambient levels. After twelve days, CO_2 in the Johnson enclosure was slightly higher than levels in the other enclosures. All outboards added considerable carbon per liter fuel consumed (Table 1).

Results of pH and oxygen measurements mirrored the CO_2 results (Figure 3). The Mercury and Honda enclosures decreased from a pH of 6.5 to a low of less than 5.0, while the Johnson decreased to a low of 5.3. After eight hours, oxygen levels were 3.4, 4.4 and 5.6 mg/l for the Honda, Mercury, and Johnson enclosures, respectively. Twelve days after the test run, both pH and oxygen were lowest in the Johnson enclosure.

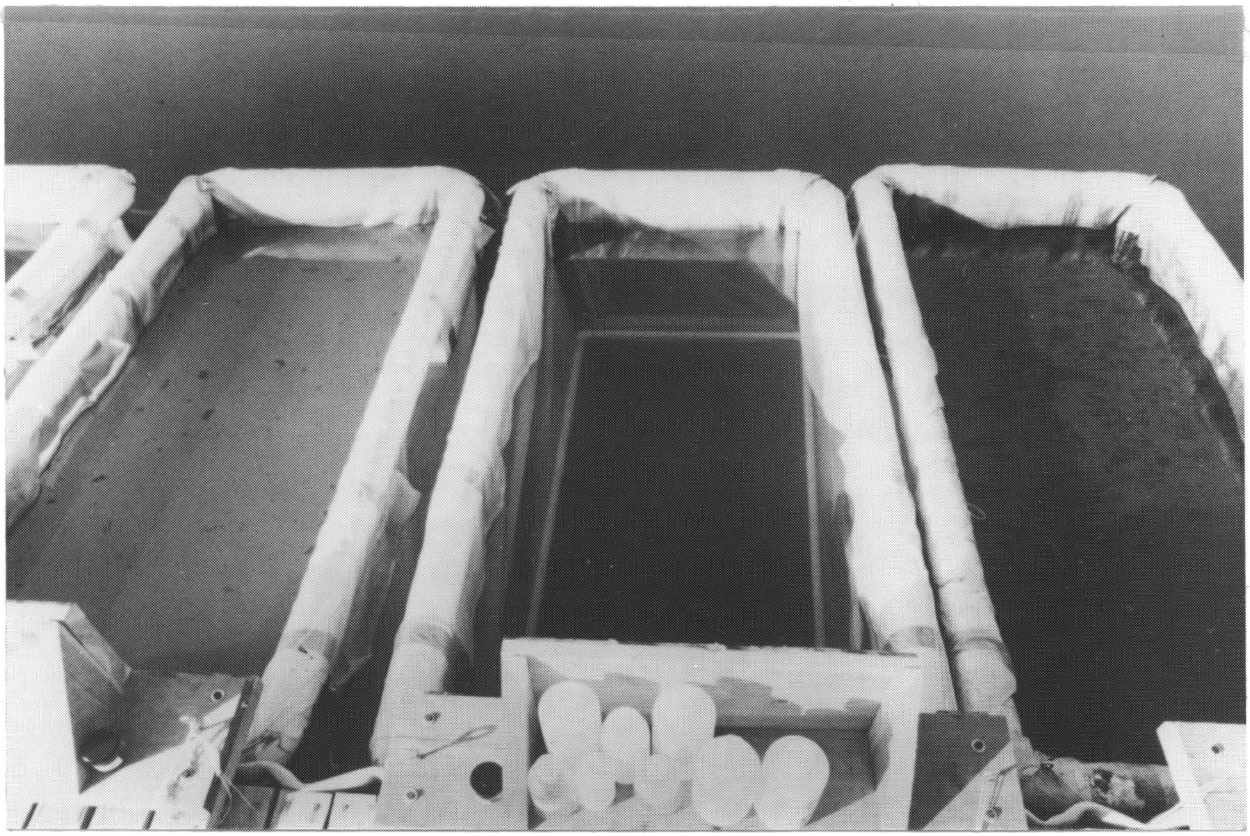
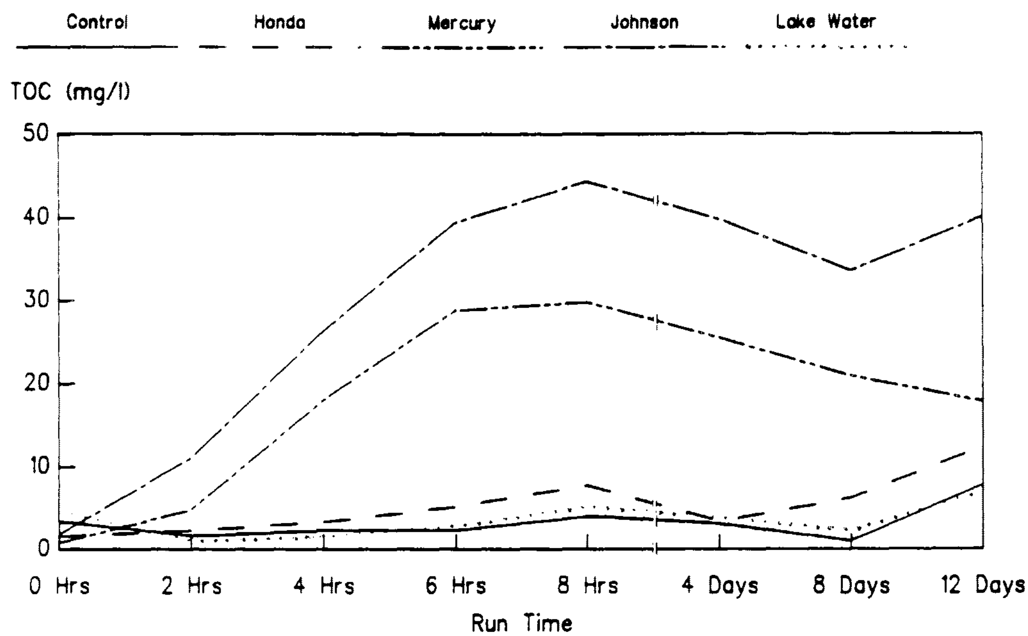


Figure 1. The three treatment enclosures 12 days after running 10 hp outboard engines for eight hours. From left to right: two-cycle Mercury, four-cycle Honda, and two-cycle Johnson.



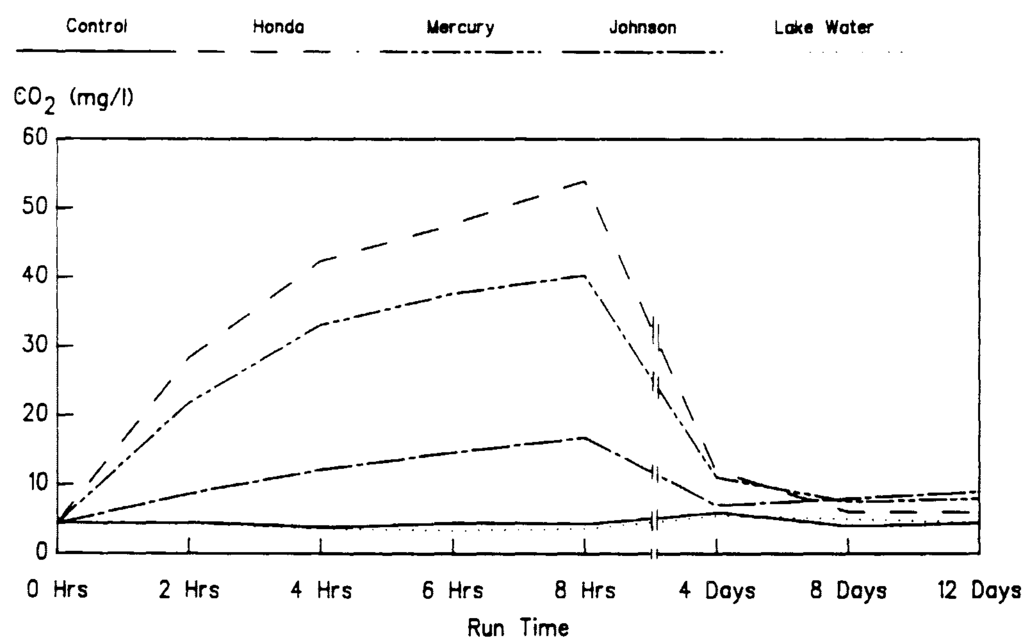


Figure 2. Total organic carbon and carbon dioxide response to outboard motor operation in enclosures (mean of three trials). Motors were operated for the first eight hours.

Table 1. Water chemistry changes (mg) attributable to outboard engine exhaust per liter gasoline consumed ± 2 standard errors.

	Honda (4-cycle)	Mercury (2-cycle)	Johnson (2-cycle)
Carbon Dioxide	14,202 ± 3,448	8,594 + 1,936	1,154 ± 275
Kjeldahl Nitrogen	26.3 ± 13.9	63.9 ± 16.7	42.9 ± 9.0
Nitrate Nitrogen	64.6 ± 20.7	235.8 ± 40.1	137.4 ± 36.4
Oxygen	-1,278 ± 136	-835 ± 96	-219 ± 21
Total Organic Carbon	1,663 ± 1,505	7,843 ± 1,916	4,202 ± 514
Total Phosphorus	0 ± 0.09	0.98 ± 1.45	0.87 ± 0.54

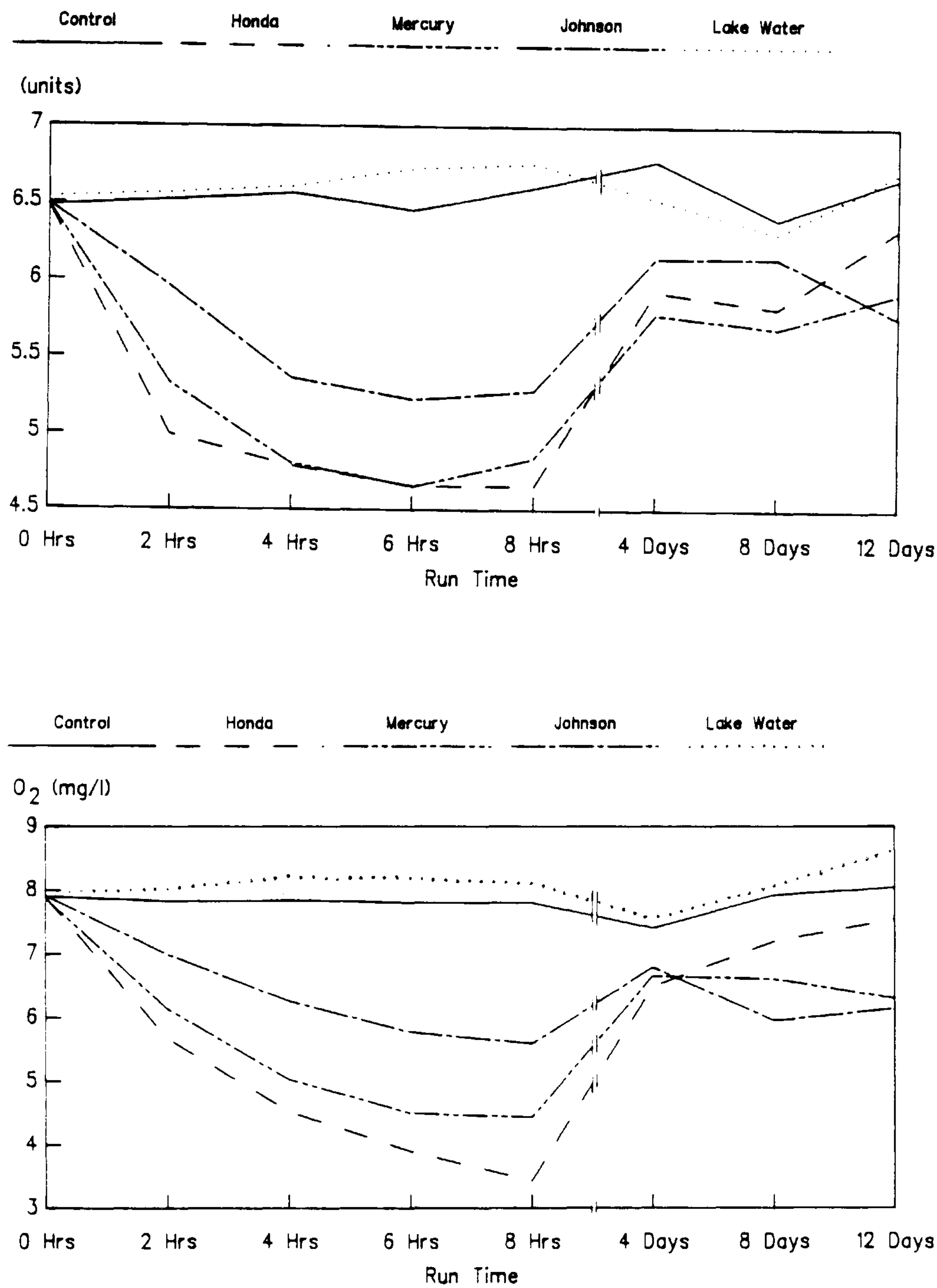


Figure 3. PH and oxygen response to outboard motor operation in enclosures (mean of three trials). Motors were operated for the first eight hours.

Alkalinity fell to 10 mg/l from 14 mg/l and did not recover, even after pH had returned to near ambient levels (ca. 6.7). Conductivity increased from 19 umhos to 26 umhos after the eight hour test but returned to ambient levels after four days. Temperature increased slightly (~4 C) in all treatment enclosures during the test (see Appendix).

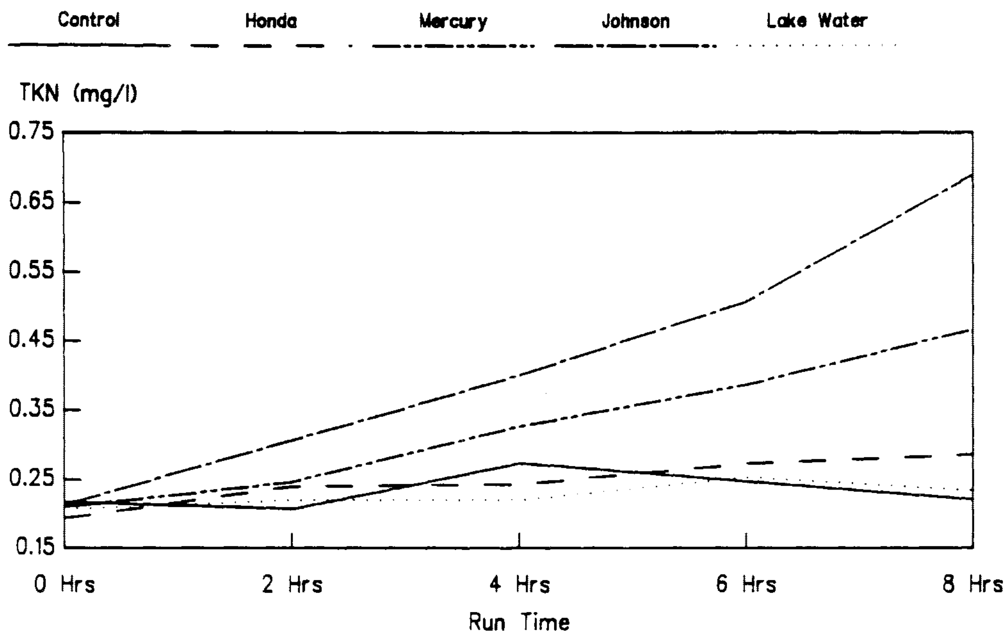
Phosphorus increased slightly in the Mercury and Johnson enclosures but showed no increase in the Honda enclosure (Table 1). Total soluble phosphorus concentrations were very low and no significant trend could be seen.

Total kjeldahl-nitrogen and especially nitrate-nitrogen increased dramatically in both two-cycle enclosures and increased slightly in the four-cycle Honda enclosure (Figure 4). The increases translate to an addition of 91 mg total nitrogen per liter fuel consumed for the Honda, 300 mg/l for the Mercury, and 180 mg/l for the Johnson (Table 1).

Biological

The biological response was moderate considering the concentrated nature of the tests (volume of fuel consumed per water volume in the enclosures was ca. 300 times annual lake use rates). After twelve days, chlorophyll *a* concentrations had decreased to less than half the pre-run levels in all treatment enclosures. Chlorophyll *a* levels declined in the control enclosure as well, though not to the same degree (Figure 5). Percent loss on ignition increased over four times in the two-cycle enclosures and not at all in the four-cycle Honda enclosure (Figure 5).

There was no consistent change in total phytoplankton biovolume (Figure 6), nor was there a consistent shift in species composition



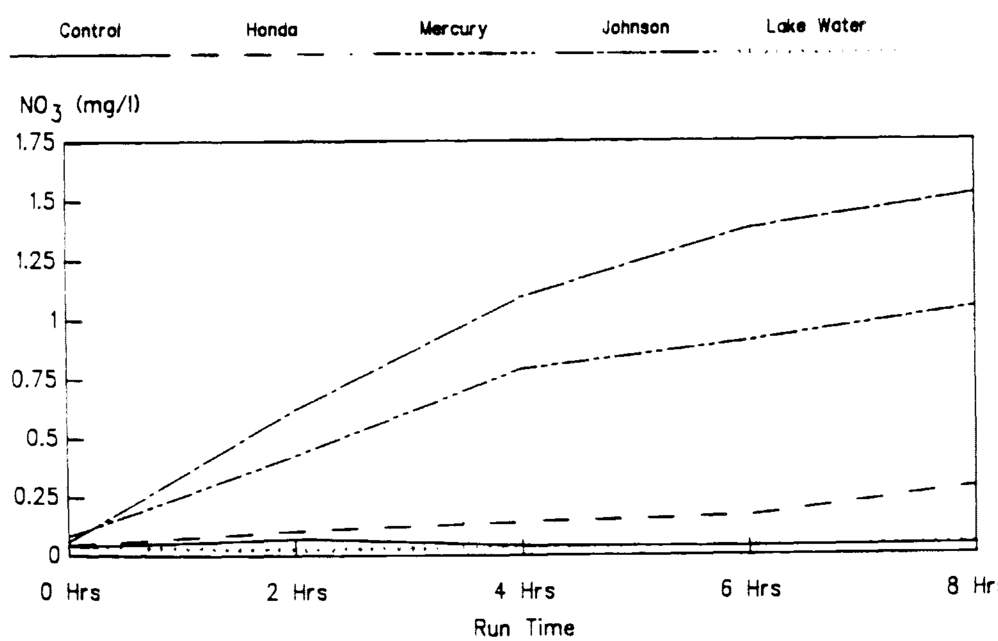


Figure 4. Kjeldahl nitrogen and nitrate nitrogen response to outboard motor operation in enclosures (mean of three trials). Motors were operated for the first eight hours.

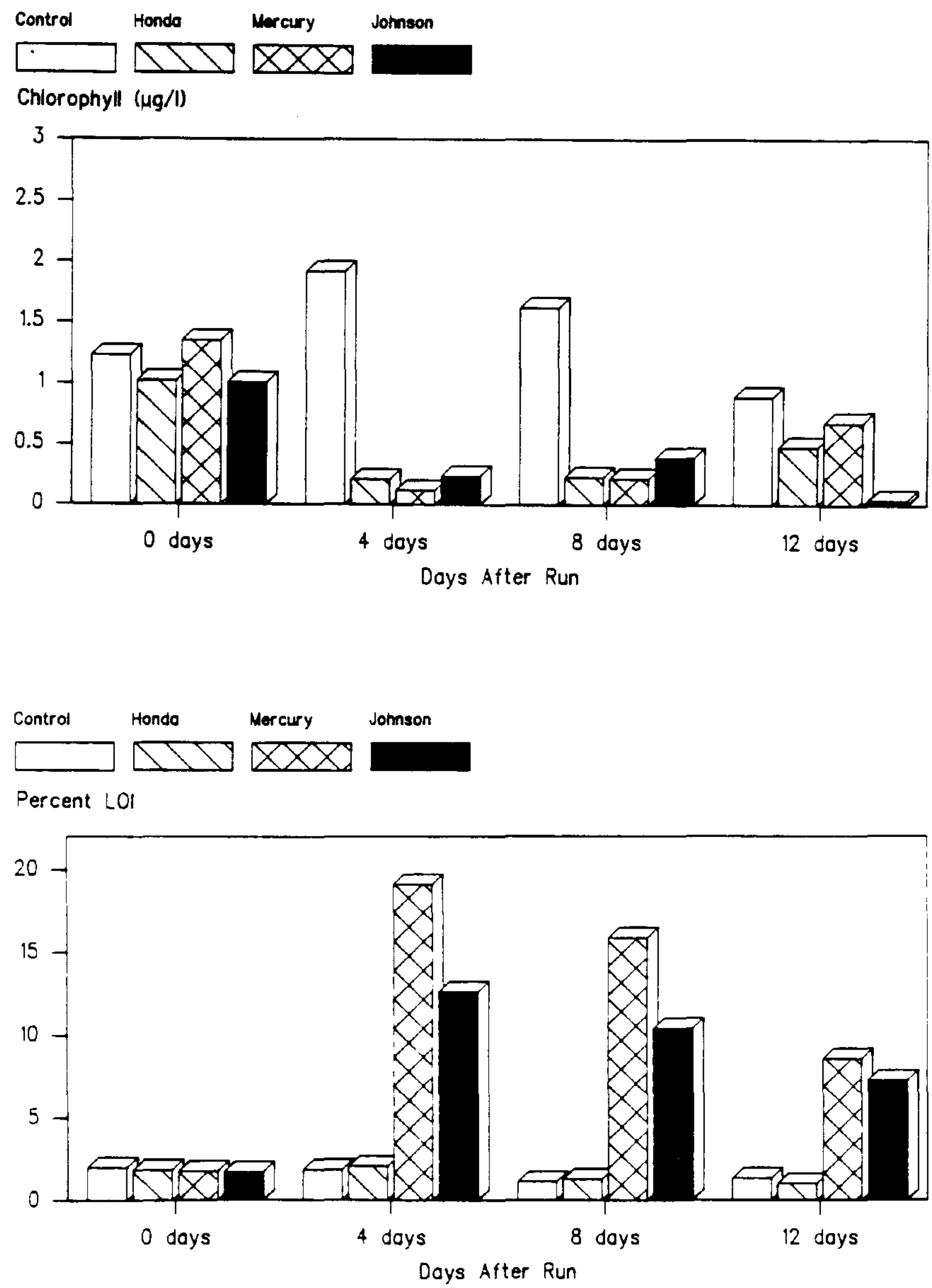
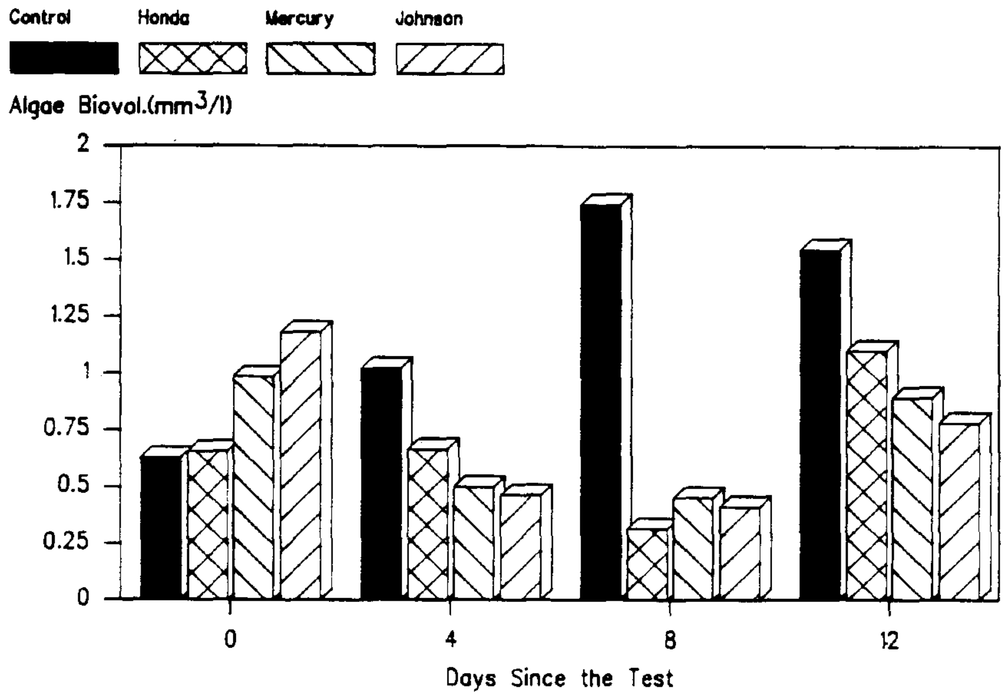


Figure 5. Chlorophyll and percent loss on ignition in enclosures before operating outboards, and four, eight, and twelve days after operating outboards for the first eight hours.



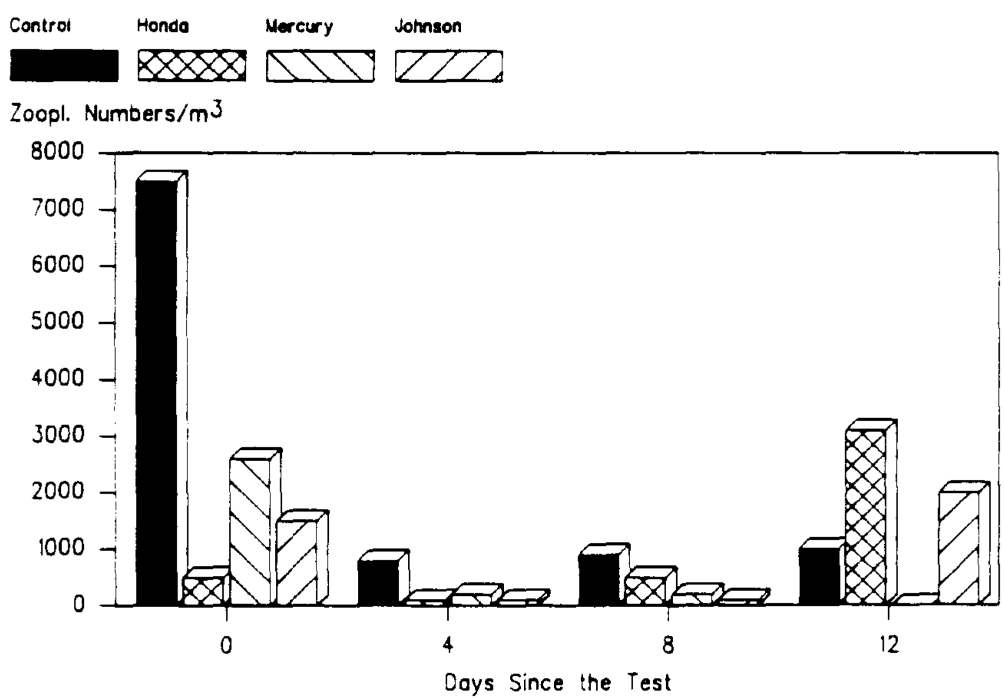


Figure 6. Phytoplankton biovolume (mm^3/l) and zooplankton numbers (no./l) in enclosures. Motors were operated for the first eight hours.

(Appendix). Algae counting, especially the micro-algae, was difficult in the treatment enclosures because of the presence of tiny oil droplets.

The actual response of zooplankton to outboard exhaust is not clear (Figure 6). After 12 days, no zooplankton were present in the sample from the Mercury enclosure but the sample from the Johnson enclosure contained 2,000 *Bosmina* per m^3 (Appendix). Because of the relatively small enclosures used, we were unable to replicate samples without adversely affecting the remaining population size.

Motorboat Use Rates

We estimated that motorboats spent 17,519 hours underway on Twin Lakes during a four-month season (May 1 to September 1) (Table 2). This equates to 50 hrs/ha/year. During the busiest part of the season, mid June to early August, and on the busiest section of the lake, boat densities reached 0.24 boats/ha on weekends and 0.08 on weekdays. Boats spent an additional 6,513 hours on the lake not underway. Because it was impossible to determine whether a boat that was not underway was idling or not, only underway boat hours were used in fuel consumption calculations. Some boat use (presumably negligable) occurred before and after the sampled "season". These boats were mostly small fishing boats. Daily boating activity occured between 0830 and 2030 with peaks at 1100, 1600, and 1900.

Most of the underway hours (11,583) were from motors larger than 45 horsepower. The average rated horsepower of boats underway was 82. The average horsepower of motors owned by Twin Lakes homeowners was 68,

Table 2. Motorboat use (hrs ± 95% confidence interval) on Twin Lakes in 1986.

Lake	Engine Size[a]	Total Hours	Underway Hours	Underway Hours/Hectare
Upper	Large	4931 + 1936	3856 + 1514	19.7 + 7.7
	Small	4152 + 1394	2673 + 897	13.7 + 4.6
	Total	9083	6529	33.4
Lower	Large	9881 + 2095	7727 + 1638	48.9 + 10.4
	Small	5068 + 2187	3263 + 1408	20.6 + 8.9
	Total	14,949	10,990	69.5
Both	Large	14,812	11,583	32.7
	Small	9220	5936	16.8
	Total	24,032	17,519	49.5

[a]Large is >45 hp, small is <45 hp.

however, indicating that bigger boats spent a greater amount of time underway.

The data above equate to 227,418 ± 66,105 liters of gasoline consumed on Twin Lakes by all motorboats in 1986 (the 95% confidence interval is derived from uncertainties in boat use rates based on the census and does not include variation in gasoline consumption rates per boat).

Nutrient Loading

Motorboats

The estimated nutrient contribution to Twin Lakes from powerboat exhaust in 1986 was 0.22 kg total phosphorus and 68 kg total nitrogen. Inorganic carbon loading is at least 1,954 kg/yr. These figures do not include increased internal nutrient loading due to entrainment of sediments by boat wash. This effect may be significant, at least in the short-term (Yousef et al. 1980); long-term effects of sediment entrainment have yet to be studied.

Other Sources

Twin Lakes received a total nutrient load of 7,782 kg total nitrogen (2.20 g $N/m^2/yr$) and 871 kg total phosphorus (0.25 g $P/m^2/yr$) in water year 1986 from all sources (Table 3). Tributaries were responsible for the majority of the annual load of both nitrogen and phosphorus. These results are explained further in Falter and Hallock (1987).

Table 3. Nutrient sources to Twin Lakes, Water Year 1986 (1 Oct 1985-30 Sept 1986).

Source	Total Nitrogen (kg)	Percent of Total	Total Phosphorus (kg)	Percent of Total
Tributaries	4,649	59.7%	495	56.8%
Cattle	240	3.1%	39	4.5%
Precipitation	2,326	29.9%	120	13.8%
Wastewater	499	6.4%	93	10.7%
Internal	--	---	124	14.2%
Motorboats	68	1%	0.2	~0%
TOTAL	7,782 kg 2.20 $g/m^2/yr$		871 kg 0.25 $g/m^2/yr$	

DISCUSSION

Experimental Design

The three outboards tested should not be viewed as replicates but as representatives of the small engine types available. The new four-cycle Honda was the most efficient and the pre-1972 Johnson was the least efficient based on both gasoline consumption and carbon dioxide production. Extrapolations to whole-lake effects were based on the newer Mercury which we consider most representative of outboards currently in use. Because the boat census and therefore the total gasoline consumption calculation included inboard engines, which are more similar to the four-cycle Honda than to the Mercury, estimates of nitrogen and phosphorus loading could be liberal (high) and estimates of carbon dioxide loading could be considered conservative.

On the other hand, because we were unable to obtain test propellers for all engines, we removed the propellers from all outboards during the tests. This may have yielded more conservative results for two reasons: 1) there was no load on the engines, and 2) exhaust bubbles may not have been sufficiently broken up and dissolved. However, an examination of the data in Hare and Springer (1973) indicates surprisingly little relationship between load or propeller action and nitrogen oxides in solution per gasoline volume consumed (there is a relationship with carbon oxides, however).

The effect of outboard motor exhaust on CO_2 levels (Table 1) was underestimated because the increase of CO_2 in the enclosures was not linear with time (Figure 2). This phenomenon is likely a result of a pH-CO_2 interaction, ie. as pH dropped (because of increasing CO_2) less

CO_2 entered solution. Ideally, a flow-through system should be used to monitor changes in dissolved inorganic carbon (DIC).

Similarly, the rate of increase of nitrate-nitrogen in both 2-cycle enclosures decreased after four hours (Figure 4). This may be a result of saturated conditions near the engine discharge in which case estimates of nitrogen loading would be low.

Total carbon loading and total nitrogen loading may also have been underestimated because we did not measure CO or NO. Carbon monoxide loading is significant but is lower than CO_2 loading (Hare and Springer (1973). Nitrous oxide loading is probably small compared to other forms of nitrogen.

We were unable to determine nitrate-nitrogen using the cadmium reduction column method (APHA 1985) because the gas and oil present in the test tanks would have interfered with the reduction column binding sites ruining the column. We therefore used the ultra-violet spectrophotometric screening method. Although this method is intended for preliminary screening of samples, we are confident in our results. Both precision and accuracy were good (Appendix). In addition, selected samples not contaminated with oil were analyzed using a cadmium reduction method and results were comparable to the spectrophotometric method. Although we applied a correction factor for organic matter, which interferes with the nitrate analysis, the higher total organic carbon in the test tanks may have biased our nitrate-nitrogen results.

Biological Response

Although the biological response was peripheral to this study, our results indicate that short-term effects of concentrated outboard exhaust on phytoplankton and zooplankton are probably minor. This was surprising considering the appearance of the 2-cycle enclosures even 12 days after the test (Figure 1) where the water in both enclosures was still milky and smelled strongly of gasoline and oil. These results support the conclusions of the Boating Industry Association (1975) with respect to the effect of boating on biota. Nevertheless, long-term effects (>18 months) of continuous and concentrated recreational boating need to be evaluated.

Nutrient Loading

Although dissolved inorganic carbon is seldom considered to be a limiting nutrient in natural lakes, lake flora can be affected by DIC concentrations. Several authors have reported that photosynthetic rates in aquatic angiosperms are sensitive to DIC availability (Adams et al. 1978, Titus and Stone 1982, and Wetzel 1983). Paerl and Ustach (1977) report that blue-green algae scums are more likely to occur during periods of low CO_2 concentrations. The time of year when DIC is most likely to be low, late summer afternoons, is also when motorboat densities are greatest. In addition to directly adding CO_2 and organic carbon, motorboats agitate the water. Wetzel (1983) states that low velocity currents can increase photosynthesis by disrupting the stagnant boundary layer, thereby increasing DIC diffusion rates. Although the influence of motorboats on macrophyte or phytoplankton access to DIC is beyond the scope of this study, it is possible that in some water bodies, heavy motorboat activity may increase photosynthetic rates but inhibit surface algae scum formation. Floating detrital debris may, however, be enhanced by motorboat activity.

Outboard engines may contribute 1.2 x 10^6 kg nitrogen and 3,949 kg phosphorus to US waters annually, based on our results and estimated gasoline consumption by outboards in 1983 (Hanchey and Holcomb 1985). It is clear that phosphorus loading from outboard engine discharges is insignificant compared to other sources. (Phosphorus loading resulting from sediment entrainment by boats operating in shallow areas may, however, be important.) Nitrogen loading from outboards will be minor in all but the most heavily used lakes. Twin Lakes, Idaho, which had only a four-month boating season in 1986, received less than 1% of its nitrogen loading from motorboats. If boating were as extensive year-round on Twin Lakes as it was from mid-June to mid-August, boat use rates would be 330 hrs/ha/yr and nitrogen loading from motorboats could be as high as 0.115 $g/m^2/yr$ or 5.3% of total annual nitrogen loading.

In this paper we have reported nutrient loading from outboard exhaust based on estimated gasoline consumption. However, fuel consumption is difficult for lake managers to measure. Figure 7 relates mean rated horsepower and boat use rates directly to nitrogen loading. The relationship between rated horsepower and fuel consumption was developed by Hare and Springer (1973) by estimating the average brake horsepower as a function of rated horsepower. The empirical relationship between brake horsepower and fuel consumption varies with engine size, hence the non-linearity of the lines representing usage rates.

Although direct phosphorus loading from outboard exhaust is insignificant, nitrogen loading should be considered by managers of high-use lakes or lakes with low nitrogen loading rates. Other questions remain about the impact of motorboats on lakes. For example:

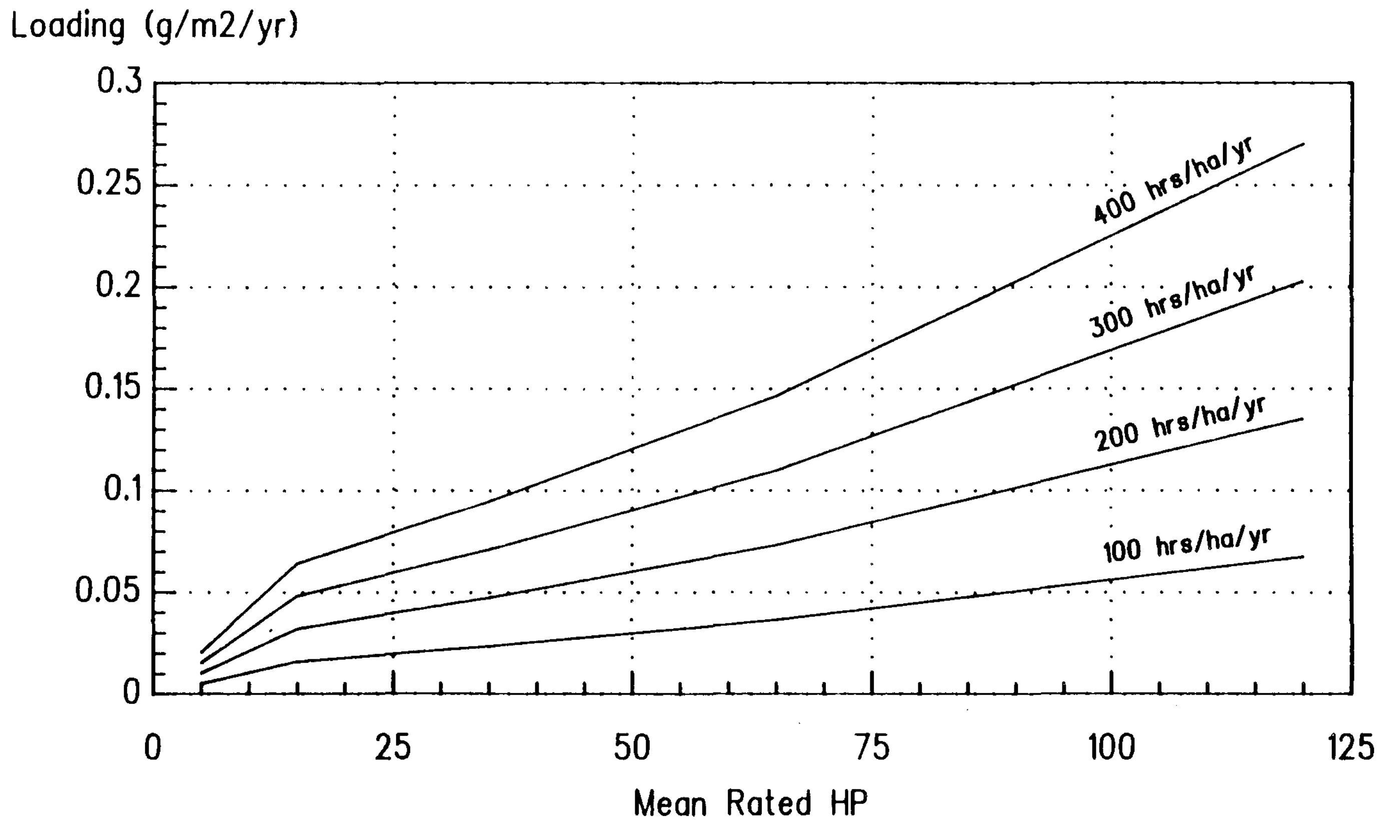


Figure 7. Areal total lake nitrogen loading as a function of mean rated horsepower and outboard motor use.

how do lakes respond to the re-suspension of bottom sediments and associated phosphorus caused by boat wash? Are pH levels affected by sustained boat use? What are the long-term impacts of motorboats on biota? What effect does inorganic carbon loading from motorboat exhaust have on aquatic flora, especially in eutrophic waters?

This study is not intended as an endorsement of a particular outboard engine manufacturer. However, 4-cycle outboards (or electric motors for trolling) obviously contribute less nitrogen to lake waters than do two-cycle outboards. All internal combustion engines should be properly maintained, both for the sake of efficiency and the health of the aquatic environment.

CONCLUSIONS

1. In 1986, motorboats were run approximately 18,000 hours on Twin Lakes, Idaho, (50 hrs/ha) in a four-month season; estimated fuel consumption was 230,000 liters. At the peak of the season, boat density reached 0.24 boats/ha on weekends and 0.08 on weekdays.

2. Phosphorus loading from outboard engine exhaust is insignificant (~1 mg P per liter fuel consumed). Nitrogen loading from outboard engine exhaust was ~300 mg per liter fuel consumed.

3. Large quantities of inorganic carbon are added by motorboats (>8,600 mg CO_2 per liter fuel consumed).

4. Nitrogen loading to Twin Lakes from outboard engine discharges in 1986 was 0.019 $g/m^2/yr$.

5. Nitrogen loading, while minor in northern latitude lakes with short boating seasons, may be near 0.15 $g/m^2/yr$ in high-use southern lakes.

6. The biological response in our enclosures was moderate. Considering the concentrated nature of our tests, it is unlikely that even high boat use will affect a lake's biota in the short-term. The biological effects of long-term powerboat use are unknown.

7. Four-cycle outboards are cleaner-burning and more efficient than two-cycle outboards, although they produce more dissolved inorganic carbon. All internal combustion engines should be tuned regularly to increase fuel efficiency and reduce undesirable emmisions, including nutrients.

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APPENDICES

Table A1. Physical and chemical parameters from the first test run.

Parameter		Time	Lake	Control	Honda	Mercury	Johnson
Total Gas Consumed (mls)					5,800	6,000	17,000
Temp- erature	(C)	0	22.5	22.5	22.2	22.3	22.2
		2	23.0	23.2	25.4	24.4	23.7
		4	24.3	24.1	26.6	25.5	25.3
		6	24.5	24.2	27.4	26.3	26.1
		8	24.4	24.2	26.8	25.3	26.3
Conduct- ivity	(umhos)	0	19	19	20	19	19
		2	20	20	21	20	22
		4	21	21	25	24	24
		6	20	20	25	24	23
		8	20	21	27	27	26
Oxygen	(mg/l)	0	7.90	7.79	7.71	7.69	7.75
		2	7.89	7.59	5.20	6.05	6.70
		4	8.05	7.65	4.00	4.85	6.05
		6	7.95	7.59	3.49	4.30	5.59
		8	7.95	7.60	3.15	4.40	5.35
Alkalinity	(mg/l)	0	13.5	13.5	14.0	13.5	14.0
		2	13.5	14.0	14.0	14.5	14.5
		4	14.0	14.0	13.5	13.5	14.5
		6	14.0	13.5	12.0	13.0	14.0
		8	14.0	14.0	10.5	10.5	12.5
Carbon Dioxide	(mg/l)	0	4.0	4.0	3.5	4.0	4.0
		2	3.5	4.0	30.0	20.0	10.0
		4	3.5	4.0	42.0	33.0	13.0
		6	4.0	6.5	50.0	39.0	16.0
		8	4.0	6.0	54.0	42.0	20.0
pH		0	6.41	6.41	6.38	6.39	6.38
		2	6.50	6.39	4.87	4.98	5.47
		4	6.55	6.33	4.50	4.55	5.02
		6	6.76	6.12	4.45	4.41	4.89
		8	6.79	6.61	4.53	4.46	4.73
Nitrate Nitrogen	(mg/l)	0	0.02	0.03	0.03	0.1	0.03
		2	<0.02	0.07	0.11	0.45	0.57
		4	0.03	0.03	0.12	0.73	0.92
		6	<0.02	0.03	0.18	0.87	1.16
		8	0.03	0.05	0.37	1.02	1.78

Table A1. Continued.

Parameter		Time	Lake	Control	Honda	Mercury	Johnson
Kjeldahl Nitrogen	(mg/l)	0	0.18	0.19	0.20	0.21	0.24
		2	0.18	0.20	0.24	0.30	0.28
		4	NA	0.20	0.25	0.34	0.40
		6	0.28	0.20	0.26	0.34	0.52
		8	0.18	0.18	0.24	0.44	0.74
Total Phosphorus	(mg/l)	0	0.020	0.014	0.012	0.013	0.016
		2	0.017	0.021	0.018	0.018	0.018
		4	0.020	<0.010	0.010	0.020	0.023
		6	0.021	0.012	0.017	0.016	0.024
		8	0.017	0.016	0.013	0.020	0.027
Soluble Phosphorus	(mg/l)	0	<0.010	0.011	<0.010	<0.010	<0.010
		2	<0.010	0.017	<0.010	<0.010	<0.010
		4	<0.010	<0.010	<0.010	<0.010	<0.010
		6	<0.010	0.014	<0.010	<0.010	<0.010
		8	0.012	<0.010	<0.010	<0.010	<0.010
Total Organic Carbon	(mg/l)	0	5.4	7.0	4.7	2.4	1.6
		2	3.1	<1.0	5.4	<1.0	11.6
		4	1.6	7.0	<1.0	24.2	27.0
		6	7.0	<1.0	<1.0	32.8	42.5
		8	<1.0	4.7	4.7	34.0	50.2

Table A2. Physical and chemcal parameters from the second test run.

Parameter	Time	Lake	Control	Honda	Mercury	Johnson
Temperature (C)	0 hrs	22.5	22.3	22.3	22.3	22.3
	2 hrs	23.7	23.4	25.1	24.3	24.1
	4 hrs	23.5	23.4	25.4	24.6	24.6
	6 hrs	23.3	24.1	26.4	25.5	25.5
	8 hrs	24.0	23.8	26.2	25.1	25.7
	4 days	21.3	21.0	21.1	21.2	21.3
	8 days	21.8	21.3	21.2	21.3	21.2
	12 days	22.5	22.4	22.3	22.4	22.6
Conductivity (umhos)	0	20	20	20	20	20
	2	20	20	21	21	21
	4	21	21	23	23	23
	6	20	21	25	24	22
	8	21	20	24	24	22
	4 days	20	20	22	22	22
	8 days	20	20	22	23	21
	12 days	19	20	23	22	22
Oxygen (mg/l)	0	7.80	7.70	7.70	7.70	7.75
	2	7.90	7.65	5.80	6.00	6.90
	4	8.11	7.60	4.82	4.95	6.28
	6	8.19	7.60	4.18	4.45	5.80
	8	8.08	7.59	3.54	4.32	5.70
	4 days	7.56	7.40	6.49	6.65	6.79
	8 days	8.09	7.93	7.20	6.60	5.95
	12 days	8.65	8.05	7.55	6.30	6.15
Alkalinity (mg/l)	0	14.0	13.5	13.5	14.0	14.0
	2	14.5	13.5	13.0	12.0	14.0
	4	14.0	13.5	12.0	12.0	13.0
	6	13.0	13.0	11.5	12.0	12.5
	8	13.9	14.5	11.0	11.5	13.0
	4 days	13.5	13.5	10.0	10.0	10.0
	8 days	13.0	13.5	10.0	9.0	10.5
	12 days	14.0	14.0	9.0	11.5	11.5
Carbon Dioxide (mg/l)	0	4.5	4.0	4.5	4.0	4.0
	2	5.0	5.0	23.0	19.0	7.5
	4	4.5	4.5	35.0	29.0	11.0
	6	4.0	4.5	41.0	35.0	12.0
	8	4.0	4.5	46.0	38.0	12.5
	4 days	5.5	6.0	12.0	11.0	7.0
	8 days	5.0	4.0	6.0	7.5	8.0
	12 days	4.5	4.5	6.0	8.0	9.0
pH	0	6.69	6.50	6.53	6.55	6.55
	2	6.69	6.66	5.30	5.28	5.99
	4	6.68	6.79	5.13	5.09	5.68
	6	6.72	6.68	4.89	4.85	5.57
	8	6.81	6.70	5.01	5.42	6.03
	4 days	6.53	6.78	5.93	5.78	6.15
	8 days	6.31	6.40	5.82	5.69	6.15
	12 days	6.71	6.67	6.34	5.92	5.76

Table A2. Continued.

Parameter		Time	Lake	Control	Honda	Mercury	Johnson
Total Gas Consumed (mls)					5,100	6,450	15,300
Nitrate Nitrogen	(mg/l)	0	0.03	0.04	0.06	0.07	0.07
		2	0.03	0.07	0.08	0.45	0.65
		4	0.04	0.04	0.10	0.73	0.98
		6	0.06	0.03	0.15	1.02	1.06
		8	0.04	0.03	0.28	1.14	1.26
		4 days	0.05	0.04	0.19	0.79	0.95
		8 days	0.08	0.09	0.24	0.74	0.90
		12 days	0.04	0.06	0.24	0.79	0.78
Kjeldahl Nitrogen	(mg/l)	0	0.22	0.24	0.16	0.20	0.18
		2	0.26	0.18	0.22	0.16	0.28
		4	0.20	0.34	0.20	0.26	0.34
		6	0.22	0.26	0.26	0.40	0.44
		8	0.18	0.22	0.28	0.44	0.56
		4 days	0.18	0.28	0.29	0.48	0.50
		8 days	0.19	0.20	0.24	0.56	0.50
		12 days	0.22	0.22	0.27	0.53	0.54
Total Phosphorus	(mg/l)	0	0.017	0.015	0.015	0.014	0.016
		2	0.020	0.012	0.016	0.015	0.020
		4	0.016	0.012	0.014	0.016	0.021
		6	0.014	0.015	<0.010	0.013	0.022
		8	0.012	0.010	0.014	0.016	0.015
		4 days	0.016	0.013	0.016	0.023	0.028
		8 days	0.014	0.014	0.010	0.020	0.028
		12 days	0.014	0.014	0.013	0.020	0.025
Soluble Phosphorus	(mg/l)	0	<0.010	0.011	0.012	<0.010	0.010
		2	<0.010	0.013	<0.010	<0.010	0.012
		4	<0.010	0.011	<0.010	<0.010	0.019
		6	<0.010	<0.010	<0.010	0.016	<0.010
		8	<0.010	0.017	<0.010	0.010	<0.010
		4 days	0.016	0.013	<0.010	<0.010	<0.010
		8 days	0.011	0.010	<0.010	<0.010	<0.010
		12 days	0.010	<0.010	0.013	<0.010	--
Total Organic Carbon	(mg/l)	0	6.2	3.1	<1.0	<1.0	3.9
		2	<1.0	4.9	1.6	14.4	10.8
		4	1.6	<1.0	<1.0	16.6	26.3
		6	1.6	5.4	3.9	30.5	40.9
		8	6.2	2.0	8.5	27.8	39.0
		4 days	3.9	3.1	3.4	25.5	39.8
		8 days	2.4	<1.0	6.2	20.9	33.6
		12 days	7.0	7.8	12.4	17.8	40.1

Table A3. Physical and chemical parameters from the third test run.

Parameter	Time	Lake	Control	Honda	Mercury	Johnson
Total Gas Consumed (mls)				5,000	7,000	18,800
Temperature (C)	0	20.7	20.7	20.7	20.7	20.7
	2	21.5	21.5	23.6	22.6	22.5
	4	23.2	22.6	25.7	24.5	24.3
	6	23.3	22.7	26.4	24.6	25.3
	8	23.4	22.6	26.3	24.4	25.1
Conductivity (umhos)	0	19	19	19	19	19
	2	20	20	23	22	22
	4	21	21	27	25	24
	6	21	21	25	25	23
	8	20	21	27	26	26
Oxygen (mg/l)	0	8.20	8.20	8.23	8.20	8.23
	2	8.28	8.22	6.00	6.35	7.35
	4	8.50	8.28	4.70	5.25	6.45
	6	8.45	8.20	4.00	4.70	5.90
	8	8.35	8.20	3.60	4.55	5.70
Alkalinity (mg/l)	0	12.5	13.0	13.5	13.0	13.5
	2	12.5	12.5	11.5	12.5	13.0
	4	13.0	12.5	8.0	10.0	12.5
	6	12.5	12.0	8.5	11.0	12.5
	8	12.0	12.5	8.0	10.0	12.0
Carbon Dioxide (mg/l)	0	5.0	5.0	5.0	5.0	5.0
	2	4.5	4.5	32.0	26.5	8.5
	4	3.0	3.0	50.0	37.5	12.5
	6	2.0	2.5	52.0	39.0	16.0
	8	3.0	2.5	62.0	41.0	18.0
pH	0	6.50	6.53	6.52	6.51	6.54
	2	6.51	6.52	4.80	5.72	6.40
	4	6.60	6.58	4.73	4.77	5.38
	6	6.71	6.57	4.63	4.70	5.21
	8	6.69	6.52	4.42	4.64	5.09
Nitrate Nitrogen (mg/l)	0	0.06	0.05	0.05	0.08	0.08
	2	0.05	0.08	0.13	0.37	0.63
	4	0.04	0.05	0.21	0.91	1.38
	6	0.05	0.05	0.17	0.83	1.92
	8	0.08	0.05	0.21	0.98	1.53

Table A3. Continued.

Parameter		Time	Lake	Control	Honda	Mercury	Johnson
Kjeldahl Nitrogen	(mg/l)	0	0.22	0.22	0.22	0.22	0.22
		2	0.22	0.24	0.26	0.28	0.36
		4	0.24	0.28	0.28	0.38	0.46
		6	0.26	0.28	0.30	0.42	0.56
		8	0.34	0.26	0.34	0.52	0.77
Total Phosphorus	(mg/l)	0	0.010	0.013	<0.010	<0.010	<0.010
		2	<0.010	0.012	0.013	0.012	0.016
		4	0.012	<0.010	<0.010	<0.010	0.018
		6	0.016	0.014	0.014	0.020	0.022
		8	<0.010	0.013	<0.010	0.010	0.024
Soluble Phosphorus	(mg/l)	0	<0.010	<0.010	<0.010	<0.010	<0.010
		2	<0.010	<0.010	<0.010	<0.010	<0.010
		4	<0.010	<0.010	<0.010	<0.010	<0.010
		6	<0.010	<0.010	<0.010	<0.010	<0.010
		8	<0.010	<0.010	<0.010	<0.010	<0.010
Total Organic Carbon	(mg/l)	0	2.4	<1.0	<1.0	<1.0	<1.0
		2	<1.0	<1.0	<1.0	<1.0	10.8
		4	1.6	<1.0	10.1	13.2	25.5
		6	<1.0	1.6	11.6	23.2	34.9
		8	9.7	5.4	10.1	27.8	44.0

Table A4. Measures of biological response 0, 4, 8, and 12 days after running outboard engines for eight hours.

Parameter	Time	Open Lake	Control	Honda	Merc.	John.
Chlorophyll *a* (ug/l)	0 days	1.26	1.23	1.02	1.35	1.01
	4 days	1.11	1.92	0.21	0.12	0.24
	8 days	1.40	1.62	0.23	0.22	0.39
	12 days	3.33	0.89	0.48	0.68	0.04
Phaeophytin (ug/l)	0 days	1.45	0.71	0.72	0.97	0.61
	4 days	0.58	0.51	0.62	3.80	2.19
	8 days	0.83	0.96	0.50	3.86	1.75
	12 days	0.41	1.50	0.57	6.93	1.49
Dry Weight (mg/l)	0 days	46.55	48.06	52.10	47.04	50.09
	4 days	47.03	61.11	49.64	58.91	54.35
	8 days	61.13	60.63	64.30	71.89	101.18
	12 days	61.34	61.56	63.39	141.60	196.48

Table A5. Numbers (x1000/l) and biovolume (mm^3/l) of the five algae genera with the greatest biovolume. Totals are for all algae, not just the top five genera. Collected prior to the test run.

Algae Genera	Open Lake No	Open Lake Vol	Control No	Control Vol	Honda No	Honda Vol	Mercury No	Mercury Vol	Johnson No	Johnson Vol
Aphanocapsa					2,910	0.023				
Asterionella	71	0.060	101	0.085						
Cosmarium	7	0.024			11	0.036				
Dinobryon	14	0.022	128	0.202	171	0.269	100	0.157	117	0.185
Gloeotrichia			112	0.025						
Melosira	64	0.150	85	0.200	53	0.125	149	0.349	187	0.437
Nostoc							57	0.109		
Synechocystis					203	0.126	146	0.090	235	0.146
Staurastrum									5	0.083
Unknown 1	43	0.046	21	0.023			146	0.158	149	0.161
TOTAL	6,706	0.375	9,373	0.628	6,534	0.657	5,534	1.020	9,386	1.182

Table A5. Continued. Collected after four days.

Algae Genera	Open Lake		Control		Honda		Mercury		Johnson	
	No	Vol	No	Vol	No	Vol	No	Vol	No	Vol
Asterionella	132	0.110			64	0.054				
Dinobryon	437	0.691	96	0.152	57	0.090	60	0.095	68	0.107
Melosira	178	0.416	96	0.224	110	0.258	110	0.258	110	0.258
Nostoc			160	0.305	14	0.027			14	0.027
Peridinium			4	0.136	4	0.136				
Spondyliosum	64	0.069								
Synechocystis	128	0.079	78	0.049			57	0.035	50	0.031
Synedra							7	0.017	4	0.009
Staurastrum							4	0.056		
TOTAL	14,178	1.496	14,417	1.023	4,691	0.666	3,627	0.500	3,840	0.465

Table A5. Continued. Collected after eight days.

Algae Genera	Open Lake		Control		Honda		Mercury		Johnson	
	No	Vol	No	Vol	No	Vol	No	Vol	No	Vol
Asterionella							107	0.090		
Cosmarium									14	0.048
Cyclotella	57	0.018								
Dinobryon	46	0.073	53	0.084	82	0.129	89	0.140	71	0.112
Oocystis									298	0.039
Melosira	71	0.166			46	0.108	18	0.042	57	0.132
Nostoc	71	0.136	291	0.557						
Peridinium			18	0.671						
Tabellaria					4	0.013				
Synechocystis	28	0.018	64	0.040	50	0.031	160	0.099	57	0.035
Unknown #1			71	0.077						
Trachylemonas					7	0.014	18	0.034		
TOTAL	9,819	0.576	7,384	1.562	2,374	0.316	17,163	0.453	5,560	0.414

Table A5. Continued. Collected after twelve days.

Algae Genera	Open Lake No	Open Lake Vol	Control No	Control Vol	Honda No	Honda Vol	Mercury No	Mercury Vol	Johnson No	Johnson Vol
Agmenellum	14,796	0.002	12,173	0.002						
Aphanocapsa			14,757	0.114						
Asterionella							36	0.030		
Cosmarium			71	0.060			4	0.012	11	0.036
Dinobryon	43	0.067	85	0.135	32	0.051	50	0.079	32	0.051
Gloeotrichia	375	0.047								
Melosira	68	0.158	100	0.261	96	0.251	85	0.200	92	0.216
Nostoc	242	0.462								
Peridinium	14	0.535	18	0.671	18	0.671	14	0.535	11	0.403
Spondyliosum									28	0.025
Synechocystis					85	0.053				
Trachylemonas					21	0.041	7	0.014		
TOTAL	19,581	1.466	27,560	1.549	2,075	0.498	2,832	0.894	2,768	0.782

Table A6. Zooplankton numbers per m^3 in enclosures during and after the test run.

		COPEPODA		CLADOCERA					OTHER	DRY WEIGHT (g/m^3)
Site	Time	Nauplii	*Diacyclops bicuspidatus thomasi*	*Bosmina longirostris*	*Polyphemus pediculus*	*Daphnia thorata*	*Holopedium gibberum*	*Sida crystallina*		
Open Lake	Before	400	200	14,300	100	1,100	400	0	100	1.600
	8 hours	500	700	1,400	0	1,400	100	0	100	1.210
	4 days	100	200	25,300	900	100	0	0	0	1.220
	8 days	0	300	3,500	0	0	100	0	200	1.150
	12 days	0	0	2,600	0	0	0	0	0	0.180
Control	Before									0.624
	8 hours	100	200	6,900	0	100	0	0	0	0.200
	4 days	200	100	200	300	0	0	0	0	0.210
	8 days	200	400	200	0	0	0	0	0	1.280
	12 days	0	200	200	500	0	100	0	0	0.070
Honda	Before									
	8 hours	300	0	200	0	0	0	0	0	0.160
	4 days	100	0	0	0	0	0	0	0	0.030
	8 days	0	0	500	0	0	0	0	0	0.512
	12 days	0	100	2,900	0	0	0	0	0	1.170
Merc.	Before	0	200	23,400	0	100	0	100	100	
	8 hours	200	400	1,700	0	0	0	300	0	
	4 days	0	100	0	0	0	0	0	0	0.020
	8 days	0	200	0	0	0	0	0	0	1.120
	12 days	0	0	0	0	0	0	0	0	1.150
John.	Before									
	8 hours	100	700	400	0	0	200	0	100	1.130
	4 days	0	100	0	0	0	0	0	0	1.180
	8 days	0	100	0	0	0	0	0	0	1.130
	12 days	0	0	2,000	0	0	0	0	0	0.550

Table A7. Nitrate-nitrogen quality assurance results. Three different samples with unknown concentrations were analyzed to check precision and four samples of known concentration were analyzed to check accuracy of the spectrophotometric method.

	Unknown Conc. (ug/l)			EPA Standards (ug/l)			
	#1	#2	#3	14	35	70	140
	60	64	7	16	37	77	142
	60	67	3	16	37	71	142
	60	67	7	16	37	74	142
	60	74	7	16	37	71	142
	60	71	7	16	37	74	139
	60	64	3	16	37	74	152
	60	67	3	26	40	84	163
	60		1				
	67		0				
	66		3				
Number	10	7	10	7	7	7	7
Mean	62	68	4.07	17.67	37.13	75.07	146.08
Std Dev	2.41	3.37	2.31	3.58	1.19	4.35	7.81
Std. Err. as % of mean	1.23%	1.87%	17.95%	7.66%	1.21%	2.19%	2.02%