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Efficacy of Offshore Breakwater Structures in a Eutrophic Midwestern Reservoir

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Efficacy of offshore breakwater structures in a eutrophic Midwestern reservoir

By

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Efficacy of offshore breakwater structures in a eutrophic Midwestern reservoir

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Shoreline erosion and near-shore sediment movements are prevalent in eutrophic midwestern reservoirs. Branched Oak Reservoir, near Lincoln, Nebraska, is a 728 hectare flood control reservoir with a turbid littoral zone. To reduce littoral disturbance and abate shoreline erosion, experimental concrete "A-jack" offshore breakwater structures with rock jetties were installed in 1999. Over a two-year period, paired control and treatment areas were monitored monthly (Apr-Oct) in five areas to determine the biological and physical effects of these offshore breakwater structures. Benthic invertebrates were more dense in treated areas for the dominant taxa, Chironomidae, in 1999 and 2000 ($P<0.001$), and Oligochaeta in 2000 ($P<0.001$). Topographic surveys conducted pre- and post-treatment showed that offshore structures also altered the pattern of shoreline erosion and sediment movement. The bank (above conservation pool) and near shore zones (up to 0.61 m below conservation pool) showed a mean loss in both the treatment (0.845, 0.069 m^2, respectively) and control (2.32, 1.37 m^2) areas, but was significantly less in both zones for the treatment sites ($P<0.001$). The offshore zone (0.61 to 1.22 m below conservation pool) was significantly different ($P<0.001$) with a mean gain of 0.42 m^2 for treatment sites and a mean loss of 1.94 m^2 for control sites. Thus, the experimental offshore breakwater structures were effective at increasing benthic invertebrate density, reducing shoreline erosion and allowing sediments to stabilize within the littoral zone.

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INTRODUCTION

New reservoir construction has slowed considerably in the past two decades, as both desirable and essential locations have been taken, funds for non-essential public projects are increasingly difficult to acquire, and land acquisition is prohibitive. Erosion of exixting impoundments, particularly shoreline erosion, is rapidly decreasing the utility of our reservoirs by decreasing storage capacity, reducing water quality (Hagen and Roberts 1972, Vanoni 1975, Lawson 1985), and reducing aesthetic appeal (Bhowmik 1978). For resource managers involved in water recreation, fisheries and wildlife, flood control and utilities, a new emphasis is needed for the management of aging, man-made lakes and reservoirs. We must now devote more attention toward protection and restoration of existing reservoirs if we are to continue to enjoy their benefits.

In contrast to marine and lotic systems, "only a very limited number of studies have actually analyzed erosion and recession of reservoir shores" (Lawson 1985). The overall process of reservoir aging has been compared to the evolution of natural lakes (Kondratjev 1966, Kachugin 1966). Undisturbed natural lakes, through geological time, have had the opportunity to form shorelines with an appropriate shape, slope, and vegetation, and to reach equilibrium with the surrounding landscape. Comparatively, reservoirs 50 years old or less are very young and have not had the time to establish equilibrium. Reservoirs are generally located in river valleys, on substrates formed by processes other than lacustrine. Consequently these shorelines are not in equilibrium with the lacustrine environment and represent an unstable configuration (Lawson 1985). An unstable configuration can manifest itself in dramatic and relatively rapid erosion of shoreline soils. We consider this process as reservoir degradation, because it limits usage in a relatively brief time frame. Lawson (1985) aptly points out, "...in general, physical changes to the shore zone will be the product of the energy of the eroding forces, the geometry of the reservoir, surrounding terrain and shore zone, and the resistance of the bank material to the different erosive forces (Krumbein 1950, Baxter 1977). The time necessary to reach equilibrium will vary from reservoir to reservoir as well as from reach to reach within a single impoundment."

Shoreline erosion and bank recession are caused by many forces, both natural and anthropogenic, with a variety of processes and conditions interacting in complex ways (Gatto 1988). Waves are the most apparent and often cited cause of shoreline change, yet because of the infinite combination of wave sources and physical conditions acting upon them, the effects can be erosional or depositional (Lawson 1985). With respect to shoreline erosion and recession, waves act in two primary ways. First, they act to disrupt and displace *in situ* bank or bluff line material, with erosion and recession resulting from a variety of forces exerted by the wave, as well as the conditions of and interactions with the bank material (Sunamura 1977, Reid 1984, Lawson 1985, Gatto 1988). Second, breaking waves remove shoreline sediments previously eroded and deposited from the bank face, as well as other depositional action. The effect of the sediment removal along the shoreline is the inability of a shoreline to establish an equilibrium profile (Lawson 1985).

A number of other contributing factors are also involved in the erosion and recession of bank and shorelines. Ice activity, which can protect shorelines by eliminating wave and current action, more frequently acts as a disruptive agent on shoreline and bank sediments allowing erosion and displacement by wave action (Dionne 1979). Human activity including operation of the reservoir can accelerate erosion and recession of shorelines and banks. Many reservoirs encounter changes in pool elevation, due to their utility in hydroelectric generation, irrigation, and flood control, which ultimately translates into a lack of shoreline equilibrium in shape, slope, and protective vegetation (Lawson 1985). Human activity within the reservoir, particularly water craft disrupting near-shore and shoreline sediments (Gucinski 1982, Engal and Nichols 1984, Wagner 1991), and removal of littoral vegetation (Murphy and Eaton 1983, Zieman 1976, Asplund and Cook 1997), have been shown to contribute to an increase in shoreline erosion and reduced water quality. Shore disturbances caused by removal or cropping of vegetation, irrigation, walking or driving near shore, and construction activities can also disrupt the structure and stability of bank soils, leading to an increase in shoreline failures (Gatto 1988).

Branched Oak Reservoir

Branched Oak Reservoir, Lancaster County, Nebraska is located on the confluence of Middle Oak Creek and Oak Creek, approximately 20 kilometers north-west of Lincoln, Nebraska (Fig. 1). Authorized by the Flood Control Act of 1958, it is the largest of 18 impoundments built on the tributaries of Salt Creek to control flooding in and around Lincoln. The 21-m high by 1.8 km earthen dam was completed in December 1967 (USACE 1981), with the lake level reaching conservation pool in 1973. The dam of Branched Oak was designed to control 37.9 cm of runoff over the drainage area of 230 km^2. At conservation pool, the lake has 720 surface hectares with capacity of 32.06 x 10^6 m^3, mean depth of 3.42 m and maximum depth of 8.5 m (USACE 1981). The lake basin lies within the Dissected Till Plains of the Central Lowlands Physiographic Province with geology and foundation conditions primarily consisting of loess and glacial drift in the abutments and alluvium in the valleys. The valley alluvium is 12-m thick, soft to stiff, inter-stratified clay that overlies a three to five meter thick stratum of Grand Island silty sands and gravels. The alluvium is described as lean, sandy and silty clay. The soft and stiff clay strata are inter-stratified such that a definite stratum of weak material does not extend continuously over any major portion of the embankment foundation (USACE 1981).

The lake is divided into two main arms. The smaller south arm of Middle Oak Creek lies primarily west of the dam with a maximum length of approximately 3.7 km and a maximum width of 1.4 km. The north arm of Oak Creek lies northwest from the dam with a maximum length of approximately 4.5 km and a maximum width of 900 m. Two small 16-ha bays extend northward from the east end of the north arm. Between 1994 and 1998, jetties were constructed across the mouths of these bays, to intercept wave action from the main basin causing erosion on the shorelines of these bays. Small stream inlet bays occur throughout but have been mostly reduced due to sedimentation and shoreline erosion.

The unprotected bank line of Branched Oak Reservoir is characterized by vertical bluffs that are rapidly receding. Shoreline bluffs throughout the lake range from a few feet to over thirty feet tall, and in many areas, shoreline recession has resulted in the setback of the shoreline by up to 50 feet or more (USACE 1981). Observed recession of the banks occurs as gravitational failure of large peds, slip and rotation of blocks of soil, and direct wave erosion into the toe of the bluff. Ice expansion along the shoreline and into the bluff is also a major disturbance factor, creating soil pushup and fracture of the bluff, and displacement of the sloughed material. Any sloughed material accumulated is then generally removed through wave and ice action, leaving nearly sediment-free shorelines. While the water level of Branched Oak is relatively constant, occasional heavy rain high water events cause scouring and undercutting of bluffs, and most importantly, transport of sloughed material away from the shoreline.

Shoreline erosion has occurred throughout much of the lake. About three percent of the shorelines have been treated with rip-rap to protect highly exposed land points, developed park areas, and adjacent to the dam to protect water control structures. Several stabilization techniques have been used in the past to reduce shoreline erosion. A floating telephone pole structure was installed in 1993 along the north shore of the north arm, and coconut fiber mats with willow stakes were installed in 1991 along the shore of Marina Bay. Both were destroyed by wave and ice action within a few years of installation.

Continued shoreline erosion, sedimentation, littoral disturbance, and nutrient loading have resulted in a reservoir that is undergoing rapid eutrophication and becoming aesthetically undesirable. In a report on the sedimentation conditions in Salt Creek projects near Lincoln, Nebraska 1963-1994 , the US Army Corps of Engineers (1995), stated that the surface area of Branched Oak at conservation pool elevation had increased by 19.8 ha due to shoreline erosion, while the storage in the sediment and flood pool zones had decreased by 567.8 (10%) and 78 ha (0.3%), respectively from 1967 to 1991. Thus, the lake has become more shallow and turbid. In addition, its unprotected shorelines have steep, rapidly eroding banks that contribute to turbid, shallow, and unconsolidated near-shore zones. Rip-rap protected banks have been stabilized, but waves continually erode and re-suspend shoreline sediments that contribute to turbidity reservoir-wide.

Offshore Breakwater Structures

The purpose of offshore breakwater structures (OBS) (Fig. 2) in Branched Oak was to reduce the rate of erosion along banks and shorelines, and reduce the resuspension of bottom sediments along shorelines and near-shore areas. OBS' were designed to intercept and reduce wave and ice energy prior to their impact on bank, shoreline, and near-shore areas. The desired results were reduction of erosion, sedimentation, turbidity, and creation of a relatively stable littoral zone that was more conducive to vegetation and associated fauna.

In September 1998, the water level of Branched Oak Reservoir was lowered approximately two meters to facilitate OBS installation. OBS' consisted of an array of concrete jacks ("A-jacks") placed parallel to the shoreline, with jetties connecting the shore to each end of the A-jack array. A-jacks were made of concrete, consisting of two sections, each with three legs. These two sections were placed together to form a six-legged structure, two meters tall, weighing approximately 340 kg. OBS arrays were created using two interlinking rows of A-jacks, placed on a footing at a depth contour

1.22 m below conservation pool. This generally coincided with 40 m from the shoreline at conservation pool. The footing for the A-jacks was prepared by placing a 2.4 m wide strip of geotextile fabric (Geoweb, TC Mirafi, Pendergrass, Georgia) covered by 153 mm of crushed limestone. Jetties from the shore to the OBS arrays were created from tire bales and type B limestone rock. Bales of compressed tires (1.2 x 1.2 x 2.4 m) were placed on a horizontally level surface from the bank to the end of the A-jack double row. The base level consisted of three rows of tire bales, with two tire bale rows placed on top of the base, and covered with limestone rock.

OBS' were installed in November and December of 1998 and jetties were installed in January through March of 1999. Three sites on the main body of the reservoir each received 91-m long treatments of A-jacks and jetties, Marina Bay (off the north central shoreline) received one 61-m long treatment of A-jacks and jetties, and Bobber Bay (off the north eastern shoreline) received two 61 m treatments of A-jacks and jetties. Additionally, one modified offshore breakwater structure was included in each of the afore mentioned bays, consisting of replacing the A-jacks with a frontage of tire bales and rock comparable to the construction of the jetties. Six 305-mm culverts were installed along this modified frontage to allow for passage of water and animals.

Objectives

The primary objective of this study was to evaluate the efficacy of OBS by assessing changes in physical characteristics of the shoreline and bank, as well as their impact on the benthic biota of the littoral zone. Physical characteristics were measured through biannual topographic surveys along transects within each OBS site and at adjacent, untreated control sites. Benthic invertebrates were used to assess biological community changes resulting from OBS'.

METHODS

Physical Characteristics

Field

Topographic surveys were conducted to document the physical characteristics of the bank, near-shore and offshore zones of OBS treated and untreated control sites from May 1999 to November 2000. Two topographic surveys were completed for each OBS and untreated control sites in study areas 3, 4, and 5 (Fig. 1). Study areas 1 and 2 were not surveyed or included in the physical analysis due to construction interference. Surveys were conducted using Sokkia Total Station Set 2B® optical survey equipment coupled to a Sokkia 2SB® data recorder (Sokkia Corporation, Olathe, Kansas), in May of 1999 and November of 2000. Sokkia Total Station data were collected using standard survey methods describing an easting, northing, and elevation location (XYZ) with respect to independent XYZ-benchmarks established at each of the three main study areas (Fig. 3).

Five permanent benchmarks were created within each study area, consisting of one meter sections of re-bar driven 15 mm below the land surface. Benchmarks were established to allow for accuracy in repeated surveys. Five transects perpendicular to shore were identified for each OBS and untreated site within each study area. These transects were established approximately equidistant within the OBS and in the paired untreated control areas. Each transect extended six meters landward from the shoreline, to the immediate inside edge of the OBS. Each untreated control transect extended from six meters landward from the shoreline, to 1.2 m below the conservation pool elevation (CP). To facilitate repeatable survey accuracy, each transect was identified and marked on the bank with two re-bar stakes. These pins were located at the time of each survey and flagged. Survey data points were taken along the transect at a minimum interval of 6 m and at all apparent elevation and landform changes to characterize topography at each transect.

Laboratory

Data for the first and fourth surveys were downloaded into AutoCad® (Autodesk, Inc., San Rafel, California) and transformed into a scaled, two-dimensional graphic for each treatment and control transect within each area. Each transect data set was divided into three zones; top of bank to CP (bank, zone 1), CP to 0.61 m below CP (near shore, zone 2), and 0.61 to 1.2 m below CP (offshore, zone 3). Data used for analysis consisted of the cross-sectional area of the difference (derived from the graphic) between the 1999 and 2000 surveys, reported as the mean net loss or gain of material for each zone by transect.

Data Analysis

To determine the interaction of the study area, zone, treatment (i.e. untreated or OBS), and transect, a general linear model was used to assess the derived net loss or gain of material from 1999 to 2000. A Student's *t*-test was used to determine significant differences for each zone, by mean cross-sectional area of transects of combined areas 3 through 5, untreated versus OBS, and by mean cross-sectional area of transects for areas

3, 4, and 5.

Biological Characteristics, Benthic Invertebrates

Field

Benthic samples were collected monthly, May through October 1999 and April through October 2000 at all five study areas. Three transects were identified within each of the eight OBS and five control sites, along which three benthic samples collected at the 0.3, 0.8 and 1.2 m below CP depth contours (Fig.3). A total of nine samples were collected per treatment or control location, for a total of 117 benthic samples per month. The three samples for each transect were combined and treated as one sample in 2000. A fish exclosure (6.35-mm mesh, 1 m diameter x 1.22 m tall) was added to OBS sites 9, 11, and 13, in fall 1999. A single benthic sample was taken from each fish exclosure monthly, April through October 2000.

Benthic samples were collected using a 15.2 x 15.2-cm Ekman dredge (Wildco, Saginaw, Michigan) mounted on a 1.52-m pole, operated while wading. Samples were sieved on site through a 541-μm mesh bucket and retained material preserved with 10% formalin.

Laboratory

Benthic samples were placed on a #30 (600-μm) sieve, washed free of formalin, and separated into light organic and heavier inorganic material with the aid of a saturated NaCl solution. Each part of the sample was sorted under a dissecting microscope and organisms were place in storage vials containing 70% ethanol. Organism were identified under a dissecting or compound microscope to genus or the lowest practicable taxon and enumerated. Identifications of organisms were made with the aid of Merritt and Cummins (1996), Hilsenhoff (1981), and Pennak (1989).

Data Analysis

To determine interactions of the variables year, month, area, treatment type (i.e. untreated and OBS), and transect, general linear modeling was conducted on the mean of natural log transformed density for each taxon and for selected groups of taxa. In addition, exclosures versus OBS were included for benthic collections in 2000. Student's *t*-test were used to test for significant differences in 1999 and 2000, by year for untreated versus OBS', by month for untreated versus OBS', and exclosures versus OBS' in 2000.

Benthic community composition was compared using Ruzicka's index of similarity (RI; Pielou, 1984) for 1999 and 2000, by year between untreated and OBS', by month between untreated and OBS' for 1999 and 2000, and by month between exclosure and OBS' for 2000. This index is a measure of percent similarity, ranging from 0 for communities with no common taxa, to 100 for communities that are identical:

$$\mathrm{RI} = 100 \text{ x } \left(\sum_{i=1}^{S} \min(x_{i1}, x_{i2}) \,/\, \sum_{i=1}^{S} \max(x_{i1}, x_{i2})\right).$$

RESULTS

Bank Erosion

The mean cross-sectional area for OBS sites within each of the three zones, showed significantly less erosion and/or greater deposition of material compared to the untreated control sites (P=0.0001) (Fig. 4, Table 1). Zone 1 (bank) had a mean loss of sediment for both the OBS treatment and untreated control sites of 0.845 and 2.32 m^2, respectively, yet was significantly less in the OBS treatment ($P=0.0001$). Zone 2 (near shore) similarly had a mean loss of material for both the OBS treatment and untreated control sites of 0.069 and 1.37 m^2 respectively, and was also significantly less in the treatments ($P=0.0003$). Zone 3 (offshore) showed a significant difference between the OBS treatments and untreated controls ($P=0.0001$), with a mean accrual of 0.42 m^2 of sediment within the OBS treatment, while the untreated control lost 1.94 m^2.

In Area 3 (North Shore), the untreated control had a mean net loss of material in zone 1 (0.27 m^2), zone 2 (1.00 m^2), and zone 3 (1.32 m^2). The OBS treatment site of Area 3 had a mean net loss of material in zone 1 (0.19 m^2), yet had a net gain for zones 2 (0.52 m^2) and 3 (1.89 m^2). The difference between the untreated control and OBS treatments was significant in zones 2 and 3 ($P<0.01$) (Fig. 4, Table 1).

In Area 4 (South Shore), the untreated control had the greatest mean net loss of material of all control sites, and greatest disparity between the untreated control and OBS treatment. The untreated control zone 1 lost 5.56 m^2, zone 2 lost 1.77 m^2 and zone 3 lost 3.31 m^2 of sedimentary material, yet Area 4 OBS treatment was very similar to the OBS treatments in Areas 3 and 5. Zone 1 of Area 4 was the only zone 1 of all the areas demonstrating a significant difference. OBS treatments zones 1 thru 3 of Area 4 lost 1.35, 0.25, and 0.59 m^2 of material, respectively. The difference between the untreated control and OBS treatment was significant for all three zones ($P<0.01$) (Fig. 4, Table 1).

In Area 5 (Lieber's Point site), differences between the zones of the untreated control and the OBS treatments were least among the three study areas ($P>0.01$). All zones in both the untreated control and OBS treatments had a mean net loss of material. Zone 1 showed no significant difference between the meant net loss of material in the untreated control and OBS at 1.14 and 1.00 m^2, respectively. Zones 2 and 3 also had losses in all zones regardless of treatment type, but were significantly different in all cases ($P<0.01$) (Fig. 4, Table 1).

Benthic Invertebrate Composition

Seven families from six orders of aquatic insects, plus the order Oligochaeta, were collected in 1999 and 2000 (Table 2). Larval Chironomidae were the most abundant group of organisms encountered during both years, and treatment types, comprising over 85% of all samples (Fig. 5). Chironomids were found in every transect sample in both 1999 and 2000, at an average density of 627 and 441 organisms m^{-2}, respectively. In both 1999 and 2000, Oligochaeta were the second most numerous group of benthic invertebrates comprising at least 4% of the samples (by density). Oligochaetes were present in greater than 50% of all transect samples, and were found at 23 and 51 m^{-2} in 1999 and 2000, respectively. Collectively, all other taxa contributed less than 5% of the total number of organisms in either study year. Of those, Ephemeridae were the third most abundant organisms found in 1999 (6.8 m^{-2}) and fifth in 2000 (2.5 m^{-2}). Ceratopogonidae were also encountered in both years, at densities of 2.0 m^{-2} in 1999 and 5.9 m^{-2} in 2000. Trichoptera accounted for only four individuals in 1999 and three individuals in 2000, all of which were collected from study area 4. Corixidae were collected only in 2000, with all individuals coming from one OBS (site 7). Libellulidae were represented by six individuals and Sialidae by three individuals collected in 2000.

The density of the total of all organisms was 472 m^{-2} in 1999 and 696 m^{-2} in 2000.

The density of organisms collected in the 2000 exclosures was considerably greater than either the offshore breakwater treatment or the untreated control (Table 2). Chironomids were found at densities of 2583 m^{-2} and occurred in 100% of all samples. Oligochaeta and Ephemeridae were both represented in 62% of the samples at densities of 125 and 74 m^{-2}, respectively for 1999 and 2000. Sialidae and Ceratopogonidae were present in 19 and 24% of samples, at 49 and 41 m^{-2}, respectively, for 1999 and 2000. Trichoptera were found only in the exclosure of study area 4 (41 m^{-2}).

Benthic Invertebrate Community, Comparisons

In 1999, the density of total organisms collected from OBS treated sites was significantly greater than the untreated control sites for May, June, July, September and October ($P<0.01$), but not August (Fig. 6). Larval Chironomidae, Oligochaeta and Ephemeridae were significantly different in their relative contribution to total annual density ($P<0.01$). Densities of the two least abundant organisms, Ceratopogonidae and Trichoptera, were not significantly different for OBS treatments and untreated controls (Fig. 7).

In 2000, the density of total organisms collected from OBS sites was significantly greater than untreated controls for April, May, June, August, September, and October ($P<0.01$), but not July (Fig. 8). Larval Chironomidae contributed most toward the total annual density in both the treatment and control and for 2000 was the only common taxon showing a significant difference ($P=0.0001$). Corixidae were significantly different ($P=0.0169$), but represented by only 1.9% (183) of total organisms, from only one OBS treatment (site 7) collected during August, September and October (Fig. 9).

The total density of organisms was significantly greater in the exclosures ($2944\ m^{-2}$) than in the OBS treatments ($510\ m^{-2}$) ($P<0.01$), yet individually, Chironomidae, Oligochaeta, Ephemeridae, and Ceratopogonidae were not significantly different between the exclosures and OBS treatments for 2000. Sialidae and Trichoptera were the only two taxa that were significantly different between the exclosures and OBS treatments in 2000 ($P<0.01$).

Ruzicka's Index (RI) values showed that the communities were not entirely similar between the OBS treatments and the untreated controls in 1999 and 2000, and in the 2000 exclosures. In 1999, OBS treatment versus untreated control comparison by month, four of the six months, May, July, September and October, had RI values <50. The RI for 1999 was 47. In 2000, OBS treatment versus untreated control comparison by month, five of seven months, April-June, August, and October had RI values <50. The RI for 2000 was 41. The comparison of 2000 OBS treatments and 2000 exclosures revealed the lowest annual RI value (30). By month, five of seven monthly RI values were <50 (April, June, July, September, and October) (Table 3).

DISCUSSION

Physical Characteristics

While shoreline losses within the Branched Oak Reservoir OBS treatments did occur, it was significantly less than in the untreated controls. This initial loss was to be expected, as the shoreline bluffs were steep, fragile, and with a toe that was relatively sediment free, all characteristics of a shoreline developed without protection. During the period of this study, the bluff of the OBS sites was in an early transitional phase of development, losing material due to terrestrial processes and wave erosion. At the top of bluff, similar recession occurred in both the OBS and untreated sites as they lost material, but within the OBS structures this material began to accumulate along the toe of the bluff, and remained as blocks of soil or as a consolidated berm above the conservation pool. Ultimately, under the lower erosion afforded by the protection of the OBS structures, it is expected that a back sloping of these bluffs will occur, as soil accumulates and the shorelines stabilize by developing a base of these soils. As Lawson (1985) emphasized, while the multitude of erosional processes working on a bank contribute to shoreline recession, the fate of this shed material determines shoreline erosion and recession.

Although quantitative studies on the effects of waves on bank erosion are rare, several support the conclusion that wave action is the dominant erosive process on shorelines (Black 1980), particularly in conjunction with interrelated terrestrial and in-lake processes (Reid 1984). Reid (1984) concluded that 76 and 88% of the bank erosion along Orwell Lake, Minnesota in 1981-1982 and 1982-1983 respectively, was attributable to wave action, thaw failure and overland flow events. He observed that during years when the lake level increased, any accumulation of sediment was removed and transported to deeper parts of the lake. The importance of this removal was, "...the removal of sediment at the base of banks controlled the degree of subsequent thaw failure and, to a lesser extent, overland flow," with all processes being interrelated (Reid 1984).

In the near-shore and offshore areas, the loss of material was consistent in the untreated control sites, while a significantly smaller loss or gain occurred inside the OBS treatments. The origin or fate of material lost or gained within these zones was not determined in this study. It is likely that part of the bank and near-shore material was retained in the OBS treatments, which would have accounted for a gain or replacement of material lost. Wave and near shore current energy is important in removal and transport of sediments away from near-shore areas and redistribution throughout a reservoir (Kondratjev 1966). Resuspension of particulate material can only occur when water movement takes place and if the current-induced bottom shear stress is sufficient to disrupt the cohesion of bottom sediments (Bloesch 1995). Generally in the shallow near-shore zone of reservoirs, course grain sediments collect, but the magnitude of wave energy is more important in determining overall sediment distribution, and is proportional to wave energy imparted (Rossman and Seibel 1977).

It is also possible that accrued sediments may be from outside the OBS structures, arriving by long shore drift or from lake turbidity (Sly 1978). Long shore drift was apparent at Branched Oak through an observed accumulation of material immediately outside of the OBS structures, creating a diagonal shoal from the connecting jetty to the bank.

Regardless of the source, near-shore material of OBS structures generally consisted of unconsolidated soil consistent with that shed from the bluff, while the untreated sites had substrates washed free of this material. In the offshore areas, this loose material was present in both OBS and untreated sites, but was noticeably greater in the OBS where there was a net accrual for all sites. Two of the three study sites had a loss in the near-shore and offshore, regardless of treatment, while the North Shore site incurred a gain in both zones for OBS treatment and a loss for untreated. The North Shore site was unique in that prior to the lake refilling, large amounts of wind blown soil from adjacent exposed flats accumulated along this north shore. The physical surveys did not create a time line to determine when the actual changes in substrate occurred; however, considerable removal of material in these zones occurred during the lake refilling period (February through April, 1999).

Erosion during filling was apparent in the form of 5 to 30 cm-high erosional berms created by wave action, with the displaced material shifting lake ward with each periodic water level adjustment. Within the OBS structures, the erosive forces of wave and ice were effectively reduced, and thus, less material was eroded, and the lake ward displacement of material was depth limited. The North Shore site, which included the deposition of wind blown material, acted as an additional mediating factor for net loss during filling, ultimately a gain of material. It must be noted that special care was made during surveying to accurately define the top of this loose layer of sediment where present, but errors undoubtably occurred, likely estimating less material (i.e. lower elevation) than was actually present. Regardless, these zones showed the effects of decreased wave energy in the OBS structures by fine sediment deposition and erosion reduction.

Benthic Invertebrate Community

In general, the composition, density and distribution of benthic organisms within any aquatic environment is a function of a variety of complex interacting biotic and abiotic factors (Resh and Rosenberg 1984). It is well known that available food resources, predation, habitat suitability, disturbance, and light can alter the density and composition as well as the apparent distribution of any given organism or community of organisms (Baker and Ball 1995, Scrimgeour and Culp 1994, Sih 1982, Matthews 1998). In lakes, the effects of suspended sediments have been shown to affect aquatic biota by reducing light penetration and primary production (Stall 1972, Oschwald 1972, Hecky and Ayles 1974, Geen 1974, Barko 1981). Habitats can also be negatively altered through sedimentation, by disturbing biological activity within the substrate (Livesay 1970, Avakyn 1975, Cooper and Bacon 1981, Widdicombe and Austin 2001). In new reservoirs benthic biomass initially increases for a period of time (Kajak 1988), but then declines with a decrease of internal nutrient loading and loss of favorable habitat (Plosky 1982). Popp and Hoagland (1995) showed that aging in Pawnee Reservoir, Nebraska accounted for a significant reductions in invertebrate taxa and biomass. These changes were in part attributed to sedimentation that limited the benthic fauna to species tolerant of periods of bottom anoxia and increased levels of organic matter. In a concurrent study to the offshore breakwaters at Branched Oak Reservoir, Vrtiska et al. (2003) documented community trends in the benthos (following Hergenrader and Lessig 1980), reporting a similar pattern of decreasing biomass and community change toward one expected under eutrophic conditions. In light of this variety of interacting factors that determine benthic community composition and density, it is difficult to predict the long-term effects of the OBS structures on the benthos in general. Nevertheless, OBS structures at Branched Oak Reservoir resulted in a significant, rapid increase in benthic invertebrate density, and an apparent change in the community structure toward one of higher diversity.

OBS structures had two predominant effects on the littoral zone, which individually and in combination had the potential to significantly alter the benthic community. OBS structures primarily stabilized sediments. The net effect can be compared to an increase in eutrophication, due to the retention of nutrients bound to clay particulates, settling of seston, and an increase in benthic productivity (Rasmussen and Rowan 1997). A slight increase in eutrophication can result in greater abundance and biomass of benthic organisms, yet a major increase is usually detrimental to all but a few taxa (Resh and Rosenberg 1984).

In addition, OBS reduced wave activity, resulting in reduced disturbance of benthic communities. While some aquatic organisms prosper in disturbed environments, the subset of organisms common to this lentic environment are more indicative of less disturbed, eutrophic conditions. In combination, the increase of nutrients retention and improved habitat conditions has a greater potential to increase both richness and density of the benthic community. Widdicombe and Austen (2001) demonstrated through mesocosm experiments on intertidal macro faunal assemblages that diversity and biomass were higher than expected when the frequency of disturbance was low and organic nutrients were high. This is similar to conditions within the OBS structures. They found that the inverse is also true: high frequency of disturbance and low nutrient potential led to lower aquatic invertebrate densities and diversity, a situation comparable to the wave swept shores of Branched Oak Reservoir.

Chironomidae, indicators of eutrophic conditions in lentic systems (Saether 1979), comprised the largest proportion of the total density of organisms sampled lake wide

(>85%), yet they appeared at densities significantly greater within OBS structures in 1999 and 2000 (Figs. 6 and 8). Vrtiska et al. (2003) found that the chironomid population of Branched Oak Reservoir consisted predominately of *Procladius, Chironomus*, and *Cryptochironomus*, genera generally indicative of bottom enrichment and eutrophic conditions (Brinkhurst 1969, Saether 1979). Rasmunssen and Rowen (1997) predicted wave associated sediment accumulation patterns and documented a strong association of *Chironomus* and *Tubifex* at high biomass in epilimnetic depositional conditions with sites with fine sediments (particularly seston) compared to non-depositional sites.

Oligochaeta were ubiquitous throughout the samples, appearing in greater than 50% of all samples, yet contributing less than 5% of total density. Oligochaeta showed only a slight preference for OBS structures, with highly variable monthly differences (Figs. 6 and 8). Often, under hypereutrophic conditions, oligochetes replace chironomids as the dominant organism, yet this did not occur in this reservoir or within OBS structures. While this may indicate a moderate eutrophic increase within the OBS structures, it is also reflective of the fact that Oligochaeta are more adaptable to (former) disturbed environments.

Most other organisms collected (e.g. Ephemeroptera, Hemiptera, Trichoptera, Megaloptera and Odonata) were represented in low to insignificant numbers. These organisms were likely limited by the lack of littoral vegetation and were patchy in distribution. Yet in several of these groups, densities were significantly greater in OBS structures, indicating a preference toward more stable substrates. An example of this can be found in the burrowing mayfly *Hexagenia,* which was once very abundant

(Hergenrader and Lessig 1980), but has dramatically declined at Branched Oak Reservoir (Vrtiska 2003). *Hexagenia* larvae are considered "eutrophication sensitive" (Rasmunssen 1988, Reynoldson et al. 1989), thus densities are generally negatively impacted by sedimentation (Rasmunssen and Rowen 1997). More *Hexagenia* were found in the OBS structures. In an extreme example of habitat alteration and organism habitat selection, the hemipteran Corixidae were found only in year 2000 samples, and only within OBS site 7, a rock-tire bale frontage structure. This location was unique, with a thick floating algal mat (June 2000 through August 2000), where corixids were found. Although not included in the physical survey, it was observed that site 7 had greater sediment retention and was afforded greater protection from wave and predation disturbances. Community compositions were different as well, with low similarity (RI) between the OBS structures and untreated controls.

Fish exclosures were installed in 2000 to address the potential role of predation and disturbance by fish within the new habitat created by OBS structures. White perch (*Morone americana*) is an invasive species that constitutes over 90% of the fish biomass in Branched Oak Reservoir (Ewell-Hodkins 2001). In the Branched Oak exclosures, only two organisms were significantly different from the remainder of the OBS', the predators Sialidae and Trichoptera. While exclosures also had significantly higher densities and low similarity indices compared to OBS sites, this also may have been due to an exclosure related micro-environment, and not solely the exclusion of white perch or other predators. Exclosures developed extensive periphyton growth that rapidly overgrew the side netting, water surface, and benthos, creating a unique habitat not otherwise present at

OBS sites. In a caging manipulation study on marine soft bottom communities, Hulberg and Oliver (1980) found that despite increases of polychaete within the exclosures, the changes were made by animals responding to cage induced habitat modifications, especially unique habitats created, sediment deposition, and erosion, rather than by predation.

MANAGEMENT RECOMMENDATIONS

The primary principle of the offshore breakwater structure is to intercept and dissipate wave or ice energy before it disrupts near shore and shoreline sediments. Reduction of these disruptions creates a new equilibrium profile of the near shore and shoreline. In effect, the result emulates what occurs in natural lakes where *in situ* soils and vegetation are in relative stasis with the impinging energy. While an absolutely static shoreline is improbable in both natural and human-made water bodies, offshore breakwater structures can be employed to create more desirable conditions.

Also important are the human considerations involved with the use of offshore breakwater structures. Given that lakes and reservoirs naturally attract people, OBS-related safety is important. The location of OBS' in Branched Oak recognized the multiple uses that the reservoir presently serves. Structures were placed in locations not generally utilized by high speed motor boats. Regardless, reflective warning signs were place at all structures. Additionally, the aesthetic appeal of the structures, and of what they create, are important concerns. While limited as a fishing platform, they create a unique habitat that is popular with fishermen.

The cost of A-jacks is high compared to other methods of breakwater construction. At approximately $855 US per linear meter of shoreline protected, this is about tenfold higher than a basic rip-rap reef (e.g., similar to the tire bale OBS'). A-jacks are labor intensive in their construction and placement and they require special heavy equipment to manipulate. A-jack structures are also impractical to repair if damaged or displaced.

In spite of the limitations, A-jacks are an effective tool at creating a desirable shoreline complex. Most importantly, the technique of offshore breakwater structures, regardless of design, can be employed to enhance and preserve lakes.

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Table 1.---Summary of the net loss or gain of sediment (m^2) for, untreated control and offshore breakwater treatments, three zones and zone means.

		Bank	Near-Shore	Offshore	Transect Total	Bank	Near-Shore	Offshore	Transect Total	Bank	Near-Shore	Offshore	Transect Total
Untreated			Site 8				Site 10				Site 12		
Transect	1	-0.50	-1.15	-1.72	-3.37	-7.23	-2.76	-3.40	-13.39	-2.04	-1.39	-1.20	-4.63
	2	-0.30	-1.12	-1.66	-3.08	-5.73	-1.42	-2.99	-10.14	-1.10	-1.29	-1.22	-3.61
	3	-0.19	-0.82	-1.18	-2.19	-3.99	-1.47	-4.29	-9.75	-1.05	-1.60	-1.66	-4.31
	4	-0.14	-0.67	-0.35	-1.16	-5.05	-1.25	-2.31	-8.61	-0.71	-1.00	-1.21	-2.92
	5	-0.22	-1.26	-1.69	-3.17	-5.81	-1.97	-3.57	-11.35	-0.81	-1.35	-0.69	-2.85
Zone Mean		-0.27	-1.00	-1.32		-5.56	-1.77	-3.31		-1.14	-1.32	-1.19	
Offshore Breakwater			Site 9				Site 11				Site 13		
Transect	1	0.36	1.23	4.14	5.73	-0.57	0.08	-0.06	-0.55	-0.81	-0.56	0.82	-0.55
	2	-0.30	0.49	2.85	3.04	-1.06	-0.08	-1.44	-2.58	-0.64	-0.56	-0.07	-1.27
	3	-0.50	0.76	1.21	1.47	-1.79	-0.23	0.15	-1.87	-2.21	-0.44	-0.17	-2.82
	4	-0.25	0.09	0.55	0.39	-1.47	0.06	0.07	-1.34	-0.69	-0.76	-0.72	-2.17
	5	-0.24	0.05	0.69	0.50	-1.84	-1.10	-1.66	-4.6	-0.65	-0.05	-0.08	-0.78
Zone Mean		-0.19	0.52	1.89		-1.35	-0.25	-0.59		-1.00	-0.47	-0.04	

Table 2.---Benthic macroinvertebrates from Branched Oak Reservoir. The number of selected organisms collected in the samples (n), and the density of organisms (m^{-2}) for 1999, 2000 and fish exclosures of 2000.

Taxa	1999		2000		2000 Exclosure	
	n	m^{-2}	n	m^{-2}	n	m^{-2}
Diptera						
Chironomidae	8,380	440	9,564	627	1,260	2,583
Ceratopogonidae	30	2	113	6	24	49
Ephemeroptera						
Ephemeridae	104	7	47	2	36	74
Hemiptera						
Corixidae	0		183	10	0	
Megaloptera						
Sialidae	0		3	0	35	72
Odonata						
Libellulidae	0		6	0	0	
Oligochaeta	352	23	962	51	61	125
Tricoptera	4	0	3	0	20	41
TOTAL	8,870	472	10,881	696	1,436	2,944

Table 3.---Summary of Ruzicka's similarity index by month and annually.

	April	May	June	July	August	Sept.	October	Annual
Treatment versus								
1999 Untreated		47	84	42	65	19	25	47
2000 Untreated	17	24	31	78	31	77	34	41
2000 Exclosure	18	58	22	20	58	22	9	30

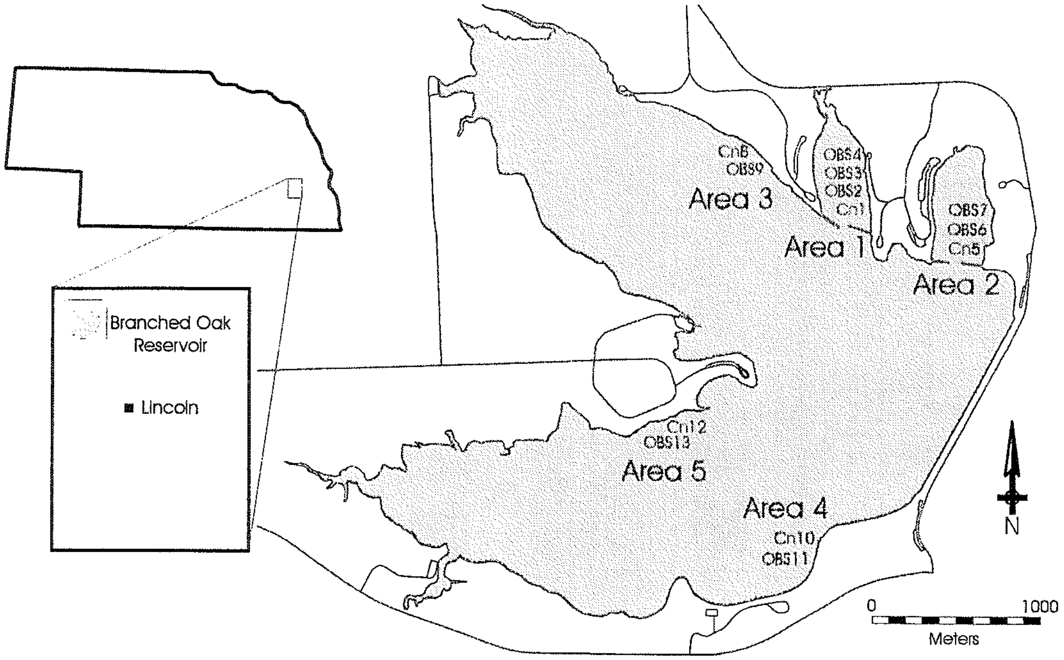

Figure 1.---Map of Branched Oak Reservoir, showing study area, offshore breakwater structure (OBS) and untreated control (Cn) locations. Inset of Nebraska map showing location of Branched Oak Reservoir.

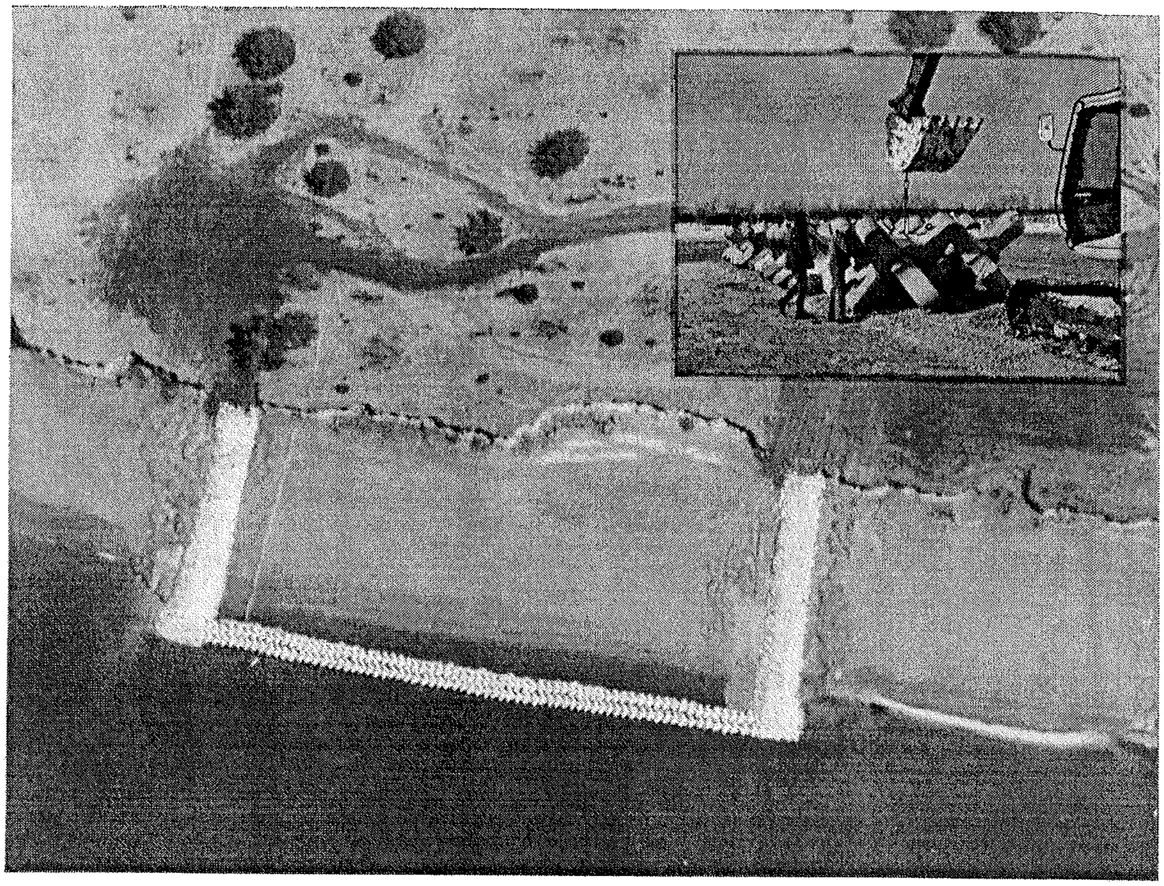

Figure 2.---Aerial view of offshore breakwater structure 11. Inset photograph of A-jacks being placed to form the offshore breakwater structure.

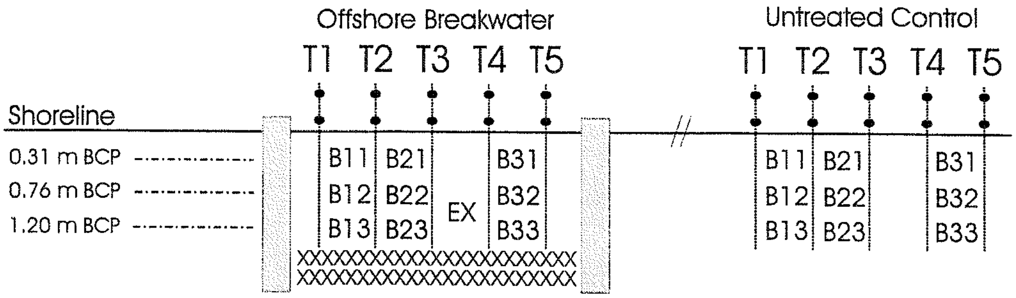

Figure 3.---Offshore Breakwater Structure study area, showing survey transects (T,n), transect benchmarks (•), benthic sample location (B,nn), exclosure location (EX), and relative shoreline bathymetric elevations below conservation pool (BCP).

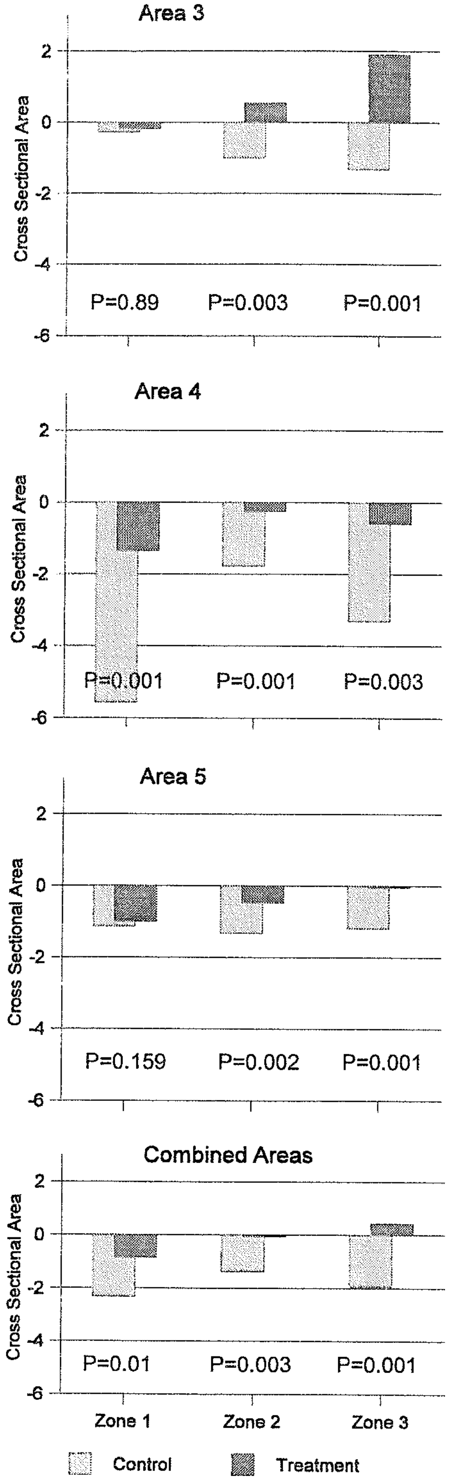

Figure 4.---Mean cross-sectional area (m^2) of loss or gain for zones 1 through 3, in study areas 3 through 5, and combine areas 3 through 5, untreated control and offshore breakwater treatment.

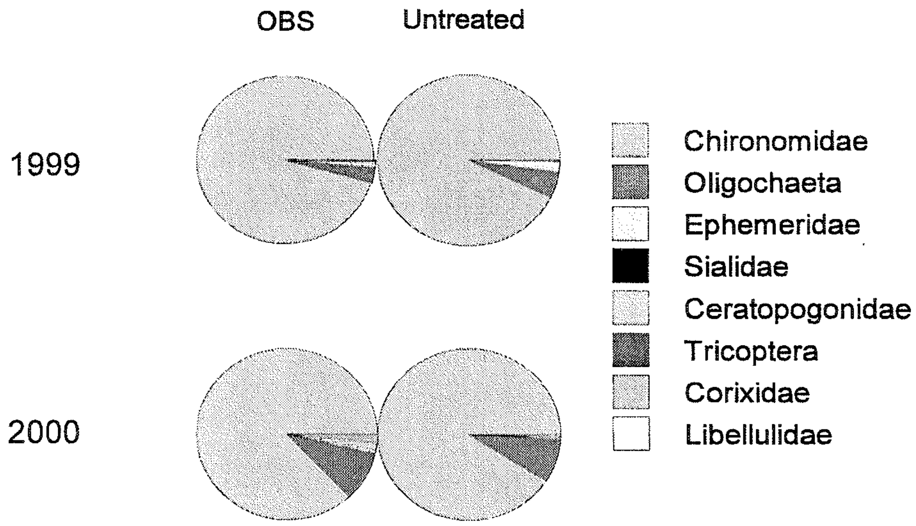

Figure 5.---Relative abundance of benthic macroinvertebrates collected in offshore breakwater structure (OBS) and untreated control sites for 1999 and 2000.

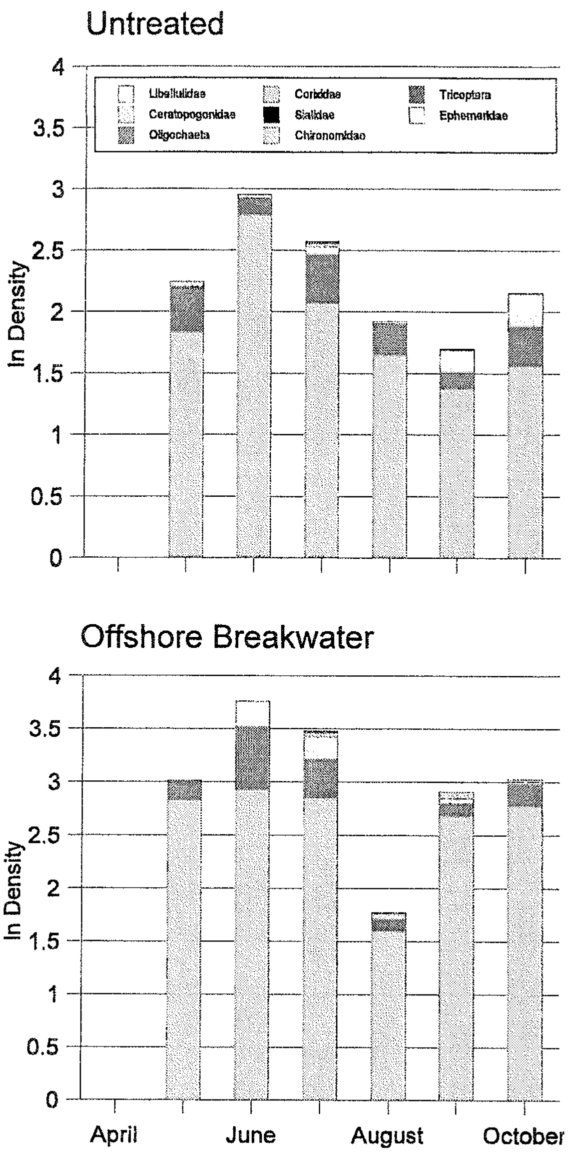

Figure 6.---Natural log (ln) of mean density of aquatic invertebrates in 1999.

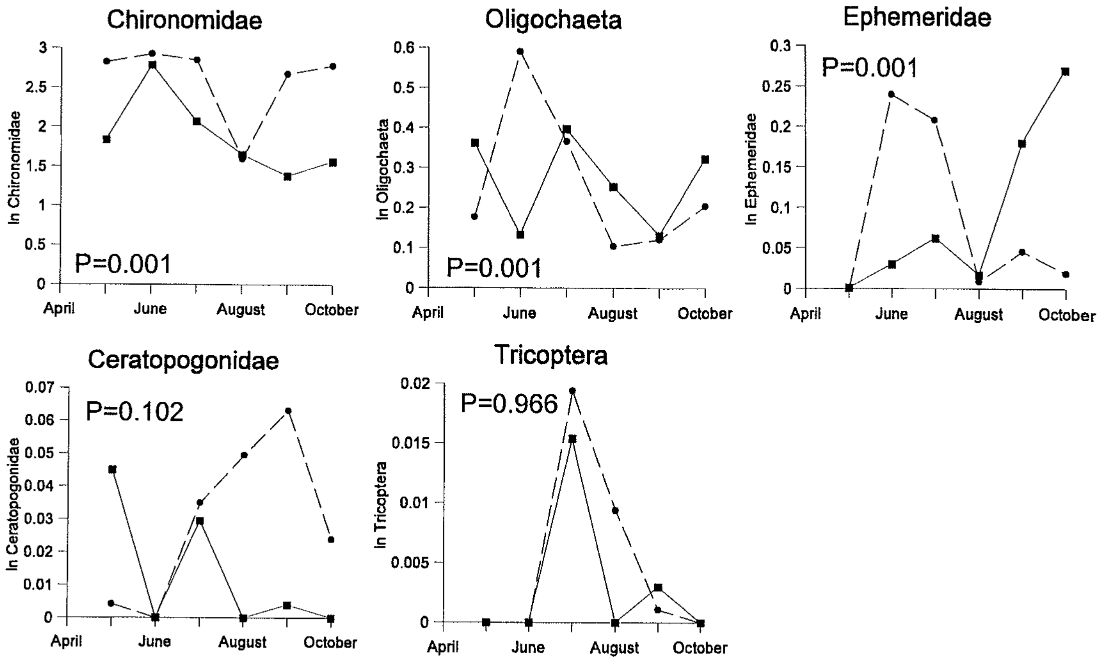

Figure 7.---Natural log (ln) of the density (no.m $^{-2}$) of selected organisms for 1999 untreated control (■) and OBS treatment (•) by month.

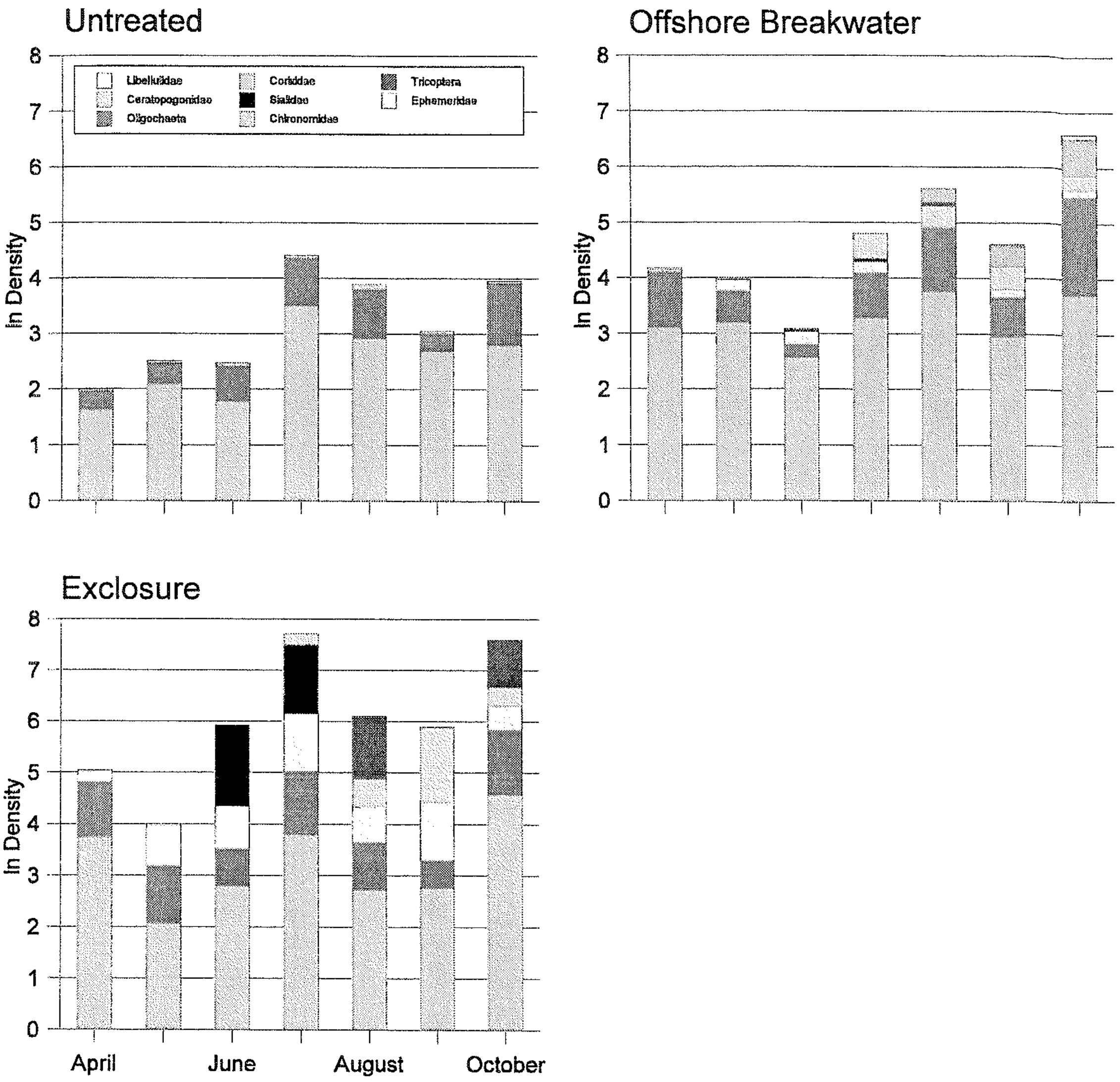

Figure 8.---Natural log (ln) of mean density of aquatic invertebrates in 2000.

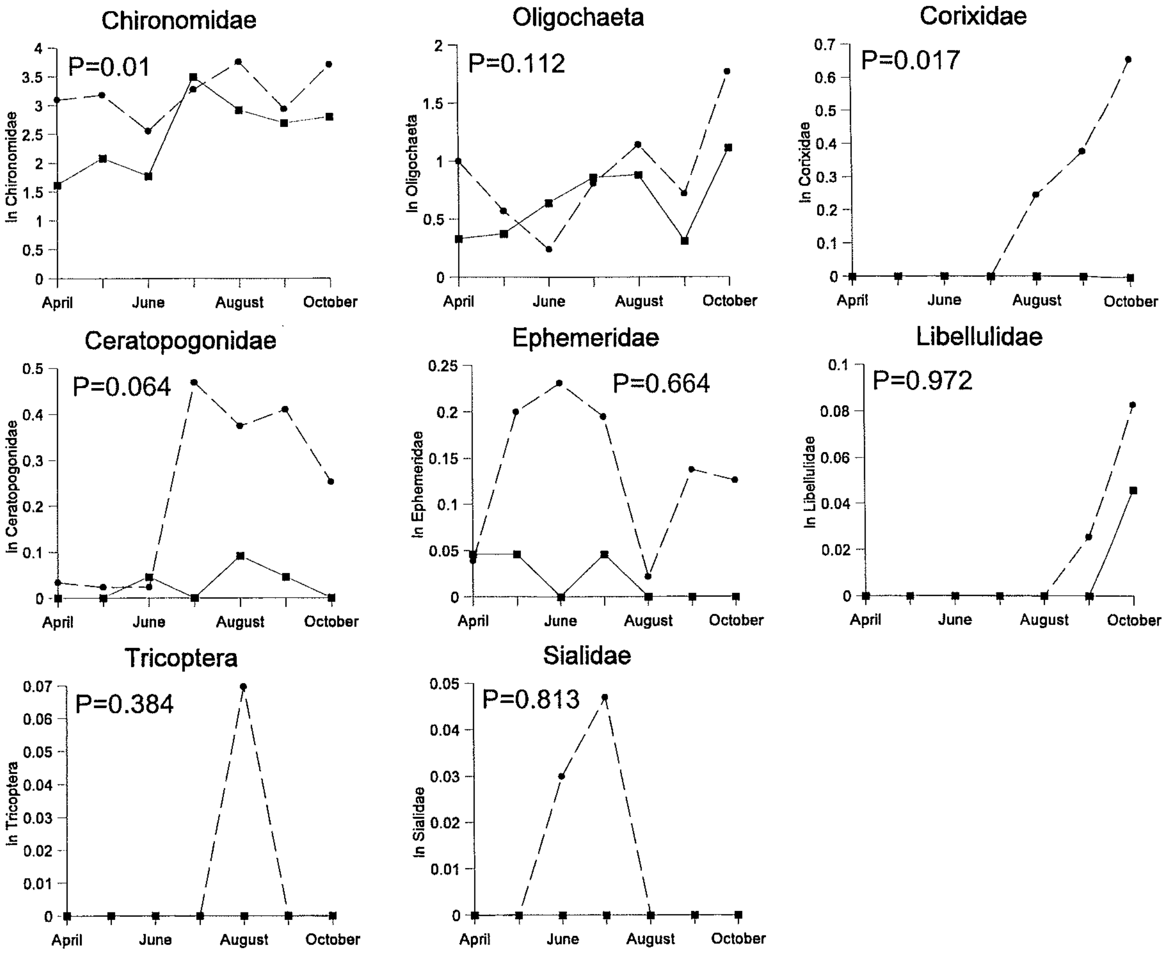

Figure 9.---Natural log (ln) of the density (no.m $^{-2}$) of selected organisms for 2000 untreated control (■) and OBS treatment (•) by month.