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AN EVALUATION OF SEVERAL BENTHIC BARRIERS

FOR AQUATIC WEED CONTROL

presented by

G. Douglas Pullman

has been accepted towards fulfillment
of the requirements for

Doctor of Philosophy degree in Fisheries and Wildlife

Clarence D. McNabb
Major professor

Date December 2, 1986

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AN EVALUATION OF SEVERAL BENTHIC BARRIERS FOR AQUATIC WEED CONTROL

By

G. Douglas Pullman

A DISSERTATION

Submitted to
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ABSTRACT

AN EVALUATION OF SEVERAL BENTHIC BARRIERS
FOR AQUATIC WEED CONTROL

By

George Douglas Pullman

A benthic barrier is a compound, fabric, or device that can be placed in contact with a sediment or the bottom of a water body, that is designed or intended to function as a barrier to light, plant growth, or the migration of ions, compounds, or any substances from one side of the barrier to the other. Several functional characteristics of benthic barriers are used to evaluate the relative merit of these devices for aquatic weed control. The ideal functional characteristics of benthic barriers include the following: benthic barriers should be opaque, permeable by gases, denser than water, durable, inhospitable to the colonization of periphyton, selectively permeable to ions, be of appropriate color or texture so as to not be a visual nuisance, inexpensive, and easy to install. Aquascreen™, Dartek®, Texel®, and a new silicone benthic barrier were evaluated *in situ* and in the laboratory for relative gas and ion permeability, plant attachment or penetrations, and

light transmission. The ecosystem impacts associated with the application of benthic barrier are also considered.

Aquascreen™ was both gas and ion permeable. It was not sufficiently opaque to control aquatic weeds by shading in shallow water. Aquascreen™ appears to be an ideal substrate for the colonization of filamentous epiphytes. Field tests indicated that heavy filamentous algal colonization could severely restrict gas permability.

Dartek® was neither gas nor ion permeable. It was opaque and a relatively poor substrate for epiphyte colonization. This material is usually slitted to permit the escape of benthigenic gases. These slits may serve as colonization or penetration sites for rooted plants.

Texel® was only moderately permeable to both gases and ions. It was not sufficiently opaque to attenuate light to a point where submersed plants were controlled in shallow water. It was an excellent substrate for the colonization of epiphytes which tended to greatly inhibit the gas permeation potential of the barrier over time.

The silicone benthic barrier was opaque and gas permeable, but was not ion permeable. It was not a good substrate for the colonization of periphyton. It more closely approximated the ideal functional characteristics of a benthic barrer than any of the other devices.

Many of the ecosystem impacts associated with the application of benthic barriers are similar to those associated with other types of aquatic vegetation management, i.e. habitat destruction. Benthic barriers applications are unique, however, in that they tend to inhibit the below barrier rate of sediment diagenesis by excluding the typical littoral zone flora and fauna and impeding gas and ion fluxes.

To My Family

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TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

Excessive aquatic plant production has a devastating impact on the economic value and recreational utility of water resources. Dense stands of hydrophytes may constitute an aesthetic nuisance, interfere with recreational pursuits and transportation, clog water intakes and plug aquaducts, harbor disease vectors, cause flooding, and waste large volumes of valuable irrigation water directly, via transpiration, and indirectly, by impeding water flows. Aquatic herbicide applications are perhaps the most commonly used means of aquatic plant control. Recent public opinion, rising costs, increasing regulatory pressures, and questions regarding the ecological implications of herbicide applications have stimulated the search for alternative nuisance plant management tools. The demand for innovative, integrative, and ecologically sound aquatic weed control strategies is increasing. This has prompted widespread application of benthic barriers for control of submersed hydrophytes.

A benthic barrier is any compound, fabric, or device that can be placed in contact with a sediment or the bottom of a water body, that is designed or intended to function as a barrier to light, plant growth, or the exchange of ions or compounds between lake sediments and the water column. There are two basic types of benthic barriers; chemical, used to seal sediment surfaces and sheets of various materials that serve as physical barriers. This study was intended to evaluate the efficacy of several physical benthic barriers for the control of nuisance aquatic vegetation and identify potential ecosystem impacts associated with their application.

Three commercially available benthic barriers, Aquascreen™ (formerly manufactured by Menardi-Southern Corporation, Augusta, Georgia, USA, availability limited), Dartek® (Du Pont Canada, Inc., Mississauga, Ontario, Canada), Texel® (Texel, Inc., Quebec, Canada), and a silicone benthic barrier, developed jointly by the Dow Gardens and Dow Corning Corporation, Midland, MI, were selected for testing and evaluation. Aquascreen™ is a PVC coated fiberglass mesh fabric that resembles window screen. Dartek® is a perforated, black-pigmented, nylon that resembles a black plastic tarpoline. Texel® is a new polypropylene and polyester fiber blend, needle punched fabric that resembles a heavy felt. The silicone benthic barrier is a latex silicone rubber laminated to a non-woven polypropylene or polyester fabric.

One of the earliest publications concerned with the use of benthic barriers for aquatic weed control is attributed to Alm (1930 in Dawson and Hallows, 1983). Another early article described the use of plastic sheets to prevent water loss by seepage in irrigation canals (World Crops, 1959). Aquatic weed control was mentioned as an "additional benefit" associated with such installations.

Polyethelene sheets were among the first materials to be used specifically as benthic barriers for aquatic weed control. They were used as both direct and indirect means of aquatic plant management. For example, polyethylene sheets have been used as an indirect means of lake vegetation management by being applied as a sealant over the vast store of plant nutrients contained in some hydrosoils (Born et al., 1973; Dunst et al., 1974; Engel and Nichols, 1984). They have also been used to control aquatic nuisances directly by shading or compression (Armour et al., 1979; Bulthuis, 1984). They may be placed over existing plant communities or applied prior to plant emergence. However, polyethylene sheets possess several characteristics that impair their utility as a benthic barrier. Because the specific gravity of polyethylene is 0.92, a large amount of ballasting is required to secure it to a substrate. Also, polyethylene is gas impermeable and must be perforated to allow benthigenic gases to escape and prevent ballooning.

Armour et al. (1979) discovered that specific habitats were destroyed by the removal of the macrophytic architecture and that sediment-water column gas and ion fluxes were impaired by the application of the plastic sheets. These impacts were considered insignificant because of the size of the application site relative to the total lake area.

Polyvinyl chloride (PVC) sheets have also been used for aquatic weed control (Armour et al., 1979) with results similar to those associated with polyethylene benthic barriers.

An inert synthetic rubber, Hypalon (manufactured by E.I. DuPont de Nemours and Co., Wilmington, DE, USA) was tested as a benthic barrier material by Armour et al., (1979). Hypalon is denser than water and was, therefore, easier to apply and secure to the sediments than polyethylene benthic barriers. Like polyethylene, it too must be perforated to allow the escape of sediment generated gases.

Dartek® is a negatively buoyant, pigmented, perforated, nylon film that is manufactured specifically as a benthic barrier. It was shown to be effective as a post emergent control of nuisance aquatic macrophytes in portions of Lake Washington and Green Lake, Washington (Perkins, 1984). Dartek® is denser than water but, like polyethylene, it must be perforated to permit the escape of sediment generated gases. Plant growth was observed through approximately six percent of the slits seven days after the initial application (Perkins, 1984). These plants were apparently eliminated by crayfish grazing, however. No indication was given as to what percent areal surface coverage may be expected by canopy forming plants that penetrate the slits in Dartek®.

Mayer (1978) was the first to document the use of polyvinyl chloride (PVC) coated fiberglass screening for the direct control of aquatic weeds. These benthic screens were denser than water and penetrable by benthigenic gases. Mayer evaluated screens with varying aperture densities in Chautauqua Lake, New York. He determined that screens with an aperture size of 1 mm^2 and 64 apertures/cm^2 were the most effective for aquatic weed control. The shading efficiency of the 64 aperture/cm^2 screens was approximately sixty percent (Mayer, 1978; Pullman and Craig, 1982). Mayer fastened the screens to the lake bottom with metal "T" - bars and bricks. Vegetal obstruction of the water column was eliminated immediately. Although the screens tended to bulge when placed over dense plant stands, the vegetal architecture collapsed within three weeks after screen application. Plants below the screens decomposed within one month of the initial application. Total macrophyte biomass above the screens was ninty-five percent less than that above the untreated control areas. Mayer concluded that fiberglass screen benthic barriers effectively controlled aquatic plant growth by shading and space limitation and that there were no adverse ecosystem impacts associated with their use.

Mayer (1978) did note, however, that some plants penetrated the 64 aperture cm^2 benthic screens. These plants appeared to be dwarfed and their total biomass equaled only five percent of the biomass that was present in adjoining control plots. Never-the-less, Mayer suggested that the screens be cleaned or moved annually to achieve multiple year controls.

All but one of the fiberglass screen evaluations in Lake Chautauqua (Mayer 1978) were initiated in the autumn or near the end of the peak growing season of the target plant species. The rapid collapse of the vegetal architecture could easily be attributed to the timing of the application as it coincides with normal seasonal senescence and collapse phenomenon. Furthermore, the degree of screen penetration by submersed plants may have been underestimated because expected total plant production would be low in the autumn.

A 64 aperture/cm^2 PVC coated fiberglass screen, Aquascreen™, was applied to a dense bed of *Elodea canadensis* Rich. in Michx. in the Dow Gardens ornamental pond, Midland, MI, during July, 1979 (Pullman and Craig, 1982). The plant bed was so dense that efforts to secure the screens to the pond bottom with wire stakes and bricks were unsuccessful. Water depths at application sites ranged from 0.1 to

1.5 m. There appeared to be no reduction in plant biomass beneath the screens six weeks after application. The screens were subsequently removed as they constituted an aesthetic nuisance. Pullman and Craig (1982) concluded that a shading efficiency of sixty percent was not adequate to control aquatic weed growth and that the primary mode of plant control by these screens must be compression and space limitation.

Aquascreen™ was deployed as a pre-emergent aquatic weed control in the Dow Gardens pond in 1980. Although this application was successful for macrophyte control during the first year post application, the screens supported a nuisance density mat of filamentous algae. Furthermore, the colonization of filamentous algae on Aquascreen™ appeared to greatly restrict penetration of the barriers by benthigenic gases causing them to balloon in several places. During the second year after the initial application the screens were completely covered with filamentous algae, thin-leaved pondweeds (*Potamogeton pectinatus* & *P. foliosus*) and elodea. There was no apparent difference between the Aquascreen™ treatment areas and adjacent non-treated areas.

Aquascreen™ was applied as both a pre- and post-emergent control of *Myriophyllum spicatum* L. in Lake Washington, Washington (Perkins et al., 1979; Perkins, 1980). One of the objectives of this study was to determine how long the barrier must be in place to eliminate *M. spicatum*. Plant stands were immediately compressed to the sediments, thereby eliminating the water column obstruction caused by the nuisance plants. *M. spicatum* biomass increased beneath the screens during the first month following application. During subsequent months, the screens began to settle to the bottom of the lake as *M. spicatum* began to senesce beneath the screens. Perkins et al. (1979) considered this slow die-back phenomenon to be an advantage, however, since any potentially deleterious impacts associated with sudden plant senescence and decay were avoided. Perkins (1980) also discovered that three months were required to reduce the density of viable milfoil root crowns in Lake Washington to a level of control that allowed the screens to be moved to another area. Hence, the timing of Aquascreen™ applications could be planned so that a single screen could be applied to several different areas during a single season.

Aquascreen™ application impacts on water column chemistry was evaluated in field, field exclosure, and laboratory experiments by Perkins et al. (1979), Perkins (1980), and Boston and Perkins (1982). Although oxygen concentrations were depressed above Aquascreen™ in the exclosure experiments, it was concluded that dilution from adjacent areas would negate any water column impacts associated with actual field applications (Boston and Perkins, 1982). Phosphorus concentrations were also observed to be elavated above Aquascreen™ in the field exclosure experiments. From these experiments, it appeared that Aquascreen™ was both gas and ion permeable.

Engel (1984a and b) installed Aquascreen™ in Cox Hollow Lake, Wisconsin. Weeds were effectively controlled during the first year of application. Sediments collected on the upper surfaces of the barriers, however, and diminished the gas permeability of the devices. Consequently, additional ballasting was required to prevent ballooning. Plants were observed to take root in sediments that collected in pockets on the barriers. Although plant production above the barriers was less than adjacent areas during the second year of application, plant control was not considered to be adequate. Engel suggested that Aquascreen™ be removed, cleaned and reinstalled annually.

Sections of benthic barriers were periodically removed during the Cox Hollow evaluations to determine the impact of such applications on the macro-benthos (Engel, 1984a and b). There was an apparent inverse relationship between total sub-barrier macrobenthos biomass and the length of time that the device had been in place.

Texel® is a polypropylene/polyester fiber blend, needle punched geotextile that is commonly used for road bed stabilization. A dark colored variant of this material, TAC 210, is manufactured specifically for use in aquatic weed control. It has been used successfully for aquatic plant control in the Dow Gardens (Pullman, unpubl.) and Canada (Truelson, 1984 and 1986; and Wallis, 1985 and 1986). Although plant nuisances may be immediatly removed from the water column, plants may persist for weeks below the device. A serious shortcoming associated with Texel® is that plants are able to adhere to the upper surface of the material. In areas where plant fragment loading is heavy, infestations have reached nuisance densities in a single growing season (Truelson, 1986).

A laminated silicone rubber benthic barrier was first successfully deployed in the Dow Gardens' pond for the post-emergent control of *E. canadensis* during the summer of 1982. This was a latex silicone rubber laminated (3.78 to 4.00 L m^{-2}) to a 120 g m^{-2} (3.5 oz yd^{-2}), nonwoven, needle-punched, polypropylene fiber, geotextile fabric. The specific gravity of the final product was assumed to be between 1.0 and 1.1 but was not known precisely because of the nature of the fabric. Other combinations of fabric weight and silicone laminant thickness were also evaluated during these initial tests but were rejected for reasons of economics or weight.

The silicone benthic barriers floated briefly on the water surface before settling to the bottom of the pond. They were secured to the substrate with gladiolus stakes and ballasted with bricks and stones. These silicone benthic barriers were of sufficient density to collapse the plant canopy into contact with the pond bottom and thereby remove the nuisance plants from the water column. Ballooning was not observed nor was plant penetration detected during the remainder of the growing season.

The silicone benthic barriers were removed at the end of the first growing season. Vascular plant recolonization rates of silicone barrier treated areas during the following year were observed to be significantly less than adjacent areas that had been defoliated by shallow dredged during the same treatment period. A similar response was observed by Jones and Cooke (1983 and 1984) for burlap during the year following the disappearance of the fabric. Silicone benthic barrier applications appeared to be a successful means of aquatic weed control.

These studies point to a number of advantages and disadvantages associated with the use of benthic barriers for aquatic weed control.

Some of the advantages include the following. Benthic barrier treatment areas may be strictly delimited because of the physical nature of the devices. Relief from excessive macrophyte production is immediate. Benthic barriers may be applied, in many instances, without special training or equipment and their use is unregulated in most states. Most benthic barriers may be used in successive years and may be used effectively in integrated aquatic vegetation management plans. Benthic barriers may also be used to impede the release of plant nutrients from sediments or the decaying plants over which they have been placed so that these compounds do not stimulate further nuisance plant production. Finally, the application of a benthic barrier may alter sediment chemistry. This could result in the accumulaton of anaerobic metabolites, depletion of nutrients, and the reduction of redox potentials. Sediment chemistry may be altered to such a degree that subsequent recolonization of treated areas by rooted plants may be inhibited, even after the device is removed.

There are a number of disadvantages associated with the use of benthic barriers for aquatic weed control. All successful aquatic vegetation management strategies, including benthic barrier applications, eliminate the vegetal architecture of the area to which they are applied. Consequently, the floristic and faunistic character of the treatment area will be altered. Benthic barriers may also impede the normal exchange of substances between lake sediments and the overlying water column and thereby alter the bio-geochemistry of the sediments. This may be considered either a disadvantage or an advantage, depending upon the application. Large benthic barrier applications also require a large initial capital investment in materials. Because most benthic barriers may be used in subsequent years with little or no additional capital outlay, use may be quite cost effective when the life of the device is considered. Finally, it is essential that benthic barriers be securely fastened to the substrate. Should a benthic barrier become dislodged and transported by currents, they may constitute a severe nuisance or threat to any cultural uses associated with the water resource to which they have been applied.

The Ideal Benthic Barrier

This study was designed to evaluate several devices for use as benthic barriers for aquatic macrophyte control. The following characteristics describe an ideal benthic barrier and are used as a standard for comparison for the following studies.

1. *Benthic barriers should be opaque.* An opaque device may be used to control nuisance aquatic plant growth directly by shading.

2. *Benthic barriers should be permeable by gases.* Gases such as carbon dioxide, methane, and hydrogen sulfide are commonly released from sediments and decaying weed masses as a natural consequence of organic matter mineralization (diagenesis). These gases may accumulate below impermeable devices causing them to be buoyed to the surface of the water body.

3. *Benthic barriers should be denser than water.* Although some devices have been used that are less dense than water, greater density

simplifies the application of benthic barrier devices by diminishing the need for ballasting.

4. *Benthic barriers should be durable.* Benthic barrier applications require a larger initial capital investment than other common aquatic weed management strategies. A relatively high initial material expenditure (relative to herbicide application) is offset, however, by the ability to use the materials in successive years (Cooke et al., 1986). Durability therefore becomes an important economic factor. Furthermore, benthic barriers should be resistant to tearing so that currents do not dislodge the devices and transport them to areas where they might constitute a hazard or nuisance. They should withstand extremes in temperature, microbial attack, and UV photo-degradation.

5. *Benthic barriers should be resistant to the colonization of epiphytes.* Personal observations of the use of several "mesh-type" benthic barriers have revealed that epiphyte colonization may inhibit the permeation of benthigenic gases and thereby cause the barrier to become buoyant.

6. *Benthic barriers should be selectively ion permeable.* It would be desirable to prevent the migration of plant nutrients, particularly phophorus, from sediments to the overlying water column so that these compounds are not recycled for the development of other plant nuisances. Conversely, it would be desirable for a benthic barrier device to permit the escape of sediment generated metabolites, and the import of suitable electron acceptors such as nitrate and sulfate, to facilitate more complete sediment metabolism (Armstrong, 1982).

7. *Benthic barriers should not detract from the aesthetic qualities of the water body to which they are applied.* They should be of appropriate color or texture so that they blend into the surrounding ecosystem.

8. *The cost of benthic barrier installation should not be prohibitive for general use.* Although the initial material costs associated with the use of benthic barriers are considerably more than those associated with the application of several other aquatic weed control strategies, most benthic barriers are cost effective when these costs are averaged over the life of the device.

9. *Benthic barriers should be relatively easy to install.* Installation effort is intimately linked to the density, durability, drapability, and rigidity of the device.

The goal of this study is to determine the relative efficay of several benthic barriers as a means of aquatic weed control. Although environmental variables may dictate the selection of one device for a specific application and another device for a different site, the most effective device would be one that satisfies most or all of the criteria outlined as the nine ideal characteristics of a benthic barrier. Such a benthic barrier could be applied to the broadest range of conditions. Some of these criteria are best evaluated by subjective judgments, such as application effort and aesthetic characteristics. Other criteria can be evaluated empirically and are tested in this study. These include tests of shading efficiency, gas and ion permeability, and the epiphyte colonization potential of the upper surfaces of several commercially viable benthic barrier devices.

METHODS

Benthic barrier light transmission studies were conducted to rank these devices according to their relative opacity, an ideal characteristic of benthic barriers. Solar radiation, from 400-700 nm, that was found to penetrate Texel®, Aquascreen™, Dartek®, and silicone bottom barriers was measured with twin Li-Cor 188-B quantum photometers (Li-Cor, Inc., Lincoln, NE, USA). Simultaneous readings were taken with cosine corrected sensors. One sensor was covered with a benthic barrier while the adjacent sensor was left uncovered. The percent difference between the covered and uncovered (control) sensor was taken as the shading efficiency of the various benthic barriers.

Field studies were conducted with benthic barriers to evaluate the gas permeability characteristics associated with each of the various devices. These experiments were used to ascertain the relative "ballooning potential" and sub-barrier ecosystem impacts associated with the devices. Twelve quadrats, 1 m^2, were made from 2.54 cm X 0.32 cm steel bars (1" X 1/8"). Aquascreen™, Dartek®, Texel®, and the silicone benthic barrier were fastened to the steel bar frames for a total of three replications of each benthic barrier treatment. These were placed over a dense homogeneous bed of *Chara sp.* in the Herbert Dow estate pond, Midland Co., Michigan, during the summer of 1986. Gas bubble collectors were constructed from standard ASTM schedule 40 PVC pipe and PVC pipe fittings and 20 cm dia. polyethylene funnels (Figure 1). The bubble collectors were filled with pond water and anchored 0.5 m above the center of each benthic barrier

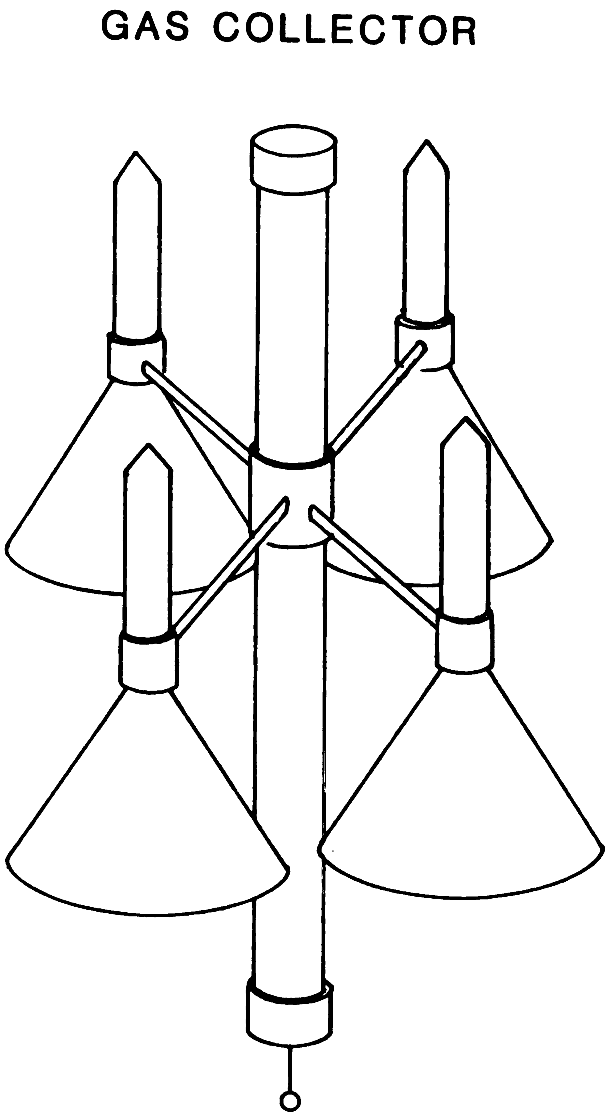


Figure 1. An *in situ* gas bubble collector.

quadrat. Figure 1 shows that four replicate measurements could be made from each collector. Sediment generated gas volumes were recorded every two to three days by measuring the volume of water displaced by bubbles in the collectors. Monitoring was discontinued after three weeks due to the accumulation of periphyton on the upper surfaces of all the bottom barriers and the potential for oxygen gas production by these plants.

A diffuser (100μm pore size) was placed below the center portion of each treatment quadrat and connected to a 0.64 cm diameter clear plastic tube to facilitate water sampling from beneath each of the plots. The diffuser was coated with Dow Corning 5700 anti-microbial agent (Dow Corning Corporation, Midland, MI) to inhibit biofouling. Water samples were taken from below the quadrats by connecting a hand vacuum pump and one liter receiving vacuum flask to the tubing and drawing water through the diffuser. Fifty mL samples were injected with a sixty mL plastic syringe into sixty mL glass serum bottles fitted with butyl rubber syringe septa. Bottles were nitrogen rinsed, then evacuated before use. Gas concentrations were determined from samples of the 10 mL "head-space" that remained above the 50 mL water samples in each of the 60 mL serum bottles. Methane, carbon dioxide, and oxygen concentrations were analyzed with a Gow-Mac model 550 (Gow-Mac, Inc., Bridgewater, NJ, USA) gas chromatography system fitted with a dual channel thermoconductivity detector. A gas tight syringe was used to inject each one hundred μl sample into the gas chromatograph. The individual gases were separated on an Altech CTR-1 concentric poropak N/molecular sieve column (Alltech-Applied

Science, Deerfield, IL, USA). Helium was used as the carrier gas at a flow rate of 115 mL min^{-1}. The injector and column were maintained at ambient temperatures while the detector was maintained at 100° C. Chromatograms were analyzed with a Hewlett-Packard model 3392B (Hewlett -Packard Corporation, Corvallis OR, USA) chromatography integrator. Results were used to compute the dissolved gas concentrations in the water samples taken below the barriers. Significant differences were determined by one-way ANOVA techniques.

Preliminary observations indicated that periphyton colonization of benthic barriers reduced gas permeation rates causing them to become buoyant. Periphyton areal colonization studies were conducted to determine a relative colonization potential for each of the devices. Circular discs (7.5 cm dia.) were made from Aquascreen™, Dartek®, Texel®, and the silicone benthic barrier and cemented to the tops of gladiolus stakes. Three replicate treatments of each barrier were placed randomly within a rectangular grid system (1.0 m X 0.75 m) and submerged to a depth of 0.5 m in the Dow Gardens Pond such that the disks were oriented in a plane that was parallel with the water surface. The grid system was installed in the pond during the first week of July 1985 and removed the second week of April 1986. The percent areal coverage of each of the benthic barriers by periphyton was estimated by visual approximation at 45X magnification with a Unitron model ZSB stereoscopic dissecting microscope.

Benthic barrier ion permeabilities were evaluated in two controlled laboratory experiments. Fifteen ion diffusion test units were constructed from standard schedule 40, 20.32 cm (8") diameter PVC pipe and pipe fittings (Figure 2). Each test unit was divided into an upper and lower chamber by cementing a barrier into the coupling that joined the ends of a unit. The upper and lower chambers contained approximately 8.5 and 8.0 L, respectively. Both the upper and lower chambers contained two valved ports through which they could be spiked, sampled, or purged. An inverted graduated cylinder was affixed to the top of each diffusion test unit to enable measurement of evolved gas volumes. A syringe septum was located at the top of each graduated cylinder to facilitate gas sampling. The diffusion test units were randomly assigned to a position in one of three water baths that were used to maintain a constant temperature of 15° C in all treatments and controls. Each water bath was large enough to contain five diffusion test units.

The impact of benthic barriers on water column/desiment anion partitioning or sediment sealing was evaluated as follows. Treatments were assigned to each of the diffusion test units in a randomized complete block design. Each treatment and control was replicated three times. The treatments were: Texel®, Dartek®, Silicone, and Aquascreen™. The lower chamber of each diffusion test unit was spiked with a solution of anions comprised of nitrite, nitrate, phosphate, and sulfate. An electrical gradient was applied to each diffusion test unit to encourage more rapid movement of anions from the lower to the upper chamber. This was imposed using a conventional, variably adjustable DC power supply. Approximately 6 volts were applied to each unit.

BENTHIC BARRIER GAS/ION
PERMEABILITY TESTING APPARATUS

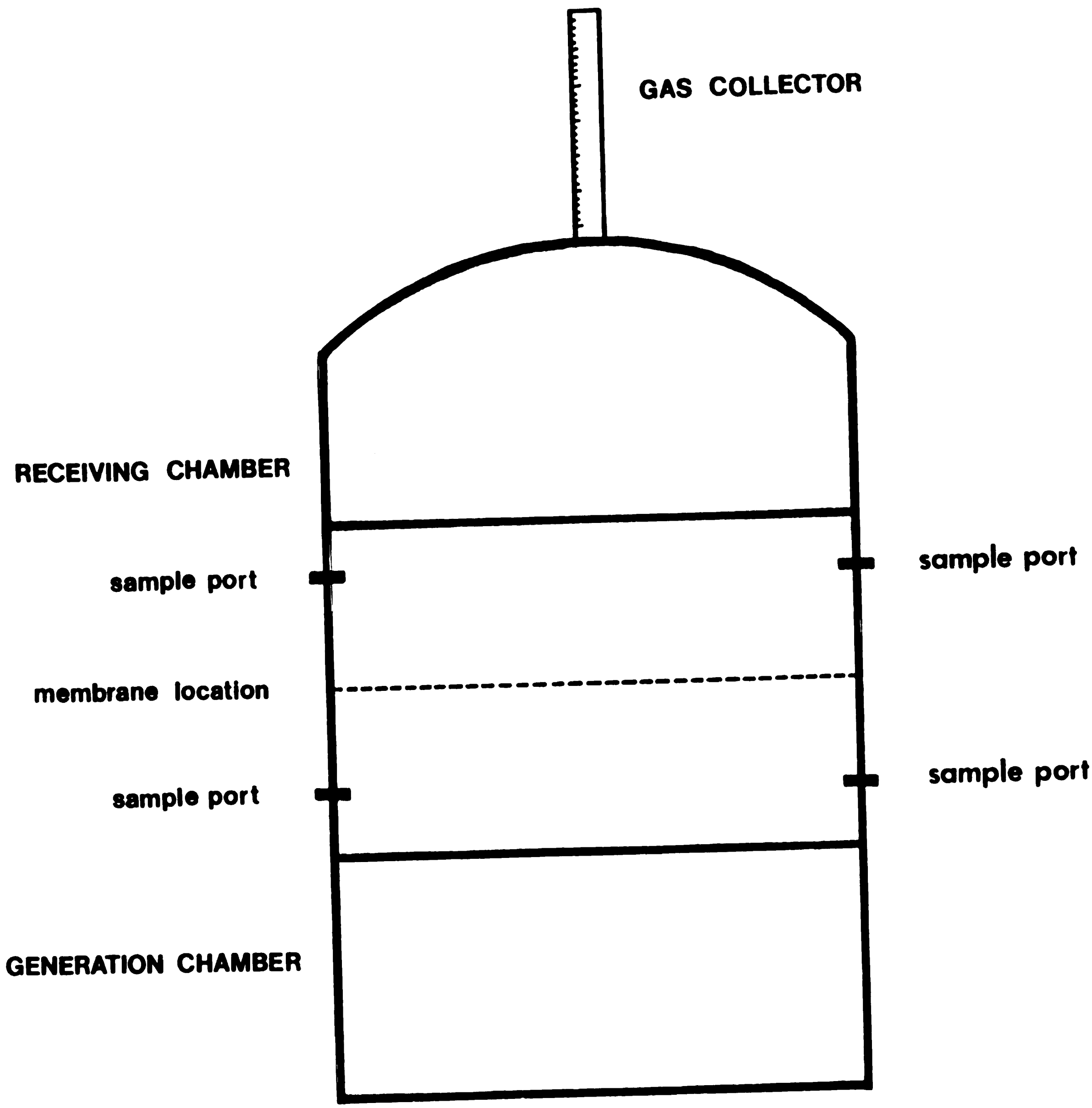


Figure 2. Diffusion testing apparatus for evaluation of the anion permeability of benthic barriers.

Fifty mL water samples were taken from both the upper and lower chambers at every sampling event. Samples were injected into acid washed 60 mL serum bottles. Anion concentrations for both the upper and lower chambers of each test were analyzed by a modification of the method of Small and Miller (1982). Analyses were performed on a Perkin Elmer model 601 liquid chromatograph (Perkin-Elmer Analytical Instruments, Norwalk, CT, USA), fitted with a Vydac injection valve, and 100 μl injection loop. Two Alltech IC-1000 anion columns (Alltech Applied Science, Deerfield, IL, USA), plumbed in series, were used for the anion separations. A Varian, model VUV-10, varia-chrom UV liquid chromatography detector (Varian Instrument Group, Sunnyvale, CA, USA), set at 273 nm and 4 nm band pass, was used for peak detection. Potassium ortho-sulfobenzoic acid (10^{-3} M) was used as the eluant. The flow rate was 1.5 mL min^{-1}. The pH of each sample was also determined with either a Sargent-Welch, model IP analog pH meter (Sargent-Welch Scientific Co., Skokie, IL, USA) or an Altex model 3560 digital pH meter (Beckman Instrument Corp., Palo Alto, CA, USA) and either a Corning replaceable reference junction pH combination electrode (Corning Glass Works, Medfield, MA, USA) or an Orion Ross™ combination pH electrode (Orion Research, Inc., Cambridge, MA, USA). All data were converted to the percent total mass of ions in either the upper or lower chambers over the total mass of ions in both chambers. These percent data were analyzed by standard one-way ANOVA techniques. There were no statistically significant changes in the proportion of any anion in the upper and lower chambers, over time, for any of the four treatments. Subsequent experiments indicated that anion diffusion occured very quickly and that the rate dynamics may have been missed by the daily to every-other-day sampling protocol. It appears that what was actually being observed was the asymptotic portion of a curve where the ion proportions are plotted over time. Consequently, data were averaged over time, for each treatment.

An anion diffusion chamber was constructed from glass, plexiglass, and styrofoam building insulation (Figure 3) to evaluate the rapid movement of ions across an imposed ion concentration gradient, separated by a benthic barrier. A two piece plexiglass divider split the chamber into a "concentration chamber" and "receiving chamber". The "concentration chamber" volume was approximately 0.485 L and the "receiving chamber" volume was approximately 1.0 L. The divider had a centrally located circular hole measuring 49 cm^2, designed to accommodate the benthic barrier materials. The divider hole was sealed with a plexiglass plug while the receiving chamber was filled with tap water and the concentration chamber was filled with 1000 mg L^{-1} solutions of either potassium phosphate (KH_2PO_4), potassium sulfate (K_2SO_4), sodium nitrate ($NaNO_3$), or sodium nitrite ($NaNO_2$). The volume of the receiving chamber was replenished with fresh tap water at a rate of four L min^{-1} to maximize the concentration gradient. A non-standard conductivity probe was used to monitor the depletion of anions in the concentration chamber over time as the anions penetrated the various benthic barrier materials to the receiving chamber side of the system. The output of the conductivity probe was analyzed by a Hewlett Packard, model 4262A, LCR meter (Hewlett Packard Corp., Corvallis, OR, USA). The unit of

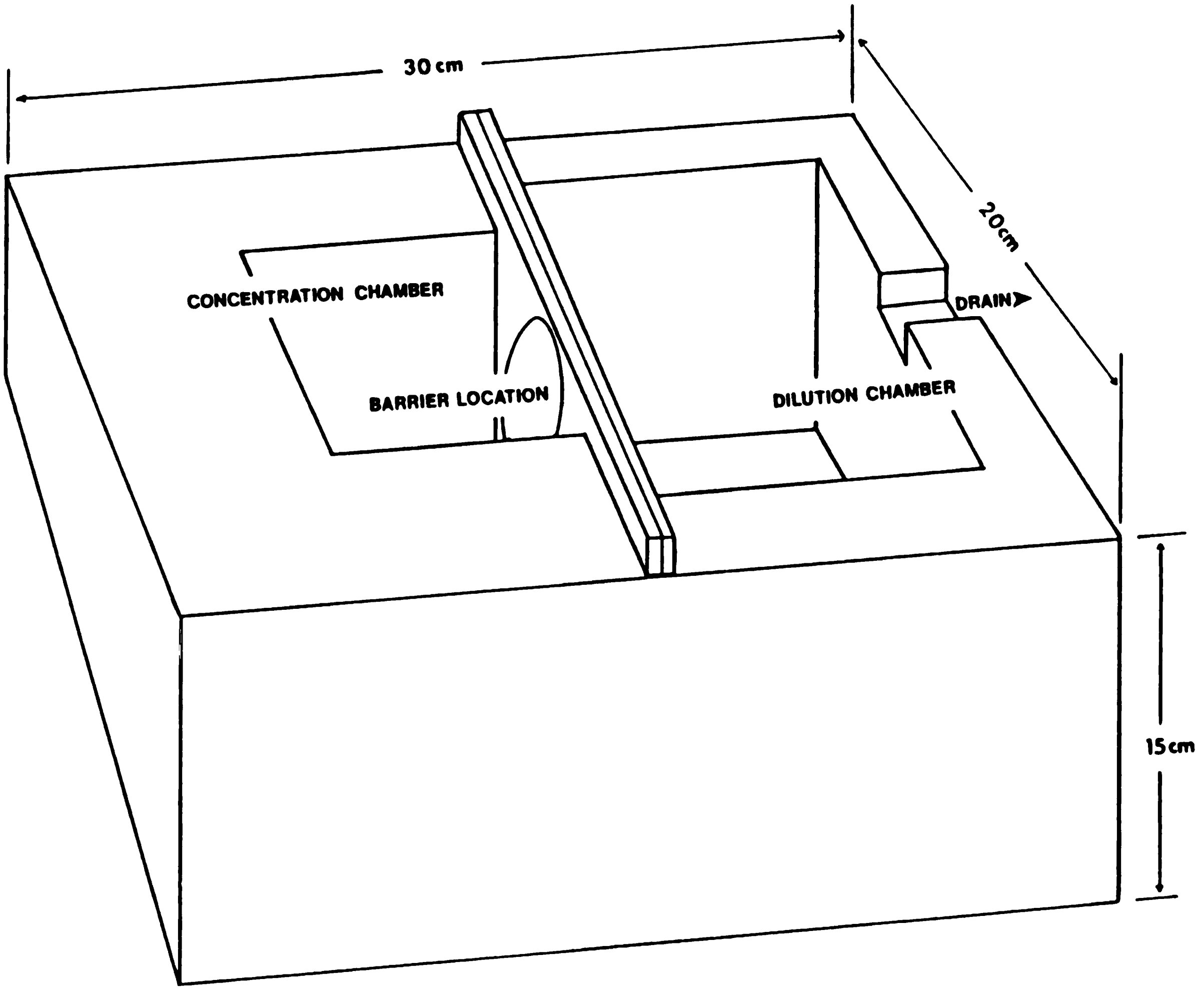


Figure 3. Diffusion testing device for evaluation of the diffusion rate of anions through benthic barriers.

analysis was the ohm (resistance). A least squares fit line was applied to a portion of a solution resistance versus time curve for data that represented the period of fastest ion migration. This time segment was determined by observing computer generated coefficients of determiniation (r^2) for various data segments and accepting those portions of a curve that yielded a value greater than 0.95. The treatment *X* coefficients generated by these analyses were examined by one-way ANOVA to determine significant differences between the permeability rates of various benthic barriers.

Laboratory investigations were also conducted to determine benthic barrier impacts on sediment/water-column gas flux. Gas generation chambers were constructed from standard schedule 40, 20.32 cm (8") diameter PVC pipe and pipe fittings (Figure 4). Benthic barriers were cemented into the center of the treatment chamber pipe connectors while the controls were left open to the water column. Diffusers were inserted into the open connectors above the benthic barriers, or above the center of a connector in the case of the controls. Aerated water was delivered through the diffusers to create a slight current as shown in Figure 4. This was done to maximize the concentration differential between the water above and below the treatments. Fresh *Elodea canadensis* Rich. in Michx. was placed in a kitchen blender to form an organic slurry. A 180 mL aliquot of this slurry was injected into the base portion of the gas generation chambers. A second 180 mL aliquot was added to the chambers 21 days after the initial injection to accelerate microbial activity. The organic matter content of the slurry was determined by the desiccation

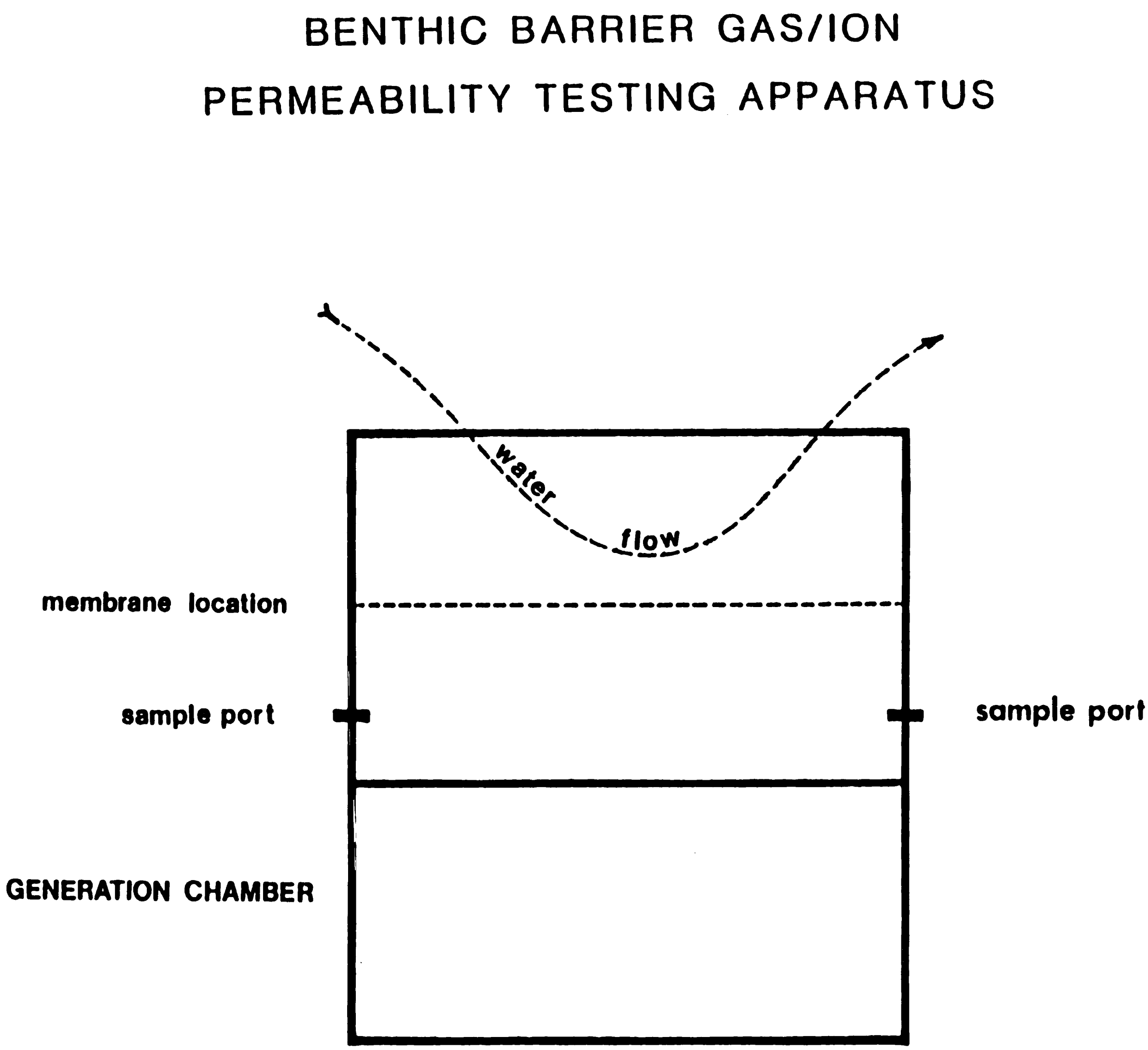


Figure 4. Diffusion testing device for evaluation of the dissolved gas permeability of benthic barriers.

of the sample at 104°C in a forced air drying oven for three (3) days followed by incineration at 550°C for six (6) hours (APHA, 1985). Wet, dry, and ash weights were determined with a two place, top-loading balance. The total organic injection volume was equivalent to 42.99 (SD ±4.34) grams dry weight or 16.63 (SD ±5.03) grams ash free dry weight, per chamber. This, in turn, is equivalent to 1,480 grams dry weight per m^2, or 260 grams ash free dry weight per m^2.

Fifty mL samples were taken periodically with a sixty mL plastic syringe from the lower chambers of each of the diffusion test units and injected into nitrogen purged and then evacuated 60 mL serum bottles, stoppered with butyl rubber syringe septa. These samples were taken at various intervals over a period of 120 days. Each sample bottle head space was analyzed for methane, oxygen, and carbon dioxide. Samples taken on days 0, 2, 3, 5, 7, 12, 22, 26, and 29 were analyzed on a Hewlett-Packard model 5710 gas chromatograph with a dual channel thermoconductivity detector. Methane and carbon dioxide were separated with a 1.83 m (6′) molecular sieve column and oxygen concentrations were determined with a Poropak QS column. The molecular sieve and Poropak columns were maintained at 84°C and 60°C respectively. The resultant chromatograms were analyzed with a Hewlett-Packard 3392B chromatography integrator. Samples taken on subsequent days were analyzed on a the Gow-Mac 550 gas chromatography system as described above. The experiment was terminated on day 122 because the Dartek® treatment diffusion test units could no longer contain the accumulated gases without breaking seals. Furthermore, microbial colonization of benthic barrier upper surfaces began to increase markedly and may have had a confounding effect on the permeation data, had the experiment continued.

The contents of the lower chambers were homogenized and sampled at the end of the experiment for solids and organic content. Samples were analyzed in a manner similar to that used to analyze the initial organic matter spikes. Differences between these values and the initial organic matter spikes were taken as a estimate of organic matter mineralization. The pH of each sample was determined with a Altex model 3560 digital pH meter and either a Corning replaceable reference junction combination pH electrode or Orion, Ross™ combination pH electrode.

All experimental data and statistical manipulations were performed on either a Hewlett-Packard 150 personal computer or Hewlett-Packard, HP-41 hand-held calculator/computer with a ROM loaded statistical package option. Lotus 1,2,3 was used for data manipulation. All differences between treatments and controls were considered significant at $P > 0.90$ except where noted otherwise. All regression data for instrument calibrations were generated on the Hewlett-Packard model 41 hand calculator/computer.

RESULTS

Light penetration studies showed that forty-six and forty-three percent of the solar radiation from 400 to 700 nm that was incident on the surface of the bottom barriers, penetrated Aquascreen™ and Texel® respectively (Figure 5). Less than one percent of this radiation range penetrated Dartek® and the silicone benthic barrier. These data, coupled with that of Pullman and Craig (1982), indicate that Aquascreen™ and Texel® do not attenuate light sufficiently to control nuisance plant production by shading. Contrastingly, Dartek® and the silicone benthic barrier attenuated light sufficiently to control plants by shading.

Field quadrat studies were designed to test the gas bubble permeability of several benthic barrier devices. Little or no gas was collected in any of the gas bubble collectors; hence, there were no statistically significant or meaningful differences between any of the treatments. These data indicate that any gases that penetrated the benthic barriers in this experiment did so in a dissolved form.

Water samples were also taken from below the benthic barrier quadrat treatments to determine the impact of these devices on sub-barrier sediment gas concentrations. Dissolved methane, oxygen, and carbon dioxide concentrations in water sampled from below the benthic barrier quadrats are presented graphically in Figure 6. Oxygen concentrations below the benthic barriers were highly variable but there were statistically significant differences between the Texel®

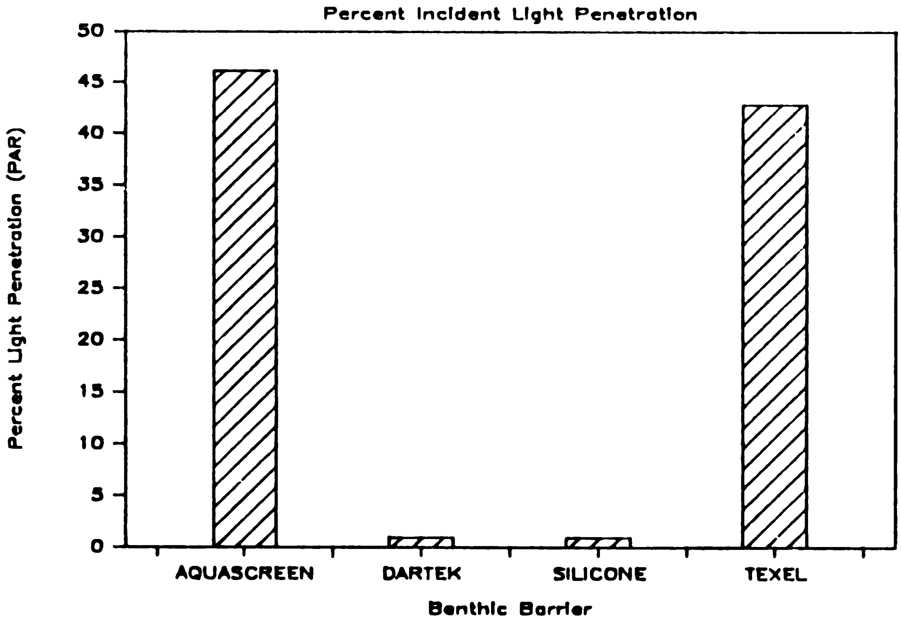


Figure 5. Percent incident light penetration of Aquascreen™, Dartek®, the silicone benthic barrier, and Texel®.

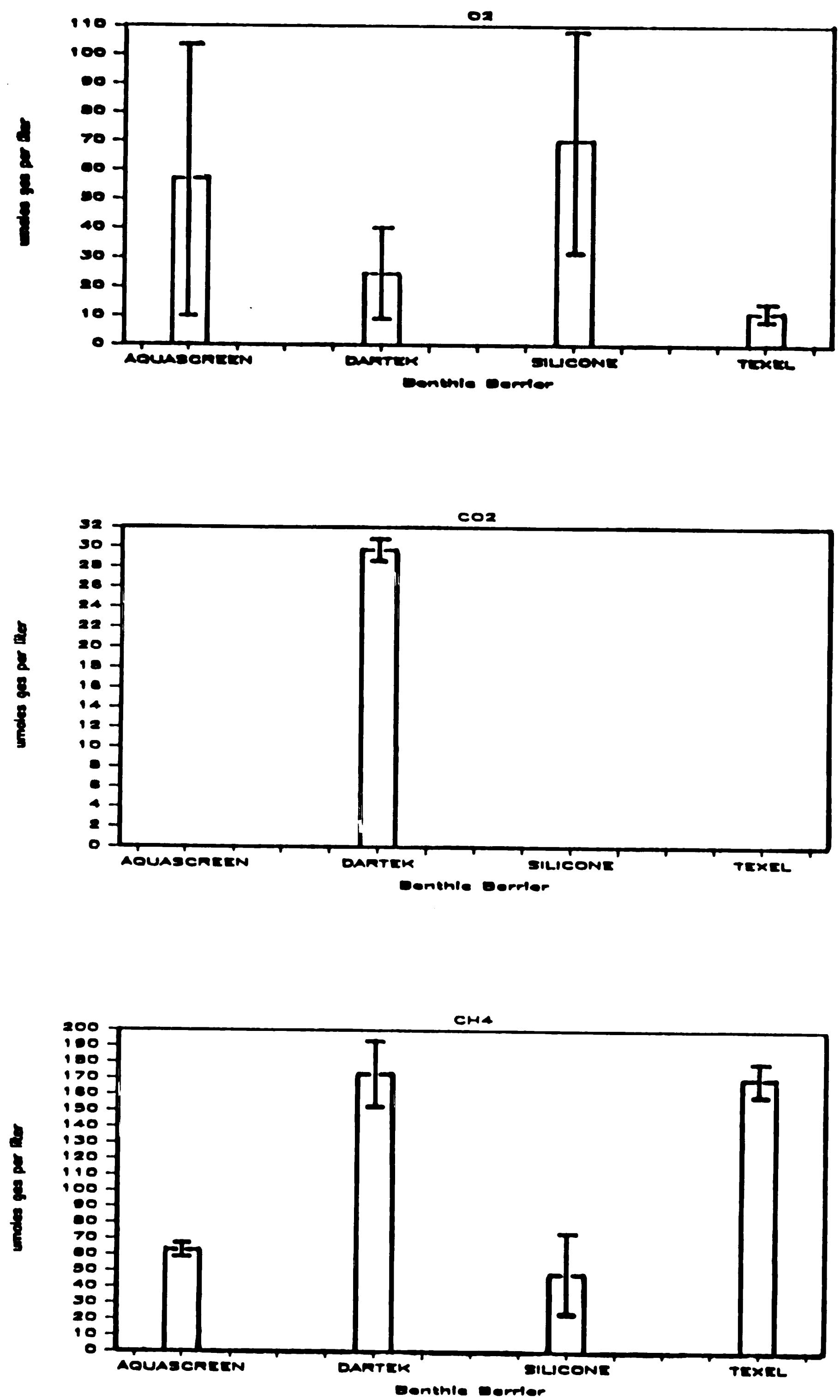


Figure 6. *In situ* dissolved gas concentrations below Aquascreen™, Dartek®, the silicone benthic barrier, and Texel®.

and the silicone benthic barrier treatments. Methane concentrations were significantly higher below the Texel® and Dartek® treatments than below the Aquascreen™ or silicone benthic barrier treatments. Carbon dioxide concentrations were below detectable limits beneath all of the treatments with the exception of the Dartek® treatment. These data indicate that the slitted Dartek® was the least gas permeable of the various treatments, and that Aquascreen™ and the silicone benthic barrier were the most gas permeable. Texel® is intermediate between the two previous treatment groupings.

The 1986 quadrat experiment was removed from the site 46 days after its initiation. Large gas bubbles were released from beneath the Dartek® and Texel® treatments when the quadrats were disturbed. Fewer and smaller gas bubbles were trapped below the Aquascreen™ and silicone benthic barrier treatments.

Chara sp. was observed to grow through Aquascreen™. Approximately 1/2 of the area below the second Texel® replicate was colonized by a vigorous stand of *Chara sp*. This was not unexpected, however. The light transparency studies above, indicated that light may not be sufficiently attenuated to inhibit plant growth in shallow water. *Najas guadalupensis* was also found attached to the upper surface of all of the Texel® replications. No macrophytes were observed to grow through, attached to, or under the Dartek® or silicone benthic barrier treatments. The upper surfaces of the Dartek® and silicone benthic barriers were also relatively devoid of periphyton.

Preliminary field testing of Aquascreen™ and a non-woven mesh material (DeWitt Weed Barrier) that is similar to Texel® suggested that these benthic barriers were gas permeable until they were covered with filamentous algae (Pullman, unpublished observations). The surfaces of the Dartek®, Aquascreen™, and silicone benthic barrier disks were covered to varying degrees by unicellular algae while the Texel® disk was totally covered and impregnated by filamentous algae. Filamentous algae also comprised 10% of the total epiphytic areal coverage of Dartek® and 41% of the cover on Aquascreen™. There were no filamentous algae found on any of the silicone benthic barrier disks. These data are summarized in Figure 7.

Laboratory anion diffusion studies tested what proportion of the total diffusion unit anion mass was found in either the upper (above barrier) or lower (below barrier) chambers over time as a function of the pressence of a benthic barrier. There were no significant differences in the proprtion of the total diffusion unit anion concentration found in the upper or lower chamber of any of the treatments for any anion species over time. Consequently, the data from each diffusion unit was averaged over time and these averages were used for comparisons.

The proportion of the diffusion unit nitrate that resided in either the upper or lower chamber did not differ significantly between the control or Aquascreen™ treatments (Figure 8). The Aquascreen™ treatment and control differed significantly from all other treatments. The Dartek® treatment did not differ significantly from

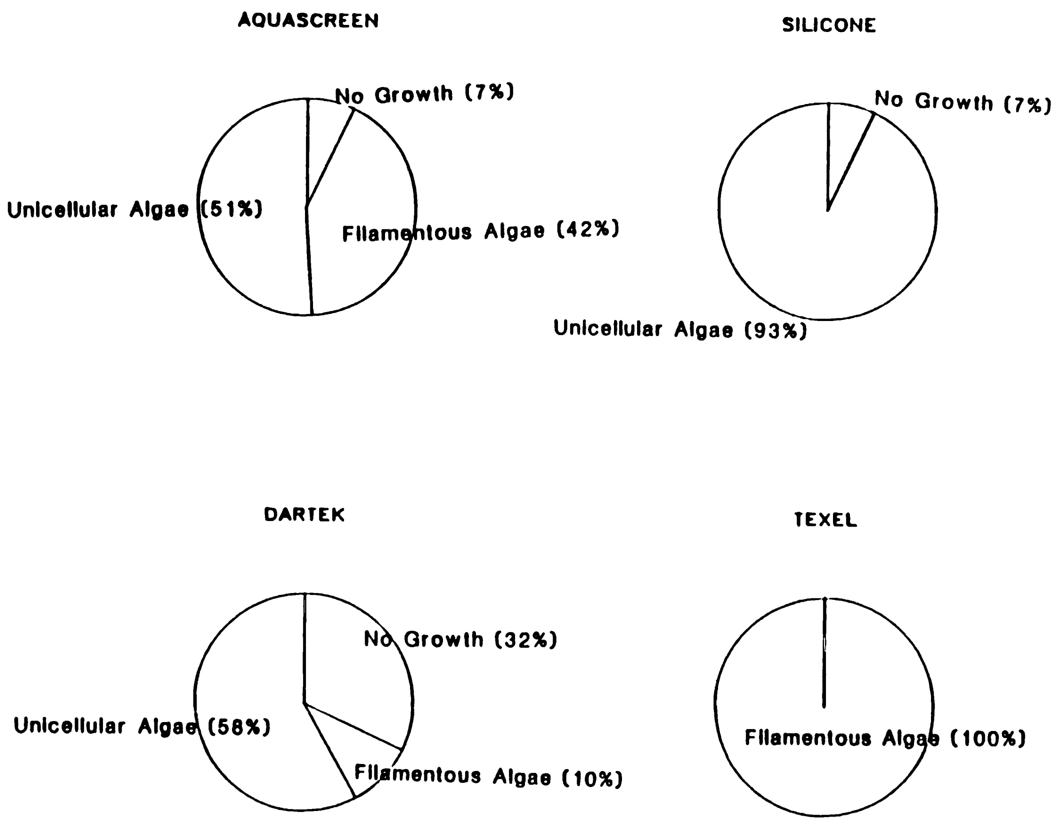


Figure 7. The percent areal coverage of Aquascreen™, Dartek®, the silicone benthic barrier, and Texel® by an epiphytic complex as determined by visual observation.

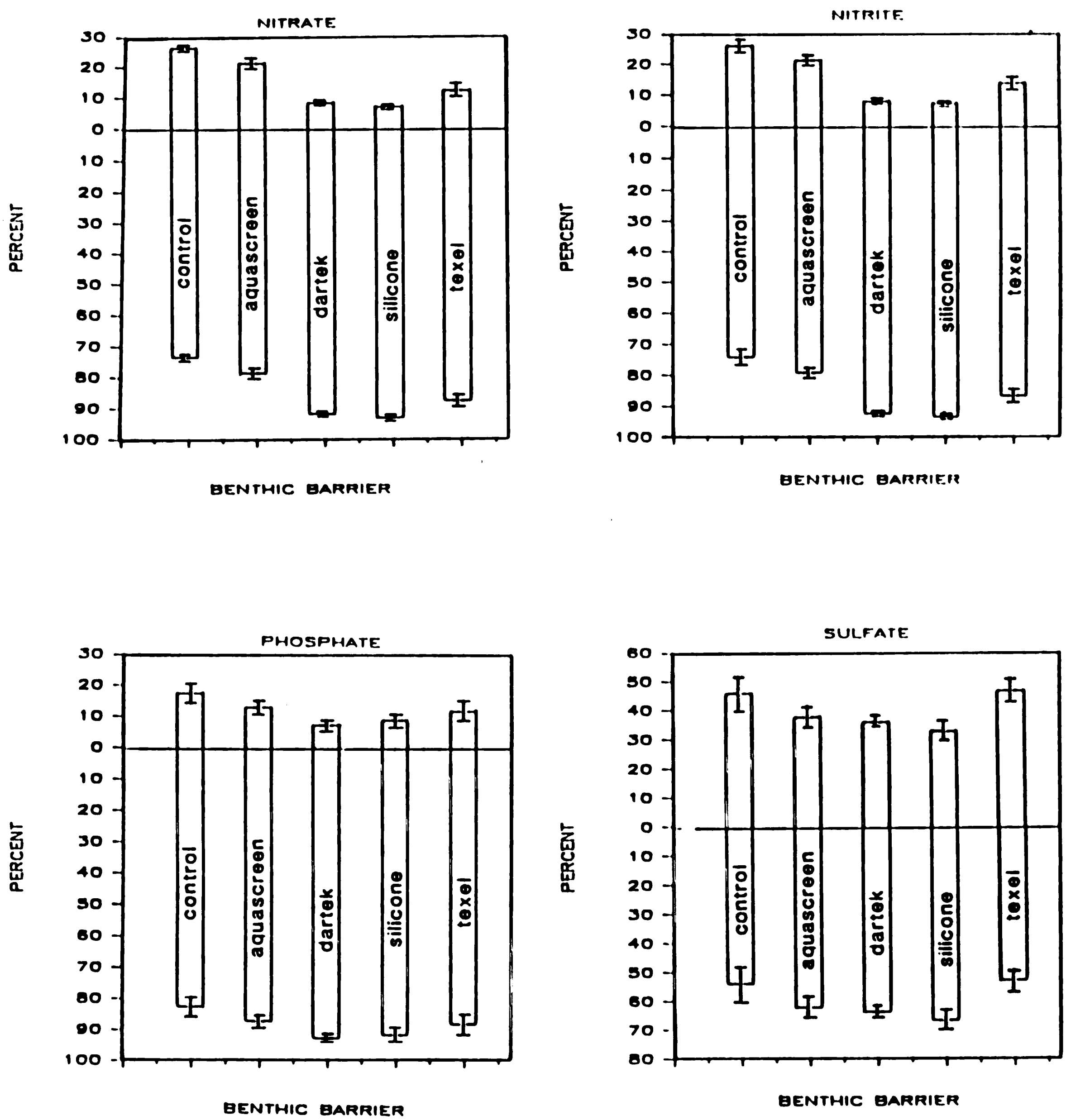


Figure 8. The distribution of nitrate, nitrite, phosphate, and sulfate above and below Aquascreen™, Dartek®, the silicone benthic barrier, and Texel® represented as a percent of the total available specific anion in the laboratory anion diffusion test units. Error bars equal plus or minus one SEM.

the Texel® or silicone benthic barrier treatments. All other conparisons were significantly different.

Analysis of upper/lower chamber proportion nitrite data variance revealed that the silicone and Dartek® treatments differed significantly from all other treatments and control but did not differ significantly from each other. The control differed significantly from all of the treatments except the Aquascreen™ treatment. Texel® differed significantly from the control, silicone , and Dartek® treatment but did not differ significantly from the Aquascreen™ treatment.

Phosphate upper/lower chamber proportion data indicated that the silicone benthic barrier treatment and Dartek® treatment differed significantly from the control and Aquascreen™ treatment. There were no other significant differences between any treatments and control.

The analysis of sulfate data variance demonstrated that the Aquascreen™ treatment did not vary significantly from any other treatment but did differ significantly from the control. The silicone benthic barrier treatment differed only from the Texel® treatment but not from any other treatment or control. There were no other significant differences.

A rapid ion diffusion study was designed to observe the rapid movement of anions through some of the benthic barriers. Comparisons were based upon a line that paralleled and intersected the point of most rapid ion diffusion. Data from the control runs of the rapid ion diffusion test indicate that nitrate, nitrite, sulfate, and phosphate migrate from one chamber to the next chamber at an equal rate. There was no perceptible movement of nitrate, nitrite, sulfate, or phosphate through Dartek® or the silicone benthic barriers. There were no statistically significant differences (P > .95) between the control or Aquascreen™ treatment nitrite, nitrate, phosphate, or sulfate maximum diffusion rates (Figure 9). Texel® differed significantly from both the control and Aquascreen™ treatment anion diffusion maximum rates.

Benthic barriers have an impact on sediment/water column gas exchange and production phenomenon. Controlled laboratory studies were designed to simulate actual field applications of benthic barriers over a dense stand of plants. Dissolved gas and hydrogen ion concentrations were measured periodically over time.

Hydrogen ion concentrations began to rise in all of the treatment chambers after the organic matter slurry injections (Figure 10). Control chamber hydrogen ion concentrations remained relatively constant for the duration of the experiment and were significanly different from all of the treatments until near the end of the experiment. Hydrogen ion concentrations peaked in all of the treatment chambers at approximately fifty days from the beginning of the experiment. Dartek® chamber hydrogen ion concentrations differed significantly from both the Aquascreen™ and silicone benthic barrier chambers at this time. Texel® treatment chambers did not differ significantly statistically from any of the other treatments. The Texel® treatment data did, however, more closely resemble the Dartek® treatments. Hydrogen ion concentrations declined steadily in all of the treatments thereafter. From these data it appears that the order

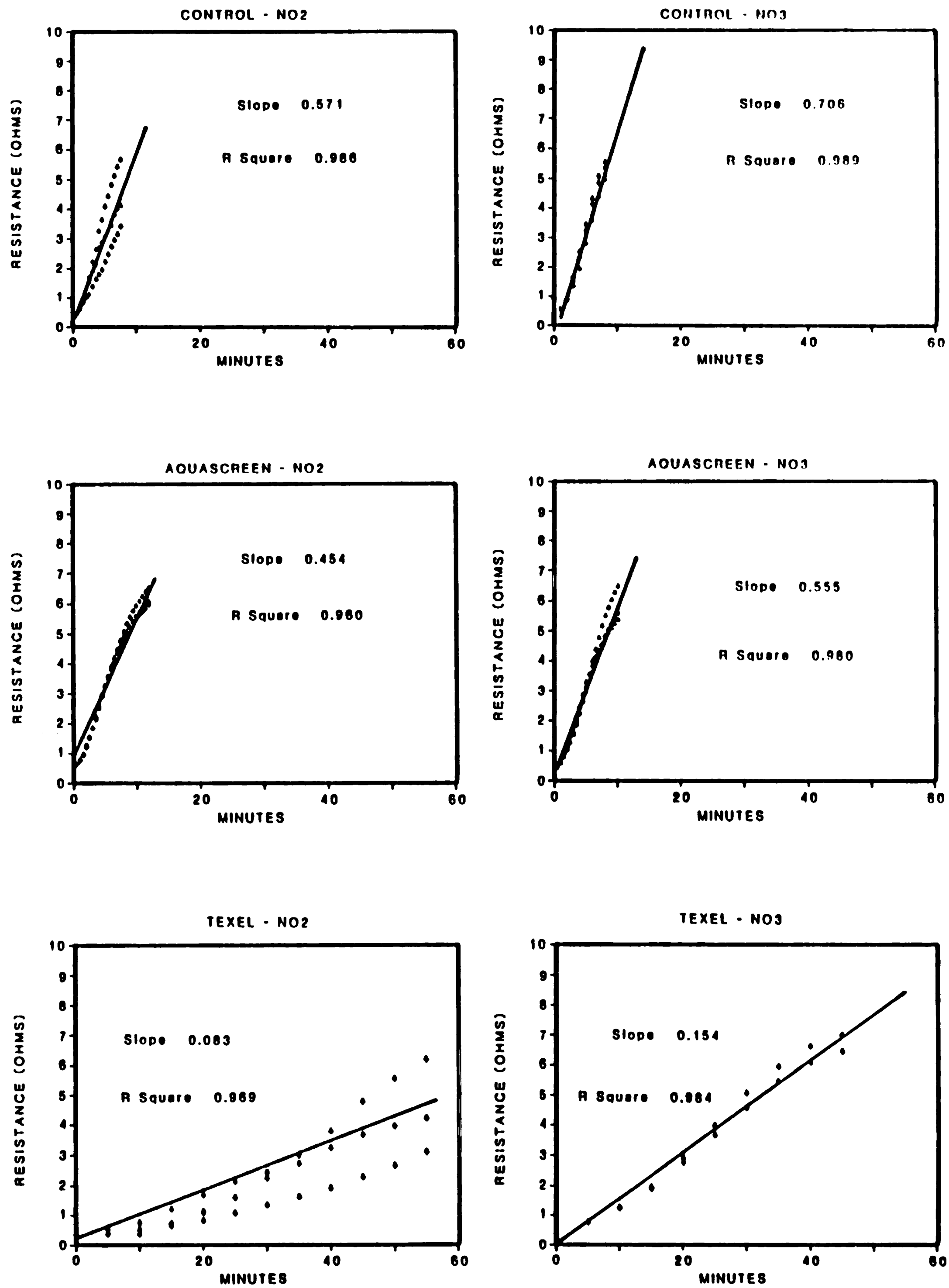


Figure 9. Resistance (ohm) of anion spiked solution over time as a function of the diffusional export of anions through permeable benthic barriers. Slopes are based on peak anion diffusion rate data.

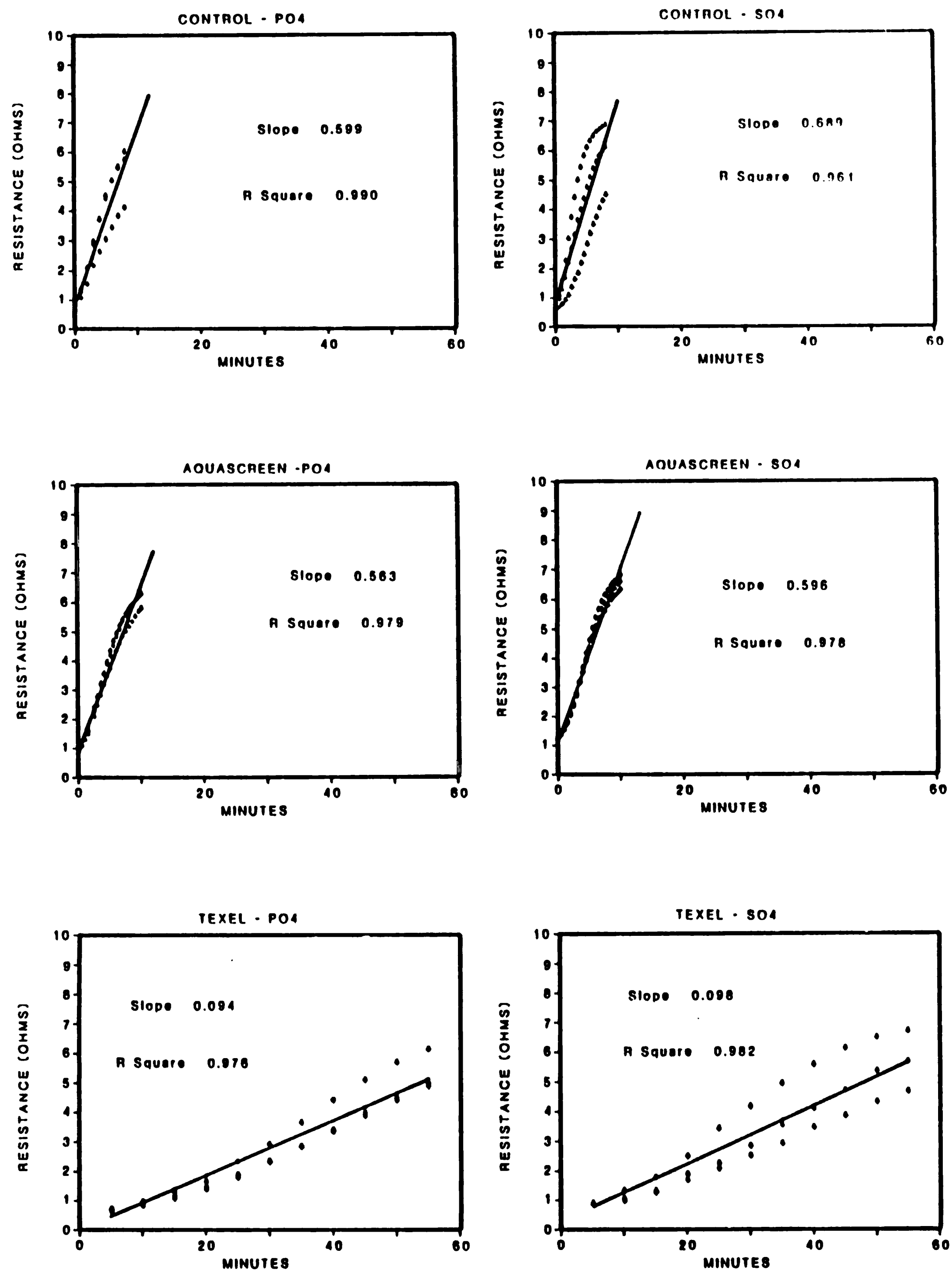


Figure 9. Continued.

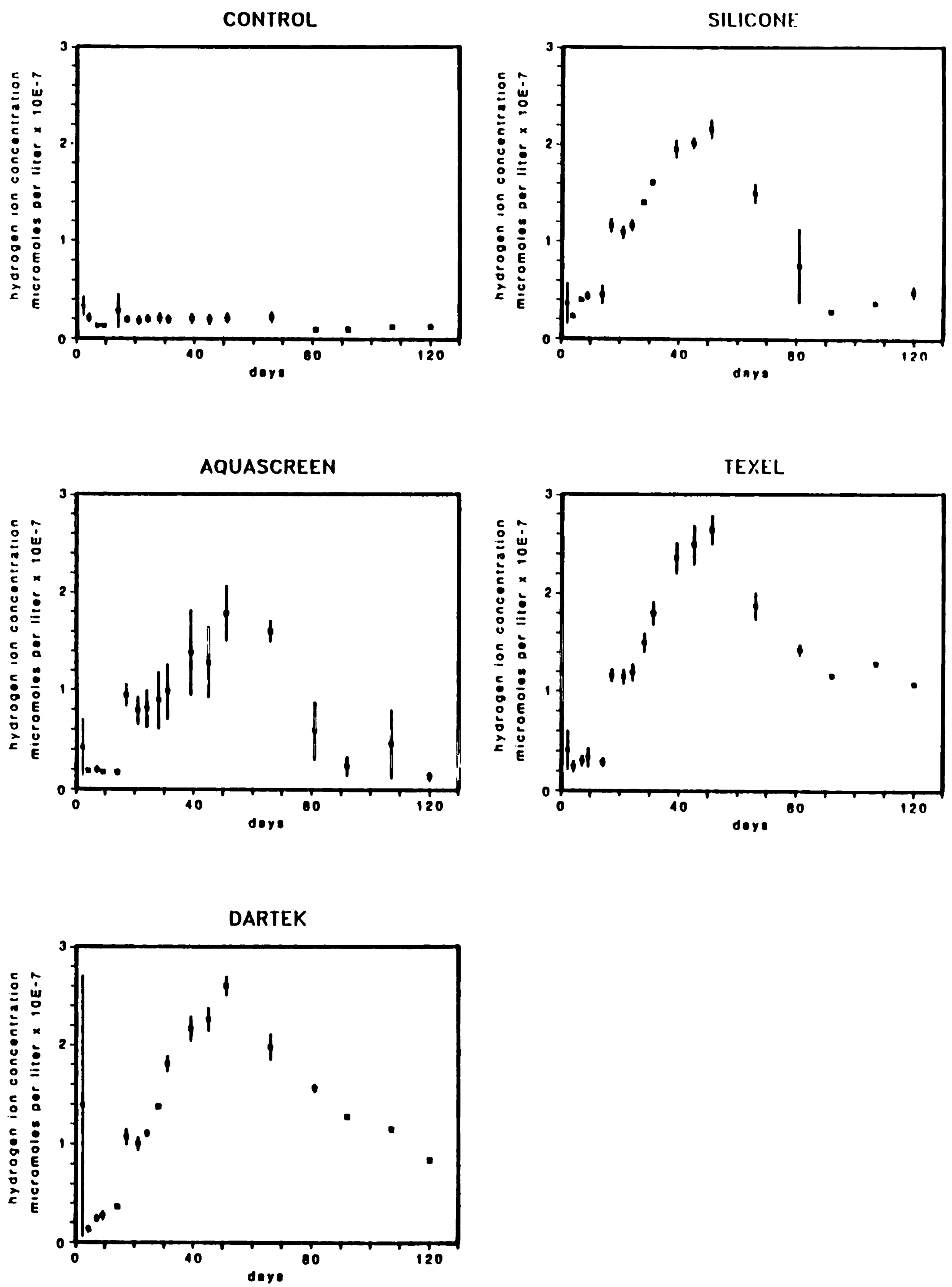


Figure 10. Hydrogen ion concentrations below Aquascreen™, Dartek®, the silicone benthic barrier, Texel®, and in control chambers, over time, from a laboratory investigation of the relative dissolved gas permeability characteristics of benthic barriers. Error bars represent plus and minus one SEM.

of increasing hydrogen ion permeability for the benthic barrier treatments is as follows:

Aquascreen™ > silicone > Texel® > Dartek®

Total dissolved carbon dioxide concentrations found in the gas generation chambers of the diffusion test units were a function of microbial metabolism of the organic matter slurry, the bi-carbonate/carbonate buffering capacity of the system, pH, methanogenesis, and the diffusion rate of carbon dioxide out of the lower chamber through the various treatments. Carbon dioxide concentrations peaked in all of the treatment and control lower chambers around day 66 (Figure 11). Concentrations declined in the control, silicone benthic barrier, and Aquascreen™ chambers after day 80 while they remained nearly constant after day 80 in the Dartek® and Texel® treatment lower chambers. Lower chamber water pH was circumneutral for all of the treatments. Plots of the dissolved carbon dioxide concentrations over time for each of the treatments and controls were remarkably similar until approximately day 70. With conditions appearing to be so similar in all of the treatment and control units and despite the complicated nature of carbon dioxide dynamics, it is assumed that deviations in carbon dioxide concentrations after day 80 are the result of differences in the diffusion characteristics of the various benthic barriers.

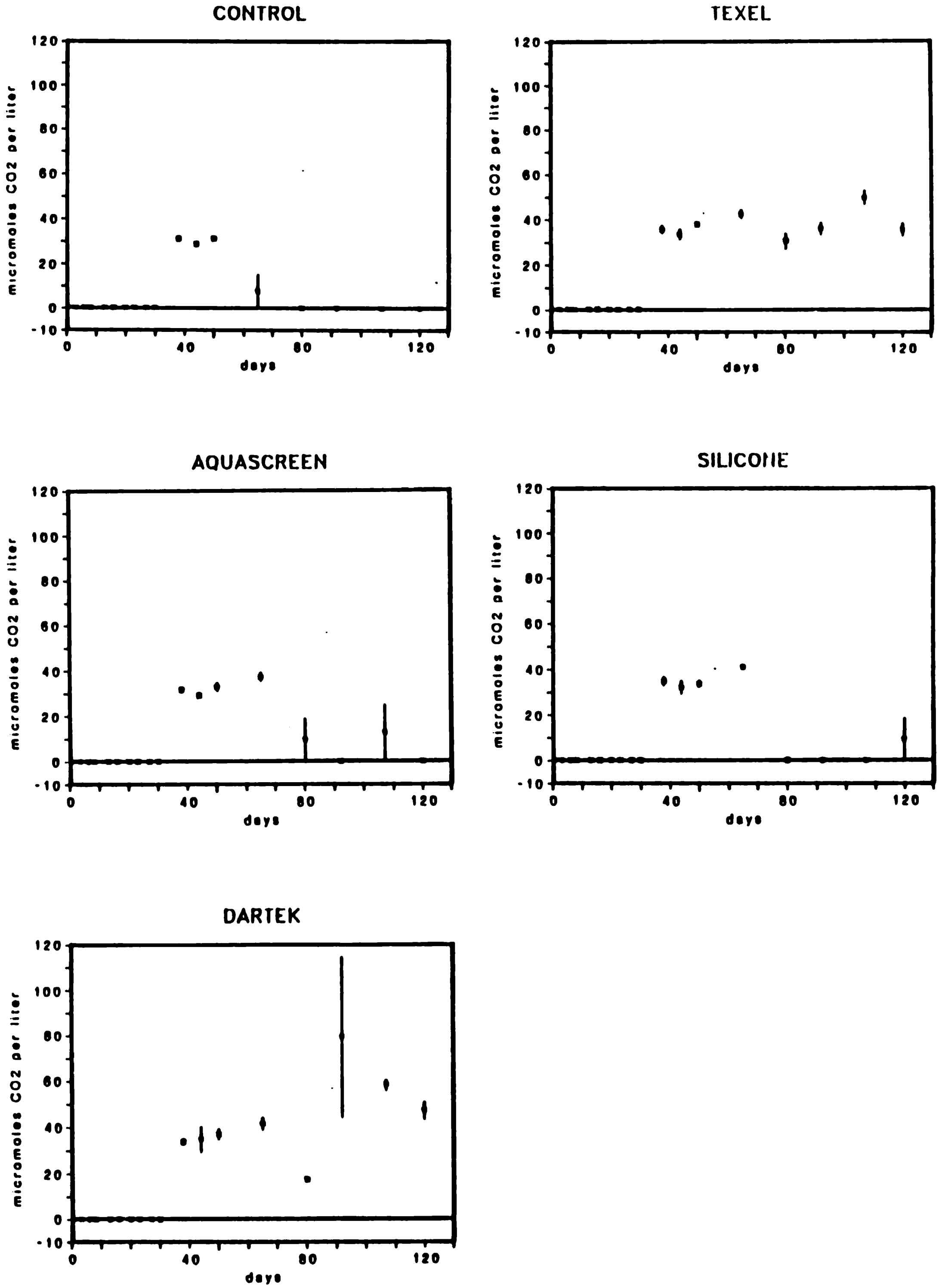


Figure 11. Carbon dioxide concentrations below Aquascreen™, Dartek®, the silicone benthic barrier, Texel®, and in control chambers, over time, from a laboratory investigation of the relative dissolved gas permeability characteristics of benthic barriers. Error bars represent plus and minus one SEM.

From these data it appears that the benthic barrier treatments may be arranged into two groups with respect to their apparent carbon dioxide permeability. The arrangement would be as follows:

Aquascreen™ , Silicone > Texel®, Dartek®

Diffusion unit lower chamber dissolved methane concentrations were the result of a number of interacting factors which may in part be controlled by the impact of the barrier on benthic community metabolic processes, i.e. restriction of electron acceptor input, carbon input, hydrogen ion export, carbon dioxide permeability. Conditions appeared to be favorable for methane oxidation to occur in all of the test chambers (Rudd and Hamilton, 1975; Devol, 1983). This could have resulted in an underestimate of methanogenesis or, more importantly, an overestimate of the methane permeability of the various treatments. It may be more appropriate, therefore, to view these data as representing a relative measure of a methane dissipation potential where the impact of methane oxidation and permeability are summed.

Methane concentrations did not reach detectable levels in any of the treatment or control chambers until day forty-nine (Figure 12). On that day, the controls differed significantly from the Texel®, silicone, and Dartek® treatments but not the Aquascreen™ treatment. The silicone benthic barrier treatment differed significantly from the Dartek® treatment on this same date. There were no other statistically significant differences. Significant differences continued to be evident throughout the remainder of the experiment.

The benthic barriers evaluated in this experiment could be placed on a continuum of increasing methane dissipation potential as follows:

Aquascreen™ > Silicone > Texel® > Dartek®

The total dissolved methane and carbon dioxide concentrations for each of the treatment and controls for each sampling date were summed as an estimate of total dissolved inorganic carbon (TDIC) concentrations. TDIC concentrations peaked at around day 66 of the experiment and declined, thereafter, in the control, Aquascreen™, and the silicone benthic barrier treatments (Figure 13). TDIC concentrations began to increase in the silicone treatment around day 92 and continued to do so until the end of the experiment. The Texel® and Dartek® treatments TDIC concentrations continued to increase after day 66 and showed no decline until around day 115. By the end of the experiment all the treatments and controls were significantly different statistically ($P > 0.90$) except for the Aquascreen™ treatment and the controls.

The benthic barrier treatments could be ordered on a continuum describing the relative total inorganic carbon permeability as follows:

Aquascreen™ > Silicone > Texel® > Dartek®

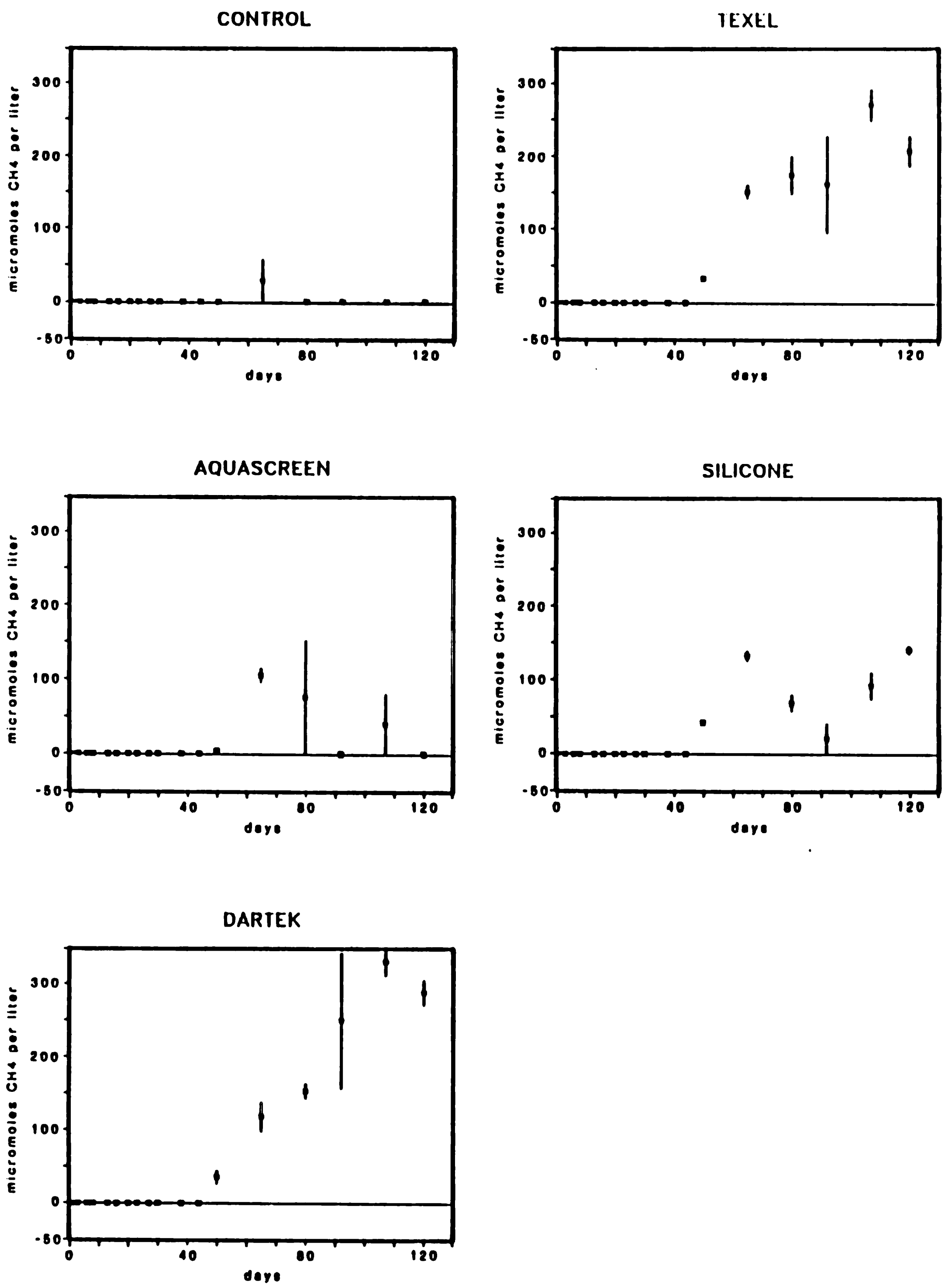


Figure 12. Methane concentrations below Aquascreen™, Dartek®, the silicone benthic barrier, Texel®, and in control chambers, over time, from a laboratory investigation of the relative dissolved gas permeability characteristics of benthic barriers. Error bars represent plus and minus one SEM.

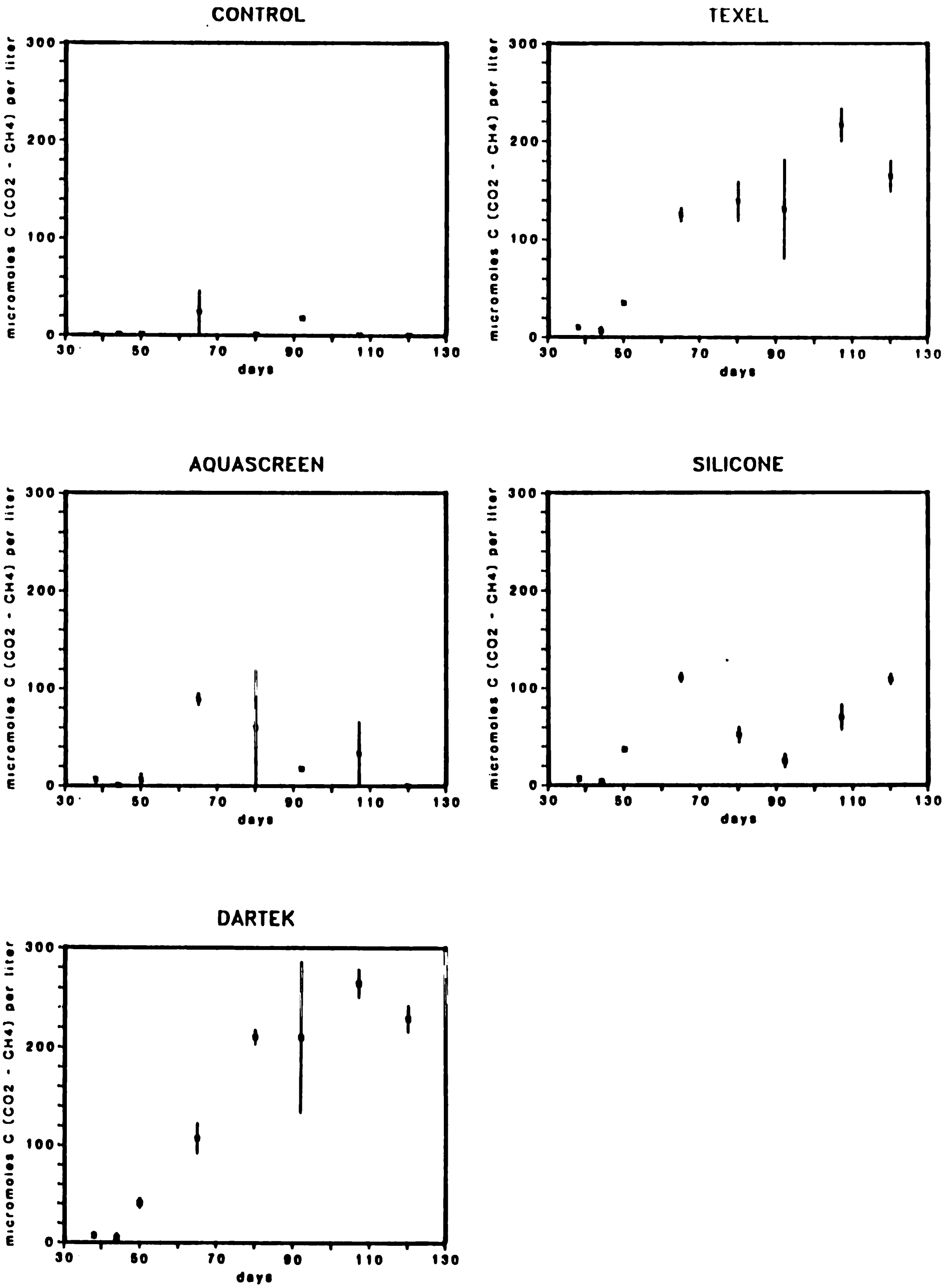
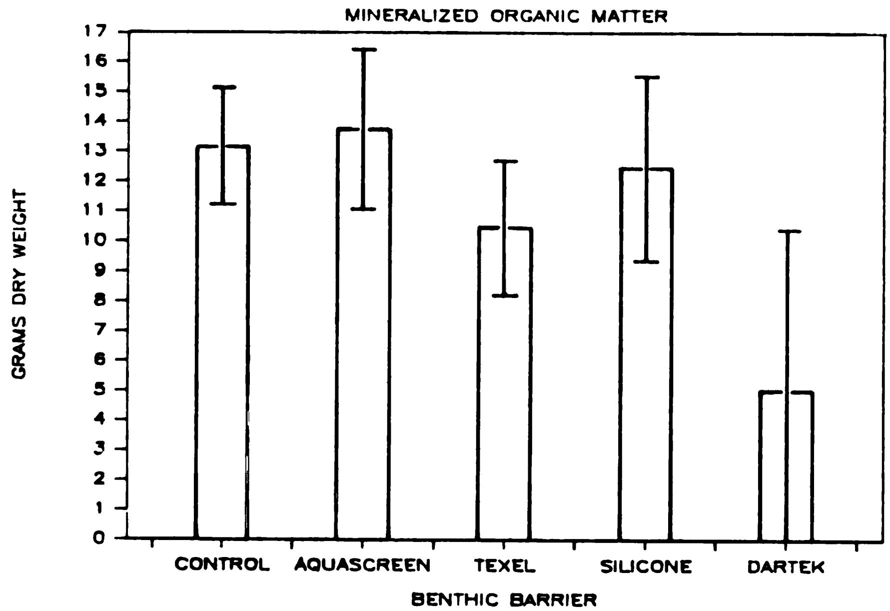


Figure 13. Total dissolved inorganic carbon concentrations, (CO_2 + CH_4), below Aquascreen™, Dartek®, the silicone benthic barrier, Texel®, and in control chambers, over time, from laboratory investigation of the relative dissolved gas permeability characteristics of benthic barriers. Error bars represent plus and minus one SEM.

It was not possible to contain all of the gas that had accumulated in the Dartek® chambers 120 days after the beginning of the experiment without breaking the chamber seals. Therefore, the experiment was terminated. The elodea/organic slurry matter that remained in the lower chambers of the control and treatment chambers were collected, dried, and ashed. Dry weights and ash free dry weights were subtracted from the initial input values to determine a rough estimate of how much organic matter had been mineralized or volatilized during the term of the experiment. This is only a rough estimate; however, because microbial colonization of the slurry substrate may contribute to an overestimate of total organic weight (Hargrave, 1972). The dry weights of these samples were not significantly ($P > 0.9$) different. The mean ash free dry weight of the control treatment differed significantly from all of the other treatments except the Aquascreen™ treatment mean (Figure 14). The silicone benthic barrier did not deviate significantly from the Dartek® treatment.



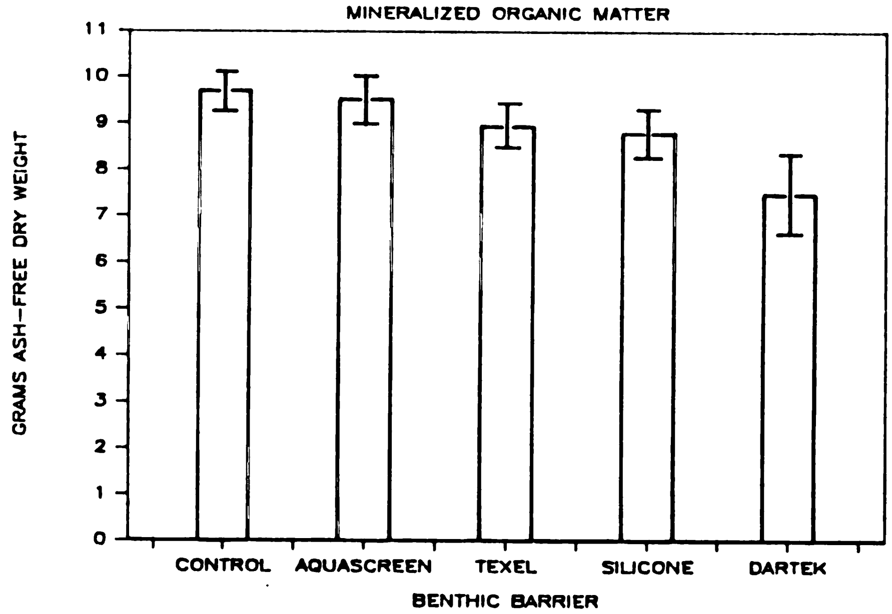


Figure 14. Total grams dry weight and ash-free dry weight organic matter that were mineralized or volatilized during the laboratory gas diffusion experiments. Error bars represent plus and minus one SEM.

DISCUSSION

The goal of most modern aquatic vegetation management strategies is to enhance the cultural utility of the water resources to which they are applied. Cultural uses are perceived broadly here and include water skiing, angling, wildlife observation, boating, irrigation, potable water supply, or swimming. An aquatic plant management effort might simply be considered a success when a vegetal nuisance is eliminated by eradication or control of target hydrophytes. But, there are other considerations that may contribute to or detract from the successful conclusion of an aquatic nuisance control effort. For example, a technology should not, by itself, constitute a threat to the cultural utility of the water body to which it is applied by obstructing the water column or becoming an aesthetic nuisance. Similarly, the ecosystem impacts associated with the application of a particular technology should not contribute to the proliferation of other nuisance plants, i.e. algae, declining fisheries production, or toxic substance mobilization.

All lake management strategies are accompanied by certain ecosystem impacts or alterations. As a consequence of ecosystem alteration, all lake management strategies will favor the development, persistence, or continuation of some component(s) of the ecosystem while simultaneously having a negative impact on other components of the same ecosystem. For example, a successful aquatic vascular plant control strategy will, by design, eliminate the plant architecture that is necessary habitat for the flora and fauna that are associated with the target vascular plant complex. No lake management strategy, including benthic barriers, is without both negative and positive ecosystem impacts. The interpretation of the negative or positive nature of a strategy; however, is a matter of perspective.

The most obvious ecosystem impact associated with the successful application of benthic barriers for the control of nuisance aquatic vegetation is the removal of the macrophytic architecture. This impact is common to all successful aquatic weed management strategies, however. Vascular hydrophyte stands serve various ecosystem functions. The vegetal architecture supports an associated flora and fauna (Pond, 1905; Watkins, et al., 1983) and may serve as a repellant for other species (Hasler and Jones, 1949; Pennak, 1973). These plants also serve as a potential conduit for gases (Dacey and Klug, 1979; Dacey, 1981), and other dissolved substances (Pond, 1905; Carignan and Kalff, 1979, 1980, 1982; Barko and Smart, 1980) between the sediment and overlying water column. This exchange is mediated by the secretion of dissolved organic matter, DOM, throughout the growing season (Wetzel, 1969; Allen, 1971; McRoy et al., 1972; Wetzel and Allen, 1970; and Wetzel and Manny, 1972) and by the sloughing and natural senescence of plant matter during and at the end of the growing season (Otsuki and Wetzel, 1974; Kisritz, 1978; Landers, 1982). Rooted hydrophytes may also be a chief determinant of redox conditions in some hydrosoils (Jaynes and Carpenter, 1986). It is clear that aquatic macrophytes have a significant impact on the sediment bio-geochemistry of the littoral zone as well as water column habitat structure, DOC, ion, and dissolved gas concentrations.

A unique feature associated with the application of benthic barriers relative to other lake management strategies is that the plant architecture is compressed below an artificial device. Benthic barriers potentially restrict current velocities and organic matter inputs to the benthic community below the device, and the flux of gases and dissolved substances between the sediments and water column. Besides the more obvious impacts on the littoral fauna and flora and water column gas and ion flux, benthic barrier applications were also found to impact sediment diagenic processes and mineralization rates.

Sediment metabolism is a function of a number of interrelated factors which include: the quantity and quality of available organic matter including its surface area, organic content, and particle size (Hargrave, 1972), availability of predominant inorganic electron acceptors, sediment redox status and capacity (Rich, 1975), macro-benthos activity, metabolite export, and temperature (Kelly and Chynoweth, 1981).

All benthic barriers impede or prevent the input of organic matter to underlying sediments by their physical presence. Consequently, if there are no other limiting factors, the metabolism of below barrier sediments should decline as available organic matter is mineralized by whatever pathways that predominate diagenic process. Other factors, however, both chemical and physical are more likely to impact sediment diagenesis.

Benthic barriers have been found to restrict the circulation of water below the area of application. Engle (1982) found that the number of macro-benthic organisms per unit area was inversely related to the amount of time a benthic barrier (Aquascreen™) remained in place. He attributed this phenomenon to reduced water circulation and low oxygen concentrations below the devices. Boynton et al. (1981) discovered a strong positive relationship between water circulation rates and benthic community respiration. These organisms can have a dramatic impact on the physical properties (McCall and Tevsz, 1982) and chemical diagenesis of freshwater sediments (Fisher, 1982). Whereas all of these devices expectedly reduce below barrier water circulation rates it is apparent that these benthic barriers would have some impact on the metabolism rate of underlying sediments by eliminating the macrobenthic community.

The availability of suitable inorganic electron acceptors such as nitrate and sulfate is also a major determinant of sediment metabolic rates and dominant terminal diagenic pathways. Anion electron acceptor diffusion through Aquascreen™ and Texel® appeared to be relatively rapid. The rate of diffusion of an ion through a membrane or device at a given set of conditions is dependent upon the solubility of the water in the solid phase of the benthic barrier, the hydration number of the ion, and the steepness of the concentration gradient from one side of the device to the other. The rate curve for the movement of anions through the selected benthic barriers was logarithmically shaped and reached an asymptotic limit that was apparently unique to each device. The most rapid diffusion rate was observed for Aquascreen™, which did not differ significantly from the control. The Dartek® and Silicone benthic barriers were relatively impermeable to anions and did not differ significantly from each other. Texel® was intermediate in anion permeability relative to the other treatments. An analysis of the asymptotic limits of the diffusion curves from the longer term laboratory anion diffusion experiments suffered from a great deal of variability which complicated efforts to make definitive statistical conclusions. Never-the-less, trends were evident from these data that would confirm the conclusions of the rapid ion migration study. Benthic barriers such as Dartek® and the silicone device could play a critical role in determining the terminal steps in the sediment diagenic process, i.e. nitrate and sulfate reduction and methanogenesis, by restricting the import of suitable electron acceptors to the mircobenthos community. Aquascreen™ would have a lesser impact, while Texel® would have an intermediate impact.

These experiments also demonstrated that Dartek®, and to a lesser extent, Texel® impede the export of gases from the below barrier benthic environment. The accumulation of sulfides and hydrogen impede sediment diagenic processes.

The major ecosystem impacts generally associated with the application of benthic barrier applications can be summarized as follows. Benthic barriers restrict the total input of organic matter to the benthic community from the overlying water column, exclude macrobenthos that may have an impact on sediment particle size and subsequent metabolism, and eliminate macrophyte mediated sediment gas/ion mobilization phenomenon through the destruction of the plant architecture. At first glance it would appear that Dartek® and the silicone benthic barrier would exert a greater relative impact on sediment metabolic processes by restricting the flow of the important electron acceptors, nitrate and sulfate from the water column to the benthic community, and thereby reduce below barrier sediment redox status and capacity. Furthermore, Dartek® would prevent the migration of oxygen to the sub-barrier sediments. Periphyton colonization, however, probably reduces the practical differences in electron acceptor permeability exhibited by all four devices. Because the silicone benthic barrier is potentially oxygen permeable in field applications it may have the least impact on sediment diagenesis in some applications. This should be the subject of further study. When these factors are taken collectively, it appears that a significant ecosystem impact associated with the use of benthic barriers is inhibition of the rate or at least nature of sediment diagenesis.

The short term impact of benthic barrier applications on sediment interactions may be similar to the application of herbicides to a well developed littoral macrophyte community or the senescence of that community at the end of the growing season. Molongoski and Klug (1980) discovered that the sudden input of a large quantity of organic matter may inhibit sediment metabolism in the lower sediment strata, i.e. greater than several millimeters. The sudden collapse of a dense vegetal hydrophyte canopy would conceivably yield a similar result. So too, would the imposition of a benthic barrier over organic substrates and well developed plant beds. The ion impermeable benthic barriers such as Dartek® and the silicone benthic barrier would differ from herbicide and naturally induced macrophyte canopy collapse phenomenon because they would tend to trap phosphorus below the barrier and prevent its release to the water column. Longer term sub-barrier impacts associated with benthic barrier applications would also differ from herbicide and natural macrophyte canopy collapse and decay phenomenon. Because benthic barriers are more inert and persistant, they would not be subject to the mediating activity of both the macro- and microfauna and flora, and consequently sub-barrier sediments may become even more reduced. Reduced metabolites, including phytotoxins (Gambrell and Patrick, 1978) may also become concentrated below benthic barriers and greatly inhibit future vascular hydrophyte recolonizaion of benthic barrier treated areas. This should be the subject of future studies. Consideration should also be given to above barrier metabolism of accumulated sediments.

The relative efficacy of benthic barriers as aquatic weed control devices differ as do the ecosystem impacts associated with each device. Benthic barrier efficacy is dependent on the ability of the material to compress the nuisance plants, attenuate light, longevity of the treatment, plant inpenetrability, and the stability (resistance to being dislodged) and durability of the fabric. Early studies indicated that the "blanket-like" benthic barriers, i.e. Aquascreen™, Dartek®, and polyethylene, may eliminate nuisance aquatic plants by shading (Mayer, 1978; Bulthuis, 1984) or compression (Boston and Perkins, 1982). Conceivably, any "blanket-like" material or benthic barrier may be used successfully for the short term control of nuisance aquatic vegetation by compression, provided enough ballasting is used or the position of the device can be maintained for sufficient time to allow for the death of the nuisance plants (Cooke, et al., 1986). Preliminary field testing of Aquascreen™, Dartek®, Texel® and the silicone benthic barrier at the Dow Gardens indicated that all of the devices were denser than water which would aid in nuisance plant compression and elimination of the water column nuisance. Furthermore, they all could be easily fastened to the bottom of a water body when used as pre-plant-emergence controls and function successfully as nuisance aquatic vegtation management devices. Preliminary testing also demonstrated that the silicone benthic barrier was relatively easy to secure over a dense bed of elodea in the Dow Gardens Pond. Aquascreen™, on the other hand, did not adequately control elodea by compression in a similar application. Additional operational testing is required to compare the relative ease or difficulty associated with the use of these various devices.

Plant death rates are also related to the shading efficiency of the benthic barrier (Mayer, 1978). Of the benthic barriers tested in this study, only Dartek® and the silicone benthic barrier attenuated light sufficiently to control nuisance macrophyte growth by shading (Pullman and Craig, 1982).

Vegetal or root penetration is a disadvantage associated with the use of porous and perforated benthic barriers. *Chara sp.* was observed to grow through Aquascreen™ in the field quadrat studies and elodea was observed to root through Aquascreen™ in earlier preliminary studies. Niads were also found attached to the upper surface of

Texel® in the field quadrat studies. Perkins (1984), Truelson (1986), and Wallis (1986) observed that Eurasian Watermilfoil penetrated the slits in Dartek® following a post-emergence trials.

All of the devices appeared to be reasonably durable and would not be expected to tear or become dislodged and thereby enter the water column. Truelson (1984 and 1986), however, experienced some problems with Dartek® tearing around its sediment pins. Texel® and the silicone benthic barrier seemed to be the most resistant to tearing.

The stability of a benthic barrier application is not only related to its resistance to tearing but is also a function of the ability of the device to vent benthigenic gases that might otherwise buoy up the barrier into the water column. When this occurs a device may become an aesthetic nuisance or potential hazard to recreational uses. Gas accumulation is avoided by perforating impermeable devices or by using semi-permeable devices or substances such as Aquascreen™, Texel®, or the silicone benthic barrier.

Technically, gas permeability is a function of diffusivity, or the mobility of the gas within the solid phase of the benthic barrier. It is also a function of the solubility of a fluid, in this case water, in the benthic barrier, and, thereby, a function of the gas activity and the partial pressure of the gas contained in the water in contact with the benthic barrier. Gas bubbles may form in the sediments below benthic barriers or may form as a result of the presence of the device if the device is responsible for an increase in the partial pressure of the underlying gases. Consequently, gas bubble surface tension effects also become an important benthic barrier gas permeation rate determinant.

Gas bubbles were visible below the Aquascreen™ and Texel® treatments in field and laboratory studies and the silicone benthic barriers in field studies. Large gas bubbles were trapped below the unslitted Dartek® treatments in laboratory gas permeability experiments and were also discovered below the slitted Dartek® in the field quadrat study. No gas bubbles were trapped above any of the treatments in the Herbert Dow Estate pond quadrat studies. It appears that the probable primary mode of benthigenic gas release by benthic barriers in these experiments can be attributed to dissolved gas migration rather than gas bubble penetration.

Gas permeability evaluations are complicated by benthic barrier periphyton colonization. All of the benthic barriers were found to be good substrates for periphyton colonization. The dominant algae differed from barrier to barrier, however. This is significant because periphyton colonization appears to impede gas permeability in some benthic barriers. Preliminary field observations indicated that the production of algae on the porous, fiber-type benthic barriers, such as Texel® and Aquascreen™, may be so great that the gas permeability potentials of these devices may be greatly impaired causing them to be buoyed up by the trapped gases. This periphyton colonization study demonstrated that bottom barriers with smooth upper surfaces such as Dartek® and the silicone benthic barrier support a predominantly unicellular algal flora which would not appear to have as great an obstructive impact on gas and ion permeability as the much thicker filamentous algal complex found on fibrous or porous benthic barriers.

Although, the laboratory gas permeability studies indicated that Aquascreen™ and the silicone benthic barrier were the most permeable to gases and would thereby be the most resistant to being buoyed upward into the water column by trapped bubbles, field studies indicated that the potential for heavy filamentous algal colonization of Aquascreen™ could severely restrict its gas permeation potential and it may thereby become buoyant with the entrapment of benthigenic gases. Consequently, the silicone benthic barrier is likely to be the most permeable to gas fluxes in the broadest range of applications of all the devices tested in this study.

Although selective ion permeability may be a desirable feature in a benthic barrier, none of the benthic barriers appeared to be selectively ion permeable. Dartek® and the silicone benthic barrier were determined to be ion impermeable, relative to the others in the rapid ion migration study. Aquascreen™ was the most ion transparant of the tested devices and Texel® was intermediate. Dartek® and the silicone benthic barrier would function as barriers to the migration of phosphorus from sediments to overlying water columns where it may contribute to the nusiance production of other plant forms. Aquascreen™ would have relatively little impact on sediment/water column phosphate flux rates. Again, Texel® would be intermediate.

CONCLUSIONS

Gas permeability should be a primary consideration when choosing a benthic barrier for aquatic weed control. This is because entrained gases may buoy up a benthic barrier and thereby form unsightly and possibly dangerous water surface obstructions. All benthic barriers function to some degree as a barrier to sediment/water column ion and gas exchange. Therefore, the selection of a bottom barrier should also be based on an estimate of the expected gas generation rates of the area over which the barrier will be applied. Consideration should also be given to what sediment accumulation and epiphyte colonization rates might be over time as these factors may greatly diminish gas permeation rates of porous barriers such as Aquascreen™ and Texel®.

Sediment/water column gas and ion exchange phenomenon are complex and are probably site specific. It is not yet possible to easily predict the volume of benthigenic gas that would be produced from a specific site as the result of the application of a benthic barrier. Such a model would be of great value, however, when selecting the best benthic barrier for a particular application.

Silicone benthic barriers possess many of the characteristics of the ideal benthic barrier. They are denser than water, opaque, gas permeable, relatively unhospitable to filimentous epiphyte colonization, impermeable to phosphorus, inpenetrable by vegetation or roots, and is durable. On the negative side, the silicone bottom barriers do not appear to allow the passage of anions, that constitute important electron acceptors for terminal diagenic processes, from the water column to the benthic community. The accumulation of anaerobic metabolites may inhibit macrophyte recolonization of treated areas for an indeterminant amount of time after the silicone benthic barrier is removed.

Texel® shows some promise as a benthic barrier for pre-emergent use. It is not sufficiently opaque, however, to control nuisance plants by shading. Algae tended to densely colonize this non-woven fabric during field studies and presumably increased the shading efficiency of the device. Periphyton colonization also appears to diminsh gas permeability, however, and would thereby be considered undesireable. It is not known what impact periphyton colonization may have on sediment/water column anion flux dynamics. Plants were also observed to attach to the upper surface of Texel® in the field quadrat studies raising questions regarding its use in lake and ponds where plant fragmentation is common.

Dartek® is the most attractive of the benthic barriers from an economic standpoint, and it is sufficiently opaque to control nuisance plants by shading. The potential for the growth of macrophytes through the slits in the barrier (Perkins, 1984) and possible gas entrapment by the device, greatly reduce the desirablity of this barrier material.

Aquascreen™ is the most gas and ion transparent of any of the tested benthic barriers. It is not sufficiently opaque, however, to control plant growth in shallow waters by shading alone. Like Texel®, its shading efficiency is increased over time with the accumulation of silts and periphyton on its upper surface, but this accumulation also decreases its gas permeability. Submersed plants have also been observed to penetrate the material in field applications.

Expanded comparative field testing and laboratory testing of the impact of epiphyte colonization on the gas and ion permeability of these and other bottom barriers are badly needed. These data are necessary to gain a better working understanding of the conditions that favor the most appropriate application of a particular benthic barrier. A greater understanding of sediment diagenesis and the impact of benthic barriers on benthic processes are also necessary to produce a practical model for proper benthic barrier selection and installation.

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