# THE EFFECTS OF WATER TURBULENCE ON THE LIMNOLOGY OF A SHALLOW, PRAIRIE WETLAND

by

Brian Glenn Kotak

A thesis presented to the
University of Manitoba
in partial fulfillment of the
requirements for the degree of

Master of Science
in
The Faculty of Graduate Studies
(Department of Botany)

Winnipeg, Manitoba

ISBN 0-315-63355-7

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"Question all things. Seek for answers,
and when you find what seems to be
an answer, question that too."

L. L'Amour

# Acknowledgements

Over the past two years I have had the privilege of working with many people from varied backgrounds. All have contributed to this thesis in one way or another. I wish to express my appreciation. I am indebted to Dr. Gordon Robinson: advisor, friend, fellow beachcomber. Thank you for your excellent guidance and suggestions, sense of humor and taste for good wine. I also would like to thank Mary Robinson for always being there with a smile at hand, and for her countless ways of deliciously preparing potatoes!

I should also like to thank the staff and students of the Department of Botany and the personnel of the University Field Station, Delta Marsh. I greatly acknowledge the use of the facilities of the University Field Station. Special thanks to D. Convery who has shown me the true meaning of comedy.

Thank you to Dr. N. Kenkel for fruitful and stimulating conversations in higher dimensions, his constructive ideas concerning this thesis, and for his participation on the examining committee. I also wish to thank Drs. F.J. Ward and S. Badour for their ideas and for their participation on the examining committee.

The field assistance of D. Sahulka, S. Wiebe, T. Sellers, D. Francois, D. Peterkin, R. Rouire and G.G.C. Robinson are greatly appreciated as well as those who helped with sampling out of curiousity or by "volunteer recruitment".

I wish to thank my fellow coworkers inhabiting the Buller basement. I thank S. Gurney, D. Francois, T. Howell and D. Hubert for conversation, encouragement and support, and fine cuisine.

Lastly, and most importantly, I wish to thank Michelle for her support and patience during these past two years. Fear not, one of these days I will be employed!

Financial support for this study was provided by an NSERC operating grant and postgraduate scholarships and a University of Manitoba Research Development Grant.

# Abstract

In the first year of this study a field survey was conducted in the Blind Channel of the Delta Marsh, Canada to determine the influence of wind-induced water turbulence on the limnology of a shallow, prairie wetland. Hourly and seasonal changes in wind stress had a marked effect on suspended particulate concentration in the water column while phytoplankton biomass was affected by wind stress on a short-term (hourly) basis only.

Research in the second field season involved a manipulative experiment. Small-diameter littoral enclosures incorporating pumps which permitted in situ control of turbulence were utilized to examine the effects of controlled water turbulence on the limnology of the marsh. Because small enclosures lack turbulence, and are therefore plagued to some extent by enclosure effects, the use of artificially-generated turbulence within enclosures was evaluated as a posible means of alleviating enclosure effects. Turbulence within enclosures influenced all limnological parameters examined (suspended particulate concentration, water clarity, oxygen and nutrient levels, phytoplankton and periphyton biomass and productivity) except water temperature. Enclsoure effects on many of these parameters were evident and turbulence within the enclosures greatly alleviated these enclosure effects. The use of small-diameter turbulent enclosures appears to provide realistic data when compared to the adjacent marsh.

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# Chapter 1 : Literature Review

## Aquatic Mesocosms

### 1.1 Introduction: Uses and Designs

Since the 1960s, the use of aquatic mesocosms such as enclosures and limnocorrals has expanded from studies concerned primarily with phytoplankton dynamics (Lund, 1972) to eloberate, manipulative experiments concerning global issues such as the eutrophication and acidification of freshwater lakes (Schindler et al., 1971;1980), heavy metal toxicity, and most recently, the environmental fate and effects of a variety of organic contaminants (e.g. dioxins, pesticides, etc.) in aquatic ecosystems (Goldsborough and Robinson, 1983; Muir et al., 1985; Corbet et al., 1988). Indeed, part of the evolution in the utility of the mesocosm has paralleled public and political motivation. Studies utilizing mesocosms have also greatly increased knowledge of ecological processes and concepts (e.g. predator/prey relationships, population biology, nutrient cycling, etc.).

There is a large diversity of types of aquatic mesocosms. Enclosure and limnocorral designs include square, triangular, and circular shapes constructed of wood, stainless steel, rubber and a wide variety of sheet plastics. Mesocosm shape, size and construction material are important considerations in both ecological studies and those involving organic contaminants. For example, since

many organic compounds are subject to sorption phenomena, care should be taken to assure that adsorption of the contaminant to the mesocosm wall material is minimized. When dealing with very hydrophobic compounds such as dioxins, adsorption to the mesocosm walls should be monitored and accounted for.

Mesocosm shape and size influence these sorption processes through surface area effects. Large diameter circular mesocosms provide the lowest surface area relative to the enclosed volume while small volume square mesocosms have a much higher surface area/volume ratio. Consequently, the risk of contaminant adsorption to the walls is increased by providing more surface area. Also, as the surface area/volume ratio is increased, additional confounding factors may become more pronounced. For example, development of periphyton on mesocosm walls may occur causing increased attenuation of light within translucent mesocosms and unnaturally high levels of nutrient consumption (Goldsborough et al., 1986). The popularity of the use of circular mesocosms may be due in part to the elimination of "corner effects". The corners of square and triangular mesocosms often lead to the concentration of large amounts of suspended inorganic and organic particulates as well as phytoplankton and zooplankton (Sanders, 1985).

## 1.2 Mesocosms and the Experimental Approach in Ecology

Odum (1984) distinguishes two schools of thought with respect to experimental design in ecology that are also applicable to

toxicology. The first is a reductionist view in which a complex system is reduced to a more simplified, controllable microcosm in order to accurately assess the effects of a perturbation or manipulation (e.g. change in species competition and/or predation, introduction of nutrients or a pesticide, etc.) on a selected species or compartment of the aquatic system. This commonly includes studies utilizing test tubes, flasks and small aquaria in the laboratory in which as many independent variables as possible are controlled. In direct contrast to the reductionist view, the holistic view stresses the need for ecosystem level (macrocosm) studies which incorporate a greater degree of environmental realism. Each approach has merits as well as disadvantages (e.g., Diamond, 1986).

There has been a growing tendency for ecologists and toxicologists to study discrete "sections" of the aquatic environment by utilizing mesocosms. Mesocosms bridge the gap between the more controllable and repeatable microcosms and the more realistic and complex macrocosms. Mesocosms offer an alternative that gives the best of both worlds. In addition to limnocorrals in lakes (Schindler et al., 1971; Lund, 1972; Solomon et al., 1980; Schindler et al., 1988; Servos, 1988) and in situ, littoral enclosures (Goldsborough et al., 1986), other designs such as artificial streams (Kosinski and Merkle, 1984), natural prairie sloughs (Jones and Moyle, 1963), artificial dugout ponds (Muir et al., 1985; Corbet et al.,1988) and concrete ponds have been used successfully in a number of studies. These range in size from 1 $m^3$ up to elaborate ecological and toxicological experiments such as MERL (Marine Ecological Research

Laboratory), CEPEX (Controlled Ecosystem Pollution Experiment; Case, 1978) and MELIMEX (Metal LIMnological EXperiment; Gachter, 1979). For example, CEPEX involves large, floating marine limnocorrals which extend below the photic zone. Although the latter mentioned examples are costly to operate, smaller versions have yielded valuable information at a cost comparable to laboratory experiments.

This review compares and contrasts the relative merits and disadvantages of the three levels of experimental design: laboratory microcosm, mesocosm and macrocosm. Mesocosm performance will be assessed by the comparisons of the results of mesocosm studies with those of both microcosm and macrocosm studies utilizing both ecological and toxicological data from aquatic systems.

## 1.3 Micro-, Meso- and Macrocosms: Merits and Limitations

To address the question of which type of experimental approach works best, one must compare the merits and disadvantages of mesocosms relative to both laboratory assays and macrocosm experiments on many levels. Microcosm experiments are perturbations produced by the experimenter in the laboratory while mesocosm experiments are perturbations imposed by the experimenter in isolated "sections" of the environment. Macrocosm experiments utilize a whole aquatic ecosystem (eg. a lake). It should be pointed out that mesocosms and macrocosms are not conceptually distinct but may overlap. For example, natural prairie sloughs may

be classified as either mesocosm or macrocosm experimental units. Diamond (1986) states that these three types of experiments differ greatly in the hypotheses which can be addressed by their use. Table 1-1 summarizes how the three experimental designs differ in their relative merits according to several criteria.

Table 1-1 shows that microcosm studies offer the greatest degree of control over independant variables and variation between sample sites (site matching), although Sanders (1985) states that there are examples in the literature where the coefficient of variation between replicate enclosures is comparable to that found in microcosm studies. Although a limited number of independent variables can be controlled in mesocosm studies (and still fewer in macrocosm studies) all treatments will recieve the same levels of variables such as light, temperature and wind, even if these factors are not accounted for. Thus, uncontrolled variables in mesocosm studies need not be a primary concern as long as all treatments receive them equally. Indeed, this may add greater realism to a study.

Clearly, microcosm experiments permit the largest number of replicates (and treatments) and therefore, greater statistical sensitivity and precision. Satisfactory replication is difficult to attain in macrocosm studies, for example in lakes, since no two lakes are sufficiently similar. Replication in such studies can also be expensive. Reference lakes, commonly used as controls, must be used with caution as natural seasonal and yearly variation may obscure true relationships (Schindler, 1987). Schindler et al. (1987)

Table 1-1. Comparison of three levels of experimental design in ecology and toxicology according to several criteria (modified from Diamond, 1986).

| Criterion | Microcosm | Mesocosm | Macrocosm |
|---|---|---|---|
| 1. Regulation of variables | High | Med | Low |
| 2. Site matching | High | Med | Low |
| 3. Replication | High | High/Med | - |
| 4. Statistical precision | High | Med | Low |
| 5. Repeatability | High | Med/Low | Low |
| 6. Max. temporal scale[a] | Low | Med/High | High |
| 7. Max. spatial scale[b] | Low | Med/High | High |
| 8. Scope[c] | Low | Med | High |
| 9. Realism | None | High | High |
| 10. Generality | None | Med | High |
| 11. Risk of contamination | Low | Low/Med | High |

Table 1-1 (cont'd)

| Criterion | Microcosm | Mesocosm | Macrocosm |
|---|---|---|---|
| 12. Ease of clean up | High | High/Med | Low |
| 13. Cost | Low | Low/Med | High |

(a) length of time an experiment can be conducted in a location
(b) size of the experimental units
(c) number of manipulations and/or variables that can be examined

have been fertilizing a small, precambrian shield lake with nitrogen and phosphorus since 1969. Changes in water chemistry and biota must be compared to reference lakes receiving no external nitrogen and phosphorus. Whole-lake acidification experiments have also been done (Schindler et al., 1985). Because of a heterogeneous environment, site matching in mesocosm work is more problematic than in laboratory studies but is offset by randomization and dispersion of the mesocosms and through replication.

Natural seasonal and yearly variation in macrocosm and mesocosm studies diminishes the degree of repeatability of experiments in comparison to microcosm studies. Variation between years may constitute a large portion of the variation during long-term experiments in mesocosm and macrocosm experiments. Microcosm experiments are usually of short duration (low maximum temporal scale) while macrocosm experiments can be theoretically operated indefinitely. Mesocosm studies are intermediate in duration; the length of time being untimately dictated by the durability and size of the mesocosm. Microcosm studies lack the temporal scale needed to elucidate long-term effects. Mesocosm and macrocosm studies are usually of a sufficient duration (2-10 years) to allow determination of such long-term effects.

Microcosm experiments have the lowest spatial scale. Microcosms in the laboratory involve use of test tubes, flasks and aquaria with small volumes of water. Mesocosms offer a opportunity for larger spatial scales while maintaining easy regulation of important variables. Macrocosm experiments offer the greatest

spatial scale but are often difficult to control. The larger spatial scale of mesocosm studies allows more realistic extrapolation to the natural environment than microcosm studies. However, Diamond (1986) states that when spatial scale is increased there is usually a concomitant decrease in replication.

Perhaps the greatest shortcoming of laboratory assays is the lack of realism and the degree to which systems fail to emulate the natural environment (Table 1-1). All variables are set such that growth conditions are optimal. This is rarely the case in nature (Solomon et al., 1985). In addition, microcosm experiments commonly involve single species cultures. To offset the single species "dilemma", some investigators have included representatives of several trophic levels in their design (Metcalf et al., 1971; Harris et al., 1980 in Larsen et al., 1986). deNoyelles et al. (1982) point out that the response of any single species to a perturbation is likely to be influenced by the presence of other species and components of the abiotic system (eg. sediments). For example, the current standards (acceptable levels) for organic contaminants in the environment come mainly from data generated from single species toxicity assays performed in the laboratory. Many recognize the artificiality of such tests (Cairns, 1983; Odum, 1984; Kimball and Levin, 1985; Schindler, 1987) and consequently the applicability of such data to the natural environment is limited. Despite the lack of environmental realism in such laboratory assays, risk and hazard assessments are made from combining these laboratory toxicity data with exposure information. Exposure is predicted from monitoring

programs while toxicity data arise from extrapolation of these single species bioassays on selected, representative organisms. In addition, many laboratory assays in test tubes or flasks do not include the sediment compartment in the design. Therefore these assays do not account for processes such as adsorption of the contaminant and degradation in the sediments. Consequently these experiments cannot yield data concerning the persistence or compartmentalization of organic contaminants in the environment.

Although reduction of complex ecosystems down to simplified laboratory microcosms allows for greater control, the validity of extrapolating such data to the real world remains unanswered. The behavior of a species or contaminant in the environment cannot be easily predicted from the behavior in the subunits of the system. Impacts at one heirarchical level do not translate well into effects at other levels (Odum, 1984). For example, microcosm toxicity assays failed to predict the detrimental effects of acid rain on fish in Sweden. High mortalities of fish occurred at a pH which was not physiologically harmful by laboratory assay standards. However, these toxicity tests could not predict the pH-mediated leaching of aluminum from the watershed which caused clogging of fish gills and disruption of ionic regulation at this physiologically "safe" pH (Odum, 1984).

Community functions such as species interactions (predation and competition), immigration and emigration, or interrelationships between organisms and biogeochemical cycles are neglected in microcosm studies (Schindler, 1987). For example, although acute

microcosm tests examining the effects of copper on fish, invertebrates and periphyton correctly assessed mortality due to copper toxicity in Ohio streams, chronic tests failed to accurately predict the impact on these streams (Greckler et al., 1976). Chronic microcosm tests looked only at mortality, growth and fecundity of fish. When subjected to a concentration of 120 $ug \cdot L^{-1}$ Cu, fish migrated out of the area to avoid the high levels of copper in the stream.

Species used for toxicological testing in the laboratory are usually those which can be cultured conveniently, rather than the most sensitive or critical species in natural environments. Larsen et al. (1986) found a 10-fold difference in $EC_{50}$ values to atrazine among 8 species of algae in laboratory single species toxicity assays. Larsen et al. (1986) also state that most toxicity protocols utilize only one species of algae. Misleading conclusions may be drawn if the representitive alga is tolerant to the toxin in question.

In contrast to the microcosm design, mesocosm studies incorporate more realism into their design (Table 1-1). Many species of different trophic levels are present and species interactions and possibly synergistic effects may occur. This is clearly an advantage over microcosm assays although synergistic effects are rarely quantified. Results can be more realistically extrapolated to the natural environment. Many species are included in the study so that the effects of, for example, a contaminant can be monitored on both resistant and vulnerable species.

In spite of the incorporation of many interacting species in the mesocosm design, the effects of a contaminant are usually monitored at the community level and not at the individual species level. This may be a disadvantage to the system as information about species tolerance to a contaminant can be lost. However, this may only be an artifact of reductionalist thinking! Gurney (1988) using littoral enclosures in the Delta Marsh, Manitoba, Canada utilized quantitative grain density microautoradiography to determine the primary production response of each species of the periphytic algal community to simazine exposure. Although this method permitted her to follow the toxicity of individual species, the technique takes considerable amounts of time (Gurney, pers. comm.) and therefore its utility in mesocosm and macrocosm studies is of limited value.

Mesocosms commonly include all the compartments found in natural aquatic environments (eg. water, sediment, biota, air-water interface, sediment-water interface) and therefore lend themselves well to investigations concerning contaminant effects, compartmentalization and environmental fate. Because all of the compartments are present, processes such as adsorption of contaminants to sediments and suspended particulates can also be monitored, something rarely studied in the lab.

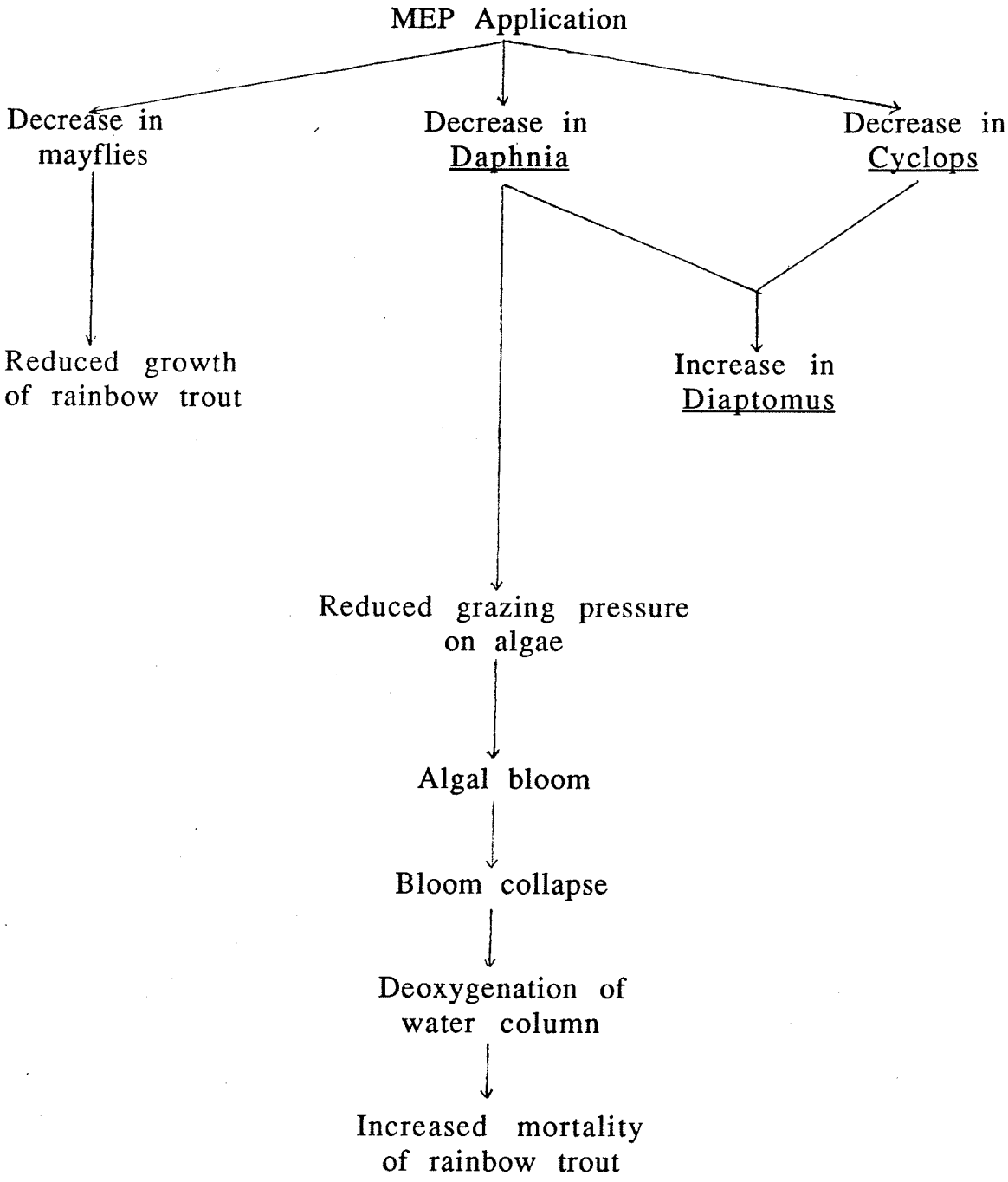
Mesocosms allow an investigation at many trophic levels simultaneously; this is rarely achieved in the laboratory. Elimination or inhibition of a species (or several species) may well have ramifications on higher trophic levels through changes in

competition or predation. Schindler (1987) refers to this as a "trophic cascading" effect. For example, Crossland (1984) examined the effects of methyl parathion (MEP) in outdoor ponds and laboratory aquaria. MEP in ponds was toxic to some species of aquatic insects and crustaceans but not to fish. This spectrum of toxicity was similar to results from laboratory tests. However, interactive, secondary effects in the ponds could not be predicted from laboratory toxicity tests. Fig. 1-1 is a flow chart depicting the sequence of secondary events after application of the ponds with MEP (100 $\mu g \cdot L^{-1}$).

Application of MEP resulted in the rapid loss of Daphnia spp. and a less severe decline in the populations of Cyclops spp. and mayflies. A large increase in the populations of Diaptomus spp. occurred in the treated ponds 20-90 d. after treatment due to the loss of its competitors (Daphnia spp.) and preditors (Cyclops spp.). Loss of mayflies from the ponds treated with MEP reduced the growth rate of rainbow trout as the trout's principle food source was eliminated. Loss of herbivorous zooplankton and mayflies also resulted in a reduction in grazing pressure on algae. An algal bloom formed as a reuslt. Collapse and subsequent decomposition of the bloom increased biological oxygen demand (BOD) in the water such that oxygen levels in the water could no longer sustain rainbow trout. Trout mortality increased dramatically.

Mesocosms also have limitations. Schindler (1987) points out that aquatic mesocosms fail to incorporate phenomena such as water turbulence and/or nutrient cycling. When using enclosures and

Fig. 1-1. Flow chart showing secondary effects of application of methyl parathion to ponds (derived from Crossland, 1984).


MEP Application
Decrease in mayflies
Decrease in Daphnia
Decrease in Cyclops
Reduced growth of rainbow trout
Increase in Diaptomus
Reduced grazing pressure on algae
Algal bloom
Bloom collapse
Deoxygenation of water column
Increased mortality of rainbow trout

limnocorrals in lakes and ponds, one must be sure that enclosure effects (the effect of isolating a water column from the rest of a water body in the absence of a treatment) are minimized (Kuiper, 1977).

Macrocosm studies provide the most realistic data in terms of what occurs in the natural environment. Results from these experiments need only be extrapolated to the general case since a macrocosm is part of a natural system (not a subset of a system). However, obtaining government and public consent, for example to intentionally introduce a contaminant into part of a natural ecosystem, can be a major challenge.

The popularity of laboratory microcosms, particularly in screening potentially harmful chemicals, is derived from the rapid generation of data and low operating cost relative to macrocosms. If one is to obtain representative samples from macrocosm studies, the cost of such chemical appraisal could greatly exceed its utility. The cost of conducting an experiment in a "dugout" pond mesocosm only slightly exceeds that of a microcosm experiment. Additional expense may include the cost of pond excavation and transportation to and from the study site. Goldsborough et al. (1986) describe 0.3 $m^3$ littoral enclosures costing $30 Can. while Solomon et al. (unpubl.) describe limnocorrals with volumes of 20, 125 and 1000 $m^3$ costing $360, $1620 and $3000 respectively.

Another factor contributing to the popularity of microcosm studies is that the data obtained yield standard end points such as

growth rates and mortality rates as well as $LD_{50}$, $LC_{50}$ and $EC_{50}$ values and NOEC (No Observable Effect Concentration) and MATC (Maximum Allowable Toxicant Concentration). These end points are rarely quantified in mesocosm studies and even less so in macrocosm studies. However, non-biological end points such as half life values of contaminants in various compartments of the aquatic environment are common to both mesocosm and macrocosm studies (Hesslein et al., 1980; Muir et al., 1980; Schindler et al., 1980; Rawn et al., 1982; Servos, 1988).

When investigating the effect of a perturbation on the environment, the decision to perform the study in the laboratory, in mesocosms or in natural ecosystems should incorporate a measure of the ease of site cleanup after use and the risk of contaminating nearby areas. Rapid cleanup is accomplished easily in the laboratory, but becomes more challenging in mesocosm or macrocosm studies. For example, in laboratory toxicology studies, flasks are easily cleaned whereas mesocosms such as dugouts may require removal of water and hydrosoil to a landfill site. Mesocosm experiments using enclosures may require disposal of the enclosures upon termination of the experiment or even enclosure removal from lakes or ponds before winter freeze up. Solomon et al. (unpubl.) however, state that their large limnocorrals could remain in the lake all year and receive no damage from winter ice.

The risk of releasing a contaminant into the environment during or after an experiment is relatively easily controlled in laboratory studies, but can prove difficult in ecosystem studies,