Pure Appl. Chem., Vol. 71, No. 1, pp. 153–160, 1999.
Printed in Great Britain.

The use of mesocosms in marine oil spill—ecological research and development*

Timothy J. Reilly

Industrial Economics, Incorporated, Cambridge, MA 02140, USA

INTRODUCTION

The use of chemical and biological agents (e.g. dispersants and bioremediation agents, respectively), as well as certain physical oil removal techniques (e.g. high-pressure, hot-water applications to oiled shorelines) during oil spill response operations requires consideration both of the gross effectiveness of such oil removal/displacement techniques and of the ecological impact of the response technique. Accordingly, the intent of response technology optimization requires the identification of suitable response agents, their application strategies, determination of mass oil removal effectiveness, and efficient coordination of alternative response strategies with conventional measures, all compared with traditional mechanical collection methods and evaluation or relative response ecological impacts. These issues often need to be examined in an experimental setting in order to acquire information required to make more effective decisions during oil spill response and cleanup operations. Controlled field studies that are designed to identify optimal response and clean-up strategies, while valuable for realism, are expensive and often difficult to implement because of regulatory barriers [1]. Conversely, results from small scale laboratory testing do not incorporate sufficient environmental realism (variables and scale) to permit confident predictions about real-world situations. However, bounded and partly enclosed outdoor experimental units, or 'mesocosms', can closely simulate natural aquatic environments [2]. Such test systems provide a simulation of real-world exposure without the costs of a controlled-release field study. Mesocosms can serve to bridge the gap between large-scale field experiments, with their inherent control difficulties, laboratory experiments which can be statistically replicated but suffer from a lack of environmental realism [3].

Mesocosms have strengths and weaknesses depending upon system design. Therefore, the type of ecological research to be conducted will dictate the choice of mesocosm design. The following discussion presents design requirements and scientific considerations for mesocosm simulations of marine environments impacted by oil spills. Two existing mesocosm systems for marine oil spill ecological research in both pelagic and nearshore environments are reviewed in some detail—the Marine Ecosystem Research Laboratory (MERL) in Narragansett, Rhode Island, and the Coastal Oil-Spill Simulation System (COSS), in Corpus Christi, Texas.

SYSTEM REQUIREMENTS FOR MESOCOSMS IN MARINE OIL SPILL ECOLOGICAL RESEARCH AND DEVELOPMENT

Mesocosm design and tank geometry can vary greatly. The choice of an appropriate type and size of mesocosm reactor chamber for a given experiment will depend upon the type of environment to be modeled, and the physical, chemical, or biological processes under study. Of particular importance in ecological impact testing is accurately modeling the physical and chemical parameters of a mesoscale ecosystem [1]. Accurate replication of the physical and chemical environments to be modeled in mesocosm test chambers will facilitate the development of representative modeled ecosystems. In other words, the physical and chemical aspects of a mesoscale system must be adequately replicated before the biological aspects of the system can be accurately modeled. For research on marine oil spills, three classes of environments are of particular interest: intertidal zones for various shoreline environments (e.g. rocky, sand/gravel, tidal flat, wetland, mangrove, etc.), shallow subtidal areas, and offshore (pelagic)

Pure Appl. Chem. **71**(1) (1999). An issue of special reports reviewing oil spill countermeasures.

environments. From an ecological impact perspective, the first two of these environmental classes are of greatest concern, since the most severe ecological impacts from oil spills generally occur in the intertidal and shallow subtidal zones. Correspondingly, these coastal areas have become the most controversial locations for the use of chemical oil spill treating agents, such as dispersants and chemical shoreline cleaners. However, pelagic impacts are also of strong interest in natural resource impact assessment because water column oil fates (especially in the upper 10 m) will dictate the amount of exposure to water column and certain benthic biota.

The biological, chemical or physical processes under investigation will dictate the size of mesocosms. The appropriate sizing of mesocosm reactors to a given experiment is a design process known as *scaling*.

Scaling

In order to accurately model coastal and marine environments, the key physicochemical and biological properties and processes must be identified (e.g. wave/sediment interactions, tidal processes, current regimes, oxygen concentrations in water, redox potential in sediments, freshwater input, degree of mixing in the water column, flora and fauna microhabitat requirements, etc.). Appropriate sizing of a test tank will result in a better predictive model for identifying ecological impacts from ecosystem perturbations, both direct impacts of the oil inputs, and the impacts of countermeasures in response. Therefore, the scaling functions of key mesocosm characteristics will be dependent upon the coastal ecosystem modeled, but will translate to physical factors as tank size and shape, degree of water exchange, tidal cycles, substrate patterns, temperature and light regimes, and other variables.

The usefulness of the mesocosm approach is that it allows more accurate modeling of the exposure of oil, treating agents, and physical oil removal technologies, predicting its impact on resident biota from both a spatial and temporal perspective. Realistic exposure profiling in mesocosm reactors enhances the predictive capability of toxicity studies. Mesocosms should have the capability to simulate the following oil weathering processes, their importance depending on the study being conducted: evaporation, photodegradation, dispersion, surface spreading (on water), stranding and vertical penetration into shoreline matrices, and biodegradation. Toxicity indices can usually be measured in more traditional laboratory investigations, and the results of laboratory tests can be extrapolated to the field situation, provided the exposure of the organism can be predicted. Exposure control provides the major difficulty in extrapolating from the laboratory investigations to the field, and has become an impetus for the use of mesocosms. In laboratory toxicity tests, hydrocarbon concentrations are maintained at a relatively constant level by regular replenishment of solutions or by the use of flow-through techniques. In the natural environment, oil is subject to several distinct weathering processes, having a profound effect on the concentration to which the organism is exposed and the duration of that exposure [4].

Mesocosm tank features useful in coastal/nearshore ecological marine oil spill research

The initial features essential to coastal and nearshore oil spill research using mesocosm test tanks were identified by a working group for marine oil spill mesocosm design, sponsored by the Marine Spill Response Organization. The design features resulting from a series of meetings held in the fall of 1992 and the spring of 1993 comprise the essential scaling elements of marine mesocosms designed for shoreline and shallow subtidal coastal environments [1]:

Minimum size: 30.5 m (length) × 2.1 m (width) × 2.4 m (depth): This tank length allows for the establishment of a wide range of shoreline environments, including rocky shores, beaches, tidal flats and wetlands; and the establishment of realistic wave spectra. The tank width allows for the propagation of waves along the axis of the tank with only minimal wave/wall effect interactions. The depth of the tank allows for the establishment of a shallow subtidal area (i.e. less than 2 m). The minimum size of the reactor tank established by the working group allows the tank to be scaled to a wide range of coastal and nearshore chemical and physical processes, facilitating the establishment of realistic biological regimes.

Wave maker for nearshore energy simulation: Waves are the principal phenomenon that control the development of beaches [5]. Waves vary somewhat randomly in height, period and length (distance from wave crest to wave crest). Therefore, an appropriate wave generation system that generates random waves is required for the type of coastal/nearshore environment to be modeled.

Flow-through seawater system: Due to the wide range of retention times of water in coastal and nearshore environments, water flow rates in a coastal mesocosm model should be able to be varied from batch (i.e. no flow) conditions to vary low retention times, i.e. on a scale of minutes to hours. Additionally, current patterns should mimic both cross-shore and long-shore currents. The placement of water influent and effluent ports can be used to simulate long-shore currents; and a wavemaker positioned at one end of a mesocosm can be used to simulate cross-shore currents.

Simulated tidal cycles: The tidal range can vary dramatically, ranging from a few centimeters in a microtidal environment to more than 10 m. An appropriate tidal range for the type of environment to be modeled should be established. Frequently, the intertidal zone is heavily contaminated during oil spills, resulting in substantial ecological impacts to this environment from both the spilled oil and subsequent response operations.

Ability to create a wide array of test environments: Oil spills have impacted practically every type of coastal and nearshore environment (e.g. manmade structures, beaches, tidal flats, wetlands, open water, etc.). Impacts to flora and fauna unique to each type of shoreline environment is essential to formulating the appropriate type of response and cleanup strategy. Further, the addition of seawater (from a real or artificial source) can be highly corrosive to many materials (e.g. metals) used in currently operating systems. Systems must be designed to accommodate seawater. The materials used also must be conducive to supporting coastal and nearshore flora and fauna. It is recommended that materials used in mesocosm testing be aquarium grade in order to support marine biota.

Ability to spill crude oil and refined petroleum products in confined tanks: A number of mesocosm facilities currently operating in North America and Europe are not designed to allow crude or refined petroleum products in their tanks due to fouling problems and oil/water treatment and discharge issues. Mesocosms designed for marine oil spill studies must address these often difficult issues.

Ability to add various chemical and biological response agents to the tanks: Similar to the addition of petroleum products, many existing mesocosm facilities do not allow for the addition of oil spill response agents (i.e. dispersants, chemical shoreline treating agents, and bioremediation agents).

Ability to simulate freshwater input through the beach: Groundwater flow through a shoreline helps to define the characteristics of the coastal and nearshore area [5]. Ground water flow influences the chemical composition of the nearshore water mass by reducing the salinity and also may be an important source of nutrients for microorganisms. Freshwater aquifers in the beach face will significantly impact the distribution of oil and chemical/biological response agents in the intertidal zone. This may be an important experimental consideration when conducting chemical and biological experiments in the modeled intertidal zone.

Availability of multiple tanks to accommodate statistical considerations: Replicates are required to statistically demonstrate a difference in the treatments between mesocosm reactor tanks. The variability exhibited in measured parameters between tanks will factor largely in the number of replicate mesocosms required for a given experimental setup [6]. Water exchange between tanks should be eliminated in order to prevent cross-contamination of experimental treatments.

Further, the mesocosms should be located outdoors in order to allow the integration of wind and solar effects in the system.

MESOCOSM SYSTEMS USED IN ECOLOGICAL MARINE OIL SPILL RESEARCH AND DEVELOPMENT: MERL AND COSS CASE STUDIES

Two mesocosm facilities located in the United States have the functionality to conduct marine oil spill ecological impact studies for coastal and marine environments. Pelagic and benthic (i.e. water column

Table 1 Summary of the applicability of the Marine Ecosystem Research Laboratory (MERL) and Coastal Oil-Spill Simulation System (COSS) mesocosm facilities to marine oil spill ecological research and development projects

	MERL	COSS
Facility location	Narragansett, Rhode Island, USA	Corpus Christi, Texas, USA
Number of mesocosms	14	9
Mesocosm geometry	Upright cylinder	Open air rectangular box, horizontally oriented
Mesocosm dimensions	Water surface area: $2.63\,m^2$ Water depth: 5 m Benthic sediment area: $2.52\,m^2$ Benthic sediment depth: 37 cm Cylinder diameter: 1.83 m	Mesocosm chamber dimensions: 33.5 m (length) × 2.1 m (width) × 2.4 m (depth). Areas of water, intertidal and benthic zones dependent on shoreline or nearshore area modeled. Total interior test area is $70.4\,m^2$.
Mesocosm volume	$13.86\,m^3$	$168.8\,m^3$
Water source	Lower Narragansett Bay (Salinity 29–30 p.p.t.)	Laguna Madre (Salinity 20–50 p.p.t., depending on rainfall/season).
Current regimes modeled	Vertical water column mixing	Tidal Cross shore currents Long shore currents
Wave generation capabilities	No	Yes
Water flow capabilities	Batch or flow through (retention time: 27 days, same as proximal area of Narragansett Bay).	Batch or flow through (retention time: hours–days, depending upon environment simulated).
Environments simulated	Water column to 5 m depth and benthic environments with a wide range of vertical mixing capabilities	Shallow open water areas to 2 m The following types of low-to-moderate energy intertidal and shallow subtidal environments: beaches, rocky shores, tidal flats and marshes
Examples of marine ecological oil spill research that could be conducted	Exposure, impact and recovery studies for water column and benthic organisms exposed to petroleum products and oil spill treating agents	Exposure, impact and recovery studies for intertidal and shallow subtidal organisms in low to moderate energy environments exposed to petroleum products and oil spill treating agents

and sea floor coupled) environmental impact studies have been modeled in the Marine Ecosystem Research Laboratory (MERL) in Narragansett, Rhode Island, whereas shoreline and shallow subtidal environments are modeled at the Coastal Oil-Spill Simulation System (COSS) facility in Corpus Christi, Texas. Each of these facilities are described below. The design parameters of these systems are summarized in Table 1.

MERL

The MERL facility was established in 1976 at the University of Rhode Island's Graduate School of Oceanography. The facility consists of 14 vertically oriented cylindrical mesocosms. Each mesocosm chamber is 5 m deep, to maintain a heterotrophic benthos, $13\,m^3$ in volume so zooplankton can be sampled without impacting population abundances, and $2.62\,m^2$ in area so that the benthos may be sampled with minor impact over annual cycles. Water column and subtidal benthic communities are modeled in MERL mesocosms. Water column mixing can be vertical, horizontal, intermittent, or constant at any reasonable intensity. The enclosures are sufficiently deep to allow thermal and salinity stratification to be simulated. Accordingly, experiments can be conducted on marine systems exhibiting different degrees of stratification. Sea water can flow constantly, or intermittently, or not at all for whatever turnover is deemed appropriate. Sediments can be present or absent; when present, they can come from various sources. Sunlight can be natural or shaded or ultraviolet enhanced [7].

Numerous comparisons have been made between MERL enclosures and the parent natural ecosystem, Narragansett Bay. Numerous measurements were made to determine how poorly or how well the mesocosms simulated nature. Comparisons of phytoplankton, zooplankton, benthic fauna, nutrient cycles, and rates, such as primary production, showed good agreement between the enclosures and nature. Some of the differences included enhanced vertical mixing, a thicker surface film at the air–water interface, lack of horizontal advection, lack of large invertebrates and large fish, and wall fouling in the mesocosms. The mesocosms are simplified models of nature and agreements and disagreements with nature continue to be defined in every new experiment [7].

Elmgren & Frithsen [8] demonstrated similar benthic recovery rates between an oil spill in the Baltic Sea and a simulated spill in the MERL tanks. Oil introduced in the Baltic Sea and the MERL tanks behaved in a qualitatively similar way, with a considerable fraction of the oil reaching the sediment. The major plankton groups reacted similarly in both systems but response times differed. Recovery time for the plankton was short (time scale of weeks) in both cases. The benthic macro-and meiofauna declined in both systems after similar oil doses and higher taxonomic groups showed consistent differences in susceptibility. Recovery of the benthos was slow in both cases (time scale of years). The comparison strengthened the case for using mesocosms with tank geometry similar to the ones found at the MERL facility in evaluating pelagic/benthic coupled ecological impacts from oil spills and chemical treating agents such as dispersants.

The MERL system has been designed to model water column and benthic environments. Petroleum exposure regimes and related ecological effects can be studied in these environmental compartments. The MERL enclosures are useful for measuring the growth and survival of sensitive larval forms under a variety of natural conditions. Larval fish like cod, winter flounder, menhaden, anchovy and colleagues have shown good survival and growth in enclosures [7]. Accordingly, MERL mesocosm reactor tanks are well suited for oil spill research and development projects which address the ecological impacts of water column and benthic communities which have been exposed to floating and mixed petroleum products, and oil spill treating agents such as dispersants, emulsion treating agents, herding agents, etc. (Table 1).

COSS

The Marine Spill Response Corporation (MSRC), in collaboration with the Texas General Land Office (TGLO), sponsored the design and construction of a multiple tank mesocosm facility known as the Coastal Oil-Spill Simulation System (COSS). The COSS system is designed to test physical, chemical, and biological oil spill response technologies in a variety of nearshore and shoreline habitats such as marshes, tidal flats, rocky shores and beaches. The facility was completed in the spring of 1997 and is located in Corpus Christi, Texas.

The goal of the COSS facility is to provide a testing platform for effective, large-scale modeling of coastal conditions, allowing research and response personnel to test a myriad of oil spill response technologies and strategies in the appropriate coastal environments where they would be deployed. Nine reactor tanks, each with dimensions of 33.5 m (length) × 2.1 m (width) × 2.4 m (depth), allow for testing with statistical confidence.

Each reactor tank at the COSS mesocosm facility is designed to accommodate variations in coastal and nearshore conditions in the following ways:

- Tank geometry allows for establishment of open water, beach, tidal flat, or marsh/wetland environments.
- Flow-through seawater system, with the ability to model varying flow rates (i.e. water retention times).

- Natural seawater source: Laguna Madre.
- Diurnal or semidiurnal tides can be modeled up to approximately 1 m.
- Regular or irregular waves can be modeled up to 0.5 m.
- Cross shore and long-shore water transport components.
- Freshwater aquifers in shorelines can be modeled.
- An electronic control system that controls the experimental parameters of each tank individually or simultaneously.
- Establishment of multispecies model biological communities.

These experimental attributes allow for the modeling of a wide range of coastal processes under a continuum of conditions, ranging from quiescent to moderate energy conditions (i.e. both accretionary or erosional shoreline environments can be modeled). Further, the electronic control system governing each mesocosm tank will allow for intertank coupling and decoupling of environmental conditions, according to the requirements of a given experiment. The system accommodates both short-term studies (e.g. shoreline cleaning agent efficacy studies) and long-term studies (e.g. ecological recovery studies).

In order to test the ability of the COSS mesocosm design to accurately model a coastal nearshore system, a full-sized prototype mesocosm was constructed and subjected to a testing program involving hydrodynamic, geomorphic, and oil spill studies. A coarse sand/gravel beach (average sediment diameter: 0.5 mm) was constructed in the prototype for the tests. Seawater was supplied from the Laguna Madre in Corpus Christi, Texas, USA via an intake canal at a local power plant which hosted the facility. A 0.61-m, semidiurnal tidal cycle was simulated in many of the tests. Hydrodynamic tests, employing current pattern measurements and beach profile surveys, found that a tank of the dimension of the COSS prototype [30.5 m (length) × 2.1 m (width) × 2.4 m (depth)] is required to reproduce realistic magnitudes and patterns of beach profile change and current flows (i.e. magnitude and direction) as occur on natural beaches. However, it was found that increasing the length of the tank by an additional 3 m (behind the wave maker unit) allowed for the placement of wave absorption media, hence, minimizing unnecessary wave reflection patterns within the mesocosm tank. The hydrodynamic studies also found that the water exchange system within the tanks did not disturb the waves and wave-induced cross-shore current pattern. Water flow patterns within the beach sediment matrix were also studied. Water level profiles were consistent with those noted in actual beach environments. Further, it was observed that the freshwater flow and wave energy simulated in the COSS design will allow for a wide range of beach environments to be modeled. Finally, simulations of both on-water and on-land oil spills were conducted in order to compare the fate of oil in the tank system to oil fate under similar real world situations. The migration of oil in the sediment under both oil spill scenarios was reflective of oil penetrations in coarse-grained beaches observed in actual spills. Accordingly, the COSS system effectively described the fate of oil and its distribution in the coastal zone through modeling key physical nearshore parameters under controlled conditions.

The COSS facility was designed to test the effectiveness and corresponding ecological effects for oil spill response technologies in low-to-moderate energy environments (i.e. environments dominated by waves heights ranging from approximately 0–0.5 m). Due to mesocosm length and wave maker considerations, realistic higher energy shoreline regimes can not be modeled. However, lower energy shorelines tend to be the focus of research and development from an oil spill response and cleanup perspective. Natural oil removal processes through wave action are minimal in low energy coastal environments, often requiring additional cleanup treatment actions. The establishment of realistic low-energy nearshore environments and oil exposure profiles will facilitate future ecological impact (and effectiveness) research in the COSS mesocosms, especially studies that address the optimization of physical, chemical and biological response strategies in the intertidal and shallow subtidal zones (Table 1).

An accurate simulation of various coastal and nearshore systems (i.e. shallow open water, beach, tidal flat and marsh environments) in mesocosms is highly complex due to a wide array of habitat-specific physical, chemical and biological considerations. The time required to reach stability in an accurately simulated ecosystem makes conducting research difficult. However, COSS mesocosms will effectively simulate a multispecies model (e.g. mud, *Spartina* sp., and blue mussels) rather than an entire nearshore habitat (e.g. a marsh). Consequently, COSS studies are designed to be conducted with a multispecies model construct, making inferences to natural systems possible [9] (Table 1).

RECOMMENDATIONS ON THE DESIGN AND USE OF MARINE MESOCOSMS IN OIL SPILL ECOLOGICAL IMPACT STUDIES

It is recommended that the following considerations be factored into the planning of marine oil spill ecological studies involving mesocosms.

- Whenever possible, both the ecological effects and effectiveness testing oil spill treatment technologies should be conducted concurrently in mesocosm reactors. This will facilitate cost savings and result in a better oil and/or spill treating agent exposure profile for target flora and fauna receptors, and importantly allow same time comparisons among test conditions.
- The variability in study parameters between reactor tanks should be minimized to the extent possible. Greater ‘intertank’ variability will increase the difficulty in detecting treatment differences between the tanks. Accordingly, intertank variability is controlled in experimental design by a definitive understanding of any residual variability, which then determines the number of tank replicates required for a mesocosm system experiment.
- Mesocosms should be sized so that key physical, chemical, and biological processes under study are scalable, and thus are accurately modeled. Also, the mesocosm chambers should be sized so that ‘intratank’ sampling activities do not disrupt the modeled coastal ecosystem.
- Generally, mesocosm cost and size are directly proportional. Smaller mesocosms (among others, the SINTEF Continuous Flow Basin System in Trondheim, Norway) may be useful for a number of mechanistic and range-finding studies, but not for ecological investigations. Such smaller systems are less expensive to operate than larger ecological mesocosms. However, for cost-containment purposes, ecological mesocosms should not be larger than required to scale the coastal process modeled.
- Frequently there is synergy between laboratory and mesocosm studies, which can complement each other by combining laboratory precision with field reality, and provide a basis for a good model that could be continually validated by additional laboratory and field experiments [2].
- The need to compare the results of mesocosm studies with field results will continue even after the field fidelity of a given mesocosm design has been established. This should not be viewed just as a search for possible artifacts of mesocosm studies, but rather as a tool to allow reinterpretation of field data, to identify problem areas requiring further research or to identify more sensitive field monitoring tools [10].
- Physical, chemical and biological system characterization studies of mesocosms are warranted before, during and after experiments for data interpretation purposes.
- The water source used in experiments ideally should be actual seawater, used in a monitored flow-through design in order to incorporate realistic water chemistry and planktonic biota into experiments.
- Ideally, the sediment source for experiments should be natural in origin. However, if this is not feasible, appropriately sized sediments can be obtained from a number of building material sources providing sand, gravel and stone. In intertidal and benthic impact experiments, colonization of such sterile sediments by bacteria and infaunal organisms from a raw seawater source should be allowed prior to the initiation of studies for an adequate period to achieve a stable or at least predictable ecosystem simulation.
- Due to the large amount of time required for mesocosms to reach stability for modeled coastal environments, mesocosms should use multispecies models (e.g. mud, *Spartina* sp. and blue mussels to simulate a marsh) rather than attempt to simulate an actual nearshore environment.

- Mesocosm layout orientation should be selected to minimize the shadowing effect of reactor walls on sunlight and wind turbulence.
- Site security should be maintained during experiments to insure experimental integrity and human safety.

CONCLUSIONS

Mesocosm experiments in marine oil spill ecological research allow for testing of the impacts of chemical, biological and physical spill response treatment methods on intertidal, benthic and water column organisms. Two mesocosm facilities, the Marine Ecosystem Research Laboratory in Narragansett, Rhode Island, and the Coastal Oil-Spill Simulation System facility in Corpus Christi, Texas, are designed to accommodate this type of research in pelagic/benthic and shoreline/shallow subtidal modeled environments, respectively. The use of these mesocosm systems in oil spill research should be viewed not as a sole solution to ecological testing of oil spill and response impacts, but rather as part of an integrated program with laboratory and field testing. Laboratory studies can provide experimental precision; mesocosm studies provide realistic oil and response treatment exposures to test organisms; and field studies provide real-world verification of laboratory and mesocosm test results.

ACKNOWLEDGEMENTS

The author would like to express gratitude to Industrial Economics, Incorporated, Cambridge, Massachusetts (USA) for supporting the production of this chapter.

REFERENCES

1 T. J. Reilly, N. C. Kraus, W. R. Wise, R. Jamail. *Coastal Oilspill Simulation System Prototype Testing Program*. MSRC Technical Report Series 94-005 (1994).

2 E. P. Odum. *Bioscience* **9**(34), 558–62 (1984).

3 J. H. Rodgers Jr, N. O. Crossland, E. R. Kline, W. B. Gillespie Jr, R. A. Figueroa, P. B. Dorn. *Ecotoxicol. Environ. Safety* **33**, 30–7 (1996).

4 N. O. Crossland, T. W. LaPoint. *Environ. Toxicol. Chemistry* **11**, 1–4 (1992).

5 R. D. Scott. *Technical evaluation of the coastal oilspill simulation system prototype*. MSRC Technical Report Series 93-029 (1993).

6 D. King. Experimental design considerations for mesocosm research in the COSS facility. In *Proc. Workshop Techn Issues Related Mesocosm Res. Coastal Oilspill Simulation System Facility* (J. H. Kucklick, ed.), MSRC Techn Report Series 95-022 (1995).

7 C. A. Oviatt. *Oceanography* **7**, 2 (1994).

8 R. Elmgren, J. B. Frithsen. The use of experimental ecosystems for evaluating impact of pollutants. In *Marine Mesocosms: Biological and Chemical Research in Experimental Ecosystem*, *MERL Publications* (G. D. Grice, M. R. Reeve, eds). Springer Verlag, NY (1982).

9 J. H. Kucklick. *Proceedings of the Workshop on Technical Issues Related to Mesocosm Research in the Coastal Oilspill Simulation System Facility*. MSRC Technical Report Series, 95-022 (1995).

10 P. L. Donaghay. *Concepts in Marine Pollution Measurements* (H. H. White, ed.), pp. 589–620 (1984).