

Watersheds, Bays, and Bounded Seas

The Science
and Management
of Semi-Enclosed
Marine Systems

EDITED BY Edward R. Urban, Jr.
Bjørn Sundby
Paola Malanotte-Rizzoli
and Jerry M. Melillo

 **SCOPE** 70

Watersheds, Bays, and Bounded Seas

*The Science and Managment
of Semi-Enclosed Marine Systems*

Edited by
Edward R. Urban, Jr., Bjorn Sundby, Paola
Malanotte-Rizzoli, and Jerry M. Melillo



A project of SCOPE, the Scientific Committee on
Problems of the Environment, of the
International Council for Science

 **ISLANDPRESS**

Washington • Covelo • London

Copyright © 2009 The Scientific Committee on Problems of the Environment (SCOPE).
All rights reserved under International and Pan-American Copyright Conventions. No
part of this book may be reproduced in any form or by any means without permission
in writing from the publisher: Island Press, 1718 Connecticut Avenue NW, Suite 300,
Washington, DC 20009.

Permission to reproduce portions of this book should be addressed to SCOPE (The
Scientific Committee on Problems of the Environment, 5 rue Auguste Vacquerie,
75016 Paris, France).

ISLAND PRESS is a trademark of the Center for Resource Economics.

Library of Congress Cataloging-in-Publication Data

Watersheds, bays, and bounded seas : the science and management of semi-enclosed
marine systems / edited by Edward J. Urban, Jr. ... [et al.].

p. cm. — (SCOPE ; 70)

Includes bibliographical references and index.

ISBN-13: 978-1-59726-502-7 (cloth : alk. paper)

ISBN-10: 1-59726-502-0 (cloth : alk. paper)

1. Coastal ecology. 2. Marine ecology. 3. Marine ecosystem management.

I. Urban, Edward J.

QH541.5.C65W38 2008

577.7—dc22

2008027634

Printed on recycled, acid-free paper ♻

Manufactured in the United States of America

10 9 8 7 6 5 4 3 2 1

About Island Press

Since 1984, the nonprofit Island Press has been stimulating, shaping, and communicating the ideas that are essential for solving environmental problems worldwide. With more than 800 titles in print and some 40 new releases each year, we are the nation's leading publisher on environmental issues. We identify innovative thinkers and emerging trends in the environmental field. We work with world-renowned experts and authors to develop cross-disciplinary solutions to environmental challenges.

Island Press designs and implements coordinated book publication campaigns in order to communicate our critical messages in print, in person, and online using the latest technologies, programs, and the media. Our goal: to reach targeted audiences—scientists, policymakers, environmental advocates, the media, and concerned citizens—who can and will take action to protect the plants and animals that enrich our world, the ecosystems we need to survive, the water we drink, and the air we breathe.

Island Press gratefully acknowledges the support of its work by the Agua Fund, Inc., Annenberg Foundation, The Christensen Fund, The Nathan Cummings Foundation, The Geraldine R. Dodge Foundation, Doris Duke Charitable Foundation, The Educational Foundation of America, Betsy and Jesse Fink Foundation, The William and Flora Hewlett Foundation, The Kendeda Fund, The Forrest and Frances Lattner Foundation, The Andrew W. Mellon Foundation, The Curtis and Edith Munson Foundation, Oak Foundation, The Overbrook Foundation, the David and Lucile Packard Foundation, The Summit Fund of Washington, Trust for Architectural Easements, Wallace Global Fund, The Winslow Foundation, and other generous donors.

The opinions expressed in this book are those of the author(s) and do not necessarily reflect the views of our donors.

About SCOPE

The Scientific Committee on Problems of the Environment (SCOPE) was established by the International Council for Science (ICSU) in 1969. It brings together natural and social scientists to identify emerging or potential environmental issues and to address jointly the nature and solution of environmental problems on a global basis. Operating at an interface between the science and decision-making sectors, SCOPE's interdisciplinary and critical focus on available knowledge provides analytical and practical tools to promote further research and more sustainable management of the Earth's resources. SCOPE's members, national scientific academies and research councils, and international scientific unions, committees and societies, guide and develop its scientific program.

Foreword

This volume was developed in partnership among three organizations of the International Council for Science (ICSU): the International Association for the Physical Sciences of the Oceans (IAPSO), the Scientific Committee on Oceanic Research (SCOR), and the Scientific Committee on Problems of the Environment (SCOPE).

IAPSO (<http://iapso.sweweb.net>) is a constituent association of the International Union of Geodesy and Geophysics (IUGG) (<http://www.iugg.org>), an ICSU scientific union. IAPSO has the prime goal of promoting the study of scientific problems relating to the oceans and the interactions taking place at the seafloor, coastal, and atmospheric boundaries insofar as such research is conducted by the use of mathematics, physics, and chemistry. IAPSO participates in SCOR and interacts with UNESCO's Intergovernmental Oceanographic Commission.

SCOR (<http://www.scor-int.org>), the first interdisciplinary body formed by ICSU, was established in 1957 in recognition that scientific questions about the ocean often require an interdisciplinary approach. SCOR activities focus on promoting international cooperation in planning and conducting oceanographic research and on solving methodological and conceptual problems that hinder research. The SCOR secretariat is located at the College of Marine and Earth Studies at the University of Delaware (Newark).

SCOPE (<http://www.icsu-scope.org>), founded in 1969, is an interdisciplinary body of natural and social science expertise focused on global environmental issues, operating at the interface between scientific and decision-making instances. A worldwide network of scientists and scientific institutions develops syntheses and reviews of scientific knowledge on current or potential environmental issues. The SCOPE secretariat is located at ICSU headquarters in Paris, France.

Watersheds, Bays, and Bounded Seas is Volume 70 in the SCOPE series, now published with Island Press. This cooperative approach among three ICSU organizations to synthesize and analyze information is an excellent example of how the scientific community can help to address a complex multidisciplinary subject of global significance.

We dedicate this book to Hal Mooney, who has been a mentor to all of us and a pioneer of studies of the importance of biodiversity on human well-being.

Bernard D. Goldstein
Editor-in-Chief, SCOPE Publications

Contents

<i>List of Figures, Tables, and Boxes</i>	ix
---	----

<i>Foreword by Bernard D. Goldstein</i>	xv
---	----

1. Introduction	1
Edward R. Urban, Jr., Bjørn Sundby, Paola Malanotte-Rizzoli, and Jerry M. Melillo	

2. Vulnerability of Semi-Enclosed Marine Systems to Environmental Disturbances	9
Michael MacCracken, Elva Escobar-Briones, Denis Gilbert, Gennady Korotaev, Wajih Naqvi, Gerardo M.E. Perillo, Tim Rixen, Emil Stanev, Bjørn Sundby, Helmuth Thomas, Daniela Unger, and Edward R. Urban, Jr.	

3. Threshold Effects in Semi-Enclosed Marine Systems	31
Johan van de Koppel, Paul Tett, Wajih Naqvi, Temel Oguz, Gerardo M.E. Perillo, Nancy N. Rabalais, Maurizio Ribera d'Alcalà, Jilan Su, and Jing Zhang	

4. Governance and Management of Ecosystem Services in Semi-Enclosed Marine Systems	49
Paul V.R. Snelgrove, Michael Flitner, Edward R. Urban, Jr., Werner Ekau, Marion Glaser, Heike K. Lotze, Catharina J.M. Philippart, Penjai Sompongchaiyakul, Edy Yuwono, Jerry M. Melillo, Michel Meybeck, Nancy N. Rabalais, and Jing Zhang	

5. Integrating Tools to Assess Changes in Semi-Enclosed Marine Systems	77
Carolien Kroeze, Jack Middelburg, Rik Leemans, Elva Escobar- Briones, Wolfgang Fennel, Marion Glaser, Akira Harashima, Kon-Kee Liu, and Michel Meybeck	

6. Physical Processes in Semi-Enclosed Marine Systems	97
Wolfgang Fennel, Denis Gilbert, and Jilan Su	
7. Cascading Filters of River Material from Headwaters to Regional Seas: The European Example.....	115
Michel Meybeck and Hans H. Dürr	
8. Fluxes of Nutrients and Selected Organic Pollutants Carried by Rivers.....	141
Kon-Kee Liu, S. Seitzinger, E. Mayorga, J. Harrison, and V. Ittekkot	
9. Biogeochemical Cycling in Semi-Enclosed Marine Systems and Continental Margins	169
Helmuth Thomas, Daniela Unger, Jing Zhang, Kon-Kee Liu, and Elizabeth H. Shadwick	
10. Dynamics and Vulnerability of Marine Food Webs in Semi-Enclosed Systems	191
Catharina J.M. Philippart and Werner Ekau	
11. Distribution and Consequences of Hypoxia	209
Nancy N. Rabalais and Denis Gilbert	
12. Ecosystem Services of Semi-Enclosed Marine Systems	227
Heike K. Lotze and Marion Glaser	
<i>Appendix: Workshop Participants and Other Contributors</i>	<i>251</i>
<i>About the Editors.....</i>	<i>255</i>
<i>SCOPE Series List.....</i>	<i>257</i>
<i>SCOPE Executive Committee 2005–2008.....</i>	<i>261</i>
<i>Index</i>	<i>263</i>

Figures, Tables, and Boxes

Color plate section follows page 144.

Figures

- 1-1 Examples of regional seas with different degrees of openness to the ocean 3
- 1-2 Map of the thirteen SEMSs considered in this volume 3
- 3-1 Graphical representation of two types of threshold responses of ecosystems to changing conditions 33
- 3-2 Plot of NO_2^- versus O_2 within the Arabian Sea O_2 -deficient zone 37
- 3-3 Phytoplankton biomass distribution in relation to the anthropogenic nutrient load and phytoplankton biomass as a function of both nitrogen load and sea surface temperature 39
- 4-1 Summary of perceived threats to ecosystem services and the spatial scales at which they operate 51
- 4-2 Flowchart of the development of management approaches 68
- 5-1 Major drivers and controls of the functioning of SEMSs 80
- 5-2 A schematic diagram of a possible integrated model 85
- 6-1 Topographic map of the Baltic Sea 102
- 6-2 Bathymetry of the Bohai and the Yellow and East China seas and sketches of the circulation in winter and summer 104
- 6-3 Shelf intrusion of the Kuroshio northeast of Taiwan in summer and winter 106
- 6-4 Exchange between the Yellow Sea and East China Sea 107

6-5	Schematics of the surface circulation in the Gulf of St. Lawrence	109
6-6	Map of the Gulf of Mexico	111
7-1	Nested filters of river material to oceans in natural Holocene conditions	117
7-2	Nested filters of river material to oceans in the Anthropocene	130
8-1	Comparison of estimates of nutrient loads predicted by the NEWS model, the LOICZ project, and the CMTT	150
8-2	Ternary diagram illustrating the relative importance of the three forms of nutrients for nitrogen and phosphorus	152
8-3	The N–P relationship of the riverine nutrient loads in different forms discharged to the SEMSs	154
8-4	Impact assessment plots showing ratios between the chemical loadings and the continental shelf areas of the SEMSs	159
9-1	The SEMSs and river systems addressed in Chapter 9	170
9-2	Biogeochemical pathways of the carbon cycle	172
9-3	Biogeochemical pathways of the nitrogen cycle	173
9-4	Biogeochemical cycles in SEMSs and shallow marine environments	175
9-5	The present-day global carbon cycle and shallow marine environments in comparison	182
10-1	Hypothetical marine trophic pyramid, showing the subsequent trophic levels, and a food chain and a more complex food web	192
10-2	Map of the thirteen SEMSs considered in Chapter 10	195
10-3	Relationship between primary production and total fish landings	196
10-4	Regional relationships between fish catch and marine trophic index (MTI) between 1950 and 2003	198
10-5	Regional relationships between fish catch and ratio of pelagic and demersal catch (PDR) between 1950 and 2003	199
10-6	Relationship between transfer efficiency and connectivity of a SEMS with the open ocean	202
10-7	Vulnerability of SEMSs to perturbation, as indicated by the relationship between fish catch and marine trophic index and the relationship between fish catch and the ratio between pelagic and demersal proportions of landings	204

- 11-1 Examples of seasonal progression and variability of thermoclines, haloclines, and oxyclines at a 20 m station in the northern Gulf of Mexico west of the Mississippi River, where hypoxia occurs from March through November 210
- 11-2 Extent of bottom-water hypoxia on the northwestern shelf of the Black Sea in relation to use of nitrogen fertilizer in the Danube River watershed in different groups of years 213
- 11-3 Oxygen content 2 m above the bottom during August–September in the Northern Adriatic Sea from 1911 to 1984 for the periods indicated 214
- 11-4 Distribution of bottom-water oxygen concentration on the northern Gulf of Mexico continental shelf of Louisiana and Texas for the dates indicated 215
- 11-5 Declining bottom-water oxygen concentration at stations west of the Mississippi River delta 216
- 11-6 The generalized relationship between production/fishery yield and nutrient loading, with varying effects of eutrophication expressed as seasonal and permanent bottom-water anoxia for a spectrum of enclosed seas 219
- 12-1 Conceptual diagram of the interactions between humans and ecosystems in SEMSs via human impacts and ecosystem services 228
- 12-2 Generic model of the linkages of SEMSs to different levels of the ecological and social systems 230
- 12-3 Regional differences in fisheries landings across fourteen SEMSs or their respective Large Marine Ecosystems (LMEs) from 1950 to 2003 236
- 12-4 Long-term changes in estuarine and coastal ecosystems 243
- 12-5 Trends and consequences of eutrophication in 138 U.S. investigated estuaries 244

Tables

- 5-1 Examples of different types of human influences on SEMSs 89
- 5-2 Indicators/descriptors of a system's abilities to provide services 90
- 5-3 Possible descriptors/indicators to assess human-induced changes in SEMSs 92
- 6-1 Comparison of the relative strengths of important physical processes of several SEMSs 99

6-2	Physical descriptors of regional seas described in Chapter 6	100
7-1	Typology of estuarine filters with regard to net river inputs to the coastal zone and selected examples among world rivers and coasts	120
7-2	Some characteristics of estuarine filters for assessing net river inputs to the coastal zone	122
7-3	Distribution of river discharge by estuarine filter types for the European continent	126
7-4	Relative weights of European regional seas river catchments and their related river fluxes in upstream estuarine filters	128
7-5	Main expected and/or actual changes in river fluxes (“river syndromes”) due to global change for total suspended solids, ionic loads, silica and nutrients, organic carbon, and toxic substances in European SEMSs, other SEMSs, and other mega-filters	132
8-1	SEMSs for Discussion: Geographic information on the marine systems and the drainage basins of rivers emptying to them	142
8-2	Riverine exports of different forms of bioactive elements and two types of hazardous organic chemicals to SEMSs	148
9-1	Fate of terrestrial carbon inputs in SEMSs and marginal seas	183
9-2	Export production from SEMSs and marginal seas	183
9-3	Anthropogenic CO ₂ uptake in SEMSs and marginal seas	184
10-1	Regional characteristics of SEMSs	194
12-1	Ecosystem services of SEMSs	229
12-2	Overview of selected ecological indicators for fourteen SEMSs	233
12-3	Overview of selected social and economic indicators for fourteen SEMSs	238

Boxes

2-1	Gulf of Mexico and ocean–atmosphere interactions	14
2-2	Changes in Gulf of St. Lawrence stratification and hypoxia	16
2-3	The Baltic Sea and the North Sea: Connected but different	18
2-4	The Black Sea: A nearly closed, freshwater-dominated basin	19

2-5	Bay of Bengal: Very open, but very vulnerable to change	22
2-6	Impacts on coral reefs fringing tropical SEMSs	24
3-1	Glossary	32
3-2	Alternative stable states and hysteretic thresholds	34
5-1	Examples of characteristics of SEMSs that complicate the development of integrated models	81

Plates

1	Horizontal-vertical sections of temperature, salinity, and oxygen as recorded during a Baltic monitoring cruise	i
2	Coastal front in East China Sea under winter northeast monsoon and summer southwest monsoon	ii
3	Horizontal-vertical sections of temperature, salinity, and oxygen along the deepest part of the Laurentian Channel, in the Gulf of St. Lawrence	iii
4	Surface salinity on the Louisiana–Texas (LATEX) continental shelf during July of 1999 and 2000, under conditions of high and low freshwater discharges, respectively	iv
5	Map of the catchment basins connected to the SEMSs analyzed in this study	v
6	Distribution of areas with coastal hypoxic bottom waters on a worldwide basis	vi
7	Processes involved in the development and maintenance of hypoxia on the northern Gulf of Mexico continental shelf where there is sustained and high freshwater discharge from the Mississippi River, year-round haline and seasonal thermal stratification, nutrient-enhanced primary production, and accumulation and decomposition of organic matter	vii
8	Near-bottom oxygen concentration measured during the 2004 and 2005 fish stock assessment surveys	viii

Introduction

Edward R. Urban, Jr., Bjørn Sundby,
Paola Malanotte-Rizzoli, and Jerry M. Melillo

Why and How This Book Was Created

Observations and images from various regions of the earth provide dramatic evidence that global change is real. Large-scale weather events that erode shorelines and flood low-lying areas make it obvious that global change affects not only the remote parts of the earth, but also the daily life of each of the planet's inhabitants. Melting ice caps and glaciers, eroding shorelines, and floods are indeed spectacular manifestations of global change. But because they are so spectacular, they may overshadow other manifestations of global change that are less visible but no less important. Regrettably, out of sight often means out of mind.

In the ocean, many effects of global change are literally out of sight because they manifest themselves below the sea surface. This also is true in the coastal ocean, the buffer zone between continents and ocean. Although global change's impacts on the hydrologic cycle will vary among regions, increasing air temperatures over the ocean are predicted (on the basis of well-known physical processes) to increase evaporation from the ocean, which may lead to increasing precipitation on the continents and increasing runoff from the continents. Increased freshwater runoff to the coastal zone—carrying with it nutrients, contaminants, and sediments—is worrisome because it can be expected to alter the local ecology; reduce the quality of the habitats of many organisms, including those useful to humans; and affect their health, growth, and ability to reproduce. The effect of global warming on runoff will not be uniformly distributed; runoff may increase in some areas and decrease in others, and regional predictions are notoriously unreliable.

Semi-enclosed marine systems (SEMSs) are important in many coastal regions; they are tightly linked with land and have restricted exchange with the open ocean. SEMSs are important to humans, who are especially numerous at the edges of the continents. Humans rely on SEMSs for often-competing services such as provision of food, protec-

tion from natural disasters, navigation and transport, disposal of waste, extraction of minerals and sand/gravel, and leisure. Society has set up institutions to manage coastal areas for the benefit of all, but these institutions often lack information, understanding, and tools to help them with their task. Thus society turns to scientists, who are trained to provide information, develop understanding, and create tools for studying the ocean. The task facing scientists is difficult, for it obliges them to venture onto the often unknown terrain where nature and human forces interact.

To address the overlapping issues of management and research in SEMSs, three organizations of the International Council for Science (ICSU)—the Scientific Committee on Problems of the Environment (SCOPE), International Association for the Physical Sciences of the Oceans (IAPSO), and Scientific Committee on Oceanic Research (SCOR)—pooled their resources and expertise to bring together a carefully designed mixture of natural scientists and social scientists. This group met for four days at the Hanse-Wissenschaftskolleg (HWK) in Delmenhorst, Germany, to deliberate on the special characteristics of SEMSs and identify management approaches and research that should be applied to these special systems. This resulting book is intended to provide information for more-effective management of SEMSs and to serve as a useful reference for coastal managers, policy makers, and scientists. It also includes original analyses of special features of SEMSs (e.g., nutrient inputs, primary production, fisheries production, and socioeconomic indicators) and directions for future research on some topics relevant to understanding SEMSs.

Definition/Description of Semi-Enclosed Marine Systems for the Purposes of This Book

A semi-enclosed marine system (SEMS) is a marginal sea, bounded by land along more than half of its periphery and separated from the open ocean by one or more of the following boundaries (Figure 1-1):

- a strait (as bounds the Baltic Sea)
- a sill and/or island chain (as bounds the East China Sea)
- a front generated by physical processes separating the coastal/shelf water from the open ocean water (as bounds the Bay of Bengal)

The SEMSs that are the focus of this book (Figure 1-2) are those that are most impacted by changes taking place on the surrounding land masses. In fact, the runoff of water with its loads of sediment and chemicals is the most important driver of the systems discussed in this book. SEMSs with positive freshwater budgets (i.e., the total of runoff and precipitation exceeds loss by evaporation) are more susceptible to influx of land-derived materials and were therefore chosen for study in this book. The systems selected are meant to provide examples of a broader set of similar systems.

The degree of openness and the efficiency of water exchange between SEMSs and the

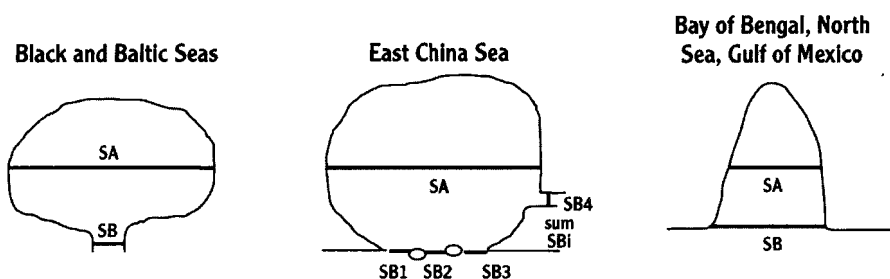


Figure 1-1. Examples of regional seas with different degrees of openness to the ocean. Provided by M. Meybeck.

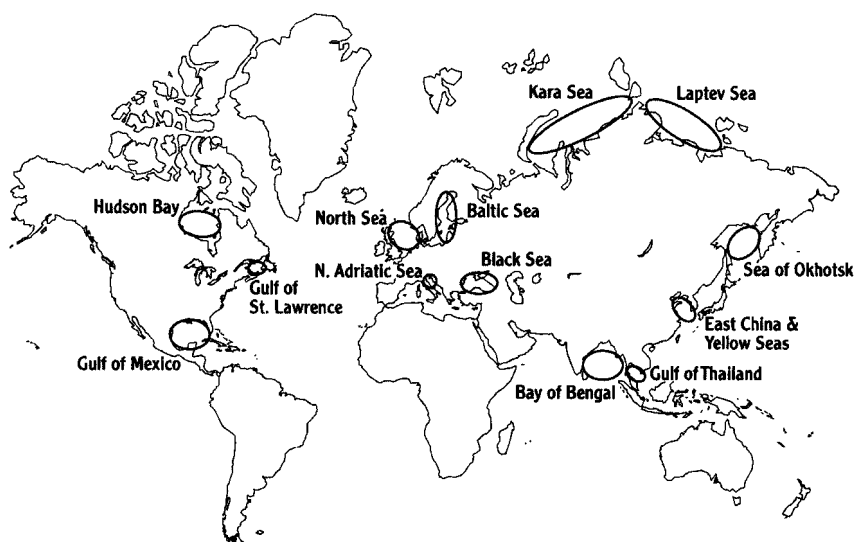


Figure 1-2. Map of the thirteen SEMSs considered in this volume (modified from Figure 10-2).

open ocean are important characteristics. The degree of openness ranges from very low (e.g., of the Black Sea) to very high (e.g., of the Bay of Bengal). As a first approximation, a measure of the degree of openness can be obtained by calculating the ratio of two cross-sectional areas: the cross-sectional area of the opening(s) to the ocean (SB in Figure 1-1) and the average cross-sectional area of the semi-enclosed body of water (SA in Figure 1-1). The thirteen systems that are the focus of this book include the Black Sea, Baltic Sea, Hudson Bay, Gulf of St. Lawrence, Northern Adriatic Sea, Gulf of Thailand, North Sea, Sea of Okhotsk, East China Sea (including the Yellow Sea), Gulf of Mexico, Laptev

Sea, Kara Sea, and the Bay of Bengal (Figure 1-2). These were selected to represent a span of latitudes and encompass different combinations of degree of openness and freshwater influence.

Because of the importance of the inputs from land, SEMSs include not only the coastal water bodies and the underlying seafloor, but also the catchment basins that drain the surrounding lands, and the adjacent ocean—hence the emphasis on system. The regional boundaries derived from this definition do not preclude potential impacts beyond the boundaries of the system.

Structure of the Book

The following chapters fall into two categories. Chapters 2–5 document the discussions that occurred at the workshop. These focused on

- vulnerability of SEMSs to environmental disturbances (Chapter 2)
- threshold effects in SEMSs (Chapter 3)
- governance and management of ecosystem services in SEMSs (Chapter 4)
- integrating tools to assess changes in SEMSs (Chapter 5)

Chapters 6–12 serve as background for the cross-cutting discussions in Chapters 2–5. All chapters and the complete book were peer reviewed.

Chapter 2 discusses the variety of forces that will cause changes to SEMSs in the future and illustrates the many processes involved. Climate change will affect SEMSs in terms of water temperatures, precipitation and ice cover, runoff, salinity, circulation, stratification, mixing, and chemistry. The chapter recommends that SEMSs be assessed as to how well they are understood and what additional research and observations are needed to enable management. Scientists, local and regional managers, and decision makers should work together in both making assessments and developing mitigation measures.

Chapter 3 discusses the concept of thresholds in ecosystems. Thresholds are environmental tipping points: When a threshold is passed, abrupt and dramatic changes, which are difficult or impossible to reverse, take place in the relationships between environmental forces and effects. Once a threshold has been surpassed, the system may not return to its initial state or it may return more slowly than expected from the speed of the initial change, even if the force or combination of forces that brought about the change is reduced to pre-threshold levels. Examples of thresholds include the oxygen level that defines hypoxia; the introduction of invasive species; the combination of light, nutrients, and mixed-layer depth that stimulates a phytoplankton bloom; the ratios of the nutrients that control the plankton species composition; the minimum population size of a fish species that ensures reproduction; and the conditions necessary for larval survival. Chapter 3 recommends that ecosystem research in SEMSs should aim to increase our understanding of thresholds and their consequences.

Chapter 4 is built around the role of the many ecosystem services that provide benefits