

Fourth Edition

# Aquatic Pollution

**An Introductory Text**

Edward A. Laws

WILEY

## **Aquatic Pollution: An Introductory Text**



# **Aquatic Pollution: An Introductory Text**

*Edward A. Laws*  
*Los Angeles, US*

Fourth Edition

**WILEY**

This edition first published 2018 © 2018 John Wiley & Sons, Ltd

First edition published 1981 by John Wiley & Sons Ltd.

Second edition published 1993 by John Wiley & Sons Ltd.

Third edition published 2000 by John Wiley & Sons Ltd.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by law. Advice on how to obtain permission to reuse material from this title is available at <http://www.wiley.com/go/permissions>.

The right of Edward A. Laws to be identified as the author of this work has been asserted in accordance with law.

#### *Registered Offices*

John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

#### *Editorial Office*

111 River Street, Hoboken, NJ 07030, USA

9600 Garsington Road, Oxford, OX4 2DQ, UK

The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

For details of our global editorial offices, customer services, and more information about Wiley products visit us at [www.wiley.com](http://www.wiley.com).

Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

#### *Limit of Liability/Disclaimer of Warranty*

The publisher and the authors make no representations or warranties with respect to the accuracy or completeness of the contents of this work and specifically disclaim all warranties, including without limitation any implied warranties of fitness for a particular purpose. This work is sold with the understanding that the publisher is not engaged in rendering professional services. The advice and strategies contained herein may not be suitable for every situation. In view of ongoing research, equipment modifications, changes in governmental regulations, and the constant flow of information relating to the use of experimental reagents, equipment, and devices, the reader is urged to review and evaluate the information provided in the package insert or instructions for each chemical, piece of equipment, reagent, or device for, among other things, any changes in the instructions or indication of usage and for added warnings and precautions. The fact that an organization or website is referred to in this work as a citation and/or potential source of further information does not mean that the author or the publisher endorses the information the organization or website may provide or recommendations it may make. Further, readers should be aware that websites listed in this work may have changed or disappeared between when this work was written and when it is read. No warranty may be created or extended by any promotional statements for this work. Neither the publisher nor the author shall be liable for any damages arising here from.

#### *Library of Congress Cataloging-in-Publication Data*

Names: Laws, Edward A., 1945- author.

Title: Aquatic pollution : an introductory text / by Edward A. Laws, Los Angeles, US.

Description: 4th edition. | Hoboken, NJ, USA : John Wiley & Sons, Inc., 2018. | Includes bibliographical references and index.

Identifiers: LCCN 2016054156 (print) | LCCN 2016056136 (ebook) | ISBN 9781119304500 (cloth) | ISBN 9781119304555 (pdf) | ISBN 9781119304593 (epub)

Subjects: LCSH: Water--Pollution.

Classification: LCC TD420 .L38 2018 (print) | LCC TD420 (ebook) | DDC 628.1/68--dc23

LC record available at <https://lcn.loc.gov/2016054156>

Cover image: Jrg Weimann / EyeEm/Gettyimages

Cover design: Wiley

Set in 10/12pt Warnock by SPi Global, Chennai, India

## Contents

Preface *xv*

- 1 Fundamental Concepts** 1
  - Simple Food Chain Theory 1
    - Ecological Pyramids 3
    - Recycling and the Microbial Loop 6
    - Food Chain Magnification 9
  - Food Webs 10
  - Food Webs and Ecosystem Stability 12
  - Questions 13
  - References 15
  
- 2 Photosynthesis** 17
  - Light Limitation of Photosynthesis 18
  - Nutrient Limitation of Photosynthesis 22
    - Nutrient Enrichment Experiments 26
      - Long Island Bays 30
      - Canadian Experimental Lakes 31
    - Nitrogen versus Phosphorus Limitation 33
  - Questions 37
  - References 38
  
- 3 Physical Factors Affecting Production** 43
  - Physical Properties of Water 43
  - Water Column Stability and Overturning 45
    - The Importance of Overturning 48
  - Seasonal Production Cycles 49
  - Trophic Status 50
  - Susceptibility of Systems to Oxygen Depletion 51
  - Estuaries: A Special Case 52
    - Chesapeake Bay 55
    - The Gulf of Mexico Hypoxic Zone 64
  - Questions 67
  - References 68

<b>4 Cultural Eutrophication Case Studies</b>	<b>71</b>
Case Study 1: Lake Washington	72
History of Eutrophication	73
Effects of Sewage Diversion	76
Nutrient Limitation	79
Oxygen Depletion	80
Water Clarity	83
Cyanobacteria	84
Theoretical Predictions	85
Case Study 2: Lake Erie	88
The Destruction of Fish Spawning and Nursery Grounds as a Result of Land-Use Modifications	89
The Depletion of Fish Stocks Due to Overfishing	90
The Creation of Anoxic Bottom Water Conditions Due to Cultural Eutrophication	93
The Disposal of Toxic Wastes	94
Sediment in Land Runoff	96
Contamination of Nearshore Areas with Sewage Wastes	96
Remedial Efforts	98
Toxic Substances	98
Eutrophication	99
Prospects for Lake Erie	105
Case Study 3: Kaneohe Bay	114
Physical Setting	114
The Coral Reefs	116
Urbanization of the Watershed	116
Changes in Land Runoff	116
Sewage Disposal	119
Effects of Sewage Disposal	120
Response to Sewage Diversion	121
Current Status and Prospects for Kaneohe Bay	123
Questions	126
References	128
<b>5 Nonpoint Source Pollution</b>	<b>133</b>
Definitions	133
Composition of Land Runoff	134
Types of Sewer Systems	136
Corrective Measures	138
Use of Settling Basins	138
Ground Recharge Basins	139
Storage in Underflow Tunnels or Tanks	140
Minimizing Runoff	141
Summary	143
A Case Study: Lake Jackson, Florida	143
Correctives	150
Questions	155
References	156

- 6 Sewage Treatment 159**  
Primary, Secondary, and Tertiary Treatment 159  
    Secondary Treatment for BOD Removal 161  
        Trickling Filters 161  
        Activated Sludge 162  
        Pros and Cons of Trickling Filter and Activated Sludge Treatment 163  
    The Anaerobic Digester 164  
    Tertiary Treatment 165  
        Phosphorus Removal 166  
        Nitrogen Removal 167  
        Pharmaceuticals and Personal Care Products 168  
    Cost of Conventional Sewage Treatment 169  
Land Application of Sewage 170  
    Results of Spray Irrigation Studies 172  
    Limiting Factors 179  
    Use of Sewage Sludge 180  
Unconventional Sewage Treatment 183  
Detergent Phosphates 185  
Questions 188  
References 190
- 7 Pathogens in Natural Waters 195**  
Sources of Pathogens 197  
Types of Pathogens and Their Detection 198  
    Bacterial Pathogens 199  
    Protozoan Pathogens 206  
    Viral Pathogens 208  
    Helminths 212  
Tests for Pathogens 213  
Treatment of Public Water Supplies 219  
    Removal of Suspended Solids 219  
    Filtration 219  
    Chlorination 220  
    Alternatives to Chlorination 221  
    Impact of Treatment 222  
Questions 222  
References 224
- 8 Toxicology 229**  
The Role of Toxicology in Water Quality Management 229  
Kinds of Toxicity 231  
    Sublethal Effects 231  
        Reproduction 232  
        Development and Growth 234  
        Behavior 237  
Determination of Toxicity 237  
    Acute Toxicity Determination 238  
    Chronic Toxicity Determination 239



Median Survival Times	240
Incipient Lethal Levels	241
Sublethal Effects	242
Water Quality Standards	243
Acute Effects	243
Chronic Toxicity	244
Acute/Chronic Ratios	245
Toxicity to Plants	247
The Two-Number Criterion	247
Complicating Factors	248
Interactions with Harmless Substances or Conditions	248
Incorporation into Water Quality Guidelines	250
Conditioning and Acclimation	252
Interactions between Toxic Substances	253
Public Health	257
Noncarcinogenic Effects	257
Application to Cadmium	260
Carcinogenic Effects	262
Protection of Wildlife	264
Commentary	264
Questions	265
References	268
<b>9 Industrial Pollution</b>	<b>273</b>
The Oxygen Sag	273
Innovative Strategies for Reducing Industrial Pollution	276
The Hawaiian Sugar Cane Industry	279
Sugar Cane Production: Field Operations	282
Sugar Cane Production: Harvesting	282
Sugar Cane Production: Factory Operations	283
Survey of Water Pollution Problems	285
Response to the EPA Survey	286
Present Status of the Industry	288
The Pulp and Paper Industry	290
Steps in the Production of Paper	292
Objectionable Characteristics of Pulp and Paper Mill Effluent	295
Suspended Solids	296
Dissolved Organics	298
Toxic Substances	299
Wastewater Treatment	300
A Case Study: The Buckeye Cellulose Corporation Pulp and Paper Mill at Perry, Florida	301
Commentary	304
Questions	306
References	307
<b>10 Pesticides and Persistent Organic Pollutants</b>	<b>311</b>
Classification of Pesticides	313
Mode of Action	315

Pesticide Use	316
Public Health	316
Use of DDT to Control Malaria	316
Agriculture	319
Forestry	321
Pesticide Effects on Nontarget Species	322
Forest Spraying with DDT to Control Spruce Budworms in New Brunswick, Canada	322
DDD Treatment to Control Gnat Populations on Clear Lake, California	323
Exaggerated and/or Erroneous Charges against Pesticide Use	324
The Destruction of Speckled Sea Trout in the Laguna Madre, Texas	325
DDT Reduces Photosynthesis by Marine Phytoplankton	326
DDT Residues of 5 ppm (Wet Weight) in the Eggs of Freshwater Trout Result in 100% Mortality of Fry	328
DDT Causes Cancer	330
Implications	331
Pesticide Persistence in the Biosphere and Food Chain Magnification	332
Pesticide Effects on Birds	336
Field Observations	337
Laboratory Studies	339
Summary of Pesticide Effects on Birds	342
Pest Resistance	343
Mechanisms of Resistance	344
The Cost of Pest Resistance	344
Alternatives to Synthetic Pesticide Use	345
Biological Control	345
Natural Predators and Parasites	345
Pathogens and Natural Toxins	346
Genetic Control	347
Resistant Plants	347
Sterile Males	348
Chemical Control	350
Integrated Pest Management	351
Commentary	353
EPA Hearings, 13 January, 1972. Afternoon Session	355
Persistent Organic Pollutants	359
Polychlorinated Biphenyls	359
Problems with PCBs	361
Persistence of PCBs	363
Questions	365
References	367
<b>11 Thermal Pollution and Power Plants</b>	<b>375</b>
Power Plant Design	376
Water Quality Criteria	377
Cooling Water System Characteristics	378
Toxic Effects of Effluent Waters on Biota	379
Sublethal Effects	381
Commentary	383

A Case Study – The Florida Power and Light Power Plant at Turkey Point	383
The Study Area	383
The Power Plant	385
Effects on Biota	386
Modifications	388
Commentary	389
Correctives	389
Cooling Canals	390
Cooling Towers	390
Problems	390
Internal Plant Kills	392
Screen Impingements	392
Inner Plant Kills	395
Commentary	397
Correctives	398
Possible Beneficial Uses of Thermal Discharges	400
Cogeneration Power Plants	400
Agriculture	402
Aquaculture	403
Other Uses	406
Questions	407
References	408

## 12 Metals 413

The Question of Biological Magnification	416
Case Studies	417
Mercury	418
Production and Uses	418
Fluxes to the Environment	422
Speciation of Mercury and Toxicology	426
Minamata Bay: A Case Study	432
Seafood Consumption	438
Cadmium	439
Distribution, Production, and Uses	439
Emissions to the Environment	442
Natural Fluxes to Aquatic Systems	445
Anthropogenic Fluxes to Aquatic Systems	445
Toxicity	445
Itai-Itai Disease: A Case Study	447
Correctives and Prospects for the Future	451
Lead	453
Production and Use	453
Emissions	457
Toxicology	462
Commentary	465
Questions	469
References	471

<b>13 Oil Pollution</b>	<b>479</b>
Oil Discharges to the Marine Environment	480
Natural Sources	480
Marine Seeps	480
Anthropogenic Sources	481
Platforms	481
Atmospheric Deposition	482
Produced Waters	482
Pipeline Spills	482
Tanker Spills	482
Operational Discharges (Cargo Washings)	483
Coastal Facility Spills (Refined Products)	485
Atmospheric Deposition (From Tankers)	485
Land-Based Runoff	485
Recreational Marine Vessels	485
Spills (Non-tankers)	485
Operational Discharges (Vessels >100 GT)	486
Operational Discharges (Vessels <100 GT)	486
Atmospheric Deposition	486
Aircraft Dumping	486
Commentary	486
The Genesis of Oil	488
Sedimentation	488
Metamorphosis	489
Migration	489
What Is Oil?	490
Alkanes: Paraffins or Aliphatic Compounds	490
Cycloalkanes or Naphthenes	491
Aromatics	491
Toxicology	493
Oiling and Ingestion	493
Weathering	496
Lethal and Sublethal Effects	498
Human Health	500
Case Studies	501
Exxon Valdez	501
The Accident and Initial Containment Efforts	501
Cleanup	502
Fate of Spilled Oil	503
Effects on Organisms	503
Summary	507
Deepwater Horizon	508
Buzzards Bay	510
Summary	513
Correctives	514
Prevention	514
Cleanup	515
Offloading	515

- Burning 516
- Chemical Dispersal 516
- Mechanical Containment and Cleanup 517
- Sinking 517
- Bioremediation 518
- Summary 519
- Oil Fingerprinting 520
- Commentary 522
- Questions 523
- References 524
  
- 14 Radioactivity 529**
  - Physical Background 529
  - Radiation Toxicology 532
    - The No Threshold and Linear Dose–Response Hypotheses 534
    - Health Effect Estimates 536
    - Current Levels of Exposure 538
    - Importance of Certain Radionuclides 541
    - Effects on Aquatic Systems 542
  - Nuclear Fission and Fission Reactors 544
  - Nuclear Fusion 550
  - Radiation Releases by Power Plants 552
    - Routine Radionuclide Releases 553
    - Accidents 556
      - The NRX Accident 556
      - Windscale 557
      - The SL-1 Incident 559
      - The Fermi Reactor Accident 560
      - The Three Mile Island Incident 562
    - Chernobyl 563
    - Fukushima Daiichi 565
      - Summary 565
  - Waste Disposal 569
    - Types of Radioactive Waste 569
    - History of Disposal 569
    - The Search for Long-Term Disposal Sites 573
  - Transmutation 576
  - Uranium Mine Wastes 576
  - Decommissioning Nuclear Reactors 579
  - Commentary 581
  - Questions 582
  - References 584
  
- 15 Acid Deposition and Ocean Acidification 589**
  - Acid Deposition 589
  - Acid Rain 590
  - History of the Acid Deposition Problem 591
  - Susceptibility of Lakes to Acid Deposition Effects 594
  - Acid Deposition Toxicology 595

Magnitude of Anthropogenic Emissions	598
Correctives	600
SO <sub>x</sub> Removal	601
Pretreatment	601
Conversion	602
Coal Gasification	602
Coal Liquefaction	602
Methanol Production	602
Combustion	603
Fluidized Bed Combustion	603
Lime Injection in Multistage Burners (LIMB)	603
Post-combustion	603
Stack Gas Scrubbing	603
Electron Beam Method	604
NO <sub>x</sub> Removal	604
Pretreatment and Conversion	604
Combustion	604
Post-combustion	605
Integrated Gasification Combined Cycle	605
Comments	605
Legal Aspects	606
A Case Study: The Netherlands	608
Commentary	610
Ocean Acidification	610
Solutions	617
Questions	618
References	618
<b>16 Groundwater Pollution</b>	<b>623</b>
Reliance on Groundwater	623
General Aquifer Information	624
Overdrafting	625
The Extent of Groundwater Pollution	627
Septic Tanks	627
Saltwater Contamination	627
Fracking	628
Sewage	628
Mining Activities	629
Leaking Underground Storage Tanks	629
Toxic Chemicals	629
Illegal Disposal	632
Magnitude of the Problem	634
A Case Study: The Rocky Mountain Arsenal	636
Legal Considerations	641
RCRA	641
SDWA	642
CWA	643
CERCLA	644
Other Legislation	646

Enforcement	647
Correctives	648
Cleanup	648
Prevention	650
The EPA Groundwater Protection Strategy	653
Questions	654
References	655
<b>17 Plastics in the Sea</b>	<b>659</b>
The Nature of the Problem	659
Effects	661
Aesthetics	661
Ingestion	662
Entanglement	664
Ghost Fishing	665
Other Causes of Entanglement	667
Damage to Vessels	668
Correctives	668
MARPOL Annex V	668
Other Legislation	671
Degradable Plastic	673
Solutions Through Technology	673
Education	674
Questions	675
References	676
<b>Units of Measurement and Abbreviations</b>	<b>681</b>
References	683
<b>Aquatic Pollution</b>	<b>685</b>
Answers to Questions	685
References	705
<b>Glossary</b>	<b>707</b>
<b>Index</b>	<b>733</b>

## Preface

Since the first edition of *Aquatic Pollution* was published in 1980, the book has served as an introduction to the subject of water pollution for many undergraduate students. The fourth edition is organized in a similar way to the first three editions. The first three chapters serve as an introduction to physical, chemical, and biological concepts that are essential to understanding the impact of pollutants and stresses on aquatic systems. Chapter 8 is likewise an introduction to toxicological concepts relevant to the remaining chapters in the book. Each of the other chapters focuses on a particular kind of pollution, and in each of these chapters, the subject is illustrated with one or more case studies. The case studies include numerous examples from events and developments that had happened since the third edition of *Aquatic Pollution* was published in 2000.

Some of the news since 2000 has certainly been good. Phase I of the City of Chicago's tunnels and reservoir project (TARP) was completed in 2006; TARP is now capable of handling about 85% of the pollution caused by combined sewer overflows from an area of 842 km<sup>2</sup>. The concentration of phosphorus in Onondaga Lake, New York, sometimes characterized as the most polluted lake in the United States, dropped from 730 µg L<sup>-1</sup> in 1970 to less than 20 µg L<sup>-1</sup> in 2010 as a result of restrictions on the use of phosphorus in laundry detergents and tertiary treatment for phosphorus removal from wastewater. Brown pelicans, whose populations had been seriously impacted by the use of dichlorodiphenyltrichloroethane (DDT) and similar pesticides, were taken off the endangered species list in the United States in 2009. Likewise, bald eagles, whose population in the contiguous 48 states had been reduced to 417 pairs in 1963, have now increased to more than 11,000 pairs. The use of insecticides on corn declined by a factor of 10 between 1995 and 2010 as a result of the planting of genetically modified corn resistant to insect pests. In 2001, the EPA issued regulations that required closed cycle cooling systems on all new electric power plants to eliminate the killing of organisms drawn into once-cycle cooling systems, and in 2014, it promulgated additional regulations that required existing power plants that draw more than 2 million gallons per day of cooling water to take steps to minimize internal plant kills. In 2016, most use of mercury in the United States had been phased out, with the exception of its use in dental amalgams, and in 2008, the European Union issued a directive that restricted most uses of cadmium. The directive was amended in 2013 to specifically prohibit the use of cadmium in most nickel–cadmium batteries, which account for over 80% of cadmium use globally. Modifications to the International Convention for the Prevention of Pollution from Ships required a transition to double-hull oil tankers for all oil tankers greater than 20,000 deadweight tons by 2007, and analogous stipulations of the US Oil Pollution Act required a phaseout of single-hull tankers that operate in US waters by January 1, 2015, in order to reduce the frequency of oil spills from tanker accidents. Emissions of sulfur oxides from electric power plants in the United States declined by 84% between 1970 and 2014,



primarily as a result of the installation of scrubbers to eliminate emissions of sulfur oxides in stack gases. In 2015, the US Department of Agriculture announced the Ogallala Aquifer Initiative, which addresses the problem of overdrafting the Ogallala Aquifer, the largest aquifer in the United States. And in 2006, the US Congress passed the Marine Debris Research, Prevention, and Reduction Act, with the goal of reducing the amount of marine debris and its adverse effects on marine organisms. Under the auspices of the US Environment Program, the Stockholm Convention on Persistent Organic Pollutants was adopted in 2001 by 179 nations with the goal of protecting human health and the environment from persistent organic pollutants. The convention initially identified 12 persistent organic pollutants, the so-called dirty dozen, the use of which was to be banned or greatly restricted. The original list of 12 has now been extended to 22.

Unfortunately, not all the news has been good. Despite considerable efforts aimed at improving the water quality of the Chesapeake Bay, the area of benthic grasses in the bay has not increased since 2000 and is far below the target of 750 km<sup>2</sup> that was established in 2003. The catch of eastern oysters in the Chesapeake Bay declined from more than 10,000 tonnes in 1980 to 40 tonnes in 2004, and although there has been some improvement since then, the productivity of the eastern oysters is very much constrained by poor water quality and infection by parasites. Although water quality standards have been established, they are met only 30–40% of the time and seasonal hypoxia is a problem throughout the Chesapeake Bay.

Literally billions of dollars have been spent to improve the water quality of Lake Erie, but problems persist. The biggest problems have been the benthification of the lake by zebra mussels and quagga mussels; the ongoing nonpoint source runoff of nutrients, particularly from the Maumee River; and the domination of the phytoplankton community by cyanobacteria of the genus *Microcystis*, which produce a very potent liver toxin called microcystin. On August 2, 2014, the 500,000 residents of Toledo, Ohio, were advised not to drink their tap water when microcystin was detected at unacceptable concentrations in the water supply.

Monitoring of recreational waters to ensure that they are safe for water contact remains a very unsatisfactory state of affairs. Counts of indicator bacteria vary widely over time and space. The fecal indicator bacteria being used (*Escherichia coli* and enterococcus) are not uniquely associated with human feces<sup>1</sup>; some human pathogens (e.g., leptospira) are not even associated with feces. The length of time required to assay for fecal indicator bacteria, combined with the temporal variability of their abundance, confounds interpretation of monitoring results. Although the use of molecular methods may greatly improve the specificity of the assays and reduce the time required to obtain a result, the use of such methods will first require careful epidemiological studies that relate assay results to human health outcomes.

The number of malaria cases in countries such as Sri Lanka, Mexico, and Namibia has declined dramatically since 2000; the use of bed nets and other forms of integrated pest management has been an important component of successful strategies to reduce the incidence of the disease. However, there were still 214 million cases and 438,000 deaths from malaria in 2015, primarily in sub-Saharan Africa.

Although flesh-eating screwworm flies were eradicated in the United States in 1983, they reappeared in 2016 in the Florida Keys, where they were responsible for the deaths of 10% of the population of Key deer, an endangered species. Eradication of the screwworm flies via release of sterile males is expected to take six months.

---

1 They are also found in soils and sand in tropical, subtropical, and temperate latitudes.

In 2014, the public water supply of the City of Flint, Michigan, became contaminated with lead, and the state of Michigan subsequently identified 43 people suffering from elevated levels of lead. The problem was caused by leaching of lead from pipes in the water distribution system, the result of an unfortunate decision to switch the water supply from Lake Huron to the Flint River. Water from the latter turned out to be highly corrosive to the pipes in the distribution system.

The largest accidental oil spill ever occurred in 2010 as a result of the blowout of the Deepwater Horizon oil platform in the Gulf of Mexico approximately 80 km from the coast of Louisiana. About 700,000 tonnes of oil and the oil equivalent of an additional 280,000 tonnes in the form of gaseous hydrocarbons were released. About 0.77 million gallons of a dispersant, Corexit 9500, was applied to the oil emerging from the wellhead in an attempt to break it up into small droplets that would remain submerged, and an additional 1.4 million gallons of a combination of two dispersants, Corexit 9500 and Corexit 9527, was applied to the oil that reached the surface. The full extent of the damage caused by the oil and dispersant may not be known for several years, but more than 400 km<sup>2</sup> of coastal land was lost as a result of the killing of wetland vegetation along the shoreline.

The following year, an undersea earthquake, the fourth most powerful earthquake to occur in the world since modern record keeping began in 1900, generated a tsunami that breached the 10-m seawall protecting the Fukushima Daiichi nuclear power plant in Japan. Loss of electrical power resulted in failure of the pumps that provided cooling water to three of the plant's nuclear reactors, which subsequently overheated as a result of the radiation emitted by fission products in their fuel elements. A series of chemical reactions then resulted in a number of hydrogen–air explosions during the next several days that blew the roof off one of the reactors and destroyed the upper part of the building housing another. The accident resulted in a release of radioactivity equal to 6–15% of the radioactivity released 25 years earlier by the Chernobyl power plant accident in Ukraine. Roughly 80% of the radioactivity entered the Pacific Ocean. Approximately 300,000 people were evacuated from the area surrounding the reactor. As a result of the accident, Japan shut down all but two of its nuclear reactors and Germany announced that it would close all of its nuclear power plants by 2022.

In addition to these recent developments, the book also includes many examples from the past, primarily because of their didactic value. Those examples include the accounts of Minamata disease and itai-itai disease in Japan, the recoveries of Lake Washington in Seattle and Kaneohe Bay in Hawaii after diversion of sewage, the history of use of DDT both in the United States and globally, the impact of the Exxon Valdez oil spill in Alaska, the consequences of the Chernobyl nuclear power plant accident in Ukraine, and the contamination of groundwater by improper disposal of toxic wastes at the Rocky Mountain Arsenal in Colorado.

The text of the fourth edition has been supplemented by a glossary of words and terms that may not be familiar to a student being introduced to the subject of water pollution. These words and terms are set in boldface where they first appear in the text, and the chapters where they first appear are noted in the glossary.

I am indebted to several people who provided me with suggestions and feedback concerning the fourth edition. Those persons include Dr Fred Dobbs at Old Dominion University, Dr Nicolas Cassar at Duke University, Dr. Alexandria Boehm at Stanford University, and Dr Eric DeCarlo at the University of Hawaii, all of whom have used the third edition in courses that they teach. I would also like to acknowledge the outstanding help of Brooks Bays, Jr., at the University of Hawaii for his help with the graphics. I am also indebted to Louisiana State University for granting me a sabbatical leave that provided me with the time I needed to complete much of the writing. I would also like to acknowledge the support of Dr Siyuan Ye at the

Qingdao Institute of Marine Geology for hosting me during my sabbatical leave. Finally, I would especially like to acknowledge my wife, Stephanie, and my two children, Ryan and Jennifer, whose love and support helped to smooth many bumps in the road.

Edward Laws  
Department of Environmental Sciences  
Louisiana State University

and

Center for Microbial Oceanography:  
Research and Education  
University of Hawaii

## 1

## Fundamental Concepts

The introduction of pollutants into aquatic systems is a perturbation that can set off a complicated series of biological and chemical reactions. Some knowledge and appreciation of basic ecological concepts is necessary to understand and anticipate the nature of those reactions. Let us consider a simple example. Assume that an industry is discharging wastewater into an estuary. The wastewater contains mercury, which is a toxic metal. The mercury in the water reduces the photosynthetic rates of algae in the vicinity of the discharge.

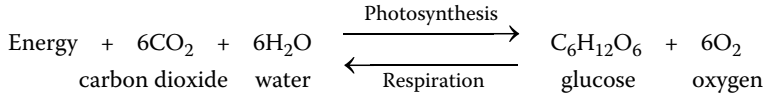
Would the stress on the algae be the extent of the impact? Unfortunately, the answer is no. The reduction of photosynthetic rates would be only the first step. To the extent that photosynthetic rates were lowered, the food supply of herbivores would be reduced, and their biomass and production rates would also be lowered. Furthermore, the herbivores would assimilate some of the mercury absorbed by the algae and become stressed by the presence of the mercury in their tissues. Thus the herbivores would be affected adversely both by a reduction in their food supply and by the presence of mercury in their bodies. Using the same logic, it is easy to imagine how animals that preyed on the herbivores could be affected through similar mechanisms and how predator/prey interactions could ultimately spread the mercury to every organism in the water. Obviously some understanding of the feeding relationships in a natural aquatic system is necessary to appreciate and anticipate the effects of such pollutants.

Now suppose that the mercury discharges ceased. Would the system recover and return to its original condition? Perhaps, but not necessarily. The stability of natural systems to perturbations such as pollutant discharges is a fundamental area of study in systems analysis and a critical consideration in the understanding of pollutant effects. The fact that a natural system is in equilibrium by no means guarantees that the system will return to the original state following a perturbation. To cite a popular example, had a very small meteor struck Earth 65 million years ago, it is possible that a few dinosaurs might have been killed or injured. However, the condition of the dinosaur population would have very likely returned to normal within a short time through natural processes. It is now generally agreed, however, that the extinction of all the dinosaurs was probably caused by a very large meteor that struck Earth about 65 million years ago. Conditions on Earth for a period of time following that event are believed to have been incompatible with the survival of dinosaurs, the result being that the system did not return to its pre-event status.

## Simple Food Chain Theory

With this introduction, let us consider some basic ecological principles that relate to the movement and transformation of pollutants within aquatic systems. All animals require food. Food may be burned (respired) to provide energy or incorporated into the animal's body in the form

of proteins, fats, carbohydrates, and other compounds to provide essential structural or metabolic components. Plants are by far the most important producers of food in most aquatic systems, although certain **bacteria** may be significant producers in some parts of the deep sea (Jannasch and Wirsen 1977). Plants utilize sunlight as an energy source to manufacture **organic compounds** from carbon dioxide, water, and various inorganic nutrients in a process called **photosynthesis**. For example, a simplified equation describing the manufacture of glucose may be written.

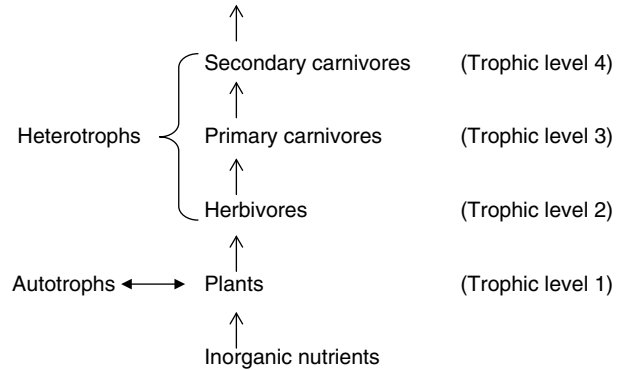


In this case glucose is the organic compound; the term organic means that the compound is found in organisms. If the reaction proceeds from left to right, the energy source is sunlight. Part of this energy is stored chemically in the glucose molecule. If the glucose is then oxidized by burning it with oxygen, the reaction proceeds from right to left, and the energy stored in the glucose is released. Some of that energy is made available to the organism mediating the respiratory process and is used to perform various metabolic functions. It is common practice to use either organic carbon or its associated chemical energy content as a metric for food supply, 1 g of organic carbon being associated with an energy content of 8–11 kilocalories (kcal). All animals have the ability to transform organic compounds from one form to another and hence to convert their food into the compounds they require. However, only plants and certain bacteria have the ability to manufacture organic high-energy compounds from inorganic low-energy constituents, and it is this transformation that is referred to as **primary production**. If the energy needed to drive the transformation comes from light, the process is called photosynthesis. If the energy is obtained from chemical reactions involving inorganic compounds, the process is called **chemosynthesis**. Only certain types of bacteria and **fungi** are capable of mediating the latter process. All living organisms depend either directly or indirectly on primary producers as a source of food. Organisms that can produce most or all of the substances they need from inorganic compounds are called **photoautotrophs** or **chemoautotrophs**, depending on whether the energy needed to effect the conversion comes from light or the reactions of inorganic chemicals, respectively. Organisms that lack autotrophic capabilities are called **heterotrophs**. The production of biomass by heterotrophs involves the conversion of some form of organic matter (food) into living biomass and is called **secondary production**.<sup>1</sup> Plants are **autotrophs**, and animals are heterotrophs. Most bacteria are heterotrophs, although some bacteria do have well-developed photoautotrophic or chemoautotrophic capabilities.

A plant-eating heterotroph, or **herbivore**, may consume food initially produced by a plant. The herbivore may in turn be eaten by another heterotroph, or **primary carnivore**, which converts part of the herbivore biomass into primary carnivore biomass. The primary carnivore may in turn be eaten by another heterotroph, or **secondary carnivore**, which in turn may be eaten by a **tertiary carnivore**, and so forth. Ecologists refer to such a system of successive food transfers as a **food chain**. Each component of the food chain is called a **trophic level**. In the example given, plants would make up the first trophic level, herbivores the second trophic

<sup>1</sup> The term secondary production has sometimes been taken to mean the production of organisms that consume primary producers (Levinton 1982) or the production of biomass by animals (Lalli and Parsons 1997). The definition given here implies that secondary production includes the production of both animal and bacterial biomass by heterotrophic processes and is consistent with Strayer (1988) and Scavia (1988).

**Figure 1.1** Diagram of a food chain through trophic level four.



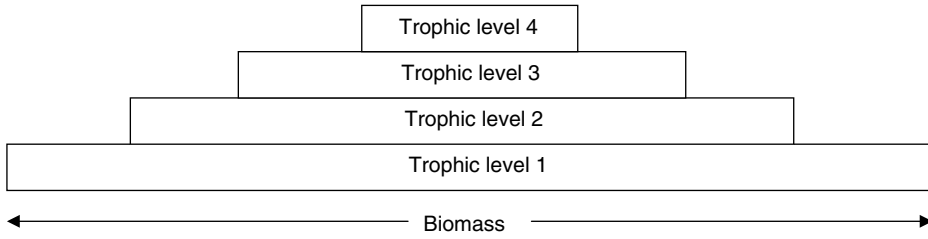
level, primary carnivores the third trophic level, and so forth. Such a food chain is depicted schematically in Figure 1.1.

In most aquatic systems the transfer of food from one trophic level to the next is believed to occur with an efficiency of only about 20%. In other words, the rate at which food is ingested by a trophic level is about five times greater than the rate at which food is passed on to the next trophic level. This efficiency is referred to as an **ecological efficiency**, or more specifically as a trophic level intake efficiency (Odum 1971, p. 76). Ecological efficiencies are generally low, because much of the food ingested by a trophic level is either respired to provide energy or excreted because it cannot be incorporated into new trophic level biomass. However, ecological efficiencies are also reduced when, for example, an organism dies from disease or a female fish releases her eggs into the water. Eggs occupy a trophic level that is always lower than the trophic level of the organism that produced them.

### Ecological Pyramids

Because ecological efficiencies are only about 20% in aquatic systems, the flux of food from one trophic level to the next steadily decreases as one moves up the food chain. The result is that the primary production rate is likely to greatly exceed the production of top-level carnivores, the magnitude of the discrepancy depending on the number of trophic levels in the food chain. Ryther (1969) has estimated that there are roughly six trophic levels in typical open-ocean marine food chains. In contrast, some coastal and upwelling areas may have food chains with as few as three trophic levels. This difference stems in part from the fact that the primary producers in open-ocean systems are dominated by very small microscopic plants called **phytoplankton**, whereas in coastal and upwelling areas the individual phytoplankton cells tend to be larger, and the cells tend to form chains and gelatinous masses. In the coastal and upwelling areas, the primary producers can therefore be efficiently grazed by rather large herbivorous crustaceans such as **copepods** or even small fish. However, in the open ocean, most of the phytoplankton are much too small to be consumed by crustaceans and small fish, and several intermediate trophic levels therefore separate these two categories of organisms.

Regardless of the length of the food chain, the steady decrease in the flux of food to higher and higher trophic levels usually results in a decrease in the biomass of organisms on successively higher trophic levels. Thus, if one were to represent the biomass of each trophic level by a bar whose length was proportional to the biomass of organisms in the trophic level and if one were to lay these bars on top of each other, the resulting figure would look qualitatively like Figure 1.2. Arranged in this way the bars of trophic level biomass form a pyramid, often referred to as an ecological pyramid.



**Figure 1.2** Trophic level biomass through trophic level four in a hypothetical food chain.

The decrease in biomass on successive trophic levels is, however, less than the factor of 5 that one might expect based on an ecological efficiency of 20%. The reason follows from the fact that the ratio of the fluxes of organic matter between trophic levels 3 and 4,  $F_{34}$ , and between trophic levels 2 and 3,  $F_{23}$ , for example, can be written as follows:

$$\frac{F_{34}}{F_{23}} = E = \frac{F_{34} \left( \frac{B_3}{B_3} \right)}{F_{23} \left( \frac{B_2}{B_2} \right)} = \frac{T_3 B_3}{T_2 B_2} \quad (1.1)$$

where  $E$  is the ecological efficiency,  $B_2$  and  $B_3$  are the biomasses on trophic levels 2 and 3, respectively, and  $T_2$  and  $T_3$  are the **turnover rates** of organic matter on trophic levels 2 and 3, respectively, and are equal to  $F_{23}/B_2$  and  $F_{34}/B_3$ , respectively. The turnover rates are just the rates at which organic matter on one trophic level is being consumed by the next trophic level divided by the biomass of organic matter on that trophic level. From Eq. (1.1), it follows that

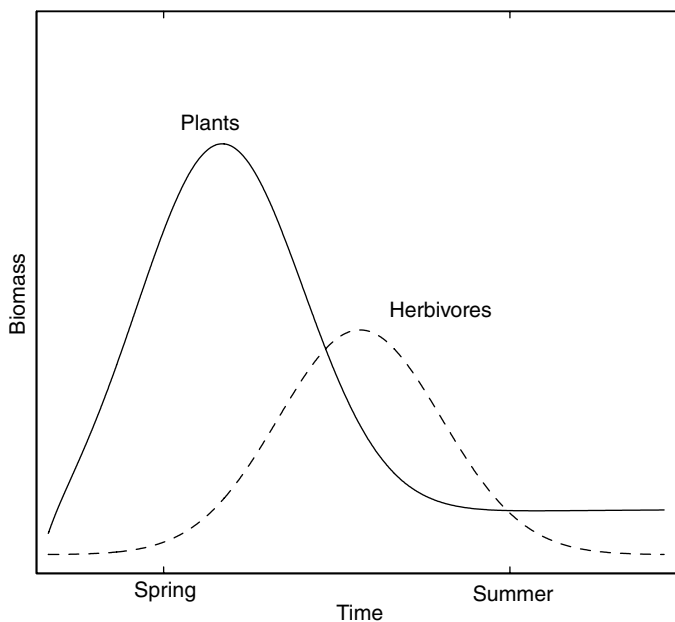
$$\frac{B_3}{B_2} = E \frac{T_2}{T_3} \quad (1.2)$$

If the turnover rates on successive trophic levels were all the same, Eq. (1.2) implies that the ratio of biomasses on successive trophic levels would equal the ecological efficiency, but in fact the turnover rates of organic matter on successive trophic levels are typically not the same. In general, one expects predators to be larger than prey, and hence higher trophic level organisms tend to be larger than lower trophic level organisms. This expectation is generally fulfilled, although there are certainly exceptions to the rule (Longhurst 1991). For example, animals that hunt in groups or packs, such as wolves or killer whales, may kill organisms larger than themselves. However, predators are usually larger than their prey, and as a result the number of organisms on successively higher trophic levels decreases even more rapidly than the total biomass. Although it is generally true that large organisms consume more food than small organisms, it is also generally true that large organisms consume less food per unit biomass (i.e., have a lower turnover rate) than do small organisms. The relationship between organism size and metabolic rate is such that, if two organisms differ in weight by a factor of 10,000, the larger organism can be expected to consume only 10% as much food per unit body weight as the smaller organism. In other words, the larger organism would consume about 1000 times as much food as the smaller organism, or  $1000/10,000 = 1/10$  as much food per unit body weight.

Now consider a case in which the size of individual organisms on successive trophic levels differs by a factor of 10,000, and the ecological transfer efficiency between the trophic levels is 20%. In this case the ratio of turnover rates on trophic levels 2 and 3, for example, would be 10,

and a steady-state situation might exist in which the total biomass of trophic level 3 was twice that of trophic level 2. In other words, in Eq. (1.2),  $E = 20\%$ ,  $T_2/T_3 = 10$ , and the ratio of biomasses equals 20% of 10, or 2. Although the third trophic level received only 20% as much food as the second trophic level, the third trophic level would need only 10% as much food to support a given amount of biomass as the second trophic level. Thus the logical arguments that lead us to expect an ecological pyramid of biomass need not apply to food chains in which the size of organisms on successive trophic levels differs greatly, because these arguments implicitly assume the food requirements per unit biomass of all trophic levels to be identical. The fact that normal ecological pyramids of biomass are found in most natural aquatic food chains (e.g., Odum 1971, p. 80; Sheldon et al. 1972) indicates that differences in organism size on successive trophic levels are not sufficiently great to invert the pyramids. Nevertheless, the difference in successive trophic level biomasses is often less than the factor of 5 that would be expected to result from transfer efficiencies of 20% if all organisms required the same amount of food per unit biomass (see Question 1.8). Thus organism size differences tend to reduce, but not eliminate, the effect of low ecological transfer efficiencies on trophic level biomass structure.

A caveat to the scenario depicted in Figure 1.2 is the fact that it is quite possible in non-steady-state systems for the distribution of biomass in two or more trophic levels to become temporarily inverted. In other words, trophic level biomass increases rather than decreases with increasing trophic level number. For example, in temperate oceans and lakes, a so-called bloom of plant biomass may occur in the spring as the water temperature and average daily solar insolation increase. This plant bloom generally does not occur at a time when the herbivore biomass is large, but the herbivore biomass begins to rapidly increase shortly thereafter in direct response to the increase in herbivore food. Typically herbivore grazing reduces the plant biomass to a low level. Herbivore biomass peaks and then declines. The fall in herbivore biomass is caused both by the decrease in herbivore food and by grazing pressure from primary carnivores. Figure 1.3 shows qualitatively how plant and herbivore biomass may vary with time during this period.



**Figure 1.3** Biomass of plants and herbivores during spring and early summer in a hypothetical temperate aquatic ecosystem.

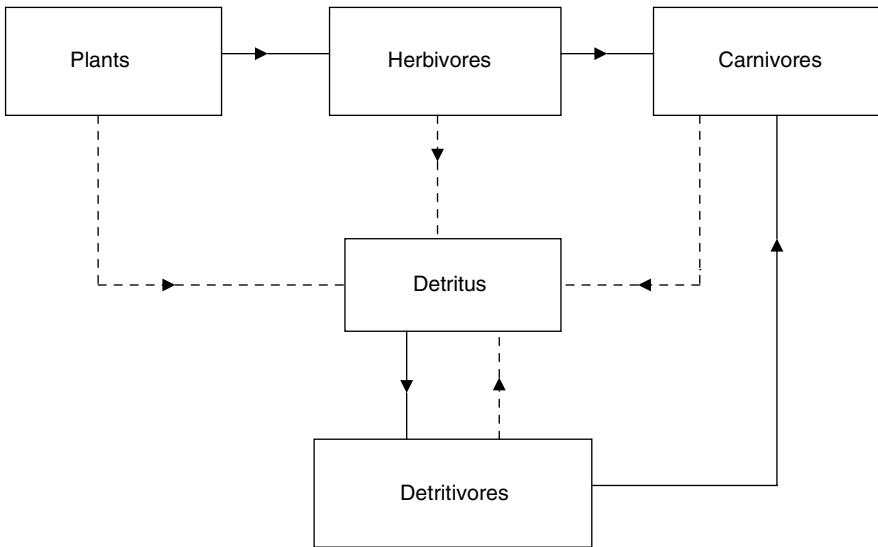


A system in which the herbivore biomass is greater than the plant biomass for a short period following the plant bloom is apparent in Figure 1.3. Such a condition may exist for a short time in many aquatic systems that are subject to large-scale seasonal cycles. During this period the first two trophic level biomasses form a so-called inverted pyramid, because the second trophic level biomass is greater than that of the first. This situation lasts for only a short time, and the average distribution of biomass is similar to Figure 1.2. The logical arguments that lead us to expect a normal pyramid of biomass do not necessarily apply in a non-steady-state system, because over short time intervals predators may consume more food than prey are producing and hence reduce the prey biomass to a low level. Obviously this situation cannot persist for long; otherwise the predators would destroy their food supply. Hence on the average one does expect to see a normal pyramid of biomass.

### Recycling and the Microbial Loop

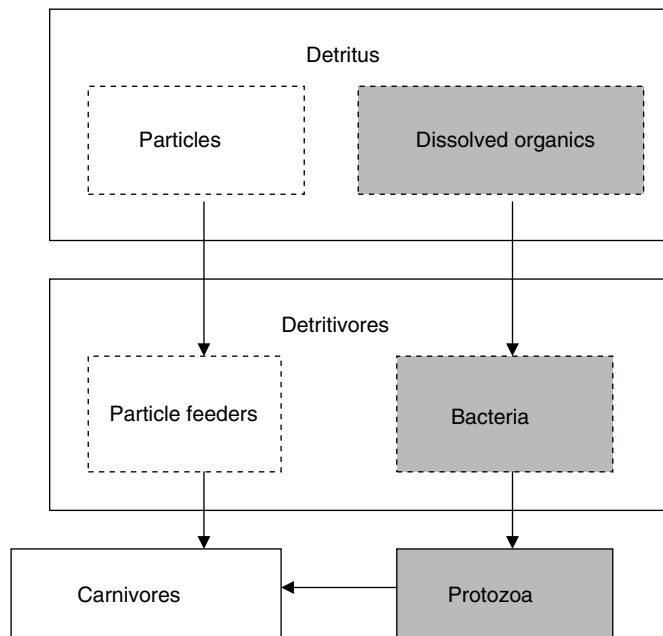
The food chain we have discussed up to this point is called the **grazing food chain**, because the second and higher trophic levels consist of predators that graze upon prey. Primary producers occupy the first trophic level of the grazing food chain. A very important companion of the grazing food chain in any healthy aquatic system is the **detritus food chain**. The first trophic level in the detritus food chain is the nonliving organic matter produced by living organisms. This nonliving organic matter may exist either as particles or as dissolved organic substances and is referred to as **detritus**. The detritus provides food for a category of organisms called **detritivores**, a designation that includes both bacteria and certain metazoans. Bacteria have no mouthparts and hence, strictly speaking, must feed entirely on dissolved organics. However, by exuding enzymes they are able to solubilize and hence make use of particulate material as well. Metazoan detritivores such as benthic worms feed primarily on particulate detritus. Because detritivores are living organisms, they respire and excrete organics, just as do the members of the grazing food chain. The organic compounds excreted by detritivores may very likely be used as food by other detritivores, and as a result only the most refractory organic compounds accumulate in the system. Most of the organic matter initially synthesized by the primary producers is ultimately respired, either by organisms in the grazing food chain or by detritivores. Animals or protozoans consume the detritivores, and in this way some of the organic carbon excreted by the grazing food chain is recycled back into the grazing food chain. The process is illustrated schematically in Figure 1.4. The portion of the detritus food chain involving dissolved organics, bacteria, and **protozoans** is often referred to as the **microbial loop** (Fig. 1.5) and is believed to account for much of the degradation of detritus in aquatic systems.

It is apparent from Figure 1.4 that the grazing food chain and the detritus food chain are interconnected and do not function independently of each other. The interaction between the two food chains is a mutualistic one, that is, favorable to both and obligatory. The grazing food chain benefits the detritus food chain by excreting much of the organic matter needed by the detritivores for food; the detritus food chain benefits the grazing food chain by removing potentially toxic waste products excreted by both food chains. An approximate balance between the **anabolism** and **catabolism** of organic matter is essential to the maintenance of a stable aquatic ecosystem. In a system in which primary production on the average exceeds respiration, organic matter in the form of either plant or animal biomass or detritus will accumulate in the system. Eventually the whole system may fill up with organic sediments. In fact, exactly this process does occur, although often at a very slow rate, in most freshwater habitats and in some marine basins. This gradual accumulation of organic debris results in part from the fact that some detritus is rather refractory and not efficiently broken down by detritivores. In contrast, if respiration exceeds primary production, then a net consumption of biomass is occurring



**Figure 1.4** Box model of the grazing and detritus food chains and the interactions between the two food chains. Solid lines represent feeding relationships. Dashed lines represent excretion.

**Figure 1.5** Box model of the detritus food chain leading to the carnivore trophic level of the grazing food chain. The gray shaded boxes constitute the microbial loop.



within the system. Such a system cannot persist unless subsidized by an external input of organic compounds, as, for example, from stream runoff.

It is important to realize that primary producers and detritivores use the waste products resulting from respiration and excretion, respectively, to create living biomass. For example, carbon dioxide, which is a direct product of respiration, is the source of carbon for primary production. Ammonia (as ammonium ions), which many aquatic organisms excrete, can be

directly assimilated by primary producers as a source of nitrogen for the production of proteins and nucleic acids. Waste products can be, and often are, toxic to the organisms that produce them. However, in a well-balanced ecosystem, waste products never reach high concentrations, because they are constantly being used as a source of food by other organisms in the system. Detritivores play a crucial recycling role in aquatic systems by consuming organic wastes and converting them to inorganic forms that are used by primary producers. The grazing food chain uses the organic matter synthesized by the primary producers and releases part of it in the form of detritus, which in turn provides the food for the detritus food chain.

Because of this internal recycling, there is a tendency for both organic and inorganic compounds to accumulate in aquatic systems. Inorganic carbon can of course escape to the atmosphere as carbon dioxide, and inorganic nitrogen may similarly escape as ammonia,  $N_2O$ , or  $N_2$ , all of which are gases. However, under normal circumstances, the latter escape routes are not very efficient for nitrogen, and removal of organic compounds and essential nutrients via washout rarely occurs with 100% efficiency. The accumulation of refractory organic debris in the sediments and buildup of organic matter and nutrient concentrations in the water column are natural processes in most aquatic systems. Associated with these phenomena are increases in the rates of primary production and respiration and a decrease in the depth of the system caused by sediment accumulation. The whole process is referred to as **eutrophication**. Eutrophication eventually causes most lakes to fill up with sediments after a time of perhaps hundreds, thousands, or even tens of thousands of years. Sediments do accumulate at the bottom of the ocean, but the sediments are removed by tectonic processes at subduction zones at rates that approximately balance their rate of formation. Obviously there is no danger that the oceans will fill up with sediments. However, some regions of the ocean are much more productive than others, and this fact directly reflects the relative efficiency with which essential nutrients are recycled by the grazing and detritus food chains in different parts of the ocean.

Eutrophication is sometimes considered to be an unnatural phenomenon, but the imbalance between photosynthesis (P) and respiration (R) associated with eutrophication is nothing new. It was a fact of life on Earth literally billions of years ago.<sup>2</sup> The atmosphere of Earth was initially devoid of oxygen, and the oxygen in the atmosphere and ocean today is the product of photosynthesis. The first primitive plants evolved in the ocean, where the water shielded them from ultraviolet radiation. The oxygen produced by those plants eventually accumulated in the ocean and atmosphere, and photochemical reactions in the atmosphere converted some of the oxygen to ozone. The oxygen and ozone in the atmosphere then became a shield against ultraviolet radiation. It was only after the establishment of this oxygen and ozone shield that organisms were able to leave the ocean and evolve on land. Thus the very habitability of the terrestrial environment today depends on the fact that there was an excess of photosynthesis over respiration on a grand scale during the early evolution of life on Earth. However, the imbalance between P and R has had other profound implications. Oxygen is one product of photosynthesis. The other product is organic matter. The imbalance between P and R during the geologic history of Earth has resulted in the accumulation of both oxygen and organic matter. The existence of oil and coal deposits is an obvious manifestation of the imbalance between P and R over geologic time.

Any unnatural acceleration of the eutrophication process due to the activities of humans is called **cultural eutrophication**. Cultural eutrophication could be caused, for example, by the discharging of sewage containing a high concentration of nutrients and organic matter. Instances of cultural eutrophication constitute one of the most common and widespread examples of water pollution problems. We will explore a few of these examples in detail in Chapter 4.

---

2 Earth is approximately 4.5 billion years old. Primitive forms of life began to appear about 3.5–4.0 billion years ago.

### Food Chain Magnification

Respiration and excretion obviously play a critical role in controlling the flux of organic and inorganic materials between the grazing and detritus food chains. However, from the standpoint of water pollution, respiration and excretion are also important in determining the movement of pollutants both between and within these same food chains. If the pollutant is biodegradable, it may of course be catabolized and rendered harmless. However, if the pollutant is nonbiodegradable, it may be passed from prey to predator and in this way be spread throughout the grazing food chain. If some of the pollutant is excreted, then it may spread to the detritus food chain as well. One of the most important applications of food chain theory to water pollution problems has been the effort to explain how these transfers of a pollutant between food chains and trophic levels affect the concentration of the pollutant in organisms. In cases where it has been possible to examine in some detail the distribution of pollutant concentrations among the trophic levels in a simple food chain, results have sometimes indicated a steady increase in concentration with increasing trophic level number. Table 1.1 shows concentrations of the pesticide DDT (plus the closely related compounds DDD and DDE) in the water and in various organisms taken from a Long Island, New York, salt marsh. The residue concentrations increase steadily from the plankton to the small fish to the larger fish and finally to the fish-eating birds. The total concentration factor from plankton to fish-eating birds is roughly 600. Observations such as this one led some scientists to believe that a common mechanism or explanation might underlie similar observations of increasing pollutant concentrations at higher trophic levels in some food chains, a phenomenon that they termed **food chain magnification**.

A logical explanation for food chain magnification is forthcoming from food chain theory if one assumes that certain pollutants ingested with an organism's food are not as effectively respired or excreted as is the remainder of the food. A metabolite of DDT, DDE, would seem to be a likely candidate for such a pollutant, because it is resistant to biological breakdown and

**Table 1.1** DDT residues in organisms taken from a Long Island salt marsh.

Organism	DDT residues (ppm) <sup>a</sup>
Water	0.00005
Plankton	0.04
Silverside minnow	0.23
Sheepshead minnow	0.94
Pickrel (predatory fish)	1.33
Needlefish (predatory fish)	2.07
Heron (feeds on small animals)	3.57
Tern (feeds on small animals)	3.91
Herring gull (scavenger)	6.00
Fish hawk (osprey) egg	13.8
Merganser (fish-eating duck)	22.8
Cormorant (feeds on larger fish)	26.4

Source: Woodwell et al. (1967).

a) Parts per million (ppm) of total residues, DDT + DDD + DDE (all of which are toxic), on a wet weight whole-organism basis.