Algae
Source to Treatment

MANUAL OF WATER SUPPLY PRACTICES

M57



First Edition

American Water Works Association

The Authoritative Resource on Safe Water®

Advocacy
Communications
Conferences
Education and Training
Science and Technology
Sections

Documents
Document Sharing Hub

Full document details: AWWA Manual M57 2010

Algae: Source to Treatment

AWWA MANUAL M57
First Edition



American Water Works Association

Documents
Document Sharing Hub

Full document details: AWWA Manual M57 2010

MANUAL OF WATER SUPPLY PRACTICES — M57, First Edition

Algae: Source to Treatment

Copyright © 2010 American Water Works Association

All rights reserved. No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopy, recording, or any information or retrieval system, except in the form of brief excerpts or quotations for review purposes, without the written permission of the publisher.

Disclaimer
The authors, contributors, editors, and publisher do not assume responsibility for the validity of the content or any consequences of its use. In no event will AWWA be liable for direct, indirect, special, incidental, or consequential damages arising out of the use of information presented in this book. In particular, AWWA will not be responsible for any costs, including, but not limited to, those incurred as a result of lost revenue. In no event shall AWWA's liability exceed the amount paid for the purchase of this book.

AWWA Publications Manager: Gay Porter De Nileon
Project Manager/Technical Editor: Martha Ripley Gray
Cover Art: Cheryl Armstrong
Production: Glacier Publishing Services, Inc.
Manuals Specialist: Molly Beach

Library of Congress Cataloging-in-Publication Data

Algae : source to treatment. -- 1st ed.
p. cm. -- (AWWA manual ; M57)
Includes bibliographical references and index.
ISBN 978-1-58321-787-0
1. Algae--Control. 2. Water--Purification--Microbial removal. 3. Drinking water--Purification. 4. Freshwater algae. I. American Water Works Association.

TD465.A425 2010
628.1'1--dc22
2010010557

Printed in the United States of America
American Water Works Association
6666 West Quincy Ave.
Denver, CO 80235
Printed on recycled paper

Documents
Document Sharing Hub

Full document details: AWWA Manual M57 2010

Contents

List of Figures, vii

List of Tables, xv

Preface, xvii

Acknowledgments, xix

Introduction, xxiii

SECTION I METHODS 1

Chapter 1 Recent Developments in Online Monitoring Technology for Surveillance of Algal Blooms, Potential Toxicity, and Physical–Chemical Structure in Rivers, Reservoirs, and Lakes 3

Summary, 3
Introduction, 5
Deployment and Operational Considerations in Online Monitoring Programs, 6
Pigment Sensors: Field Measurements Versus Laboratory Methods, 8
Multiparameter Water Quality Sondes and Pigment-Specific Sensors, 11
Examples of Water-Column Monitoring: Profiling Platforms, AUV Technology, and Buoy-Based Systems, 14
Online Instruments for Characterizing Source Waters, 17
Limitations of Online and Real-Time Monitoring Equipment, 20
Field Methods Used in Conjunction With Online Monitoring, 20
Future Directions, 22
References, 23

Chapter 2 Sampling and Identification: Methods and Strategies 25

Aquatic Environments and Algal Communities in Surface Water Utilities, 26
Sampling, 28
Analytical Methods, 44
Quality Assurance, 65
References and Bibliography, 65

Chapter 3 Detection of Cyanotoxins During Potable Water Treatment. . . 71

Cyanotoxin Standards, 72
Sample Preparation, 72
Total Cyanotoxins, 75
Screening Assays, 76
Analytical Techniques, 79
Qualitative and Quantitative Methods for Toxic Cyanobacteria, 79
References, 86

Documents
Document Sharing Hub

Full document details: AWWA Manual M57 2010

Chapter 4 Algal Chlorophylls: A Synopsis of Analytical Methodologies . . 93

Sample Processing and Pigment Extraction, 97
Spectrophotometric Assessment, 99
Fluorometric Assessment, 101
Chromatographic Assessment, 104
Chlorophyll Radiolabeling, 109
In Situ Assessment, 110
Summary and Evaluation, 113
References, 115

SECTION II THE ORGANISMS 123

Chapter 5 Cyanobacteria 125

Biology, 125
Taxonomy, 128
Ecology, 129
Significance, 131
Management and Mitigation of Cyanobacteria and Their Toxins, 132
Identification, 133
Key to Common Cyanobacteria Genera, 134
References, 143

Chapter 6 Chlorophyta 147

Biology, 147
Taxonomy, 152
Ecology, 154
Significance, 157
Identification, 159
Key to Morphological Group, 161
References, 164

Chapter 7 Euglenophyta 167

Biology, 167
Taxonomy, 168
Key to Freshwater Genera of Photosynthetic Euglenoids, 169
References, 174

Chapter 8 Dinophyta 177

Biology, 177
Taxonomy, 179
Ecology, 182
Key to Genera, 184
References, 184

Documents
Document Sharing Hub

Full document details: AWWA Manual M57 2010

Chapter 9 Cryptophyta 187

Biology, 188
Ecology, 191
Significance, 192
Key for Identification of Cryptomonad Genera, 193
Descriptions of Genera, 194
References, 202

Chapter 10 Bacillariophyta: The Diatoms. 207

General Introduction to the Diatoms, 207
Significance of Diatoms to the Drinking Water Industry, 212
Diatom Identification to Genus, 219
Acknowledgments, 246
References, 246

Chapter 11 Chrysophyta 249

General Description, 249
Biology, 250
Ecology, 260
References, 262

Chapter 12 Xanthophyta and Phaeophyta 271

Biology, 271
Ecology, 275
Significance, 279
Key for Identification to Divisions and Classes, 281
Useful Information and References for Identification,
With Keys to Common Genera, 282
References, 284

Chapter 13 Rhodophyta 289

General Introduction to Red Algae, 289
Biology, 289
Key to Genera, 291
Ecology, 292
Significance, 294
Identification, 294
References, 296

SECTION III MANAGEMENT. 297

Chapter 14 Source Water Assessment and Control/Treatment Strategies for Harmful and Noxious Algae 299

Summary, 299
Introduction, 301

Documents
Document Sharing Hub

Full document details: AWWA Manual M57 2010

Source Water Assessment, 302
Mitigative and Control Strategies, 314
Future Directions, 323
References, 325

Chapter 15 Algal Taste and Odor 329

Introduction, 329
Diagnosing the Species and Their Chemicals, 331
Chemistry, 346
Algal Odor Compounds: Pathways, Properties, and Producers, 349
Algal Taxa, 361
Nonalgal Biological Odor Moderators and Sources, 363
Large-Scale Factors, 365
Protocols, Measures, and Other Considerations, 366
Summary and Conclusions, 367
References, 369

Chapter 16 Control of Cyanotoxins in Drinking Water Treatment 377

Physicochemical Characteristics of Freshwater Cyanotoxins, 378
Intracellular Cyanotoxins versus Extracellular Cyanotoxins, 378
Health-Based Guidelines for Cyanotoxins, 379
Cyanotoxin Occurence, 380
Cyanotoxin Control, 380
Summary, 391
Acknowledgments, 392
References, 392

Chapter 17 Algae Removal Strategies 395

Treatment Processes, 396
Plant Optimization, 408
Conclusions, 412
References, 412

Glossary 415

Index 425

List of AWWA Manuals 439

Documents
Document Sharing Hub

Full document details: AWWA Manual M57 2010

Figures

1-1 A generalized flow diagram of data acquisition and product dissemination, 7
1-2 Whole water-column structure of site located at a municipal water plant reservior intake using profiler technology, 9
1-3 Close-up photographs of six commercially available water quality sondes equipped with multiple sensors and antifouling wipers, 12
1-4 A time series of data acquired in the upper Potomac (brackish waters) using YSI phycocyanin (PC) and phycoerythrin (PE) sensors, 13
1-5 Two commercially available water-column profilers, 14
1-6 Contour plots, constructed using Surfer (version 7.0), of water-column profiles acquired at a municipal water plant reservoir intake using profiler technology during 2005, 16
1-7 Illustration of YSI AUV available for monitoring reservoirs in three dimensions and associated data, 17
1-8 The Turner Designs AlgaeWatch online fluorometer, 18
1-9 Fish ventilatory and behavior patterns monitored using the IAC 1090 Fish Biomonitor system and Expert Software, 19
2-1 Horizontal and vertical gradients in *in vitro* chlorophyll *a*, 29
2-2 Vertical profile of *in situ* chlorophyll *a*, showing metalimnetic concentration of phytoplankton, 31
2-3 Phytoplankton net, 35
2-4 Metal Kemmerer sampler, 37
2-5 Van Dorn sampling bottles: (A) vertical, (B) horizontal, 37
2-6 Integrating water sampler, 38
2-7 Use of an integrating sampler off of a boat, 39
2-8 Use of the Solinst® peristaltic pump, 40
2-9 Use of the Teledyne Isco compositing sampler with peristaltic pump, 40
2-10 Various Hester-Dendy periphyton samplers, 41
2-11 Wildeo periphyton sampler, 42
2-12 Utermöhl sedimentation chambers, 43
2-13 Gridded Sedgewick-Rafter counting cell, 48
2-14 Palmer-Maloney counting cell, 48
2-15 Medical hemacytometer, 48
2-16 Direct examination of 5-mL Utermöhl chamber, 49
3-1 Schematic of cyanotoxin methodology, 72
4-1 *In vitro* absorbance of select chlorophylls distributed among the spectral classes of algae, 94
4-2 Schematic of the light reaction of photosynthesis denoting electron transport within photosystems I and II, 95
4-3 Chromatogram of purified chlorophyll and carotenoids standards, 105

Documents
Document Sharing Hub

Full document details: AWWA Manual M57 2010

4-4 Chromatogram of purified chlorophyll and carotenoids standards, 106
4-5 Depiction of chlorophyll *a* concentrations throughout the northeastern Gulf of Mexico, 112
5-1 Some cyanobacteria species commonly form surface blooms, 126
5-2 Cyanobacteria are morphologically diverse ranging from (A) unicellular to (B) colonial to (C) filamentous, 126
5-3 Many cyanobacteria have mucilage associated with them, 126
5-4 Aerotopes (gas vacuoles) allow some cyanobacteria to contro their buoyancy, 127
5-5 Heterocytes (heterocysts) are specialized cells found in some filamentous cyanobacteria where nitrogen fixation occurs, 127
5-6 Akinetes are specialized resting cells found in some filamentous cyanobacteria, 128
5-7 *Synechococcus*, 137
5-8 *Cyanodictyon,* 137
5-9 *Radiocystis*, 137
5-10 *Eucapsis,* 137
5-11 *Merismopedia,* 137
5-12 *Snowella*, 137
5-13 *Woronichinia*, 138
5-14 *Gomphosphaeria,* 138
5-15 *Coelosphaerium*, 138
5-16 *Coelomoron,* 138
5-17 *Chroococcus,* 138
5-18 *Aphanothece,* 138
5-19 *Gloeocapsa,* 139
5-20 *Aphanocapsa,* 139
5-21 *Microcystis,* 139
5-22 *Gloeotrichia*, 139
5-23 *Anabaenopsis*, 139
5-24 *Cylindrospermopsis*, 140
5-25 *Nodularia*, 140
5-26 *Nostoc*, 140
5-27 *Anabaena*, 140
5-28 *Aphanizomenon*, 140
5-29 *Planktolyngbya,* 141
5-30 *Lyngbya*, 141
5-31 *Phormidium* (in part), 141
5-32 *Arthrospira*, 141
5-33 *Spirulina,* 141
5-34 *Oscillatoria*, 141
5-35 *Pseudanabaena*, 142
5-36 *Limnothrix*, 142

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

5-37 *Planktothrix*, 142
5-38 *Phormidium* (in part), 142
6-1 *Chara*, 148
6-2 (A) *Hydrodictyon*, (B) *Stigeoclonium*, (C) *Chara*, (D) *Cladophora*, 148
6-3 Pyrenoid (*Zygnema*), 149
6-4 (A) *Chlamydomonas*, (B) *Tetraselmis (Pyramichlamys)*, 150
6-5 (A) *Volvox*, (B) *Eudorina*, (C) *Pandorina*, 150
6-6 (A) *Oocystis*, (B) *Scenedesmus*, (C) *Pediastrum*, 150
6-7 (A) *Ankistrodesmus*, (B) *Sphaerocystis*, (C) *Botryococcus*, 150
6-8 (A) *Micrasterias*, (B) *Closterium*, 151
6-9 (A) *Bulbochaete*, (B) *Sprirogyra,* (C) *Microspora*, (D) *Ulothrix*, 152
6-10 *Oedogonium* (A, B), 153
6-11 *Cosmarium,* 153
6-12 *Mougeotia,* 154
6-13 *Scenedesmus,* 155
6-14 *Micractinium,* 156
6-15 *Botryococcus,* 156
6-16 *Sphaerocystis,* 157
6-17 *Tetraselmis (Pyramichlamys),* 158
6-18 *Pithophora,* 159
7-1 Labeled *Euglena*, 168
7-2 *Eutreptia viridis*, 170
7-3 *Colacium vesiculosum*, 170
7-4 *Euglena caudata*, 171
7-5 *Lepocinclis steinii*, 171
7-6 *Phacus pleuronectes*, 172
7-7 *Strombomonas fluviatilis*, 172
7-8 *Trachelomonas armata*, 172
7-9 *Ascoglena vaginicola*, 173
7-10 *Cryptoglena pigra*, 174
7-11 *Euglenamorpha hegneri*, 174
8-1 Outline of armored dinoflagellate showing (A) apical view, (B) antapical, (C) dorsal, (D) ventral with cingulum and sulcus; plates annotated, 178
8-2 *Gloeodinium montanum*, showing a red colored body inside cell, 178
8-3 *Ceratium hirundinella* with large, centrally located nucleus, 179
8-4 *Ceratium hirundinella*: note three posterior horns, golden color, 180
8-5 *Ceratium rhomvoides*: note two posterior horns, 180
8-6 *Peridinium gatunense*: note golden color and Saturn appearance, 181
8-7 *Gymnodinium aeruginosum*: note blue-green color, noticeable cingulum, and red eyespot, 181
8-8 *Peridiniopsis polonicum*: note single antapical spine, 182
8-9 *Peridinium bipes*: empty theca showing plates, large 1´ plate and apical pore, 182

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

9-1 Diagram of a generalized cryptomonad cell showing the cellular details, 188
9-2 *Chilomonas*: (A) scanning electron micrograph, (B) diagram, 195
9-3 *Goniomonas*: (A) scanning electron micrograph, (B) diagram, 195
9-4 *Kathablepharis*: (A) scanning electron micrograph, (B) diagram, 196
9-5 *Hemiselmis*: (A) scanning electron micrograph, (B) diagram, 197
9-6 *Komma*: (A) scanning electron micrograph, (B) diagram, 197
9-7 *Chroomonas*: (A) scanning electron micrograph, (B) diagram, 198
9-8 *Plagioselmis*: (A) scanning electron micrograph, (B) diagram, 199
9-9 *Storeatula*: (A) scanning electron micrograph, (B) diagram, 200
9-10 *Rhodomonas*: (A) scanning electron micrograph, (B) diagram, 200
9-11 *Cryptomonas*: (A) scanning electron micrograph, (B) diagram, 201
9-12 *Campylomonas*: (A) scanning electron micrograph, (B) diagram, 202
10-1 Cross-section through a diatom cell showing the two halves of the box, 208
10-2 Photomicrographs of diatoms showing many of the cell wall features, 209
10-3 Structure of living diatom cells and chloroplasts (plastids), 210
10-4 Different ecological microhabitats for diatoms in various ecosystems, 212
10-5 *Aulacoseira*, 225
10-6 *Acanthoceras*, 225
10-7 *Pleurosira*, 225
10-8 *Melosira*, 225
10-9 *Skeletonema*, 226
10-10 *Cyclotella*, 226
10-11 *Cyclostephanos*, 226
10-12 *Stephanodiscus*, 226
10-13 *Thalassiosira*, 227
10-14 Septa, 227
10-15 *Tetracyclus*, 227
10-16 *Tabellaria*, 228
10-17 *Meridion*, 228
10-18 *Diatoma*, 228
10-19 *Hannaea*, 228
10-20 *Asterionella*, 229
10-21 *Martyana*, 229
10-22 *Staurosirella*, 229
10-23 *Synedra*/*Synedrella*/*Ulnaria*, 229
10-24 *Fragilaria* and related genera, 230
10-25 *Rhoicosphenia*, 230
10-26 *Cocconeis*, 231
10-27 *Achnanthidium*, 231
10-28 *Planothidium*, 231
10-29 *Rossithidium*, 231
10-30 *Achnanthes*, 232
10-31 *Actinella*, 232

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

10-32 *Eunotia*, 232
10-33 *Bacillaria*, 232
10-34 *Plagiotropis*, 233
10-35 *Campylodiscus*, 233
10-36 *Cymatopleura*, 233
10-37 *Entomoneis*, 234
10-38 *Stenopterobia*, 234
10-39 *Surirella*, 234
10-40 *Denticula*, 235
10-41 *Tryblionella*, 235
10-42 *Hantzschia*, 236
10-43 *Nitzschia*, 236
10-44 *Epithemia*, 236
10-45 *Rhopalodia*, 237
10-46 Symmetrical axis of symmetry in diatoms, 237
10-47 Asymmetrical axis of symmetry in diatoms, 237
10-48 *Gyrosigma*, 238
10-49 *Pleurosigma*, 238
10-50 *Gomphoneis*, 238
10-51 (A) *Gomphonema*; (B) *Didymosphenia*, 239
10-52 *Reimeria*, 239
10-53 *Amphora*, 239
10-54 *Cymbella*, 240
10-55 *Encyonema*, 240
10-56 *Luticola*, 240
10-57 *Anomoeoneis*, 241
10-58 *Mastogloia*, 241
10-59 *Diploneis*, 241
10-60 *Frustulia*, 242
10-61 *Amphipleura*, 242
10-62 *Neidium*, 242
10-63 *Capartogramma*, 242
10-64 *Stauroneis*, 243
10-65 *Caloneis*, 243
10-66 *Pinnularia*, 243
10-67 *Sellaphora*, 244
10-68 *Craticula*, 244
10-69 *Brachysira*, 244
10-70 *Diadesmis*, 245
10-71 *Navicula* and related genera, 245
11-1 Chrysophyceae illustrations from Skuja (1956), 250
11-2 *Chrysocapsa vernalis* showing the capsoid nonmotile colony (A) and individual cells (B), 251

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

11-3 The amoeboid *Chrysamoeba pyrenoidifera* cells showing the many pseudopods used to capture bacteria, 251
11-4 A colony of *Synura petersenii* showing the chloroplasts, nucleus, contractile vacules, and flagella, 252
11-5 *Mallomonas insignis* cell showing the two plastids, the nucleus, the posterior contractile vacuoles, and the silica-scale covering, 252
11-6 A siliceous cyst of *Ochromonas* cf. *gloeopara,* 253
11-7 Shadow-cast preparation demonstrating the tripartite flagellar hairs of *Ochromonas*, 253
11-8 General illustrations of the flagella, microtubular roots, and rhizoplasts for the *Chrysophyceae* (A) and Synurophyceae (B), 255
11-9 *Synura uvella* (top micrograph); *Synura petersenii* (bottom micrograph), 256
11-10 The colorless and phagotrophic *Paraphysomonas vestita* showing its silica scales, 257
11-11 Individual silica scales from *Mallomonas striata* (A), *Synura spinosa* (B), *Synura petersenii* (C), 258
12-1 *Tribonema* species: (A) *Tribonema affine*, with two parietal chloroplasts; (B) *Tribonema vulgare,* with multiple discoid chloroplasts, 273
12-2 *Botrydium* cf. *granulatum* (A) macroscopic view of coenocytic vesicles in soil; (B) single vesicle with rhizoids, 273
12-3 *Vaucheria* species: (A) vegetative filaments from a rocky stream; (B) *V. sessilis* reproductive structures; (C) *V.* cf. *geminata* showing five oogonia and curled antheridia, 274
12-4 *Pleurocladia lacustris,* showing branching filaments, 274
12-5 *Heribaudiella fluviatilis* (A) macroscopic view of crusts on rocks from a creek; (B) microscopic view of prostrate (horizontal) crust of filaments; (C) microscopic view of vertical series of filaments with unilocular sporangium at arrow, 274
12-6 *Gonyostomum semen* (A) from a bloom collected via plankton net; (B) close-up of a single cell and forward flagellum, 276
12-7 *Chlorobotrys* sp., a coccoid member of the *Eustigmatophyceae*, 277
12-8 *Bumilleria* sp. showing filament and fragmented H-pieces, 283
12-9 (A) *Goniochloris* sp.; (B) *Ophiocytium* cf. *capitatum,* 284
13-1 *Porphyridium purpureum*, a unicellular red alga with an axial, stellate chloroplast (A); and *Chroodactylon ornatum*, a pseudofilamentous red alga (B), 289
13-2 *Audouinella hermannii*, a simple, branched filament (A); *Balliopsis prieurii*, an opposite-branched filament (B); and *Batrachospermum gelatinosum*, a whorled-branched filament (C), 290
13-3 *Compsopogon coeruleus*, a uniseriate filament with an outer layer of small cortical cells (A); *Polysiphonia subtilissima*, a uniseriate filament with elongate outer pericentral cells (B); and *Thorea hispida*, a branched multiseriate filament with the medulla as a dark, inner layer (C), 290

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

13-4 *Boldia erythrosiphon*, a hollow saccate tissue-like thallus (A); *Lemanea fluviatilis*, a cartilaginous tubular thallus (B); *Caloglossa leprieurii*, a dichotomously divided blade with a central midrib (C); and *Hildenbrandia angolensis*, a crustose red alga with short files of cells (D), 290
13-5 *Batrachospermum gelatinosum* reproduction showing colorless ovoid spermatangia at branch tips (A); carpogonium with a lance-shaped trichogyne (B); fertilized carpogonium (C); gametophyte whorls containing carposporophytes appearing as dense spherical masses (D); and a chantransia stage filament with an attached young gametophyte with whorled branching (E), 291
13-6 *Bangiadulcis atropurpurea*, a filament with a unsiseriate base and multiseriate apex (A); *Paralemanea catenata*, a cartilaginous tubular thallus with a prominent ring of spermatangia (B); *Tuomeya americana*, a cartilaginous filament with compacted whorls (C); and *Sirodotia suecica* carposporophyte that creeps along the main axis (D), 294
13-7 *Flintiella sanguinaria*, unicell with a lobed, parietal chloroplast (A); *Kyliniella lativica*, a reddish pseudofilament with parietal chloroplasts (B); and *Nemalionopsis tortuosa*, multiseriate filament with peripheral archeosporangia (C), 295
14-1 Relationship between chlorophyll *a* (chl*a*) content and (a) total phosphorus, TP or (b) total nitrogen, TN in surface and near-surface waters of natural lakes in Japan during summer, 305
14-2 Linear regression analysis showing the relationship between log(chlorophyll *a*, chl*a*) and (A) log(total phosphorus, TP) and (B) log(total nitrogen, TN) for 11 meso-eutrophic, turbid run-of-river impoundments, 305
14-3 Relationship between cyanobacteria biomass (fresh weight) and total phytoplankton biomass (fresh weight) in 165 Florida (US) lakes, 306
14-4 Example of continuous data from RTRM: Depth versus time contours of chlorophyll (as relative fluorescence units) during January–mid-November 2006 in a major potable water source of North Carolina, 306
14-5 Microscopic and PCR methods for detecting and identifying toxic and nontoxic cyanobacteria, 310
14-6 Comparison of high- and low-density urban land cover (> 70% impervious and 10–70% impervious, respectively; areas in red circles enlarged) in the upper Neuse River watershed between 1992 and 2001, 312
14-7 Example of nonmetric multidimensional scaling ordination of phytoplankton data, showing that river discharge emerged as an important factor regulating shifts among diatom and dinoflagellate species dominance, 313
14-8 Relationship between microcystins and chlorophyll *a* concentrations in 58 lakes and reservoirs located in New York state, USA, 318
14-9 Survey of 45 cyanobacterial species for odor (geosmin, 2-methylisoborneol, or ß-cyclocitral) and cyanotoxin production (microcystins and/or neurotoxins), 322

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

14-10 Examples of algal overgrowth in conduit drainage ditches and channelized river segments, 323
15-1 Large- and small-scale processes contributing and modifying algal taste and odor production, 330
15-2 Odor threshold concentrations of major algal VOCs as a function of molecular weight, 349
15-3 Chemical structures of isoprene and major odorous terpenes and terpenoids produced by algae and cyanobacteria, 350
15-4 Taste and odor producing algae, 356
15-5 Terrestrial and aquatic biological sources of taste and odor, 366
16-1 General chemical structure of the microcystins, 379
16-2 Chemical structure of cylindrospermopsin, 379
16-3 Chemical structure of anatoxin-a, 379
16-4 Microcystin concentrations for raw and finished waters at the Oshkosh, Wisc., water treatment plant during the summer of 1998, 383
16-5 Average microcystin removals at different stages in the Oshkosh, Wisc., drinking water treatment plant during the summer of 1999, 384
16-6 Adsorption of microcystin-LR onto activated carbon depends on the activated carbon used, 385
16-7 Influence of pH and CT value on inactivation of microcystin-LR by free chlorine, 388
17-1 Riverbank filtration schematic, 397
17-2 Conventional water treatment plant schematic, 399
17-3 Direct filtration water treatment plant schematic, 401
17-4 Dissolved air flotation water treatment plant schematic, 403
17-5 Membrane range and size exclusion, 404
17-6 Ozone and biologically active carbon filtration plant schematic, 406
17-7 Ultraviolet AOP and biologically active carbon filtration plant schematic, 407
17-8 Example treatability index data sheet—filter clogging ratings, 410
17-9 Example treatability index data sheet—taste and odor ratings, 411

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

List of Tables

1-1 Selected commercially available kits for cyanotoxin detection/quantification, 21
2-1 Guide for matching sampling apparatus and sites in a river, 29
2-2 Use of sampling equipment in lentic environments, 31
2-3 Size classification of plankton, 35
2-4 Selection and seasonal use of freshwater plankton nets, 35
2-5 Utermöhl chamber sizes and settling times, 46
2-6 Comparisons of algal classification schemes (major groups), 51
2-7 Chemotaxonomy of major algal groups, 53
2-8 Standard phytoplankton counting units, 56
2-9 Accuracy of various sized counts within 95% confidence limits, 58
3-1 Concentration and extraction methodologies for intracellular, extracellular and total cyanotoxins, 73
3-2 Summary of available ELISA microplate assays for the priority cyanotoxins, 78
3-3 Physical properties of priority microcystins and other cyanotoxins, 81
3-4 Published DNA methodologies for microcystin-producing cyanobacteria, 85
4-1 Occurrence and characteristics of select algal chlorophylls and their derivatives, 96
4-2 Summary and evaluation of analytical methodologies for algal chlorophylls, 108
10-1 Summary of ecological information for freshwater diatom genera, 213
12-1 Diagnostic characteristics of freshwater algae distinguishing the four main classes from the Xanthophyta and Phaeophyta, 272
14-1 Considerations for watershed contamination source inventories, emphasizing nutrient pollution and susceptibility analyses of groundwater and surface water sources of drinking water, 303
14-2 Some direct and indirect sources of nutrient overenrichment in watersheds, 303
14-3 Management actions that have been used to reduce (mitigate or "control") algal blooms in waterways, 315
14-4 Chlorine CT values for reducing microcystin concentration to 1 µg L^{-1} for a batch reactor, 319
14-5 Treatment of drinking water to remove or inactivate cyanotoxins, 320
14-6 Some recent studies on cyanotoxin removal in raw and finished water at drinking water utilities, 321
15-1 List of major taste and odor causing algal volatile organic compounds (VOCs), with odor descriptors (where known), known producers listed with their taxonomic groups, 332

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

15-2 Survey of odor threshold concentrations (OTC; µg/L) and odor descriptives reported for algal metabolites, 348
15-3 Planktonic (P), benthic (B), or epiphytic (E) cyanobacteria identified as VOC producers, 353
15-4 Odor compounds produced by picoplankton, 364
15-5 Critical cell densities estimated for specific VOCs (from measured cell production and OTCs) or from nonspecific sensory detection (SD), 368
17-1 Removal rates of various algae, 398

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

Preface

The increased incidence of algae in drinking water supplies triggers a wide range of concerns for drinking water professionals. Our ability to mitigate biofouling, taste and odor, and toxin production issues depends on having a clear understanding of the organisms with respect to their biology, monitoring strategies, and treatment options. This is the inaugural edition of M57, *Algae: Source to Treatment*. This manual was written by a group of experts in their respective fields and provides background information regarding the most commonly found groups of algae. It provides practical information for identification of these organisms and their related toxins, along with strategies for reducing their occurrence and mitigating the harmful effects of these organisms when they do occur.

The Organisms in Water Committee of the American Water Works Association (AWWA) prepared this manual for water utility management, water quality, and public relations personnel to use as a reference tool. The manual provides scientific information in a concise, readable format that will be helpful to media, city and state government, and water customers who inquire about algae issues. Public health and environmental workers will also find it a convenient reference.

This manual includes chapters on the organisms, methods, and recommended management practices associated with algae. Each chapter has a reference section, and a detailed glossary is included at the end of the manual. Nine groups of organisms are described in detail. The organisms are grouped using older division names; however, each chapter provides taxonomic updates and references.

Regrettably, a Haptophyta chapter is not included in this edition because Paul Kugrens, the selected expert, unexpectedly passed away. Inclusion of specific information on haptophytes is planned for the second edition.

AWWA and the Organisms in Water Committee would appreciate any comments on the manual. Contact Elise Harrington, AWWA Environmental Engineer, or Molly Beach, Manuals Specialist, at (303) 794-7711, 6666 W. Quincy Avenue, Denver, CO 80235, or manuals@awwa.org with any feedback.

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

Documents
Document Sharing Hub

Full document details: AWWA Manual M57 2010

Acknowledgments

Chapter authors were recruited for their scientific expertise from various fields, including university, state health, and water quality laboratories; drinking water utilities; and federal health and environmental protection agencies. Authors represent North America.

Algae Manual Steering Committee
Mrs. Rhonda Duncan
CH Diagnostic & Consulting Service Inc.
512 5th Street
Berthoud, CO 80513

Mr. James E. Hoelscher Jr.
Water Quality Consulting
P.O. Box 461
Fayetteville, AR 72702-0461

Ms. Rebecca M. Hoffman
Wisconsin State Laboratory of Hygiene
2601 Agriculture Drive
Madison, WI 53718-6780

Ms. Patricia T. Klonicki
CSC Water Programs
11664 Millbank Lane
Cincinnati, OH 45249-1584

Mrs. Connie K. Schreppel
Mohawk Valley Water Authority
1 Kennedy Plaza
Utica, NY 13502-4236

Dr. Mina Shehee
North Carolina Division of Public Health
Occupational & Environmental Epidemiology Branch
MS 1912
Raleigh, NC 27699-1912

Mr. Greg D. Sturbaum, Ph.D.
CH Diagnostic & Consulting Service Inc.
512 5th Street
Berthoud, CO 80513

Documents
Document Sharing Hub

Full document details: AWWA Manual M57 2010

Introduction
Jeff Janik, California Department of Water Resources, Sacramento, Calif.

Section I: Methods
Recent Developments in Online Monitoring Technology for Surveillance of Algal Blooms, Potential Toxicity, and Physical–Chemical Structure in Rivers, Reservoirs, and Lakes: Robert E. Reed, Ph.D., Center for Applied Aquatic Ecology, North Carolina State University, Raleigh, N.C.; JoAnn M. Burkholder, Ph.D., Center for Applied Aquatic Ecology, North Carolina State University, Raleigh, N.C.; Elle H. Allen, Center for Applied Aquatic Ecology, North Carolina State University, Raleigh, N.C.

Sampling and Identification: Methods and Strategies: Linda Ehrlich, Ph.D., Spirogyra Diversified Environmental Services, Burlington, N.C.

Detection of Cyanotoxins During Potable Water Treatment: Judy A. Westrick, Ph.D., Lake Superior State University, Sault Sainte Marie, Mich.; Ben Southwell, Lake Superior State University, Sault Sainte Marie, Mich.; David Szlag, Ph.D., Lake Superior State University, Sault Sainte Marie, Mich.; Paul V. Zimba, Ph.D., Catfish Genetics Research Unit, Agricultural Research Service, US Department of Agriculture, Stoneville, Miss.

Algal Chlorophylls: A Synopsis of Analytical Methodologies: David F. Millie, Ph.D., Florida Institute of Oceanography, University of South Florida & Florida Wildlife Research Institute, Florida Fish and Wildlife Conservation Commission, Saint Petersburg, Fla.; Ryan J. Pigg, College of Marine Science, University of South Florida & Florida Wildlife Research Institute, Florida Fish and Wildlife Conservation Commission, Saint Petersburg, Fla; Gary L. Fahnenstiel, Ph.D., Great Lakes Environmental Research Laboratory–Lake Michigan Field Station, National Oceanic and Atmospheric Administration, Muskegon, Mich.; Hunter J. Carrick, Ph.D., School of Forest Resources, Pennsylvania State University, University Park, Pa.

Section II: The Organisms
Cyanobacteria: Andrew D. Chapman, MSc., GreenWater Laboratories, Palatka, Fla.

Chlorophyta: Ann St. Amand, Ph.D., Phycotech Inc., St. Joseph, Mich.

Euglenophyta: Grant G. Mitman, Ph.D., Montana Tech of The University of Montana, Butte, Mont.

Dinophyta: Susan Carty, Ph.D., Heidelberg College, Tiffin, Ohio

Cryptophyta: Paul Kugrens, Ph.D. (dec.), Department of Biology, Colorado State University, Fort Collins, Colo.; Brec L. Clay, Ph.D., CH Diagnostic & Consulting Service Inc., Berthoud, Colo.

In Memoriam
Members of the Organisms in Water Committee and water utility personnel who personally knew Paul Kugrens appreciated his dedication to the pursuit of basic and applied knowledge of algae, specifically the cryptomonads. His involvement with the Phycological Society of America and other professional organizations helped the

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

planning committee identify prospective authors and contributors to this manual. Paul's knowledge, interest, and enthusiasm for all things algae will be missed.

Bacillariophyta: The Diatoms: Joshua T. Cooper, The University of Oklahoma, Norman, Okla.; Miriam Steinitz Kannan, Ph.D., Northern Kentucky University, Highland Heights, Ky.; Diane E. Kallmeyer, Ball State University, Muncie, Ind.

Chrysophyta: Robert A. Andersen, Ph.D. (ret.), Provasoli-Guillard National Center for Culture of Marine Phytoplankton, Bigelow Laboratory for Ocean Sciences, West Boothbay Harbor, Maine

Xanthophyta and Phaeophyta: John D. Wehr, Ph.D., Louis Calder Center–Biological Field Station, Fordham University, Armonk, N.Y.

Rhodophyta: Robert G. Sheath, Ph.D., California State University San Marcos, San Marcos, Calif.

Section III: Management
Source Water Assessment and Control/Treatment Strategies for Harmful and Noxious Algae: JoAnn M. Burkholder, Ph.D., Center for Applied Aquatic Ecology, North Carolina State University, Raleigh, N.C; William Frazier, City of High Point Water Quality Laboratory and Pretreatment, High Point, N.C.; Meghan B. Rothenberger, Ph.D., Department of Biology, University of North Carolina–Greensboro, Greensboro, N.C.

Algal Taste and Odor: Sue B. Watson, Ph.D., Aquatic Ecosystem Management Research Division, Environment Canada, Canadian Centre for Inland Waters, Burlington, Ont., Canada.

Control of Cyanotoxins in Drinking Water Treatment: Gregory W. Harrington, Ph.D., Department of Civil and Environmental Engineering, University of Wisconsin–Madison, Madison, Wis.; Ryan Swank, Department of Civil and Environmental Engineering, University of Wisconsin–Madison, Madison, Wis.

Algae Removal Strategies: Kevin D. Linder, Aurora Water, Aurora, Colo.; Kerry J. Meyer, CH2M HILL, Englewood, Colo.

Reviewers:
Jeff Janik, California Department of Water Resources, Sacramento, Calif.
Wayne Carmichael, Wright State University, Dayton, Ohio (ret.)
Dawn Perkins, Wisconsin State Laboratory of Hygiene, Madison, Wis.
Claudia Hidahl, Modesto Irrigation District, Modesto, Calif.
William D. Taylor, Metropolitan Water District, La Verne, Calif.
Alan Sims, Southern Nevada Water Authority, Boulder City, Nev.
Shane Snyder, Southern Nevada Water Authority, Las Vegas, Nev.
Mark LeChevallier, American Water, Voorhees, N.J.

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

This manual has been written under the auspices and support of the American Water Works Association's (AWWA's) Organisms in Water Committee, which had the following membership at the time of approval:

C. Schreppel, Mohawk Valley Water Authority Lab, Utica, N.Y.
J. Hoelscher, Water Quality Consulting, Fayetteville, Ark.
J. Clancy, Clancy Environmental Consultants, Saint Albans, Vt.
K. Scwab, John Hopkins Bloomberg School of Public Heath, Baltimore, Md.
F. Schaefer, United States Environmental Protection Agency, Cincinnati, Ohio
P. Klonicki, CSC Water Programs, Cincinnati, Ohio
M. Marshall, University of Arizona, Tucson, Ariz.
T. Straub, Pacific Northwest National Laboratory, Richland, Wash.
M. Shehee, North Carolina Division of Public Health, Raleigh, N.C.
C. Meyer, Las Vegas Valley Water District, Boulder City, Nev.
S. McFadyen, Health Canada, Ottawa, Ont., Canada
M. Stevens, Melbourne Water, East Melbourne, Victoria, Australia
M. Pope, CSC Biochemistry & Microbiological Method Studies, Slidell, La.
J. Olszewski, United States Environmental Protection Agency, Cincinnati, Ohio
G. Sturbaum, CH Diagnostic & Consulting Service, Inc., Loveland, Colo.
A. Degnan, University of Wisconsin–Madison, Madison, Wis.
W. Klement, Advanced Concepts & Tech., Waco, Texas
P. Warden, Analytical Services Inc., Williston, Vt.
B. McGrath, Water Authority, Grand Cayman, Cayman Islands
N. Ruecker, University of Calgary, Calgary, Alta., Canada
J. Hernandez, City of Scottsdale Water Resources, Scottsdale, Ariz.
C. Durden, Shealy Environmental Services, Inc., West Columbia, S.C.
C. Ferguson, Ecowise Environmental, Penrith, New South Wales, Australia
J. Best, United States Environmental Protection Agency, Cincinnati, Ohio
L. Villegas, Shaw, Environmental and Infrastructure, Cincinnati, Ohio

Former members of the AWWA Organisms in Water Committee throughout the M57 Manual process (since 2006):

R. Hoffman, Wisconsin State Laboratory of Hygiene, Madison, Wis.
A.B. Margolin, University of New Hampshire, Durham, N.H.
J. Standridge, Standridge Consulting, Madison, Wis.
W.J. Robertson, Health Canada, Ottawa, Ont., Canada
C.P. Chauret, Indiana University–Kokomo, Kokomo, Ind.
P.A. Rochelle, Metropolitan Water District, La Verne, Calif.
K. Connell, CSC Biology Studies Group, Alexandria, Va.
G. Widmer, Tufts University, North Grafton, Mass.
D. Sharp, Tampa Water Department, Tampa, Fla.
G.D. Di Giovanni, Texas A&M University, El Paso, Texas
Z. Bukhari, American Water, Voorhees, N.J.
B.E. Boris, Broad River Water Authority, Marion, N.C.
M. Smith, Olathe, Kan.
D. Mauldin, Columbia, S.C.

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

Introduction

Jeff Janik

Finding solutions to drinking water problems caused by algae is an ongoing challenge to the water industry, from tastes and odors, to clogging of filters in water treatment, to harmful algal blooms of toxin-producing cyanobacteria. There is widespread belief that the frequency and severity of surface water impairment by algae is increasing, largely from human activities, leading to degradation of watersheds and increased eutrophication. The increase in taste and odor (T&O) events and cyanobacterial blooms have also been linked to drought and climate change. While the news is not all dire, there are many challenges facing those responsible for producing and delivering potable water. These new challenges necessitate an increased awareness, knowledge, and understanding by water professionals in dealing with problems caused by algae. Water professionals must be familiar with all aspects of solving algae-related problems, from identification of the problem-causing algal species, to design and implementation of monitoring programs using a larger array of tools, and finally, management and treatment strategies that are mindful of the overlying costs of these programs.

AWWA Manual M57, *Algae: Source to Treatment*, is a comprehensive collection written by experts in each respective subject area. The book is broadly divided into three main sections: Section I is devoted to methods of sampling and analysis; Section II provides a detailed overview discussion of the organisms, the major taxonomic groups of algae; and Section III consists of four chapters aimed at management of algae from taste and odor to toxins.

The four chapters in Section I provide guidance on methods for monitoring, sampling, and detecting algae.

New developments in online monitoring using Web-based technologies and real-time or near-real-time sensors useful in detection and monitoring of algae are addressed in Chapter 1. Specific instruments and their advantages and limitations are described, as well as case studies of monitoring programs that are currently operational. Suggestions are included on appropriate strategies for managing a program with the ultimate goal of tracking algal blooms and associated physical–chemical conditions in surface freshwater sources.

The process of obtaining useful qualitative and quantitative information about algal assemblages begins with the thoughtful planning of sampling objectives, knowledge of scientifically accepted sampling methods, and use of appropriate water sampling equipment. Chapter 2 provides guidance (especially for water utilities) on matching appropriate sampling strategies and equipment to the specific aquatic environments and algal communities being examined.

The water industry has two types of methodologies that can be used to detect cyanotoxins in potable water: screening assays and analytical methods for identification and quantification of cyanotoxins. In Chapter 3, sample preparation, screening assays, analytical methods, and genomic/proteomic techniques are reviewed. Methodologies for assessing the presence of these compounds are discussed, with recommendations on methodologies found effective by the authors' experiences and review of literature.

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

Since chlorophyll *a* is present in both eukaryotic and prokaryotic algae, chlorophyll *a* concentration is most often used as a measurement of algal biomass. Accordingly, chlorophyll *a*–based assessments are useful in quantifying algal population/assemblage dynamics, physiological state, and growth rate in response to changing environmental variables. Likewise, this measure is also useful in comparing assemblage structure among systems and providing a basis for the understanding of cellular processes and energy cycling in algal assemblages.

Chapter 4 presents a synopsis of sampling and processing procedures, technological approaches, and general applications for the analytical methodologies most commonly utilized for algal chlorophyll measurement. For spectrophotometric, fluorometric, and chromatographic methodologies, the theoretical bases, history of methods development, and strengths and limitations associated with analytical protocols are presented.

In Section II, each of the nine chapters (5–13) is devoted to a major taxonomic group of algae. The biology, ecology, taxonomy, significance (to water supplies), taxonomic keys to identification of the common genera,* and glossary of terms are presented. For those seeking more information, all chapters are filled with extensive citations including recent literature. These chapters can serve as both an introduction to the algae for the nonspecialist and a source of detailed information for the specialist seeking the most up-to-date research.

The four chapters in Section III are devoted to management of algae including control and treatment strategies.

Chapter 14 considers source water assessment and protection from the perspective of noxious algal growth and treatment strategies for removing algal cells, toxins, and other undesirable bioactive substances. Examples are also presented of advanced technologies and approaches that are being applied to improve assessment, treatment (at potable water treatment plants), control (in surface source waters), and early warning systems for safeguarding water supplies from noxious algae.

Chapter 15 provides the background for understanding T&O production in algae. T&O compounds are produced by most algal groups though production of 2-methylisoborneol (MIB) and geosmin by cyanobacteria (blue-green algae) and are often the most problematic to water utilities. The T&O products in source water span the range from earthy, musty (MIB, geosmin), grassy, sulfurous, fishy/rancid, and cucumber-smelling to floral-smelling. A diversity of these volatile organic compounds is produced by a wide array of algal species. However, most T&O is caused by a relatively small number of these chemicals and taxa, and the majority of algal species have not yet been characterized relative to their T&O-causing abilities.

The focus of Chapter 16 is on strategies used for control of cyanotoxins. The appropriate strategy to be employed is dictated by a number of factors, including the cyanotoxin to be removed, whether the cyanotoxin is present within cyanobacteria cells or present outside of the cells, the cyanotoxin concentration in the source water, the target cyanotoxin concentration at the entry point to the distribution system, and technical capabilities of the control strategy.

Source water control of algae and a treatment plant's ability to remove algae from source water is an important step in delivering safe drinking water to the public. The focus of Chapter 17 is the removal of algae through drinking water treatment. Source water algae control and the removal of algal metabolites are discussed elsewhere in this text.

---

* The key is a series of couplets with questions to answer while trying to make an identification. The number at right indicates where to go in the key next. For example, by answering yes to 2a, proceed to couplet 3, and by answering yes to 2b, proceed to couplet 16. Continue until you answer yes to a question that has a genus name next to it.

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

Section I

Methods

Documents
Document Sharing Hub

Full document details: AWWA Manual M57 2010

Documents
Document Sharing Hub

Full document details: AWWA Manual M57 2010



Chapter 1

Recent Developments in Online Monitoring Technology for Surveillance of Algal Blooms, Potential Toxicity, and Physical–Chemical Structure in Rivers, Reservoirs, and Lakes

Robert E. Reed, JoAnn M. Burkholder, and Elle H. Allen

SUMMARY

Disclaimer: The vendors, manufacturers, and equipment described in this work were chosen as representative examples of the types of instrumentation currently commercially available for use in the water-quality monitoring field. The inclusion of these examples does not constitute an endorsement by the Center for Applied Aquatic Ecology, North Carolina State, or AWWA. Sensor development and the area of online monitoring is changing rapidly, therefore individuals interested in specific monitoring areas or equipment types are encouraged to use an Internet Web search to determine all possibilities.

Previous AWWA manuals and review papers have discussed the application of many online monitoring tools (e.g., Grayman et al. 2001, Knappe et al. 2004, Glasgow

AVA Documents
Document Sharing Hub

Full document details: AWWA Manual M57 2010

et al. 2004), but in the last ca. five years significant advances have been made in communication technology and instrument development, resulting in the introduction of many new products that are useful in monitoring algae and associated water quality parameters. The main objective of this chapter is to introduce the reader to new developments in online monitoring using Web-based technologies and real-time or near-real-time sensors useful in the detection and monitoring of algae. Specific instruments and their limitations will be described, as well as case studies of monitoring programs that are currently operational. Suggestions are included of an appropriate strategy for managing a program with the ultimate goal to track algal blooms and associated physical–chemical conditions in surface freshwater sources.

A successful online monitoring program requires appropriate planning in the installation and deployment of online monitoring equipment, and in choosing methods for the acquisition and postprocessing of the data for efficient operational and management decisions. Large amounts of data are acquired by this type of program due to the short-time-scale sampling that is possible with presently available equipment. Moreover, efficient communication systems enable rapid uploads of data to the data acquisition computer (DAC) and Web site. The rapid development in this technology has led to availability of dedicated hardware and software through many commercial vendors. It is also possible for a water treatment plant or municipality to create custom-designed systems for specific problems using commercially available hardware and in-house information technology personnel. Initial investment in planning will yield an online system with functional, valuable data products to assist operators and managers.

Recent important developments in pigment sensor technology have enabled improved tracking of algal blooms in real time and provide an early warning system for water treatment plant operators and managers. Various manufacturers have integrated both chlorophyll (indicator of total phytoplankton biomass) and phycocyanin pigment sensors (the latter, a major pigment in cyanobacteria) into multiparameter water quality sondes, allowing remote assessments of relative fluorescence. These remote data inform interested parties of impending or existing changes in algal biomass in real time or near-real time. With this early warning, dedicated field samples can be taken to quantitatively assess biomass, species composition, cyanotoxins, taste and odor compounds, and other parameters of interest. Remotely acquired online data for algal pigments are in relative fluorescence units, however, and should be calibrated for each bloom event by dedicated discrete field sampling for chlorophyll *a* and phycocyanin concentrations, and through analysis by standardized laboratory methods.

Many options for instrumentation and modes of deployment are available for establishing a Web-based online monitoring system. Laboratory-based instruments include various flow-through devices that can be installed in-line with source water to give an accurate real-time assessment of algal blooms. In addition to standard packages for environmental conditions, these instruments include the above-mentioned pigment sensors. Recently, a quantitative biosensor also became commercially available, which uses bluegill sunfish as "sentinels" for toxic conditions in source waters. This technology senses not only the presence of harmful algal toxins, but also other substances that are toxic to fish. Instruments and systems available for field deployment include fixed-structure and buoy-based water-column profilers and autonomous underwater vehicles (AUVs) that can be programmed to assess water quality in large reservoirs.

The data acquired by profilers and in-line source water instruments are limited spatially since they are fixed site deployments, whereas data from AUV technology are limited temporally because of the high cost and effort involved to continually run AUVs. Online real-time monitoring systems need to be supported by both regularly scheduled and event-driven field sampling efforts to calibrate the instruments. In

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

addition, remotely sensed pigment data require calibration with samples analyzed using standard laboratory methods. Overall, the online monitoring programs built around this equipment, in concert with standard Web-based information technology, can provide operators and managers with valuable early warning system capability for detecting and tracking harmful algal blooms in real or near-real time.

INTRODUCTION

Potable water treatment plants need to monitor source water conditions on a timescale as close to real time as possible. Such data provide managers and operators the capability to detect changing conditions, such as developing algal blooms or turbidity/pollutant spikes, that require immediate action for efficient, cost-effective water treatment. Increases in the nutrient pollution (cultural eutrophication) of surface waters can lead to algal blooms, the occurrence of taste and odor causing organisms, and potentially toxic algal species (here including cyanobacteria; e.g., Wetzel 2001, Touchette et al. 2007, Burkholder et al. 2010, Botana 2007). Anthropogenic impacts on reservoirs will continue to intensify in the future due to increases in population growth and watershed development. Algal blooms can develop rapidly at distant sites and can then be transported to municipal source water intakes by increased precipitation/flow, by changes in wind magnitude and direction, or from controlled water release from dams as examples. In order to sample and monitor the dynamic nature of algal blooms, source waters should be monitored, insofar as economically feasible, at both high temporal and small spatial scales.

The need for drinking water is on the rise due to urban development and population growth in many parts of the United States. At the same time, water shortages and usage restrictions are becoming more frequent due to shortages caused by climatic events, such as long-term droughts (Arnell 1999, Lettenmaier et al. 2004, Milley et al. 2005). The lower flushing rates imposed by droughts often promote algal blooms in nutrient-enriched (eutrophic) surface waters (Wetzel 2001). Many water plant operators and managers often do not have the lead time to sample small-scale events or the early warning notification to control problems such as increases in potentially toxic algal blooms. Thus, commonly warning of impending, in-progress, or recent increases in algal biomass is captured during field-based sampling of a water source by water plant personnel or following complaints from recreational users and other concerned citizens.

Traditional field efforts for water quality monitoring are cost and labor intensive due to the requirement of personnel, vehicles, and sampling gear, and can be augmented and strengthened using online and real-time-accessible equipment. Instruments such as multiparameter sondes are underutilized when monitoring programs depend on field sampling efforts exclusively. Infrequent sampling is conducted in most standard field monitoring programs, and this frequency misses many pollutant-loading events that occur on smaller timescales. New Web-based technologies and developments in real-time monitoring equipment, with hourly or more frequent sampling capability 24/7, can be valuable in the assessment of algal blooms and the deleterious changes in coupled physical–chemical conditions (e.g., increases in nutrients, turbidity, pH, and dissolved oxygen). The information gained from the detection of developing algal blooms and pollutant spikes in real or near-real time can be a powerful tool in guiding day-to-day decisions in water treatment protocols.

Recent introductions of commercial water quality monitoring equipment have included buoy- and piling-mounted water-column profilers useful in monitoring biological and physical–chemical parameters throughout the entire water column. Extended deployment water quality instruments equipped with antibiofouling measures have

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

pigment-specific sensors that allow real-time monitoring of algal biomass as relative chlorophyll or phycocyanin fluorescence. AUV technology recently has been designed to assess water quality in entire reservoirs, providing three-dimensional representations of the reservoir environment. In addition, the recent application of biomonitoring technology using fish as biosensors has resulted in a commercially available system to monitor a wide range of chemicals and environmental stressors, including emerging and unknown toxicants in source waters. These significant new hardware developments have been accompanied by new water quality software management tools. The large amounts of data acquired by these technologies require user-friendly postprocessing and visualization software packages for rapid, accurate management decisions and public notification.

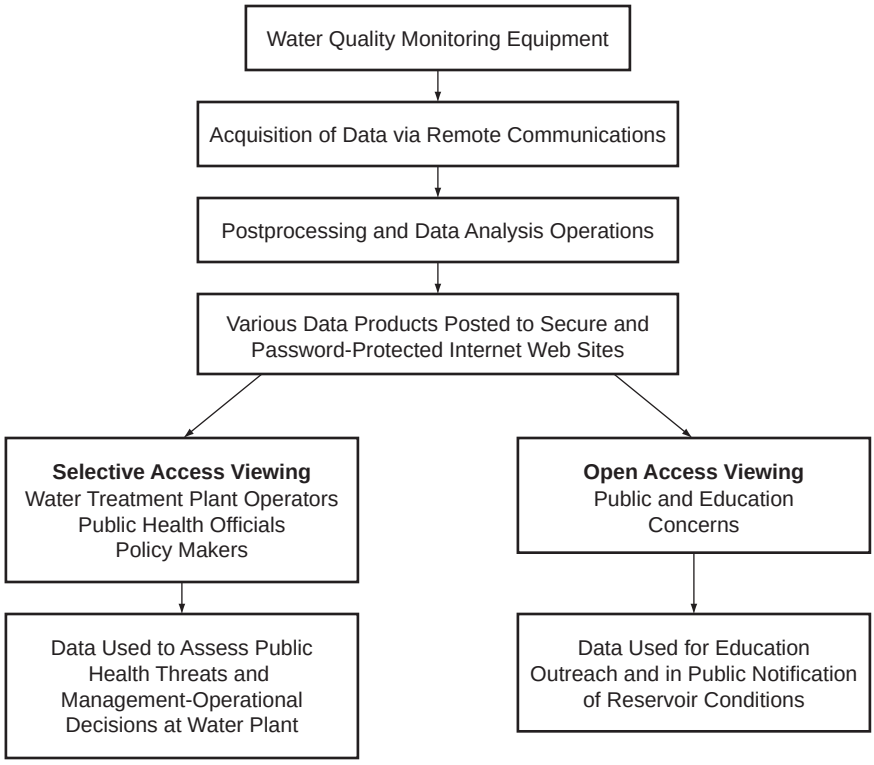
DEPLOYMENT AND OPERATIONAL CONSIDERATIONS IN ONLINE MONITORING PROGRAMS

The development of a sound strategy that considers the data of interest, the site or sites of interest, and the amount of funds dedicated to the effort is necessary for maximum success before initiating an online monitoring program. Depending on the number of monitoring units that are economically feasible for a given real-time program, the primary sensor should be placed at or near the intake to drinking water treatment plants to afford depth profiles in real-time assessment of physical–chemical conditions and algal abundance. Instruments can also be placed in-line with raw water intake pipes between the reservoir and the water treatment plant. Secondary sensors that are deployed should be located at sites distant from the intake where the majority of the upstream or incoming flow and pollutants can be assessed; for example, sensors mounted upstream from the intake on bridge pilings, situated in an area where the reservoir narrows and large volumes of water flow past. If a suitable hard structure such as on a bridge piling or channel marker is not available for mounting instruments, a floating platform or buoy system can be used. However, floating systems are often logistically hard to maintain and there are potential difficulties related to liability and in obtaining the proper permits for deployment. Problem areas in a reservoir known to have recurrent algal blooms or water quality problems are also candidates for real-time monitoring, such as where algal blooms historically occur or where there are extended water residence times or low flushing rates. The acquisition of online and real-/near-real-time field data can be programmed to occur at varied timescales depending on the user's requirements. Due to the stand-alone nature of the equipment, timescales of minutes to hours can be achieved, giving maximum temporal resolution in the data.

Large amounts of data can be acquired quickly in an online monitoring program, which can overwhelm a facility that has limited data acquisition, management, and decision-making power. It is important to acquire high-quality, properly calibrated data that can be viewed by managers and other users with short lead-time. It is also vital that programs with numerous field sites have the ability to manage, process, and present the large amounts of data in an easily interpretable format. To this end, a necessary feature of online monitoring programs is a robust data acquisition and postprocessing software package. Web-based technologies and software packages (e.g., MATLAB, LabView, Campbell Scientific RTMCPRO) are available that can seamlessly integrate data acquired in real time with user-specific programming based on individual needs. These software packages can be specifically configured for data acquisition, visualization, and dissemination via the Internet.

The construction of a user-friendly Web site consisting of graphics that are easily understood is also essential in online monitoring programs. Multilevel,

AVA Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010



Note: After data acquisition and postprocessing, water quality data managers can post various data products to Web sites based on final use. Products used in water plant and public health management and operational uses can also be password-protected to allow access only by authorized personnel. The acquisition of high temporal- and spatial-scale data allows more confidence for managers and policy makers in decisions about appropriate water treatment protocols during algal blooms. Educational organizations and the general public can access the data for use in instructional and recreational activities, respectively.

Figure 1-1 A generalized flow diagram of data acquisition and product dissemination illustrating how water quality monitoring products can be distributed to both public and private concerns (Courtesy of the NC State University Center for Applied Aquatic Ecology)

password-protected sites on the same Web site are a popular method of providing data to various user groups. Web pages can be constructed to provide the public with information concerning water quality conditions and the presence of algal blooms or unusual physical–chemical conditions. More detailed Web pages, accessible via a password, can be constructed for a specific audience (Figure 1-1). Graphics and data sets addressing specific geographical locations or water plant operations can be made available to local utility managers and operators to assist in decision making. For instance, the presence of large numbers of taste and odor causing algal species can be communicated through a secure Web site, and appropriate actions can be taken by personnel responsible for water plant operations. Other important considerations in the acquisition and dissemination of algal and physical–chemical data are the duration between data acquisition and posting and in the validation and calibration of online/real-time data. Developers of online monitoring systems must decide the minimum timescale that is acceptable and then build the system accordingly. This decision will have bearing, as well, on the type of offsite communication technology selected for use. If the timescale of interest is

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

minutes to hours, for example, RF modems (spread spectrum radio) or satellite methods of communication would provide appropriate support. If the timescale of interest is multiple hours or even days, then cell phone modems can be used. Also, depending on the length of a program and the data acquisition timescale, a large archive of data can be obtained that can then be mined at a later date for information such as seasonal changes and the response of the source water (e.g., reservoir) to event-driven inputs (e.g., turbidity spikes from rain events, algal blooms, other physical–chemical events). The long-time-series data provided by these monitoring efforts can be valuable in assessing trends in water quality parameters in concert with changing land use and climatic events, and the efficacy of management strategies to reduce loadings of nutrients and other pollutants of concern.

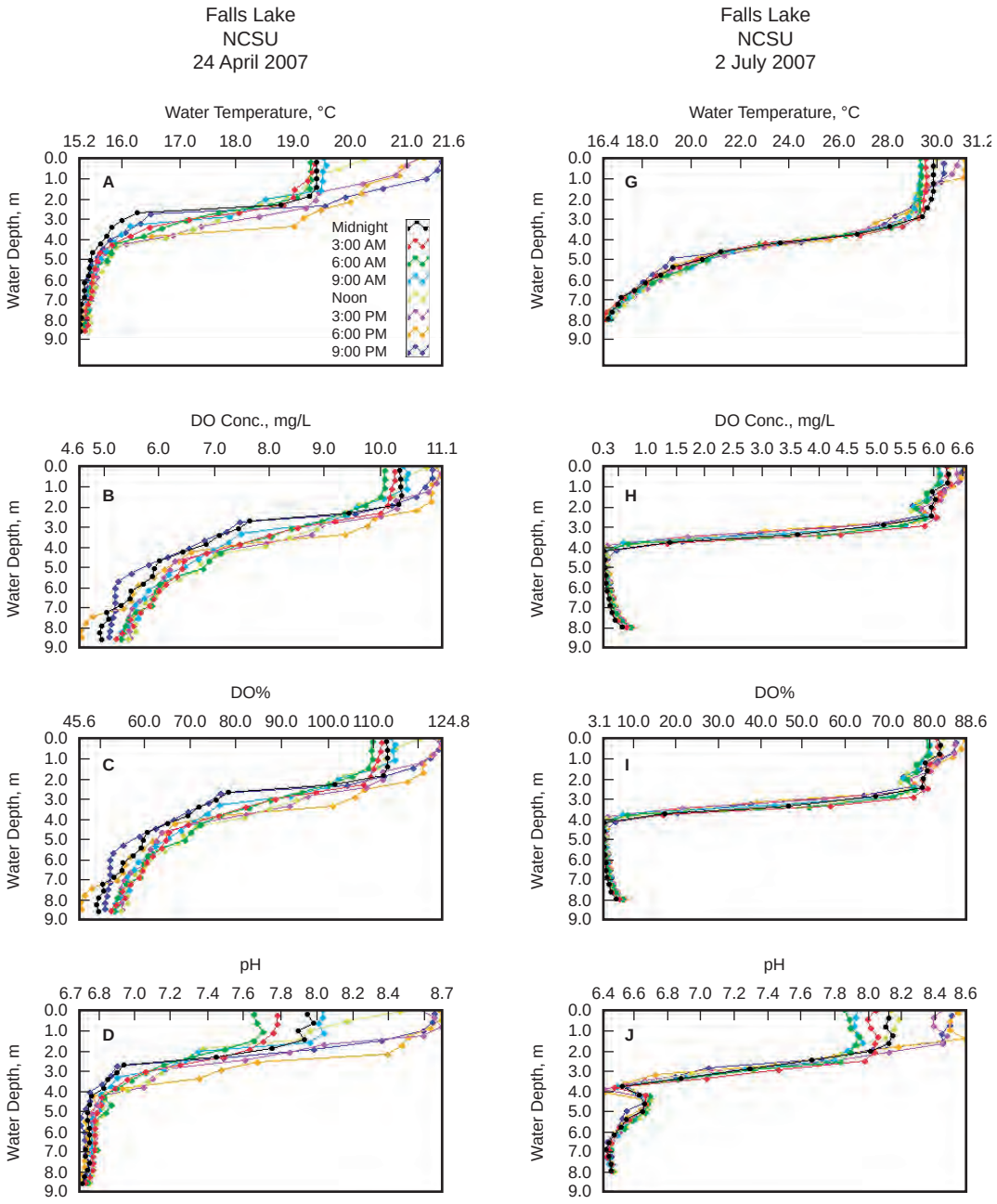
An example of an online field monitoring program that uses currently available commercial technology for real-time collection and rapid dissemination of algal and physical–chemical water column structure in a reservoir is the North Carolina State University (NCSU) Center for Applied Aquatic Ecology North Carolina Reservoirs Cyanobacteria Project, originally funded by the North Carolina Department of Health and Human Services and the US Centers for Disease Control and Prevention. Using data acquired from water quality sondes, profiler technology, and custom LabView programming, investigators can monitor the water column from depth profiles for six parameters taken in both local and distant reservoirs. The parameters are user-selectable and can be chosen based on need. Data are acquired from each station's sonde by a data logger and then communicated via cell phone modem to a central DAC where the information is automatically posted to a Web site (www.ncsu.edu/wq and www.ncsu.edu/wq/RTRM/dp14/ index.html) for viewing. Depth profiles of these data (e.g., Figure 1-2) at 3-hour intervals show hydrological conditions during spring and summer. The first set of profiles (Figure 1-2A–F), taken 24 April 2007, shows a spring phytoplankton bloom and the associated water-column conditions. The second set (Figure 1-2G–L) document the water-column structure during well-stratified summer conditions on 2 July 2007. These data are being used by local water plant managers to assess changes in source water quality in near-real time for modifying treatment protocols.

Commercial enterprises have recently developed data management services that include the acquisition of the data and/or data postprocessing and delivery of final data summaries including graphic visualizations. For example, EcoNet® (YSI Inc.) is an Internet-enabled data management system designed to collect and analyze water quality and hydro-meteorological data. This Web-enabled remote monitoring and control system is designed to acquire and postprocess large amounts of data that are then available via the Internet for user accessibility and management decisions. An example of such an operational system is the Mecklenburg County, N.C., Continuous Monitoring and Alert Notification Network (CMANN). This system includes 24 continuously sampling multiparameter water quality sondes linked to the Internet via EcoNet. The purpose of the CMANN program is to provide real-time water quality information to public works officials and other end users via specific Web sites when environmental changes occur on a short timescale.

PIGMENT SENSORS: FIELD MEASUREMENTS VERSUS LABORATORY METHODS

Fluorescence-based sensors are powerful tools for monitoring relative algal biomass, but care is needed in interpreting the fluorescence measurements with actual algal numbers or chlorophyll concentration data (Kirk 1994). These sensors can provide both discrete and continuous data concerning the presence of algae but are relative in comparison to

AVA Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

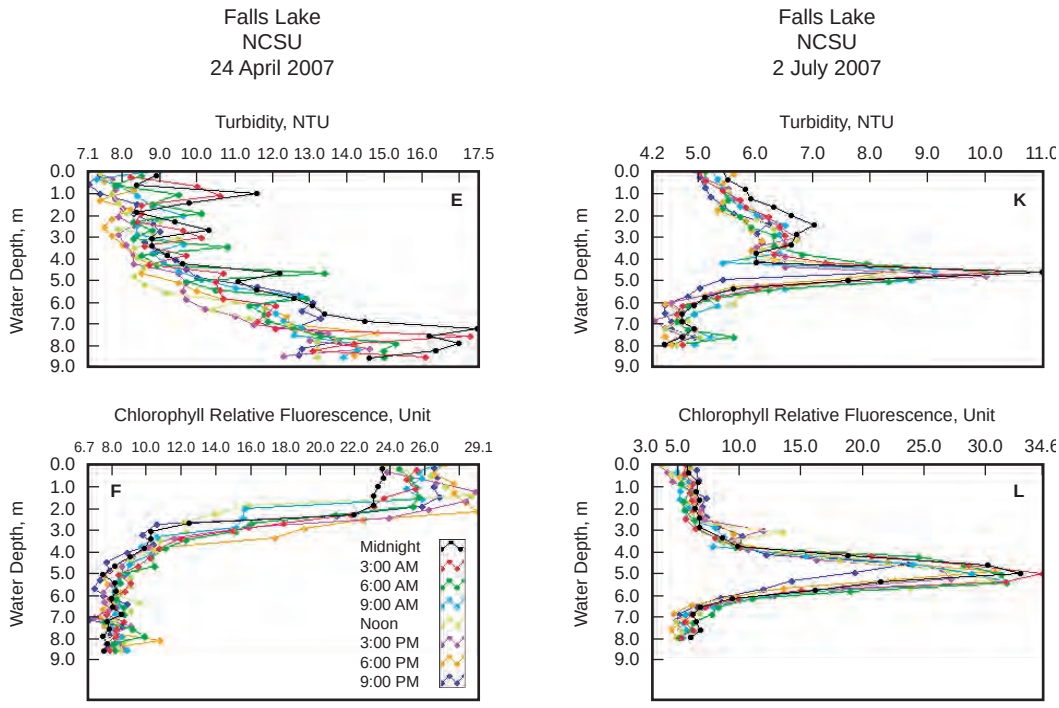


NOTE: The graphs illustrate two selected days, which include three hourly casts resulting in eight complete profiles per day. The first series (panels A–F) show water temperature, DO, pH, turbidity, and chlorophyll relative concentration on 24 April 2007. These plots reveal interesting structure concerning the thermocline, high pH values, turbidity structure, and chlorophyll structure due to a spring bloom. The second series (panels G–L) show the same parameters on 2 July 2007, revealing a strong thermocline, anoxic conditions below 4 m, and peaks in turbidity and chlorophyll structure just below the thermocline.

Figure 1-2 Whole water column structure of site located at a municipal water plant reservoir intake using profiler technology (Courtesy of NC State University Center for Applied Aquatic Ecology)

Figure continued next page

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010



NOTE: The graphs illustrate two selected days, which include three hourly casts resulting in eight complete profiles per day. The first series (panels A–F) show water temperature, DO, pH, turbidity, and chlorophyll relative concentration on 24 April 2007. These plots reveal interesting structure concerning the thermocline, high pH values, turbidity structure, and chlorophyll structure due to a spring bloom. The second series (panels G–L) show the same parameters on 2 July 2007, revealing a strong thermocline, anoxic condition below 4 m, and peaks in turbidity and chlorophyll structure just below the thermocline.

Figure 1-2 Whole water column structure of site located at a municipal water plant reservoir intake using profiler technology (continued)

standard laboratory methods, and thus the data are reported as relative fluorescence units. Many phytoplankton have a pronounced diurnal signal in fluorescence (Geider and Osborne 1987). The fluorescence yield measured by the sensor provides "snapshot" information on the photoadaptive state of the algal cells, and the specific light regime, at the time of measurement. For example, if an algal cell is adapted to high irradiance, the fluorescent yield will be less than the same cell adapted to lower irradiance (Falkowski and La Roche 1991). Fluorescence yield is also temperature dependent. Therefore, the sondes provide information about relative phytoplankton abundance but not quantitative data on algal biomass or chlorophyll concentrations. For specific blooms of interest, quantitative data on algal biomass (biovolume) can be obtained for comparison using standard light microscopy techniques (e.g., Lund et al. 1958, Burkholder 1992, Wetzel and Likens 2000). Chlorophyll concentration data can be obtained using standard laboratory instruments (fluorometers, spectrophotometers, high-performance liquid chromatography [HPLC]) after extraction in organic solvents (USEPA 1997, method 445.0; APHA et al. 2005, standard method 10200 H; Schlüter et al. 2006).

Recommendations from researchers and sensor manufacturers are to calibrate the relative fluorescence measured by the instrument to a known biological entity for each specific bloom of interest; for example, a unialgal culture can be used in the case of monospecific blooms, or a known concentration of an extracted pigment (e.g.,

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

chlorophyll *a* or phycocyanin) can be used for mixed blooms. Highly purified algal pigments can be purchased from various chemical suppliers and used to standardize sensor readings to a known pigment concentration. The same calibration factor should not be relied upon from bloom to bloom because of the factors previously mentioned. The best comparative approach for a specific bloom of interest is to collect several grab samples in the field concomitantly with fluorescent sensor measurements and then determine the pigment concentration of the grab samples using standard laboratory extractive methods. The pigment concentration measurements can then be used to "normalize" the field fluorescence sensor data.

MULTIPARAMETER WATER QUALITY SONDES AND PIGMENT-SPECIFIC SENSORS

If one type of instrument is to be recommended as the standard instrument for water quality monitoring in both field and water treatment plant monitoring efforts, it is the multiparameter water quality sonde (the most common form factor is shown in Figure 1-3). These instruments are manufactured by many companies, for example, YSI, Hach-Hydrolab Inc., Turner Designs Inc., Greenspan Inc., In Situ Inc., and Eureka Environmental Engineering. The first three of these vendors manufacture multiparameter sondes that are equipped with pigment-specific sensors (i.e., for freshwaters, chlorophyll *a*, and phycocyanin) along with standard sensors such as temperature, dissolved oxygen (DO), pH, and oxidation reduction potential. These instruments are equipped with a sensor head area and a body that contains the microprocessor, which is responsible for data acquisition and computational functions necessary for calibration and communication. It should be noted that various vendors specialize in optical measurements of ocean water, including devices to measure chlorophyll, phycocyanin, and phycoerythrin (two common cyanobacterial pigments), but these companies are not active in equipment manufacture for water plant operations so they are not considered here.

Recent developments in sensor technology and other mechanical improvements have increased the utility of the multiparameter sonde, hereafter referred to only as "sonde." Two primary improvements are the use of luminescent detection technology to design improved pigment-specific sensors and the use of DO sensors. Chlorophyll *a*- and phycocyanin-specific sensors are presently available from YSI, Hach-Hydrolab, and Turner Designs; luminescence-based DO sensors are available from YSI and Hach-Hydrolab. This new technology replaces the standard Clark type and pulsed electrodes that were previously used on sondes to measure DO. Increases in DO and pH values are often indicative of an algal bloom; therefore, the data can often be used as a proxy for the occurrence of algal blooms when a fluorescence-based sensor is not available. The distinct advantages in use of luminescent DO sensors are (1) no membrane or electrode solution to replace and (2) longer deployments between calibrations. Another development in sonde technology is the use of automated wipers to clean biofouling organisms that grow on sensor surfaces. These wipers can be programmed to clean the sensor on a regular basis, thereby allowing greater accuracy in field measurements and longer intervals between maintenance.

A primary advantage in using sondes is that they can be set up for automatic data acquisition using industry standard data loggers and can also be deployed unattended where data is logged to an internal memory. Most sondes are configured to communicate with data loggers using standard SDI-12 and RS-232 protocols. A program resident in the data logger queries the sonde for data, which is then logged to a data logger. The data can be accessed via various communication methods such as cell phone,

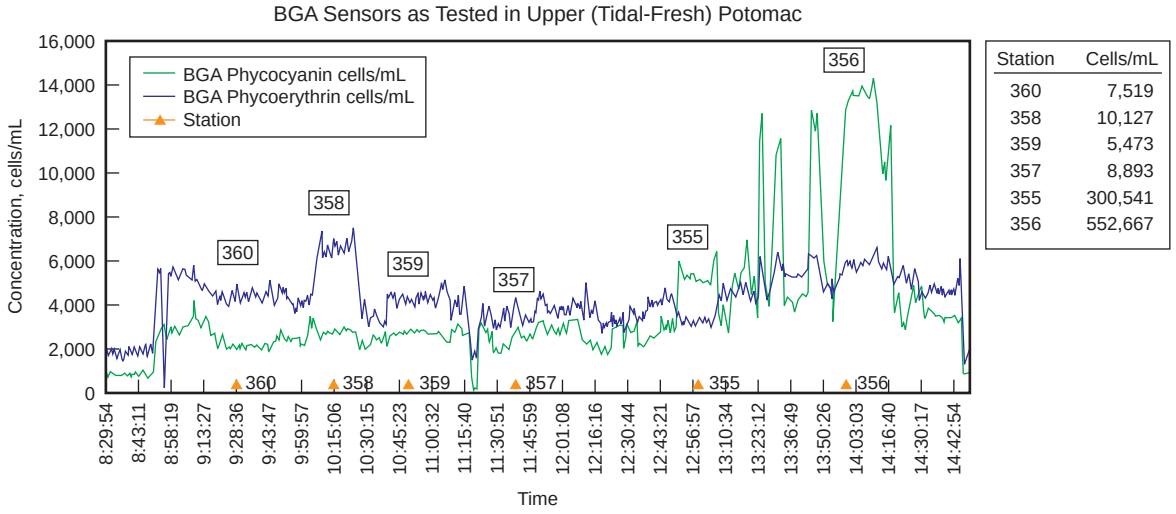
Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010



Figure 1-3 Close-up photographs of six commercially available water quality sondes equipped with multiple sensors and antifouling wipers: (A) YSI 6600V2 (Courtesy of R. Ellison, YSI, with permission); (B) Turner Designs C6 (Courtesy of Turner Designs, with permission); (C) Troll (Courtesy of In Situ); (D) CS304 sonde (Courtesy of Greenspan); (E) Hach-Hydrolab DS5x (Courtesy of R. Reed); (F) Manta (Courtesy of Eureka Environmental). These instruments can be controlled using standard industry data loggers in either the SDI-12 or RS232 modes, for data acquisition, postprocessing, and posting to Internet sites for user viewing.

satellite, and spread spectrum RF radio modems after the data have been recorded, postprocessed, and posted to a Web site for viewing. These multiparameter systems can be deployed in reservoirs distant from a water treatment plant (e.g., upstream) to provide warning of incoming algal blooms. They can also be configured to acquire data automatically at a specific time interval while sampling water pumped onboard or towed behind a boat, resulting in high resolution data. A detailed time series of test

AVA Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010



NOTE: The white-boxed numbers indicate the station numbers. The sensors were compared to evaluate whether the PC or the PE sensor was more effective in this estuarine area, which is known for extensive *Microcystis* blooms. The PC sensor provided better response to cyanobacterial biomass. Cell count data (via light microscopy) from samples taken at each station are indicated on the right side of the chart. The PC data correlate well with the cell counts. This time series illustrates the patchy nature of cyanobacteria biomass along the transect.

Figure 1-4 A time series of data acquired in the upper Potomac (brackish waters) using YSI phycocyanin (PC) and phycoerythrin (PE) sensors (Note: PE detectors are not available for freshwaters). (Courtesy of R. Ellison, YSI, with permission.)

data acquired in the upper Potomac (Figure 1-4) illustrates the variability in cyanobacteria biomass over long distances. This information is useful in assessing the present condition of source water in reference to the occurrence and location of algal blooms. These instruments can also be deployed at water intake structures. They are small and can be moved to other areas on short notice if deemed necessary. Readers are encouraged to check sonde manufacturers' Web sites for new technological developments and products regarding these instruments.

In order to ensure the acquisition of valid data that can be relied on for management, planning, and research efforts, a rigorous quality assurance/quality control protocol must be in place and documented with a quality assurance project plan. It is suggested that individuals involved in environmental monitoring and technology visit the USEPA Web site at www.epa.gov/quality for up-to-date information on quality management tools and other guidance specific to the proper acquisition of environmental data. One example of the need for detailed and accurate record keeping is in the case of sensors deployed under harsh field conditions where it is important to maintain individual calibration and maintenance logs for each sensor. For example, initial values of the sensors should be recorded before and after calibration to give a record of any sensor drift. This data is also useful as an early warning to sensor failure, allowing the technician to be proactive in the replacement of equipment. Manufacturer recommendations should be strictly adhered to at a minimum concerning calibration and maintenance; however, site-specific conditions will oftentimes require a more vigorous approach to equipment maintenance and calibration due to biofouling. Many manufacturers of water quality sondes have introduced self-cleaning features that remove biofouling films with wipers (e.g., YSI, Turner Designs, Hach-Hydrolab). Systems using older equipment or equipment not equipped with self-cleaning features must be rigorous in calibration and maintenance to avoid erroneous data due to biofouling, especially in highly eutrophic systems and during the warm seasons.

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

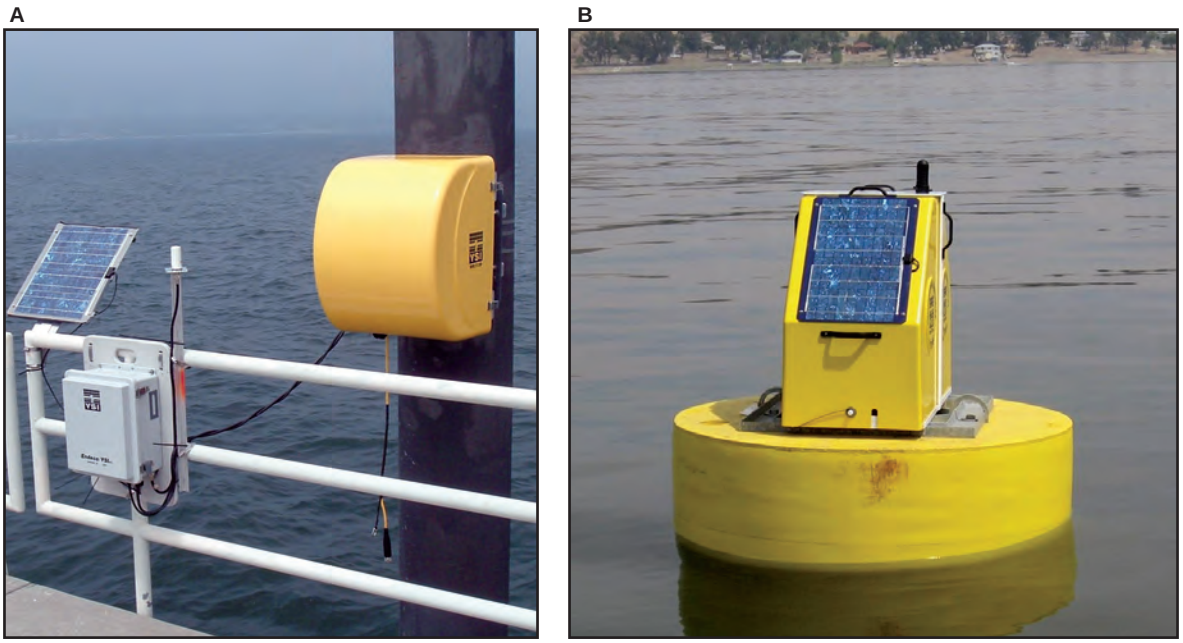


Figure 1-5 Two commercially available water-column profilers. (A) The fixed structure-mounted version is designed to be mounted on hard structures such as water intakes, piers, or bridge pilings. (B) The buoy-mounted profiler version is deployable in open water using two-point mooring. Both units are accessible via commercially available communications devices such as RF modem, cell phone, and satellite. The fixed structure-mounted instrument is also accessible via landline phone. (Courtesy of R. Ellison, YSI, with permission.)

Flow-through systems installed in-line to raw water intake pipes should also be inspected and cleaned regularly to remove any biofouling or foreign material.

EXAMPLES OF WATER-COLUMN MONITORING: PROFILING PLATFORMS, AUV TECHNOLOGY, AND BUOY-BASED SYSTEMS

Buoy and fixed-structure water quality profiling systems, which monitor the entire water column, recently have become commercially available. These systems can monitor depth-dependent structures for issues including turbidity spikes, chlorophyll spikes, high and low DO, pH variability, and phycocyanin spikes, providing valuable information for water plant operators in selecting appropriate filtration and other treatment protocols. If the water plant has a raw-water intake structure that allows water to be pulled from various depths, the data can inform plant operators of undesirable, depth-dependent changes in water quality that can then be avoided by taking water from a different depth. Examples of currently available commercial equipment are the YSI model 6952 buoy-based vertical profiling system and the model 6950 fixed system (Figure 1-5). The latter system is based on technology developed by scientists at the NCSU Center for Applied Aquatic Ecology (US Patent 7,040,157). A water quality sonde along with a computer-controlled winch allow acquisition of water-column biological and physical–chemical data at user-selected intervals. The data are communicated from the remote site to the water treatment facility using various commercially available devices (cell phone modems, spread spectrum RF modems, satellite, and so

AVA Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

forth). A pontoon-mounted system (model 6951), similar to the buoy-mounted form factor, is also available for use in quiescent waters.

Examples of water-column data acquired by a fixed mount system are shown in Figure 1-2 (also see Deployment and Operational Considerations in Online Monitoring Programs). Contour plots of all water-column profiles acquired for a complete year at a municipal water plant reservoir intake using profiler technology illustrate the detailed biological, physical, and chemical structure that can be documented (Figure 1-6). Both longer-term (seasonal) and small-time-scale events can be recognized with multiyear or continuous profiler deployments, allowing managers the ability to be proactive in decision making, especially regarding problems that arise on a seasonal basis. The massive database acquired can also be useful in modeling efforts to improve predictive capability.

The advantages and disadvantages should be considered when selecting which system to deploy, especially site-specific characteristics of the reservoir. The fixed system can be mounted on water intake structures, piers, and bridge pilings and will be more stable from high wave action due to wind events. Moreover, if the system is mounted on a readily accessible water intake structure, operators will be able to maintain and calibrate the system easily. Buoy-mounted systems are less stable in high wind and wave conditions, but can be relocated to areas of interest by towing with a boat. On the other hand, a boat is required for maintenance and calibration of this system.

Monitoring large areas in a source water, or the entire source water, has been problematic because of the amount of man-hours and equipment that are required. The recent advent of commercially available AUV technology enables source water quality monitoring in three dimensions, permitting an assessment to be performed on the entire water body with limited personnel. The YSI EcoMapper AUV (Figure 1-7) is designed to be launched by one person; it autonomously surveys a water body using preprogrammed course and depth values. The AUV is fitted with standard sensors to allow the same multiparameter data to be acquired as with water quality sondes. The vehicle can measure a maximum of 10 water quality parameters at one-second intervals during missions up to 12 hours in length. Examples of turbidity and depth data acquired with this system are shown in Figures 1-7C and 1-7D, respectively. The high variability in the data, captured by the AUV, demonstrates the need for such high temporal and spatial sampling to provide operators and managers an overall assessment of depth-dependent water quality conditions, for example, near a potable water treatment plant, over small timescales. This system would be especially valuable in source waters where motorized boat traffic is not allowed, such as many restricted-access municipal reservoirs and recreational lakes. On the other hand, autonomous deployment of this equipment in source waters with high recreational use could be deleterious both to the equipment and to the general public, due to the probability of encounter with boat traffic.

Campbell Scientific Inc., Logan, Utah, markets a series of water quality monitoring buoys that can be used in freshwater ponds and small lakes with minimal wave action. These buoys are suitable for monitoring at a single fixed depth and do not have profiling capacity. The CSBUOY-DT and CSBUOY-NS buoys are self-contained packages that offer managers the ability to monitor water quality parameters via wireless technology. The effective range of these buoys is approximately ~1.6 km (1 mi) using a 7-A·h, 12-Vdc battery recharged with a 5-watt solar panel. Options are available to increase range to more than 16 km using a higher gain antenna with clear line of sight. After data acquisition and postprocessing with dedicated software, visualization software packages (e.g., LabView, MATLAB, Campbell RTMCPRO, or Vista Data Vision VDVSE) can be used to post the data from these platforms to Web sites.

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

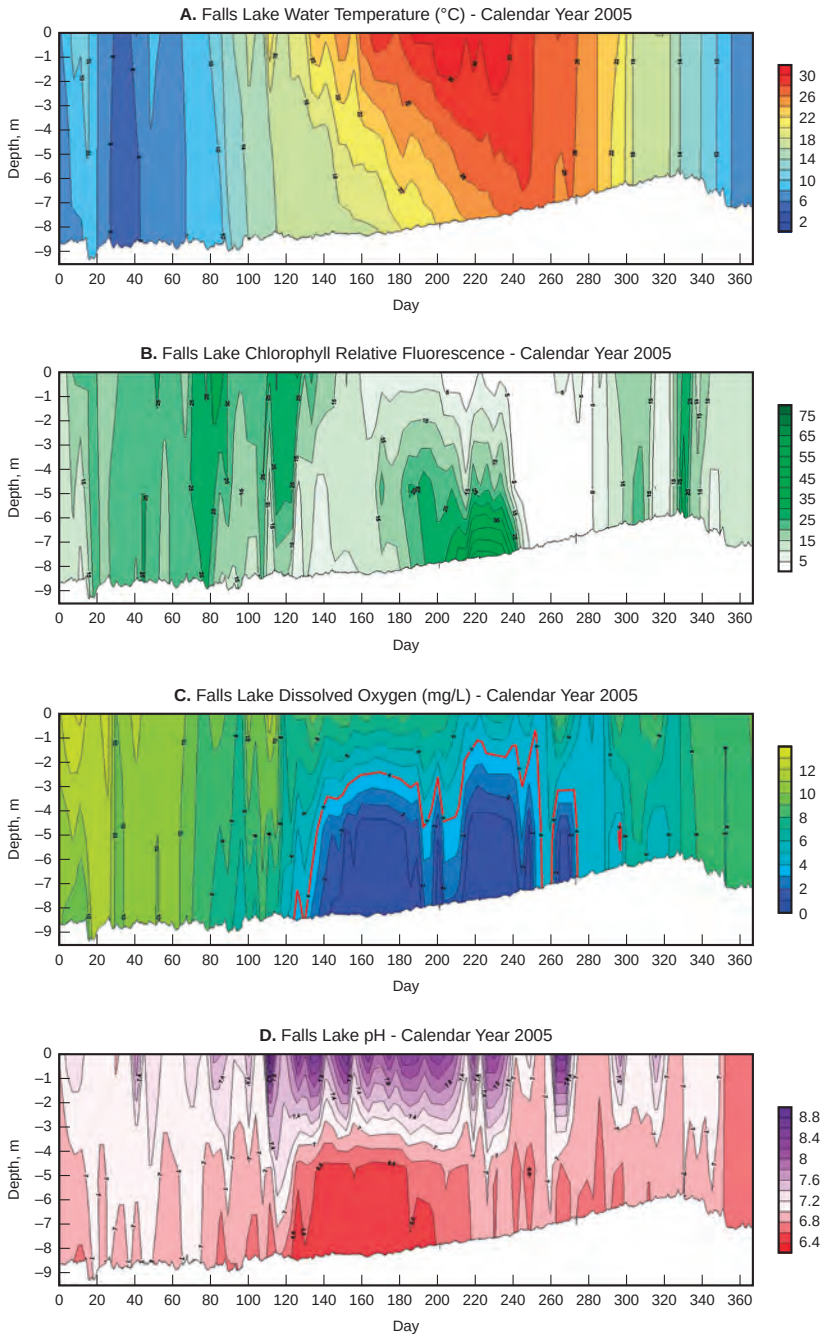


Figure 1-6 Contour plots, constructed using Surfer (version 7.0), of water-column profiles acquired at a municipal water plant reservoir intake using profiler technology during 2005, showing strong temporal and spatial resolution in all parameters: (A) Temperature. (B) Chlorophyll relative fluorescence; note spring phytoplankton blooms indicated at days ~80 and 120, and fall blooms at days ~320–330. (C) Dissolved oxygen, showing stratified DO conditions throughout the summer with low seasonal DO conditions from days 140 to ~260, followed by tropical storms that resulted in a well-mixed water column. (D) pH, again showing seasonally stratified conditions. Seasonal trends are clear in all parameters, as well as shorter-timescale signals in DO, pH, and chlorophyll relative fluorescence. These plots are useful to managers, water treatment plant operators, policy makers, and other end users in visualizing and presenting large amounts of data. (Courtesy of NC State University Center for Applied Aquatic Ecology.)

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

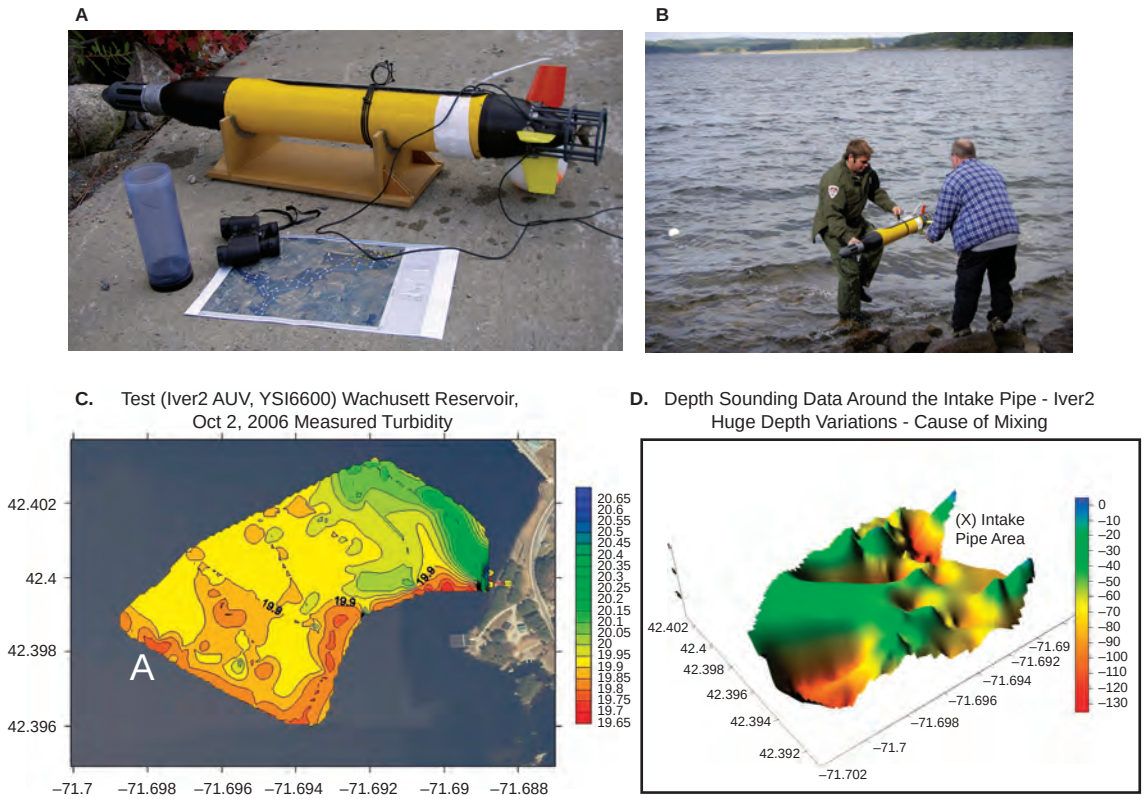


Figure 1-7 Illustration of YSI AUV available for monitoring reservoirs in three dimensions and associated data: (A, B) AUV is self-contained and is equipped with standard water quality sensors currently available, which can be seen at the tip of the AUV. The unit is small, which enables easy deployment and recovery. (C, D) Examples of turbidity and depth data acquired by AUV (Iver2, YSI6600) at the Wachusett Reservoir, illustrating the small-scale spatial variability of both parameters. (Courtesy of R. Ellison, YSI, with permission.)

ONLINE INSTRUMENTS FOR CHARACTERIZING SOURCE WATERS

The advent of online fluorescent monitoring equipment in recent years has provided early warning of the onset of blooms of taste and odor causing and/or toxic algae. It also enables background monitoring of algal biomass through daily and seasonal changes. Two variants of similar technology are offered by Turner Designs (Sunnyvale, Calif.) to monitor chlorophyll *a* and phycocyanin in source water. The AlgaeWatch™ and CyanoWatch™ instruments are based on fluorescence detection systems (relative fluorescence units), which Turner Designs has engineered and manufactured since 1972. AlgaeWatch monitors chlorophyll *a*, and CyanoWatch is designed to monitor phycocyanin, which can be used, along with simple confirmation by light microscopy, to detect cyanobacteria (Figure 1-8). Both instruments are designed to be installed in-line with source water pipes. The use of these sensors can assist management decisions on the need for various filtration and other treatment processes. These systems can be remotely accessed via a 4–20 mA output to a data logger, with dedicated software that allows 24-hour access to data via a Web-based computer.

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010



Figure 1-8 The Turner Designs AlgaeWatch online fluorometer. This instrument was installed by a municipal potable water treatment plant to sample source water for algal blooms. (Courtesy of Turner Designs, with permission.)

The use of fish as biomonitors for water quality is widespread in various parts of the world where water treatment plants use fish "sentinels" in tanks and other devices to assess changes in behavior due to stress from toxic substances and low water quality (Grayman et al. 2001). Concerns over water security have risen in recent years and have led to an increased interest in technology that is amenable to rapid toxic detection for water supplies (van der Schalie et al. 2001a, 2006). Research by investigators at the US Army Center for Environmental Health and Research has resulted in a commercially available product (US Patent 6,058,763) that monitors specific fish behavior parameters directly related to stress and toxicity. The device, called the intelligent Aquatic BioMonitoring System®, or iABS (Figure 1-9A), is currently marketed by Intelligent Automation Corporation (www.iac-online.com). This innovative aquatic biomonitoring system uses fish to assess toxicity of water supplies and source waters in a controlled and quantitative manner (Mikol et al. 2007, Shedd et al. 2001). The system is automated and includes exposure chambers that each hold a bluegill sunfish (*Lepomis macrochirus* Rafinesque). Body movements and ventilatory behavior (Figure 1-9B) are sensed by electrodes, recorded, postprocessed using the dedicated software Biomonitor Expert for visualization, and posted to a Web site. These data are easily viewed via the Web, and the software system can be configured to issue alarms triggered

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

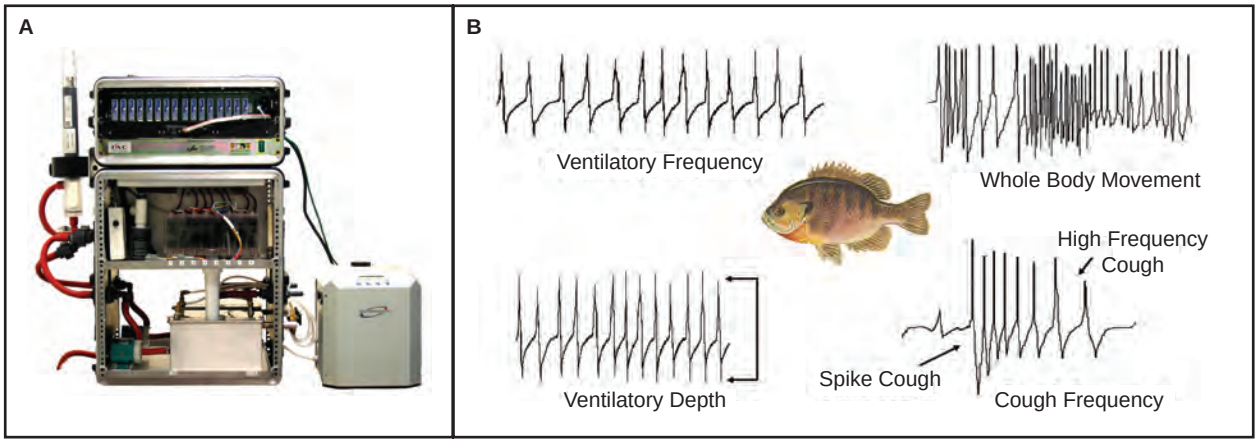


Figure 1-9 Fish ventilatory and behavior patterns monitored using the (A) IAC 1090 Fish Biomonitor system and Expert Software, which evaluates (B) ventilatory frequency, whole body movement, ventilatory depth, and cough frequency to determine the health and stress state of the fish. Deviations from baseline values result in an alarm and notification to water plant managers for further evaluation. (Courtesy of B. Lawler, Intelligent Automation Corporation Inc., with permission.)

by fish stress from toxic substances. This system has been tested successfully with some harmful algal species (van der Schalie et al. 2001b), illustrating its potential to provide early warning of toxic substances such as cyanotoxins in source water protection.

Other commercially available online biomonitoring equipment that uses biological entities to serve as sensors for water quality problems includes the Daphnia Toximeter, Fish Toximeter, and Algae Toximeter manufactured by bbe Moldaenke (www.bbe-moldaenke.de). These instruments are engineered such that the organism is exposed to a sample water stream and is monitored by motion analysis software in the case of the Fish and Daphnia Toximeters or software that records changes in fluorescence, in the case of the Algae Toximeter. Changes in organism response is recorded and interpreted by the dedicated software to trigger alarms or indicate changes caused by toxic or deleterious conditions, providing water system operators early warning to potentially hazardous events. The AlgaeOnlineAnalyser, also from bbe Moldaenke, continuously measures in real time chlorophyll fluorescence, algae class, and photosynthetic activity of natural algal assemblages in sample stream water. This instrument is useful in monitoring changes in algal communities and physiology that may occur over long periods of time due to various environmental impacts.

It should also be noted that existing instrumentation in water treatment plants can be integrated into an online monitoring program to assess changes in water quality due to algal blooms. For example, turbidimeters and particle counters from various vendors (e.g., HF Scientific Inc. [www.hfscientific.com] and Hach Inc. [www.hach.com]—turbidimeters; Hach—particle counters) use a variety of communication protocols (RS232, RS484, modbus, etc.), that allow maximum flexibility in online system integration. Increasing trends and spikes in turbidity and particle numbers are valuable information that can warn water plant operators as to changing conditions in raw water supply.

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

LIMITATIONS OF ONLINE AND REAL-TIME MONITORING EQUIPMENT

There are specific limitations to all monitoring technologies due to basic design features that can affect the spatial and temporal scale of data acquisition. Instruments that are designed to be mobile, for example an AUV, may be limited due to deployment-recovery considerations such as the duration of deployment in the source water and the amount of effort that can be invested for maintenance, calibration, and troubleshooting. An AUV gives excellent temporal and spatial resolution in characterizing the biological and physical–chemical environment of a reservoir, but long-term assessment of the environment can be limited if the instrument is not deployed to provide a continuous database. The timescale of dedicated AUV deployments will constrain the characterization of rapidly changing conditions, such as initiation of algal blooms or event-driven changes in water quality, unless the system is operated on short timescales that allow maximum resolution.

Data acquired by sondes deployed at a single fixed depth, and profiling devices that are located at a single site obviously will be limited to characterization of that site and will miss environmental changes at distant sites. In the case of sondes deployed at a fixed depth, the user will not gain information on water-column conditions above or below the sonde. Another limitation in acquiring chlorophyll or phycocyanin fluorescent data using sondes and profilers occurs when trying to assess the abundance of algae that form benthic or floating mats, for example the potentially toxic cyanobacterium *Plectonema wollei* Farlow ex Goment (previously known as *Lyngbya wollei*).

Lakes and rivers are dynamic systems that can change rapidly because of variability in flow due to both anthropogenic and natural occurrences. Acoustic Doppler current profiler (ADCP or ADP) technology using either fixed and/or boat-mounted instruments can be used to monitor flow patterns important in tracking algal blooms and other water quality conditions (e.g., turbidity events and spills). Many commercial products are available and can be found with a general Web search using keywords such as ADCP, ADP, ADV, acoustic Doppler current profiler, or current meters.

FIELD METHODS USED IN CONJUNCTION WITH ONLINE MONITORING

There are many published manuals and textbooks with information and methods that describe basic considerations and methodologies for sampling source waters (e.g., APHA et al. 2005, Wetzel and Likens 2000). Field methods used for collecting algal samples and associated toxins must be adequate to enable further identification, molecular, and toxicity testing by water plant or supporting laboratories. In characterizing source waters, monitoring sites should be chosen to maximize the user's ability to characterize incoming pollutant sources, including known "hot spots" for algal blooms, fish kills, and DO deficits, as well as waters with the highest probability of human contact through recreational use (Meriluoto and Codd 2005). Real-time data should be groundtruthed by additional field sampling for parameters of interest such as phytoplankton biomass and dominant species, nutrients, and other pollutants.

Dedicated field sampling and associated analytical methods are useful in determining areas of high bloom activity and in identifying potentially harmful algae and their toxins. Commercially available toxin kits are available for some algal toxins and may be either quantitative or qualitative depending on the method and manufacturer (examples given in Table 1-1). Use of these kits can help water utilities assess the condition and toxin concentrations of source water and also the efficacy of filtration in the

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

Table 1-1 Selected commercially available kits for cyanotoxin detection/quantification

Toxin	Product Number	Vendor	Description of Product
Microcystin	EP 022	Envirologix	ELISA Microtiter® plate kit for quantitative detection of microcystins in surface waters. Limit of detection, 0.147 ppb microcystin-LR equivalents. Limit of detection for the high-sensitivity alternate protocol (potable water), 0.03 ppb assay range 0.16–2.5 ppb.
	ET 022	Envirologix	QualiTube kit for microcystin, ELISA tube field kit for qualitative determination of presence/absence of microcystin in surface waters (limit of detection 0.3 ppb); tubes read visually or with a photometer; assay range 0.5–3.0 ppb.
	520011	Abraxis, LLC	Microcystins/Nodularins (Adda), ELISA kit, Microtiter plate. Limit of detection 0.10 ppb (assay range 0.15–5 ppb).
	520012	Abraxis, LLC	Microcystin tube kit; quantitative, requires photometer.
	520012F	Abraxis, LLC	Microcystin tube kit; qualitative, requires photometer.
	CPP-023	Beacon Analytical Systems Inc.	ELISA Microcystin plate kit. Limit of detection ~0.05 ppb.
Cylindrospermopsin	522011	Abraxis, LLC	Cylindrospermopsin ELISA kit, Microtiter plate for quantitative detection; limit of detection 0.04 ppb, assay range 0.05–2.0 ppb.
Saxitoxin	52255B	Abraxis, LLC	Saxitoxin ELISA kit, Product No. 52255B: Microtiter plate, quantitative determination, limit of detection 0.015 ng/mL, assay range 0.02–0.4 ppb.

final product. It is important, however, to cross-confirm enzyme-linked immunosorbent assays (ELISAs) and protein phosphatase inhibition assays with standard HPLC, liquid chromatography/mass spectroscopy (LC/MS), and other methods as appropriate (Tillmanns et al. 2007). Advanced LC/MS/MS methods may be used for toxin variant determination (Meriluoto and Codd 2005).

All sampling devices and containers must be free of any biological or inorganic residue before sample collection. Standard washing and acid stripping of glassware is necessary, along with the use of a cleaner that removes DNA such as DNA Away by Molecular Bio-Products or DNase Displace from Fisher Scientific. These precautions are especially important in the collection of material for DNA, nutrient, and algal toxin analyses to eliminate the possibility of contamination. It is also recommended that all sampling devices be rinsed twice with source water from the site prior to collection.

Most standard methods for determining algal toxins describe collecting the algal material from water samples or surface scums and then extracting toxins from algal cells collected by filtration or lyophilized bloom material. Samples should be processed and analyzed as soon as possible within 24 hours after collection to minimize degradation of toxin and algal material and to maximize recovery. If samples are to be sent to commercial laboratories for toxin analysis, they should be prepared the same day of collection according to the receiving laboratory specifications and shipped under appropriate conditions (containers, temperature, light) within 24 hours.

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

Various commercially available sampling devices can be used to collect water samples at discrete depths or integrated samples collecting water from many depths. For example, water samplers are commercially available from Aquatic Ecosystems Inc. (www.aquaticeco.com) and Wildco (www.wildco.com). A Labline sampler can be used to take integrated water samples by lowering and raising the device at a constant rate between the depths of interest. The Labline sampler also allows discrete depth sampling, for example when physical parameters indicate fluorescence activity, elevated DO, or pH at a specific depth. A phytoplankton net tow is useful for collecting appreciable algal biomass from horizontal or vertical tows for qualitative determination of cell-bound toxin content. Net efficiency (depending on the mesh size and other features) needs to be considered in efforts to use these samples to estimate toxin content (Wetzel and Likens 2000). Water for toxin analysis should be collected in glass rather than plastic bottles to minimize toxin adsorption to the container walls. Toxin samples should be stored on ice during transport and filtered the same day of collection. The processed filtrate sample (soluble fraction) and the filter disc (cell-bound fraction) should be frozen separately at a minimum of –20°C to a maximum of –80°C (preferable; see appropriate references for further details, such as Chorus and Bartram 1999, Codd et al. 1999, and Meriluoto and Codd 2005).

FUTURE DIRECTIONS

The demand for drinking water will surely increase in the future due to population growth and the resulting development of municipal infrastructure. Watersheds will continue to be affected by a variety of anthropogenic and natural stressors, such as stormwater runoff due to increases in impervious surfaces, increases in harmful algal blooms, and extremes in climate. These synergistic stressors will increasingly challenge potable water treatment operations. The exceptional 2007 drought experienced by the southeastern United States (US Drought Monitor, www.drought.unl.edu/dm/monitor.html) provides a compelling example of how climate can quickly change the availability of water for the general public. The use of online monitoring and dedicated field techniques to assess source water for harmful algae will be a necessity to optimize management of decreasing water resources. Development of new online and field technologies is anticipated to grow in importance as a high priority for both government and private concerns.

The integration of molecular and analytical techniques with electronic sensors has great potential for future development and use in online monitoring programs. This emerging technology is based on analytical methods that detect specific toxic substances. Examples of these technologies include the electric cell-substrate impedance sensing system, which measures toxicant-induced changes in the electrical impedance of a cell monolayer (Keese et al. 1998), and the neuronal microelectrode array device, which evaluates changes in the action potential of a neuronal network via noninvasive extracellular recordings (Pancrazio et al. 2003). These sensors have been successfully employed in laboratory studies (van der Schalie et al. 2006), and future efforts are expected to include incorporation of this type of technology into online equipment and field deployment tests in source waters used for potable supplies.

It is also probable that additional municipalities will incorporate online monitoring into their water assessment programs in the future to assist managers and water treatment plant operators in planning for episodic events that negatively affect source water. The powerful information that can be gained from a robust online and field monitoring program will allow more accurate projections of costs related to water plant operations, such as the purchase of chemicals, filter material, and associated labor

Documents
Document Sharing Hub
Full document details: AWWA Manual M57 2010

expenses. It is likely, as well, that manufacturing cost efficiency for online monitoring equipment will be realized by vendors. The resulting reduced initial monetary investment for the tools and associated software needed to implement this technology will make online monitoring an attractive addition to source water assessment programs for tracking harmful and noxious algal blooms that are expected to flourish in increasingly nutrient-enriched watersheds.

REFERENCES

American Public Health Association (APHA), American Water Works Association (AWWA), and Water Environment Federation (WEF). 2005. *Standard methods for the examination of water and wastewater*. 21st ed. Washington, D.C.: APHA.

Arnell, N.W. 1999. Climate change and global water resources. *Global Environ. Change*, 9:S31–S49.

Botana, L.M., ed. 2007. *Phycotoxins: Chemistry and biochemistry*. Ames, Iowa: Blackwell.

Burkholder, J.M. 1992. Phytoplankton and episodic suspended sediment loading: Phosphate partitioning and mechanisms for survival. *Limnol. Oceanogr.*, 37:974–988.

Burkholder, J.M., W. Frazier, and M.B. Rothenberger. 2010. Source water assessment and control/treatment strategies for harmful and noxious algae. In *Manual M57, Algae: Source to treatment*. Denver, Colo.: AWWA.

Chorus, I., and J. Bartram, eds. 1999. *Toxic cyanobacteria in water: A guide to their public health consequences, monitoring, and management*. London: E&FN Spon.

Codd, G.A., I. Chorus, and M. Burch. 1999. Design of monitoring programmes. In *Toxic cyanobacteria in water: A guide to their public health consequences, monitoring, and management*. I. Chorus and J. Bartram, eds. London: E&FN Spon.

Falkowski, P.G., and J. La Roche. 1991. Acclimation to spectral irradiance in algae. *Jour. Phycol.*, 27:8–14.

Geider, R.J., and B.A. Osborne. 1987. Light absorption by a marine diatom: Experimental observations and theoretical calculations of the package effect in a small *Thalassiosira* species. *Mar. Biol.*, 96:299–308.

Glasgow, H.B., Jr., J.M. Burkholder, R.E. Reed, A.J. Lewitus, and J.E. Kleinman. 2004. Real-time remote monitoring of water quality: A review of current applications, and advancements in sensor, telemetry, and computing technologies. *Jour. Exper. Mar. Biol. Ecol.*, 300:409–448.

Grayman, W.M., R.A. Deininger, and R.M. Males. 2001. *Design and early warning and predictive source water monitoring systems*. Denver, Colo.: AWWA.

Keese, C.R., N. Karra, B. Dillon, A.M. Goldberg, and I. Giaever. 1998. Cell-substratum interactions as a predictor of cytotoxicity. *In Vitro Molec. Toxicol.*, 11:182–193.

Kirk, J.T.O. 1994. *Light and photosynthesis in aquatic ecosystems*. 2nd ed. Cambridge, UK: Cambridge University Press.

Knappe, D.R.U., R.C. Belk, D.S. Briley, S.R. Gandy, N. Rastogi, A.H. Rike, H. Glasgow Jr., E. Hannon, W.D. Frazier, P. Kohl., and S. Pugsley. 2004. *Algae detection and removal strategies for drinking water treatment plants*. Denver, Colo.: AWWA.

Lettenmaier, D.P., A.W. Wood, R.N. Palmer, E.F. Wood, and E.Z. Stakhiv. 2004. Water resources implications of global warming: A US regional perspective. *Clim. Change*, 43:537–579.

Lund, J.W.G., C. Kipling, and E.D. Le Cren. 1958. The inverted microscope method of estimating algal numbers and the statistical basis of estimations by counting. *Hydrobiologia*, 11:143–170.

Meriluoto, J., and G.A. Codd, eds. 2005. TOXIC: Cyanobacterial monitoring and cyanotoxin analysis. *Acta academiae aboensis, Ser. B, Mathematica et physica*, Vol. 65, No. 1. Turku, Finland: Åbo Akademi University Press.

Mikol, Y.B., W.R. Richardson, W.H. van der Schalie, T.R. Shedd, and M.W. Widder. 2007. An online real-time biomonitor for contaminant surveillance in water supplies. *Jour. AWWA*, 99:107–115.

Milley, P.C.D., K.A. Dunne, and A.V. Vecchia. 2005. Global pattern of trends in streamflow and water availability in a changing climate. *Nature*, 438:347–350.

Pancrazio, J., S.A. Gray, Y.S. Shubin, N. Kulagina, D.S. Currino, K.M. Shaffer, K. Eisemann, A. Curran, B. Zim, G.W. Gross, and T.J. O'Shaughnessy. 2003. A portable microelectrode array recording system incorporating cultured neuronal networks for neurotoxin detection. *Biosens. Bioelectron.*, 18:1338–1347.

Schlüter, L., T.L. Lauridsen, G. Krogh, and T. Jørgensen. 2006. Identification and quantification of phytoplankton groups

Documents
Document Sharing Hub

Full document details: AWWA Manual M57 2010

in lakes using new pigment ratios: A comparison between pigment analysis by HPLC and microscopy. *Freshwater Biol.*, 51:1474–1485.

Shedd, T.R., W.H. van der Schalie, M.W. Widder, D.T. Burton, and E.P. Burrows. 2001. Long-term operation of an automated fish biomonitoring system for continuous effluent acute toxicity surveillance. *Bull. Environ. Contam. Toxicol.*, 66:392–399.

Tillmanns, A.R., F.R. Pick, and R. Aranda-Rodriquez. 2007. Sampling and analysis of microcystins: Implications for the development of standardized methods. *Environ. Toxicol.*, 22:132–143.

Touchette, B.W., J.M. Burkholder, E.H. Allen, J.L. Alexander, C.A. Kinder, C. Brownie, J. James, and C.H. Britton. 2007. Eutrophication and cyanobacteria blooms in run-of-river impoundments in North Carolina, USA. *Lake Reservoir Manage.*, 23:179–192.

US Environmental Protection Agency. 1997. *Method 445.0. In vitro determination of chlorophyll a and pheophytin a in marine and freshwater algae by fluorescence.* Cincinnati, Ohio: USEPA.

van der Schalie, W.H., T.R. Shedd, P.L. Knechtges, and M.W. Widder. 2001a. Using higher organisms in biological early warning systems for real-time toxicity detection. *Biosens. Bioelecton.,* 16:457–465.

van der Schalie, W.H., T. Shedd, M. Widder, A. Kane, E. Silbergeld, R. Reimschuessel, M. Poli, C. Sarabun, J. Burkholder, and H. Glasgow Jr. 2001b. *Real-time monitoring for toxicity caused by harmful algal blooms and other water quality perturbations.* Technical Report EPA/600/R-01/103. Washington, D.C.: USEPA.

van der Schalie, W.H., R.R. James, and T.P. Gargan II. 2006. Selection of a battery of rapid toxicity sensors for drinking water evaluation. *Biosens. Bioelectron.*, 22:18–27.

Wetzel, R.G. 2001. *Limnology*. 3rd ed. New York: Academic Press.

Wetzel, R.G., and G.E. Likens. 2000. *Limnological analyses.* 3rd ed. New York: Springer-Verlag.

Documents
Document Sharing Hub

Full document details: AWWA Manual M57 2010



Chapter 2

Sampling and Identification: Methods and Strategies

Linda Ehrlich

There are numerous reasons for water utility managers, analysts, and operators to be interested in using biological methods to assess water quality. Many of the compliance and process issues facing utilities result from the growth of the aquatic primary producer organisms broadly termed "algae." These issues include total organic carbon (TOC) removal, filtration and coagulation, tastes and odors, and toxins. Algae may drift freely as phytoplankton in the water column of reservoirs, tributary streams, impoundments, and basins; or they may be attached to bottom sediments and other surfaces in those water bodies, in which case they are known as periphyton. The physical and chemical characteristics of water bodies affect the abundance, species composition, stability, productivity, and physiological condition of algal populations.

Conducting assessments of algal populations can provide information on a number of source water quality and treatment issues (see Section 10010, Biological Examination, *Standard Methods*, APHA et al. 2005). Compliance and daily operational issues constitute the primary category of treatment concerns for utilities. Operational issues include

1. Detecting early warning of biogenic turbidity and taste and odor episodes;
2. Monitoring for clogging of pipes, screens, and filters;
3. Measuring fluctuations in chemical parameters, such as alkalinity, pH, and oxygen; and
4. Determining the algal removal efficiency and effectiveness of drinking water treatment stages in order to optimize chemical dosages and physical treatment processes.

Documents
Document Sharing Hub

Full document details: AWWA Manual M57 2010