Table of Contents

Preface  xiii

1 Hydrobiological modelling - its role in environmental management and science  .................... 1
   1.1 Introduction 1
   1.2 What is a hydrobiological model? 1
   1.3 What is the purpose of hydrobiological models? 2
   1.4 Scientific and management objectives 3
   1.5 The management context 4
      Modelling in the planning process 6
      Operational models of harmful algal blooms 8
   1.6 Prediction using models 8
   1.7 The scientific context 9
      Scientific models 10
   1.8 Who models? 10
   1.9 What is the nature of hydrobiological models? 11
   1.10 Examples of model types 12
      The zero-dimensional dynamic model (CSTR) 12
      Zero dimensional steady state model 14
      Variable volume 15
   1.11 Steady state models with one spatial dimension 16
      Multiple sources - superposition 18
      Effects of variations in the river flow 19
   1.12 Plug flow reactors 19
   1.13 Advection-diffusion-reaction systems 21
   1.14 Numerical techniques, scales and discretization 23
   1.15 Examples of aquatic ecosystem model types 24
      Small well mixed pond 24
      Larger shallow lake with wind-wave driven sediment releases 24
      Small, deep stratified reservoir or lake– 1D vertical 24
      Lake or estuary – 3D hydrodynamics split scale ecosystem 24
      Continental shelf frontal system - fully coupled biophysical model 24
      Deep ocean - non-spatial –empirical mixed layer depth- Fasham model 24
   1.16 Commercial packages 25
   1.17 Model calibration and confidence limits of predictions 25
   1.18 Further reading 26
   1.19 Problems 27
   1.20 References 27

2 The physics of natural waters..................................................................................................  33
   2.1 Introduction 33
   2.2 Properties of water 33
      Density changes with temperature, salinity and pressure 33
   2.3 Observations on flowing water 35
      Viscosity 36
      Laminar and turbulent flow 37
      Advection 37
   2.4 Turbulence and mixing processes 38
   2.5 Jets and plumes 42
   2.6 Wind stresses, wave motion and wind driven currents 43
   2.7 Apparent forces due to the rotation of the earth - Coriolis forces 43
   2.8 Atmospheric pressure 44
   2.9 Tides 45
5  *Stratification and mixing processes*  ........................................................................................................ 171
   5.1  Introduction 171
   5.2  Stratification and circulation in lakes 171
       Dimensionless ratios 173
   5.3  Energy fluxes 175
   5.4  Mixed layer models 177
       Potential energy change in mixing 178
   5.5  Seiching in semi-enclosed bodies of water 179
   5.6  Shear flow dispersion 180
       Fickian dispersion models in rivers 180
       Solution 182
       Dead zone models 185
   5.7  Jets and plumes 185
       Simple jets 186
   5.8  The simple plume 189
   5.9  Buoyant jets 191
   5.10  Cross-flows 193
   5.11  Modelling and measuring plumes 193
   5.12  Further reading 193
   5.13  References 194

6  *Numerical solution of differential equations*  .......................................................................................... 197
   6.1  Introduction 197
   6.2  A very brief review of finite difference methods 197
       Order of accuracy 198
       Methods for solving initial value ordinary differential equations 201
   6.3  Implementation of boundary conditions 203
   6.4  FTCS method for the diffusion equation 203
       Dirichlet boundary conditions 205
       Neumann boundary conditions 206
       Robin boundary conditions 206
   6.5  Consistency, stability and convergence of numerical solutions 208
       Intuitive explanation for the stability constraint 211
       Simplification of von Neumann stability analysis 211
   6.6  Implicit methods for the diffusion equation 211
       Stability of the forward-time implicit method 214
       Implicit or explicit? 215
   6.7  The method of lines 216
   6.8  The finite volume approach 217
   6.9  The finite element method 218
   6.10  Numerical solution of the one-way wave equation - advection 226
       Upwind explicit scheme 228
       The Courant-Friedrichs-Lewy (CFL) condition 231
       The Lax-Wendroff scheme 232
       Stability of the Lax-Wendroff scheme 234
       MacCormack’s scheme 235
       MPDATA 236
       The QUICK scheme and subsequent developments 239
       Multi-level schemes - the leap-frog scheme 239
   6.11  Implicit finite difference methods for the advection equation 240
       One-sided schemes 240
       Crank-Nicholson Method 240
       Implicit Lax-Wendroff 241
       The Preissman or box scheme 241
   6.12  Numerical diffusion, dispersion and dissipation 242
9.3 Finite element method 307
9.4 Finite volume models 308
9.5 Semi-Lagrangian methods 309
  Casulli’s semi-Lagrangian model 312
9.6 Mass conserving semi-Lagrangian schemes 314
9.7 Multi-grid methods 314
9.8 Calibration 314
9.9 Further Reading 315
9.10 References 315

10 Computation of three-dimensional hydrodynamics and transport ..................................... 321
10.1 Introduction 321
10.2 The Princeton Ocean Model (POM) 322
  σ–coordinates 322
  Basic equations 323
  External mode computation 328
  Internal mode computations 330
  Surface and bottom boundary conditions 332
  Stability criteria- choosing timesteps 333
  Using Matlab to plot output from POM 334
10.3 Other members of the POM family 336
10.4 The Hydrodynamic Eutrophication Model (HEM-3D) 336
  HEM-3D numerical approach - external mode 339
  HEM-3D numerical approach - internal mode 345
  Transport equations 348
10.5 Implicit and semi-implicit methods 352
  Casulli and Cheng’s semi-implicit 3-D model 352
10.6 Finite element models 358
  RMA model 358
  ADCIRC 358
  TELEMAC 359
  ROMS 359
10.7 Non-hydrostatic shallow water models 359
10.8 Open boundary conditions in 3-D models 359
10.9 Land boundaries - mud flats - wetting and drying 361
10.10 Fully three-dimensional models 361
10.11 Calibration 362
10.12 Further reading 362
10.13 References 362

11 Modelling transport -scales and aggregation ..................................................................... 369
11.1 Introduction 369
11.2 Ecosystem scales, modelling and sampling 370
11.3 Spatially lumped biological models 370
11.4 Advection-diffusion models 371
11.5 Particle tracking models 371
11.6 Particle tracking in two dimensional (depth integrated) models 373
11.7 Langevin and Fokker-Planck Equations 374
11.8 Implementation of particle tracking models 376
11.9 Interpolation 376
11.10 Three dimensional particle tracking 378
11.11 Model implementation 378
11.12 Particles hitting rectangular boundaries 379
  Land boundaries 379
11.13 Future investigations in particle modelling 379
11.14 Box systems 380
Epiphytes 434
Measurement of biomass of benthic macrophytes 435
Hydrodynamics 435
13.12 **Macroalgae 435**
13.13 **Zooplankton 435**
  Dominant species 436
  Spatial characteristics - aggregation and diel vertical migration 436
  Grazing on phytoplankton 437
13.14 **Benthic fauna 438**
13.15 **Ecosystem dynamics 438**
  Seasonal changes 438
  The paradoxes 439
  The paradox of the plankton 439
  Paradox of enrichment 440
13.16 **Ocean biogeochemistry in the global carbon cycle 440**
13.17 **Characteristics of some important aquatic ecosystems 442**
13.18 **Biological and chemical measurement in aquatic systems 442**
  Remote sensing 443
13.19 **Bibliographic notes and further reading 444**
13.20 **References 445**

14 **Elements and behaviour of mathematical ecosystem models ......................... 467**
14.1 **Introduction 467**
14.2 **Phytoplankton growth and mortality rates, NP models 468**
  Nutrients 469
  Light 471
  Self-shading 474
  Temperature effects on maximum growth rate 475
  Exudation 476
  Inhibited growth (logistic) models 477
  Phytoplankton mortality 478
  Light limited phytoplankton growth models 478
14.3 **Zooplankton growth (predation) and mortality models 479**
  Zooplankton mortality 480
14.4 **Nutrient-phytoplankton-detritus (NPD) systems 480**
14.5 **PZ models: predator-prey interaction with growth limited by grazing 484**
  Other forms of predator-prey models 490
14.6 **NPZ - nutrient-phytoplankton-zooplankton models 491**
14.7 **NPZD - nutrient-phytoplankton-zooplankton-detritus models 492**
14.8 **NPiZiD - multi-plankton functional group models 496**
14.9 **The Droop model 496**
14.10 **Mathematical behaviour of simple models 497**
  Stability 497
  Bifurcation 500
  Lyapunov exponent 500
  General model dynamics 501
  Should we worry about chaos in real ecosystems? 501
14.11 **Paradoxes and arguments 501**
  The paradox of the plankton 501
  May’s diversity/complexity issue 502
  Rosenzweig’s paradox of enrichment 503
  Species and process aggregation 503
14.12 **Individual based models and cellular automata 503**
14.13 **Size-based and mechanistic models 503**
14.14 **Population models 506**
14.15 Stochastic models 506
   Stochastic Lotka-Volterra model 507
   Fokker-Planck equation methods 509
   Ito stochastic equation models 509
   The random equation approach 509
   Random evolution or transition matrix modelling 510
   Monte Carlo models 510
14.16 Benthic plant models 510
   Wetzel’s Zostera model 510
14.17 Sediment flux and diagenetic models 513
14.18 Small scale processes and turbulence 514
14.19 Further reading 514
14.20 Problems 515
14.21 References 515

15 Hydrobiological models -history and examples ................................................................. 531
15.1 Introduction 531
15.2 A brief history of hydrobiological modelling 532
15.3 The Fleming and Riley models 533
15.4 Williams’ Port Phillip Bay Model - WASP 533
   Solution of the differential equation model 537
   The WASP model 538
15.5 Chesapeake Bay models 538
15.6 Lake Okeechobee modelling - resuspension in shallow lakes 539
15.7 CSIRO Pt Phillip Bay model and extensions 540
   Hydrodynamics and transport 540
   Biogeochemical model 540
15.8 DYRESM - a stratified lake model and CAEDYM 543
15.9 Fasham’s mixed layer ocean model 543
   Yool’s 4 and 5 state reductions of the Fasham model 547
   Other mixed layer and one-dimensional models 549
15.10 Coupled Franks models and variations thereon 550
15.11 Harmful bloom modelling 551
   Operational models 552
15.12 Zooplankton models 552
15.13 The ERSEM model 552
15.14 The ERSEM III pelagic model 553
   Phytoplankton 554
   Temperature 555
   Light 555
   Nutrients 556
   Phytoplankton nutrient dynamics 557
   Chlorophyll a computation 558
   Phytoplankton sinking 558
   Pelagic bacteria 558
   Zooplankton 560
   Mesozooplankton 562
   Dissolved inorganics 564
   DOM and POM 565
15.15 The ERSEM III benthic model 566
   Pelagic-benthic coupling 567
   Benthic organisms 568
   Carbon and nutrient dynamics 568
   Benthic decomposers 570
   Organic sediment matter 572
The benthic nutrient system 573
Ammonium and nitrate model 575
Phosphate model 575
Silicate model 576
Reduction equivalents 577
Oxygen penetration depth and sulphide horizon 577
Estimation of parameters 578

15.16 PROTECH and cyanobacteria buoyancy models 578
15.17 Seagrass-phytoplankton models 581
15.18 Modelling for planning and management of biomanipulation 585
15.19 Further reading 585
15.20 References 586

16 Model practice: structuring and estimation ................................................................. 599
16.1 Introduction 599
16.2 Choosing a model - selecting scales and variables 599
16.3 Model performance 600
16.4 Model implementation 601
16.5 Parameter estimation 601
   Errors in ecological models 602
   Errors of construction 603
   Errors of evaluation 603
   Errors of inference 603
   Errors of abstraction 603
16.6 Error Models 604
16.7 Estimation of parameters in Williams’ Pt Phillip Bay (WPPB) model 608
16.8 Further reading 613
16.9 References 613

17 Modelling of lakes and estuaries for management ...................................................... 617
17.1 Introduction 617
17.2 Management in a stochastic environment 618
17.3 The MAUDE framework 621
17.4 Initial desktop study - describing the problem 622
   A graphical model of the system 622
   Spatial and temporal scales 623
   The system network model’s role in the management process 624
17.5 Setting management objectives 624
   Multi-criteria decision making 625
   Objectives and measures of effectiveness 626
17.6 Establishing a preliminary (baseline) probability distribution for the SHI 629
17.7 Generate a list of management options or strategies 629
17.8 Analysis of the ecosystem network and construction of Bayes networks 629
17.9 Propagating Bayesian uncertainty in the networks 632
17.10 Decision making 634
17.11 Monitoring and revisit all phases on planned schedule 634
17.12 Biswas’ basic rules for modelling for environmental decision-making 634
17.13 Further reading 637
17.14 References 637

Appendix A. Some notes on plotting with MATLAB ...................................................... 641
A.1 Introduction 641
A.2 Fundamentals 642
A.3 Control structures 642
A.4 Getting data to and from files 643
A.5 Saving your current work 643