

**HYDRODYNAMICS**

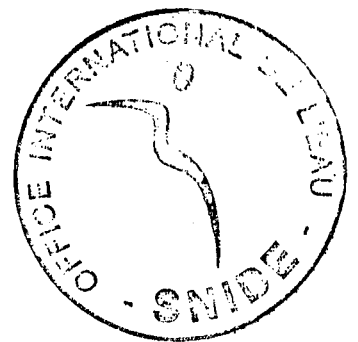
**AND TRANSPORT**

**FOR**

**WATER QUALITY  
MODELING**

**James L. Martin  
Steven C. McCutcheon**

*with contributions by*  
**Robert W. Schottman**



**LEWIS PUBLISHERS**

Boca Raton London New York Washington, D.C.

---

# Table of Contents

## Part I

### Fundamentals

#### 1

#### *Fundamental Relationships for Flow and Transport*

I.	Mechanistic Versus Empirical Modeling .....	7
II.	General Principles .....	8
A.	Laws of Conservation .....	8
B.	Extrinsic Versus Intrinsic Properties .....	9
C.	Net Accumulation: Application of the Laws of Conservation .....	10
D.	Control Volumes .....	12
III.	Physical Properties of Water .....	13
A.	Density and Specific Weight .....	13
B.	Compressibility .....	15
C.	Newtonian Fluids and Molecular Viscosity .....	16
D.	Molecular Diffusivity .....	19
IV.	Instantaneous Equations for Fluid Flow and Transport .....	23
A.	Fundamental Form of the Conservation Equations .....	23
B.	Instantaneous Equation for Continuity of Water .....	27
C.	Instantaneous Equations for the Conservation of Momentum .....	28
D.	Instantaneous Equations for the Conservation of Constituent Mass or Thermal Energy .....	29
V.	Reynolds Time-Averaged Mean Flow and Transport Equations .....	30
A.	Turbulent Motion .....	31
B.	Statistical Relationships .....	33
C.	Turbulence Closure .....	38
VI.	Model Complexity: Selection and Development .....	44
A.	Model Resolution .....	47
1.	Scales of Interest .....	49
2.	Time Variation .....	53
3.	Spatial Dimensions for Solving the Governing Equations .....	55
4.	Methods to Simulate the Water Surface .....	56
5.	Turbulence Parameterization .....	58
6.	Forcing Functions or Sources and Sinks .....	60
a.	Water Mass .....	60
b.	Momentum .....	61
c.	Constituent Mass .....	62
B.	Solution Techniques .....	66
1.	Analytical Solutions .....	67
2.	Numerical Solution Techniques .....	67

VII. Data Requirements .....	74
A. Boundary Conditions.....	74
B. Initial Conditions.....	75
C. Data for Model Application and Evaluation.....	77
1. Statistical Tests of Paired Observations and Simulations.....	80
2. Sensitivity Analysis.....	87
3. Error Analysis.....	88
D. Data for Evaluation of Environmental Control.....	88
VIII. Definitions .....	89
IX. Dimensionless Numbers .....	90

## 2

### *Measurement and Analysis of Flow*

I. Introduction.....	93
II. Measurement of Velocity and Flow .....	94
A. Float Methods .....	94
B. Current Meters.....	97
1. Mechanical Current Meters.....	98
2. Acoustic Current Measurement .....	100
3. Electromagnetic Current Measurement .....	103
4. Deployment of Current Meters .....	105
C. Flow Measurement at Control Structures.....	107
D. Remote Sensing.....	109
III. Measurement of Stage.....	109
IV. Computation of Discharge.....	111
V. Tracer Studies.....	114
A. Measurement of Fluorescent Dyes.....	115
B. Properties of Fluorescent Dyes.....	118
1. Temperature Effects.....	118
2. Background Interference .....	119
3. Sorption.....	119
4. pH Effects .....	120
5. Photodegradation.....	120
6. Chemical Reactions and Quenching.....	120
7. Density Effects .....	121
8. Toxicity.....	121
C. Types of Dye Studies.....	121
1. Instantaneous Release.....	121
2. Continuous Release.....	124
D. Planning Dye Studies.....	131
1. Estimating Mean Velocities .....	131
2. Mixing Considerations .....	131
3. Estimating the Quantity of Dye Releases.....	132
4. Determining Locations of Sampling Stations.....	132
VI. Estimating Design Flows.....	133
A. Design Conditions for Dynamic Flows .....	135
B. Design Conditions for Steady Flows .....	135
1. Extreme-Value-Based Design Flows.....	138

D.	Methods Based on Continuity .....	229
----	-----------------------------------	-----

## 5

### *Hydraulic Methods for Steady Flows*

I.	Steady, Uniform Flows.....	237
A.	The Chezy Equation.....	238
B.	The Manning Equation.....	239
C.	Simulating Frictional Resistance Using the Manning Equation.....	246
II.	Hydraulic Methods for Steady, Nonuniform Flows.....	248
A.	Bernoulli Energy Equation Modified for Friction Losses.....	248
B.	Classification of Flow Regimes.....	249
1.	Normal and Critical Flow Conditions.....	249
2.	Froude Number .....	252
3.	Hydraulic Jump .....	253
4.	Classification of Water Surface Profiles.....	254
C.	Energy Losses and Momentum Corrections .....	255
1.	Friction Losses in Steady, Nonuniform Flow .....	255
2.	Minor Losses .....	256
3.	Kinetic Energy Corrections .....	257
D.	Application of Nonuniform Flow Concepts.....	258
1.	The Step Method .....	258
2.	Iterative Solution .....	261

## 6

### *Hydraulic Methods for Unsteady Flows*

I.	Introduction.....	267
II.	Solution Techniques .....	268
A.	Method of Characteristics .....	268
B.	Finite-Difference Methods.....	269
C.	Finite-Element Methods .....	274
D.	Numerical Properties .....	274
E.	Boundary and Initial Conditions .....	276
III.	Unsteady-Flow Methods .....	277
IV.	Kinematic-Wave Model .....	278
A.	Exact Solution .....	280
B.	Numerical Solution: Backward Finite-Difference Approach .....	283

## 7

### *Solutions of Complete Unsteady Flow Models*

I.	Explicit Solution of a Link-Node Model.....	289
A.	Description of the Method .....	289
B.	Solution Technique.....	291
C.	Example Applications.....	293
D.	Linkage with Water Quality Models .....	299

II. Implicit Solution Using the Four-Point Method .....	301
A. Numerical Scheme .....	301
B. Solution Technique .....	304
C. Examples of Implicit Models .....	308
D. Linkage with Water Quality Models .....	310
References .....	315
Symbols Used in Part II .....	319
Problems .....	325

## Part III

### Lakes and Reservoirs

#### 8

#### *Stratification and Heat Transfer in Lakes and Reservoirs*

I. Introduction to Lakes and Reservoirs .....	335
II. Origin and Characteristics of Lakes and Reservoirs .....	336
A. Origin of Lakes .....	336
B. Size and Number .....	337
C. Water Use and Reservoir Purpose .....	338
D. Important Lentic Zones and Shoreline Conditions .....	342
E. Hydraulic Retention Time .....	343
III. Stratification in Lakes and Reservoirs .....	343
A. Stratification Cycle .....	344
B. Classification of Lakes and Reservoirs Based on Stratification .....	347
C. Stratification Potential .....	348
IV. Temperature Simulation .....	349
A. Full Heat Balance .....	350
1. Short-Wave Radiation .....	350
2. Long-Wave Radiation .....	360
3. Back Radiation from Lakes and Reservoirs .....	361
4. Evaporation .....	362
5. Conduction and Convection .....	365
B. Beer's Law and the Solar Radiation Penetration .....	367
C. Equilibrium Temperature Method .....	370
1. Use of Equilibrium Temperature to Solve for the Heat Flux .....	372
2. Coefficient of Heat Exchange .....	374
3. Other Methods .....	376
D. Data Requirements .....	377
V. Ice Formation and Cover .....	379
A. Ice Formation .....	381
B. Light Penetration Through Ice and Snow .....	381
C. Thickening of the Ice Cover .....	382
D. Lake Ice Decay .....	383

## *Mixing in Lakes and Reservoirs*

I.	Introduction.....	385
II.	Inflow Mixing Processes.....	387
	A. Characteristics of Inflow Mixing.....	388
	B. Analysis of Inflows.....	390
	1. Plunge or Separation Point.....	391
	2. Thickness and Width of Overflow.....	396
	3. Underflow Mixing.....	396
	4. Interflows.....	399
III.	Outflow Mixing Processes.....	403
	A. Characteristics of Outflow Mixing Processes.....	403
	B. Analysis of Outflow Processes.....	404
IV.	Mixing by Wind, Waves, Convective Cooling, and Coriolis Forces.....	412
	A. Progressive Surface Waves.....	413
	B. Langmuir Circulation.....	417
	C. Convective Mixing.....	418
	D. Internal Waves, Seiches and Upwelling.....	418
	E. Earth's Rotation—the Coriolis Force.....	426
V.	Reservoir Management and Mixing Processes.....	427

## 10

## *Water Balances and Multidimensional Models*

I.	Introduction.....	431
II.	Water Balance for Lakes and Reservoirs.....	432
	A. Components of the Water Balance.....	433
	1. Storage.....	433
	2. Inflow and Outflow Measurements.....	436
	3. Direct Precipitation onto the Lake Surface.....	437
	4. Evaporation.....	438
	5. Groundwater Seepage and Infiltration.....	444
	B. Reservoir Routing Methods.....	446
III.	Zero-Dimensional or Box Models of Lake and Reservoir Quality.....	449
IV.	One-Dimensional, Longitudinal Models of Lakes and Reservoirs.....	453
V.	One-Dimensional, Vertical Models of Lakes and Reservoirs.....	455
	A. Mixed Layer Models.....	456
	B. Vertical Turbulent Diffusion Models.....	464
	1. Empirical Expressions.....	464
	2. Dye or Tracer Studies to Determine Vertical Mixing.....	471
VI.	Two-Dimensional (Laterally Averaged) Models.....	474
	A. Box Model Approach.....	475
	B. Hydrodynamic and Mass Transport Models.....	480
VII.	Two-Dimensional Depth Averaged Models.....	486
VIII.	Three-Dimensional Models.....	488

References.....	491
Symbols Used in Part III.....	501
Problems .....	507

## Part IV

### Estuaries

#### 11

##### *Introduction to Estuaries*

I. Introduction.....	527
II. General Characteristics of Estuaries .....	527
A. Chemical Characteristics .....	528
B. Density .....	529
C. Tides and the Salt-Wedge Estuary .....	530
III. Classification Schemes.....	534
A. Geomorphology.....	534
B. Degree of Stratification .....	535

#### 12

##### *Factors Affecting Transport and Mixing in Estuaries*

I. Introduction.....	543
II. Tides .....	543
A. Tidal Amplitudes.....	544
B. Tidal Currents .....	553
III. The Coriolis Force.....	556
IV. Freshwater Inflow .....	558
V. Meteorological Effects.....	559
VI. Bathymetry .....	561
VII. Model Complexity.....	562
A. Spatial and Temporal Resolution .....	563
1. Spatial Resolution.....	564
2. Temporal Resolution.....	566
B. Complexity of Governing Equations.....	568

#### 13

##### *Turbulent Mixing and Dispersion in Estuaries*

I. Eddy Viscosity and Eddy Diffusivity .....	569
A. Formulation of Coefficients .....	570
B. The Closure Problem.....	572
1. Zero-Equation Closure .....	572

2.	One-Equation Closure .....	573
3.	Two-Equation Closure .....	573
4.	Turbulent Stress and Flux Equation Closure.....	574
II.	Dispersion in Estuaries.....	575
III.	Estimation of Mixing Terms.....	576
A.	Eddy Viscosity and Eddy Diffusivity .....	576
B.	Dispersion.....	586

## 14

### *Tidally Averaged Estuarine Models*

I.	Introduction.....	593
II.	Fraction of Freshwater Method .....	599
III.	Modified Tidal Prism Method .....	601
IV.	Pritchard's Method.....	604
V.	Lung and O'Connor's Method.....	609
VI.	Computing Tidal Transport from Measured or Predicted Velocities.....	616
A.	Computing Tidally Averaged Advection and Dispersion.....	616
1.	Computing Tidally Averaged Advection.....	618
2.	Computing Tidally Averaged Dispersion .....	619
3.	Numerical Diffusion .....	628
B.	Spatial Averaging of Fine Scale Intratidal Simulations.....	628
C.	The Lagrangian Transport Equation.....	629
D.	Computing the Stokes Drift.....	634
E.	A Final Note on Tidal Averaging.....	640

## 15

### *Dynamic Modeling Of Estuaries*

I.	Introduction.....	643
II.	Factors That Distinguish Modeling Approaches .....	645
A.	Forces and Boundary Conditions.....	646
1.	Riverine Boundary Conditions.....	646
2.	Open Water Boundary Conditions .....	646
3.	Forces Due to the Coriolis Effect, Atmospheric Pressure, Barotropic Setup, and Baroclinic Pressure.....	647
4.	Water Surface Conditions.....	649
5.	Bottom Boundary Conditions.....	650
6.	Shoreline Conditions.....	653
B.	Dimensionality.....	655
C.	Grid Structure .....	655
1.	Horizontal Finite Difference Grids .....	656
a.	Rectangular Grids with Fixed-Grid Spacing.....	656
b.	Stretched Rectangular Grids.....	656
c.	Curvilinear Boundary-Fitted Coordinate Systems.....	658
d.	Adaptive Grids .....	662
2.	Vertical Coordinate Systems .....	663
a.	Cartesian Vertical Coordinate.....	663



	b.	Stretched Grid.....	664
	c.	Isopycnic Coordinate System .....	665
	3.	Finite Element Grids .....	666
	D.	Numerical Solution Scheme.....	666
III.		One-Dimensional Models Of Estuaries.....	668
	A.	Examples of Available Models .....	671
	1.	Branch-Network Flow Model.....	671
	2.	CE-QUAL-RIV1 .....	672
	3.	Dynamic Estuary Model (DEM).....	672
	4.	EXPLORE-1 .....	673
	5.	MIT Transient Water Quality Network Model.....	673
	B.	Case Study .....	674
IV.		Two-Dimensional (Horizontal Plane) Models .....	678
	A.	Examples of Available Models .....	680
	1.	TABS-MD and RMA2-WES.....	681
	2.	WIFM-SAL.....	682
	3.	HSCTM-2D.....	683
	4.	FESWMS-2DH .....	683
	5.	Tidal, Residual, Intertidal Mudflat Model.....	684
	6.	SIMSYS2D or SWIFT2D.....	685
	7.	CAFEX.....	686
	8.	H.S. Chen's Model.....	687
	9.	FETRA, Sediment-Contaminant Transport Model.....	687
	10.	NELEUS.....	688
	11.	SEDZL .....	688
	12.	Other Models .....	689
	B.	Case Study .....	689
V.		Two-Dimensional (Vertical Plane) Models .....	690
	A.	Examples of Available Models .....	694
	1.	CE-QUAL-W2.....	694
	2.	Blumberg's Model .....	695
	B.	Case Study .....	695
VI.		Three-Dimensional Models.....	701
	A.	Examples of Available Models .....	709
	1.	CH3D/CH3D-WES.....	709
	2.	EHSM3D .....	709
	3.	John Paul's Hydrodynamic Model .....	709
	4.	ECOM-3D/POM .....	709
	5.	Model for Estuarine and Coastal Circulation and Assessment (MECCA) .....	710
	6.	EFDC/HEM3D .....	710
	7.	HOTDIM.....	711
	8.	RMA Models .....	711
	9.	TEMPEST.....	711
	B.	Case Study .....	711
VII.		Coupling Flow and Water Quality Models .....	718
	A.	Directly Linked Models .....	718
	B.	Indirect Linkage.....	719
		References.....	721
		Symbols Used in Part IV.....	747

Problems .....763

Appendixes

IV.A. Node Factors ( $f_i$ ) at the Middle of Each Calendar Year (1990-2029) .....772

IV.B. Equilibrium Argument ( $V_o + \alpha_o$ ) for the Greenwich Meridian at the  
Beginning of Each Calendar Year (1990-2029).....776

Index.....781