
Table of Contents

Part I

Fundamentals

1

Fundamental Relationships for Flow and Transport

I.	Mechanistic Versus Empirical Modeling .....	.71
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. Merhanical 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
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

a.	Distribution-Free Method .....	.138
b.	Known or Estimated Probability Distribution..	.143
2.	Biologically Based Design Flows .....	.147
References		151
Symbols Used in Part I .....		.159
Problems		171
Appendixes		
I.A)	Physical Properties of Water .....	.180
I.B)	Unit Conversion Factors..	.182
I.C)	Values of Frequency Factor K for Use in the Log Pearson Type III Distribution for Low-Flow Analyses..	.191
I.D)	Values of Frequency Factor K for Use in the Log Pearson Type III Distribution for High-Flow Analyses..	.192
I.E)	Standard Variant z_c Associated with Typical Return Intervals..	.193

Part II

Rivers and Streams

3

Flow Models for Rivers and Streams

I.	Introduction .....	.199
II.	Flow Model Complexity..	.200
A.	Spatial and Temporal Resolution..	.201
B.	Complexity of Governing Equations..	.202
III.	Data Requirements..	.204
A.	Boundary Conditions..	.205
B.	Channel Geometry .....	.206
C.	Bottom Roughness .....	.209
D.	Model Calibration and Evaluation .....	.210
IV	Estimating Mixing in Streams and Rivers .....	.211
A.	Methods Based on Shear Stresses .....	.213
B.	Methods Based on Tracer Studies .....	.215
C.	Estimating Mixing Lengths..	.219

4

Non-Hydraulic Methods for Flow Estimation

I.	Flow Relationships..	.221
II.	Hydrologic Routing Methods..	.222
A.	Empirical Techniques..	.222
B.	Hydrographic Theory..	.223
C.	Hydrographic Relationships..	.226

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	3 9 6
	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
	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

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
. 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
.	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.....	65 8
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-I	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
		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