

## Contents

**Preface to the Second Edition** XIII

**Preface to the First Edition** XV

<b>1</b>	<b>Water Resources: Quantity and Quality</b>	<b>1</b>
1.1	Water Pollution and Risk Analysis	3
1.1.1	A Systemic View of Water Resources	4
1.1.1.1	Examples of Application	5
1.1.2	The New Paradigm of Water Quality	7
1.1.2.1	Human Well-being and Health	9
1.1.2.2	Ecological Impacts and Biodiversity	9
1.1.2.3	Fishing and Oyster Farming	10
1.1.2.4	Tourism	10
1.1.2.5	Algal and Chlorophyllic Photosynthesis	12
1.1.2.6	Zooplankton Growth	13
1.1.2.7	Bacteria	13
1.1.3	Integrated Water Resources Management	13
1.2	Water Pollution in Transboundary Regions	18
1.2.1	The UNECE Convention (Helsinki, 1992)	19
1.3	The EU Water Framework Directive	19
1.4	Uncertainties in Water Resources Management	21
1.5	Environmental Risk Assessment and Management	23
1.6	Aim and Organisation of the Book	25
1.7	Questions and Problems – Chapter 1	28
<b>2</b>	<b>Risk Identification</b>	<b>31</b>
2.1	Definition of Risk	32
2.2	Typology of Risks and the Precautionary Principle	38
2.2.1	Unacceptable versus Acceptable Risks	38
2.2.2	Controllable versus Uncontrollable Risks	39
2.2.3	Gradual versus Sudden Risks	39
2.2.4	The Precautionary Principle	40

2.3	Uncertainties in Water Pollution Problems	41
2.3.1	Aleatory Uncertainties or Randomness	43
2.3.2	Epistemic or Man-induced Uncertainties	43
2.4	Water Quality Specifications	46
2.4.1	Water Quality Standards	46
2.4.2	Effluent Standards	49
2.5	Probabilistic Risk and Reliability	49
2.6	Fuzzy Risk and Reliability	51
2.7	Questions and Problems – Chapter 2	53
<b>3</b>	<b>Risk Quantification</b>	<b>55</b>
3.1	Stochastic Approach	56
3.1.1	Direct Evaluation	56
3.1.1.1	Margin of Safety	59
3.1.1.2	The Safety Factor	62
3.1.2	Second-Moment Formulation	64
3.1.3	Frequency Analysis of Data	66
3.1.3.1	Probability Distribution of Extremes	71
3.1.3.2	Analysis of Frequency	72
3.1.4	Stochastic Modelling	77
3.1.4.1	Deterministic Modelling	78
3.1.4.2	Stochastic Modelling	80
3.1.5	Monte Carlo Simulation	83
3.2	Fuzzy Set Theory	87
3.2.1	Fuzzy Regression	87
3.2.1.1	Fuzzy Regression as an Extension of Interval Analysis	88
3.2.1.2	Statistical Regression	88
3.2.1.3	Interval Regression	89
3.2.1.4	Fuzzy Regression	90
3.2.2	Fuzzy Modelling	95
3.3	Time Dependence and System Risk	96
3.3.1	Failure and Reliability Functions	96
3.3.2	Failure Rate and Hazard Function	98
3.3.3	Expected Life	99
3.3.4	System Risk and Reliability	101
3.3.4.1	Series Systems	101
3.3.4.2	Parallel Systems	103
3.4	Questions and Problems – Chapter 3	104
<b>4</b>	<b>Risk Assessment of Environmental Water Quality</b>	<b>109</b>
4.1	Risk in Coastal Water Pollution	110
4.1.1	Uncertainties in Coastal Water Quality Processes	110
4.1.2	Mathematical Modelling	113
4.1.2.1	Molecular Diffusion	114
4.1.2.2	Turbulent Diffusion	118

4.1.2.3	Turbulent Dispersion	120
4.1.2.4	Growth Kinetics	121
4.1.2.5	Coastal Circulation	125
4.1.3	Random Walk Simulation	128
4.1.4	Dispersion by Wind-generated Currents	134
4.2	Risk in River Water Quality	136
4.2.1	Introduction	136
4.2.2	Mathematical Modelling and Simulation	137
4.2.2.1	Physically Based Mathematical Models	137
4.2.2.2	Numerical Simulation	140
4.2.3	Time Series of Water Quality Data	141
4.2.4	Risk Assessment	142
4.3	Risk in Groundwater Contamination	145
4.3.1	Importance of Groundwater Resources	146
4.3.1.1	Groundwater in the Hydrological Cycle	146
4.3.1.2	Steps in Groundwater Development	147
4.3.2	Properties and Field Investigation of Groundwater Systems	149
4.3.2.1	Water in Geological Formations	149
4.3.2.2	Space and Time Scales	152
4.3.3	Aquifer Hydraulic Properties	154
4.3.3.1	Scale Effects	154
4.3.3.2	Measurements and Field Investigations	157
4.3.4	Conceptual and Mathematical Models	158
4.3.4.1	Conceptual Models and Flow Equations	158
4.3.4.2	Analytical Solutions	160
4.3.5	Spatial Variability and Stochastic Modelling	163
4.3.5.1	Uncertainties in Aquifer Contamination Studies	163
4.3.5.2	Stochastic Description	164
4.3.6	Risk Assessment of Groundwater Pollution	166
4.3.6.1	Immiscible Fluids	166
4.3.6.2	Solute Transport and Random Walks	169
4.4	Questions and Problems – Chapter 4	172
<b>5</b>	<b>Risk Management</b>	<b>173</b>
5.1	Performance Indices and Figures of Merit	173
5.2	Objective Functions and Optimisation	175
5.2.1	Economic Optimisation under Certainty and under Risk	175
5.2.2	Optimisation Methods	179
5.2.2.1	Mathematical Programming	180
5.2.3	Discontinuous Decision Problems	184
5.3	Basic Decision Theory	188
5.3.1	Main Elements of Decision Making	188
5.3.1.1	Decision under Certainty	190
5.3.1.2	Decision under Risk	191
5.3.1.3	Decision under Uncertainty or Imprecision	191

5.3.1.4	Decision under Conflict	191
5.3.2	Decision Criteria	191
5.3.2.1	Decision Making under Uncertainty	191
5.3.2.2	Decision Making under Risk	193
5.3.3	Baye's Analysis and Value of Information	194
5.3.3.1	Perfect Information	195
5.3.3.2	Imperfect Information	195
5.4	Elements of the Utility Theory	197
5.5	Multi-objective Decision Analysis	198
5.5.1	Feasible, Non-dominated and Efficient Solutions	201
5.5.2	Solution Procedures and Typology of MCDA Techniques	202
5.6	Questions and Problems – Chapter 5	203
<b>6</b>	<b>Case Studies</b>	<b>205</b>
6.1	Coastal Pollution: the Thermaikos Gulf (Macedonia, Greece)	206
6.1.1	Description of the Thermaikos Gulf	207
6.1.2	Water Circulation Patterns	211
6.1.3	Water Quality Assessment	212
6.1.4	Risk of Pollution under Climate Change	219
6.1.4.1	Temperature and Climate Change	219
6.1.4.2	Monte Carlo Simulation	221
6.2	River Water Quality: the Axios River (Macedonia, Greece)	226
6.2.1	Present Situation	226
6.2.1.1	Axios River	227
6.2.2	Mathematical Modelling	229
6.3	Groundwater Pollution: the Campaspe Aquifer (Victoria, Australia)	231
6.3.1	The Study Area	232
6.3.2	Risk of Salinisation	235
6.3.2.1	Groundwater Hydrodynamics	235
6.3.2.2	Random Walk Simulation	235
<b>Appendix A: The Probabilistic Approach</b>		<b>241</b>
A.1	Basic Probability	241
A.2	The Multiplicative Law	243
A.3	Statistical Independence	244
A.4	Rare Events	244
A.5	Theorem of Total Probability	246
A.6	Bayes' Theorem	246
A.7	Random Variables	248
A.7.1	Discrete Random Variables	249
A.7.2	Continuous Random Variables	251
A.8	Expectation, Variance and Standard Deviation	251
A.9	Derived Distributions	252
A.10	Two-dimensional Distributions	254
A.11	Functions of Random Vectors	254

A.11.1	Sum of Random Variables	254
A.11.2	Difference of Random Variables	255
A.11.3	Product of Random Variables	256
A.11.4	Ratio of Random Variables	257

## **Appendix B: The Fuzzy Set Theory** 259

B.1	Basic Definitions	259
B.2	Fuzzy Sets	260
B.3	$h$ -Level Sets, Normal and Convex Fuzzy Sets	266
B.4	Fuzzy Numbers	266
B.4.1	L-R Representation of a Fuzzy Number	268
B.4.2	Triangular and Trapezoidal Fuzzy Numbers	268
B.4.3	Support and $h$ -Level of a Fuzzy Number	269
B.5	Cartesian Product	270
B.6	Extension Principle	271
B.7	Arithmetic Operations on Fuzzy Numbers as Extension of Interval Analysis	272
B.8	Arithmetic Operations on Intervals	272
B.8.1	Addition and Subtraction of Intervals	273
B.8.2	Multiplication and Division of Intervals	273
B.8.3	Addition of Fuzzy Numbers	274
B.8.4	Subtraction of Fuzzy Numbers	275
B.8.5	Multiplication of Fuzzy Numbers	275
B.8.6	Division of Fuzzy Numbers	276
B.8.7	Minimum and Maximum of Fuzzy Numbers	276
B.8.8	Mean and Width of Fuzzy Numbers	278
B.8.9	Convolution of Fuzzy Numbers	278

## **Appendix C: Hints for Answering Questions and Solutions to Problems** 279

C.1	Answers to Questions and Problems – Chapter 1	279
C.2	Answers to Questions and Problems – Chapter 2	283
C.3	Answers to Questions and Problems – Chapter 3	286
C.4	Answers to Questions and Problems – Chapter 4	289
C.5	Answers to Questions and Problems – Chapter 5	290

## **References** 293

## **Index** 301

