

## TABLE OF CONTENTS

### PART I. BASIC PRINCIPLES

<b>CHAPTER 1: FUNDAMENTALS OF SMALL CATCHMENT HYDROLOGY</b> .....	<b>1</b>
<i>J.M. Buttle</i>	
1.1 Introduction to Small Catchments .....	1
1.2 The Catchment Water Balance .....	1
1.2.1 General components of the water balance .....	1
1.2.2 Precipitation, interception, net precipitation .....	2
1.2.3 Snowmelt .....	10
1.2.4 Infiltration and soil water storage .....	11
1.2.5 Evaporation and evapotranspiration .....	19
1.2.6 Storage in lakes, wetlands and stream channels .....	24
1.2.7 Runoff outputs via streamflow .....	26
1.2.8 Mechanisms of stormflow generation .....	27
1.2.9 Groundwater flow .....	32
1.3 Questions of Spatial and Temporal Scale in Catchment Hydrology .....	33
1.4 Use of Isotopes in Catchment Research .....	35
1.4.1 Evaporation, evapotranspiration, interception .....	36
1.4.2 Pore-water mixing (the mobile-immobile water issue) .....	37
1.4.3 Soil and groundwater recharge rates .....	38
1.4.4 Soil water, groundwater and surface water residence times .....	39
1.4.5 Storm runoff components .....	40
1.4.6 Water sources versus water flowpaths .....	41
1.4.7 Sources of solutes .....	42
1.5 New Research Directions .....	42
1.6 Summary .....	43
<b>CHAPTER 2: FUNDAMENTALS OF ISOTOPE GEOCHEMISTRY</b> .....	<b>51</b>
<i>C. Kendall and E.A. Caldwell</i>	
2.1 Introduction .....	51
2.2 Fundamentals of Isotope Geochemistry .....	53
2.2.1 Definitions .....	53
2.2.2 Terminology .....	55
2.2.3 Standards .....	56
2.3 Stable Isotope Fractionation .....	57
2.3.1 Properties of isotopic molecules .....	57
2.3.2 Fractionation accompanying chemical reactions and phase changes ..	57

2.3.3	The Rayleigh equations	61
2.3.4	Isotopic fractionation in open and closed systems	61
2.3.5	Biological fractionations	70
2.4	Sample Collection, Analysis, and Quality Assurance	72
2.4.1	Sampling guidelines	72
2.4.2	Analytical methods and instrumentation	75
2.4.3	Quality assurance of contract laboratories	77
2.5	Applications of Isotope Tracers in Catchment Hydrology	78
2.5.1	Water isotope hydrology	79
2.5.2	Solute isotope biogeochemistry	79
2.5.3	Mixing	80
2.5.4	Isotopically labeled materials	82
2.5.5	Stable isotopes in geochemical modeling	82
2.5.6	Use of a multi-isotope approach for the determination of flowpaths	83
2.6	Summary	84

## PART II. PROCESSES AFFECTING ISOTOPIC COMPOSITIONS

### CHAPTER 3: ISOTOPIC VARIATIONS IN PRECIPITATION . . . . . 87

*N.L. Ingraham*

3.1	Introduction	87
3.1.1	Global hydrologic cycle	88
3.2	Natural Fractionation of Isotopes in Precipitation	91
3.2.1	Co-variance of hydrogen and oxygen isotopes in precipitation	91
3.3	Systematics of Isotope Variations in Precipitation	94
3.3.1	System fractionation	94
3.3.2	Unique types of precipitation	96
3.3.3	Observed effects	100
3.3.4	Temporal variation in precipitation	103
3.3.5	Geographic variation in precipitation in convective systems	104
3.3.6	Continental effect in precipitation	104
3.3.7	Dependence of rain on ambient temperature	106
3.3.8	Exchange with atmospheric vapor	106
3.3.9	Evaporation on the canopy	108
3.4	Mesoscale Circulation and Storm Trajectories	108
3.5	Tritium	110
3.5.1	Origin	110
3.5.2	Recent elevated levels and decline	111
3.5.3	Observed terrestrial and marine distributions	112
3.5.4	Uses of tritium in catchment basin research	112
3.6	Implications for Catchment Basin Research	113
3.6.1	Scale issues	113
3.6.2	Sample collection	113
3.7	Summary	115

<b>CHAPTER 4: ISOTOPIC FRACTIONATION IN SNOW COVER</b> .....	<b>119</b>
<i>L.W. Cooper</i>	
4.1 Introduction .....	119
4.2 Isotopic Changes to a Snowpack .....	120
4.2.1 Changes during snow accumulation .....	120
4.2.2 Changes during snowmelt .....	123
4.2.3 Isotopic water balance and evaporation .....	128
4.2.4 Catchment scale and runoff considerations .....	129
4.3 Future Directions for Research .....	131
<b>CHAPTER 5: ISOTOPIC EXCHANGE IN SOIL WATER</b> .....	<b>137</b>
<i>C.J. Barnes and J.V. Turner</i>	
5.1 Introduction .....	137
5.1.1 General discussion of isotopes .....	137
5.1.2 Analytical considerations .....	138
5.1.3 Soil-water extraction techniques .....	139
5.2 Processes Leading to Soil Water Concentration Variations: Meteorological Inputs .....	139
5.3 Processes Leading to Soil Water Concentration Variations: Evaporation .....	141
5.3.1 Introduction .....	141
5.3.2 Saturated soils .....	142
5.3.3 Unsaturated soils .....	147
5.3.4 Unsteady evaporation .....	150
5.3.5 Temperature effects .....	155
5.3.6 Oxygen-18/deuterium relationship .....	158
5.3.7 Further modifications due to salinity and transpiration .....	161
5.4 New Research Directions .....	161
5.5 Summary .....	162
<b>CHAPTER 6: PLANTS, ISOTOPES AND WATER USE: A CATCHMENT-SCALE PERSPECTIVE</b> .....	<b>165</b>
<i>T.E. Dawson and J.R. Ehleringer</i>	
6.1 Introduction .....	165
6.1.1 Plants and catchment-level processes .....	165
6.1.2 Working premise concerning plants, isotopes and water use .....	166
6.2 Water Uptake and Water Transport in Plants .....	167
6.2.1 Background .....	167
6.2.2 Measurements of water uptake and transport by plants .....	169
6.3 Stomatal Regulation of Water Movement in the Soil-Plant-Atmosphere Continuum .....	173
6.3.1 Water movement and the regulatory role of plants: the leaf-level ...	173
6.3.2 Water movement and the regulatory role of plants: the stand-level .	175

6.4	Water Sources and Water Use by Plants: Case Studies Using Stable Isotopes . . . . .	177
6.4.1	Riparian forest communities . . . . .	178
6.4.2	Arid and semi-arid plant communities . . . . .	179
6.4.3	Temperate forest communities . . . . .	180
6.4.4	Coastal plant communities . . . . .	186
6.5	Current Issues Involving Plants and Catchment-Scale Hydrologic Processes . . . . .	188
6.5.1	Invasive plants and site water balance . . . . .	188
6.5.2	Stream diversions and riparian manipulations . . . . .	189
6.5.3	Deforestation, reforestation and desertification . . . . .	190
6.6	Long-term Record of Water Use by Plants . . . . .	192
6.7	Merging the Study of Stable Isotopes in Water with Studies of Water Uptake and Water Use in Plants and the Hydrology of Catchments . . . . .	194
 <b>CHAPTER 7: ISOTOPES IN GROUNDWATER HYDROLOGY . . . . .</b>		<b>203</b>
<i>R. Gonfiantini, K. Fröhlich, L. Araguás-Araguás and K. Rozanski</i>		
7.1	Introduction . . . . .	203
7.2	Isotopic Variations in Waters Recharging the Aquifers . . . . .	204
7.2.1	The isotopic composition of precipitation . . . . .	204
7.2.2	The isotopic composition of surface waters . . . . .	206
7.3	Isotopic Effects in the Unsaturated Zone . . . . .	207
7.3.1	Mechanisms of infiltration . . . . .	207
7.3.2	Water movement in the unsaturated zone . . . . .	207
7.3.3	Dissolution processes . . . . .	209
7.4	Shallow Aquifers . . . . .	211
7.4.1	Recharge by precipitation . . . . .	211
7.4.2	Recharge from surface waters . . . . .	214
7.4.3	Hydrodynamical models of shallow groundwater systems based on isotopic data . . . . .	217
7.5	Deep Groundwater . . . . .	225
7.5.1	Groundwater movement in confined aquifers . . . . .	225
7.5.2	Groundwater age . . . . .	225
7.5.3	Interconnections between aquifers . . . . .	233
7.5.4	Geothermal groundwaters . . . . .	234
7.6	Groundwater Studies in Catchments . . . . .	234
7.6.1	Present situation and case study examples . . . . .	234
7.6.2	Research trends and needs . . . . .	238
 <b>CHAPTER 8: LITHOGENIC AND COSMOGENIC TRACERS IN CATCHMENT HYDROLOGY . . . . .</b>		<b>247</b>
<i>G.J. Nimz</i>		
8.1	Introduction . . . . .	247
8.2	Processes that Affect Lithogenic and Cosmogenic Isotopic Compositions in Hydrologic Systems . . . . .	248

8.2.1	Lithogenic and cosmogenic solutes used in hydrologic analysis . . . .	248
8.2.2	Origin of lithogenic nuclides in natural waters: mineral reactions . . . . .	248
8.2.3	Origin of lithogenic nuclides in natural waters: trace element exchange . . . . .	249
8.2.4	Origin of isotopic variations: radiogenic nuclides . . . . .	251
8.2.5	Origin of isotopic variations: the mineral weathering sequence . . . .	253
8.2.6	Origin of isotopic variations: uranium isotopes and alpha recoil . . .	255
8.2.7	Origin of isotopic variations: cosmogenic nuclides . . . . .	257
8.2.8	Origin of isotopic variations: fission products . . . . .	258
8.2.9	Hydrologic application of cosmogenic nuclides . . . . .	259
8.3	The Application of Lithogenic and Cosmogenic Nuclides to Catchment Hydrology . . . . .	262
8.3.1	Input: precipitation, dry deposition, and throughfall . . . . .	263
8.3.2	The shallow system: hydrograph separation, weathering, and arid-region infiltration . . . . .	266
8.3.3	Evaporation / transpiration . . . . .	272
8.3.4	The deep system: groundwater flow . . . . .	272
8.3.5	System (basin) closure: mixing of water masses . . . . .	274
8.3.6	Streamflow: mass balance within the catchment . . . . .	276
8.3.7	Lithogenic and cosmogenic nuclides: summary . . . . .	276
8.4	New Directions in Lithogenic and Cosmogenic Nuclides . . . . .	277
8.4.1	The other geologic giant: neodymium . . . . .	277
8.4.2	Lithogenic elements with fractionating isotopes . . . . .	278
8.4.3	New directions in catchment hydrology for cosmogenic nuclides . . .	280
8.5	Lithogenic and Cosmogenic Tracers in Catchment Hydrology: Concluding Remarks . . . . .	281

**CHAPTER 9: DISSOLVED GASES IN SUBSURFACE HYDROLOGY . . . . . 291**  
*D.K. Solomon, P.G. Cook and W.E. Sanford*

9.1	Introduction . . . . .	291
9.2	Occurrence and Transport of Dissolved Gases . . . . .	291
9.3	Shallow Groundwater Dating . . . . .	294
9.3.1	$^3\text{H}/^3\text{He}$ . . . . .	297
9.3.2	Chlorofluorocarbons . . . . .	299
9.3.3	$^{85}\text{Kr}$ . . . . .	302
9.3.4	Radiogenic $^4\text{He}$ . . . . .	303
9.3.5	Field examples of groundwater dating . . . . .	305
9.4	Groundwater Surface-Water Interactions . . . . .	308
9.4.1	$^4\text{He}$ . . . . .	308
9.4.2	$^{222}\text{Rn}$ . . . . .	309
9.5	Injected Dissolved Gas Tracers . . . . .	309
9.5.1	Field example: noble gas tracer experiment . . . . .	311
9.6	Future Directions . . . . .	313

## PART III. CASE STUDIES IN ISOTOPE HYDROLOGY

<b>CHAPTER 10: OXYGEN AND HYDROGEN ISOTOPES IN RAINFALL-RUNOFF STUDIES</b> .....	<b>319</b>
<i>D.P. Genereux and R.P. Hooper</i>	
10.1 Introduction .....	319
10.2 Hydrograph Separation .....	320
10.2.1 Terminology .....	320
10.2.2 Requirements and assumptions in hydrograph separation .....	321
10.2.3 Findings and examples .....	321
10.2.4 Scale dependence of $f_{pe}$ values .....	330
10.2.5 Intra-component variability in tracer concentrations .....	332
10.2.6 Recommendations for field studies .....	338
10.3 New Directions .....	339
10.3.1 Subsurface mixing and residence time .....	339
10.3.2 Use of isotopes in model calibration .....	341
10.4 Conclusions .....	343
<b>CHAPTER 11: HIGH RAINFALL, RESPONSE-DOMINATED CATCHMENTS: A COMPARATIVE STUDY OF EXPERIMENTS IN TROPICAL NORTHEAST QUEENSLAND WITH TEMPERATE NEW ZEALAND</b> .....	<b>347</b>
<i>M. Bonell, C.J. Barnes, C.R. Grant, A. Howard and J. Burns</i>	
11.1 Introduction .....	347
11.2 Previous Studies in High Rainfall, Response - Dominated Catchments .....	348
11.2.1 The Maimai catchments .....	348
11.2.2 Linkages between the Maimai and Babinda studies .....	349
11.3 Physical Background .....	349
11.4 Experimental Methods .....	353
11.4.1 Precipitation .....	353
11.4.2 Streamflow .....	353
11.4.3 Hillslope instrumentation .....	354
11.5 Results: Event of February 16, 1991 .....	355
11.5.1 Antecedent catchment storage and rainfall-runoff of sample storm .....	355
11.5.2 Matric and hydraulic potential changes on sample slope transects .....	360
11.5.3 Hydrograph analysis .....	366
11.6 Stream Hydrograph Analysis and Isotopic Response .....	368
11.6.1 Event analysis - general considerations .....	368
11.6.2 Soil and groundwater isotopic changes .....	370
11.7 How High Rainfall Catchments Work .....	379
11.7.1 The Babinda model .....	379
11.7.2 The secondary store issue .....	382
11.7.3 New water dominance at Babinda vs old water dominance at Maimai .....	383
11.8 Future Research Directions .....	385

**CHAPTER 12: SNOWMELT-DOMINATED SYSTEMS ..... 391***A. Rodhe*

12.1	Introduction .....	391
12.1.1	Basic hydrological processes .....	392
12.1.2	Global geographical distribution .....	397
12.1.3	Isotopic characteristics of snowmelt .....	397
12.2	Hydrograph Separation Studies .....	399
12.2.1	Historical studies .....	399
12.2.2	Recent studies with more complete characterization .....	401
12.3	Vertical Unsaturated Flow .....	418
12.3.1	Estimates of groundwater recharge and particle velocity .....	419
12.3.2	Piston flow versus macropore flow .....	420
12.3.3	Transit times and flow pattern from lysimeter studies .....	422
12.3.4	Flow pattern in two and three dimensions .....	426
12.3.5	Implications for catchment flow studies .....	429
12.4	Conclusions and Future Research Directions .....	429

**CHAPTER 13: ARID CATCHMENTS ..... 435***N.L. Ingraham, E.A. Caldwell and B.Th. Verhagen*

13.1	Introduction .....	435
13.2	The Use of Isotopes in Arid Catchment Studies .....	437
13.2.1	Precipitation .....	437
13.2.2	Lakes .....	440
13.2.3	Rivers .....	441
13.2.4	Rivers displaying isotopic enrichment .....	443
13.2.5	Rivers without isotopic enrichment .....	446
13.2.6	Soil water .....	446
13.2.7	Infiltration and recharge in arid regions .....	447
13.2.8	Groundwater .....	451
13.2.9	The 'd' value in arid groundwater .....	452
13.3	Sampling .....	453
13.3.1	Precipitation .....	454
13.3.2	Surface water .....	454
13.3.3	Soil water .....	455
13.4	Non-Traditional Techniques .....	455
13.4.1	Strontium .....	456
13.4.2	<sup>3</sup> He/Tritium .....	457
13.4.3	Chlorine-36 .....	458
13.4.4	Noble Gases .....	459
13.4.5	Chlorofluorocarbons .....	460
13.5	Future Directions .....	460

**CHAPTER 14: GROUNDWATER AND SURFACE-WATER INTERACTIONS IN  
RIPARIAN AND LAKE-DOMINATED SYSTEMS** ..... 467  
*J.F. Walker and D.P. Krabbenhoft*

14.1	Introduction	467
14.1.1	Importance of lake-dominated systems	467
14.1.2	Dominant hydrological processes	467
14.2	Previous Studies in Lake Systems	469
14.3	Estimating Groundwater Exchange with Lakes	470
14.3.1	Stable-isotope mass-balance method	471
14.3.2	Index-lake method	474
14.4	Wisconsin WEBB Case Study	478
14.4.1	Study area	478
14.4.2	Study design	480
14.4.3	Isotopic flow-system progression	482
14.4.4	Isotopic complexity	484
14.5	Concluding Remarks	486

**PART IV. CASE STUDIES IN ISOTOPE GEOCHEMISTRY**

**CHAPTER 15: USE OF STABLE ISOTOPES IN EVALUATING SULFUR  
BIOGEOCHEMISTRY OF FOREST ECOSYSTEMS** ..... 489  
*M.J. Mitchell, H.R. Krouse, B. Mayer, A.C. Stam and Y. Zhang*

15.1	Introduction: Forest Ecosystem Sulfur Dynamics	489
15.2	Controls on Sulfur Isotope Composition	491
15.2.1	Isotope fractionation	492
15.2.2	Atmospheric sources of sulfur	495
15.2.3	Geological sources of sulfur	495
15.2.4	Sulfur isotopes in the hydrosphere	497
15.2.5	Sulfur isotopes in soil and terrestrial vegetation	499
15.3	Natural Abundance Studies	500
15.3.1	Hubbard Brook Experimental Forest, New Hampshire	500
15.3.2	Bear Brook Watershed, Maine	502
15.3.3	Experimental Lakes Area, Ontario, Canada	505
15.3.4	Rocky Mountains, Colorado and Wyoming	505
15.3.5	Black Forest, Germany	507
15.4	Applied Tracer Studies	508
15.4.1	Hubbard Brook Experimental Forest, New Hampshire	508
15.4.2	Bear Brook Watershed, Maine	510
15.4.3	West Whitecourt, Alberta, Canada	511
15.4.4	Bavaria, Germany	512
15.4.5	Höglwald, Germany	512
15.4.6	Black Forest, Germany	513
15.4.7	Skjervatjern Catchment, Norway	514
15.4.8	Lake Gårdsjön Catchment, Sweden	514
15.5	New Research Directions	514
15.6	Summary	515



**CHAPTER 16: TRACING NITROGEN SOURCES AND CYCLES IN CATCHMENTS . . . . . 519**
*C. Kendall*

16.1	Introduction . . . . .	519
16.1.1	Fundamentals of nitrogen isotopes . . . . .	520
16.1.2	Methods . . . . .	520
16.2	The Nitrogen Cycle . . . . .	523
16.2.1	Isotopic fractionations . . . . .	523
16.2.2	Processes affecting N isotopic compositions . . . . .	526
16.3	$\delta^{15}\text{N}$ Values of Nitrogen Sources and Reservoirs . . . . .	531
16.3.1	Atmospheric sources . . . . .	532
16.3.2	Fertilizers . . . . .	534
16.3.3	Animal waste . . . . .	534
16.3.4	Plants . . . . .	534
16.3.5	Soils . . . . .	535
16.3.6	Groundwaters . . . . .	537
16.4	$\delta^{18}\text{O}$ Values of Nitrate Sources and Reservoirs . . . . .	538
16.4.1	Atmospheric nitrate . . . . .	539
16.4.2	Synthetic fertilizers and reagents . . . . .	542
16.4.3	Microbial nitrate . . . . .	542
16.4.4	Other processes affecting nitrate $\delta^{18}\text{O}$ values . . . . .	545
16.5	Tracing Sources and Cycling of Nitrate . . . . .	545
16.5.1	Mixing . . . . .	547
16.5.2	Denitrification . . . . .	548
16.6	Application Studies . . . . .	552
16.6.1	Agricultural and urban sources of nitrate . . . . .	552
16.6.2	Sources of N in acid-rain affected forested catchments . . . . .	556
16.6.3	Nitrogen-limited systems . . . . .	560
16.6.4	Labeled-tracer studies . . . . .	560
16.6.5	Food web studies . . . . .	562
16.7	New Frontiers . . . . .	563
16.7.1	Applications of the dual isotope method . . . . .	564
16.7.2	Tracing sources and sinks for DOM . . . . .	564
16.7.3	Applications of compound-specific isotope ratio mass spectrometry . . . . .	565
16.7.4	Use of isotopic techniques to assess impacts of changes in land-management practices and landuse on water quality . . . . .	566
16.7.5	Use of a multi-isotope or multi-tracer approach . . . . .	568
16.7.6	Development of linked hydrologic/geochemical models . . . . .	568
16.8	Summary . . . . .	569

<b>CHAPTER 17: CARBON CYCLING IN TERRESTRIAL ENVIRONMENTS</b> .....	<b>577</b>
<i>Y. Wang, T.G. Huntington, L.J. Osher, L.I. Wassenaar, S.E. Trumbore, R.G. Amundson, J.W. Harden, D.M. McKnight, S.L. Schiff, G.R. Aiken, W.B. Lyons, R.O. Aravena and J.S. Baron</i>	
17.1 Introduction .....	577
17.2 Carbon Isotopes and Terminology .....	578
17.3 Carbon Dynamics in Soils .....	580
17.3.1 $^{14}\text{C}$ age of soil organic matter .....	581
17.3.2 Use of $^{14}\text{C}$ to study C turnover in soils .....	585
17.3.3 The use of $^{13}\text{C}$ to study C turnover in soils .....	590
17.3.4 Use of carbon isotopes in understanding carbon dynamics in peatlands .....	593
17.4 Isotope Studies of Dissolved Organic Matter in Groundwater .....	595
17.4.1 Stable carbon isotopes .....	598
17.4.2 Nitrogen, sulfur and hydrogen isotopes .....	599
17.4.3 Radiocarbon in DOC .....	599
17.5 Isotope Study of DOC in Lacustrine Environments .....	600
17.6 Isotope Studies and the Carbon Budget .....	602
<b>CHAPTER 18: TRACING OF WEATHERING REACTIONS AND WATER FLOWPATHS: A MULTI-ISOTOPE APPROACH</b> .....	<b>611</b>
<i>T.D. Bullen and C. Kendall</i>	
18.1 Introduction .....	611
18.1.1 Rationale for using water and solute isotopes as tracers in catchments .....	611
18.1.2 Theoretical bases of the strontium, lead and carbon isotope systems .....	613
18.1.3 Geological/environmental factors leading to successful tracing with solute isotopes .....	618
18.2 Influences on Isotopic Composition of Sr, Pb and C in Catchment Waters .....	619
18.2.1 Lithologic controls on the isotopic composition of strontium and lead .....	619
18.2.2 Atmospheric/anthropogenic inputs of Sr, Pb, and C .....	624
18.2.3 Effects of organic and inorganic cycling on isotopic composition of carbon .....	625
18.3 Multi-Isotope Studies at Selected Watersheds .....	627
18.3.1 The combined use of O, H and Sr isotopes to understand differences in chemical evolution along different flowpaths in a sandy aquifer in northern Wisconsin .....	627
18.3.2 Sr, Pb and C isotopes as surrogate tracers of water movement at a catchment nested in calc-silicate rocks, Sleepers River, Vermont .....	630
18.3.3 C and Sr isotopes as tracers of sources of carbonate alkalinity at Catoclin Mountain, Maryland .....	635
18.3.4 Synthesis: an isotopic view of a catchment .....	638
18.4 Additional Solute Isotope Tracers: Li, B, Fe .....	640
18.5 Summary .....	643

**CHAPTER 19: EROSION, WEATHERING, AND SEDIMENTATION ..... 647**

*P.R. Bierman, A. Albrecht, M.H. Bothner, E.T. Brown, T.D. Bullen,  
L.B. Gray and L. Turpin*

19.1	Introduction .....	647
19.2	In Situ Produced Cosmogenic Nuclides .....	648
19.2.1	Cosmogenic nuclides in exposed outcrops .....	648
19.2.2	Cosmogenic nuclides in sediments .....	650
19.2.3	Case studies .....	652
19.3	Atmospheric Nuclides: $^{210}\text{Pb}$ .....	655
19.3.1	Methods .....	656
19.3.2	Interpretation .....	658
19.3.3	Applications .....	659
19.4	Combined Approaches To Catchment Landscape Analysis: $^{137}\text{Cs}$ and $^{210}\text{Pb}$ ...	659
19.4.1	Lake sediments .....	660
19.4.2	Soils .....	661
19.4.3	Water samples .....	662
19.4.4	Case studies .....	662
19.5	Tracing of Sediment Sources and Identification of Erosion Processes Using Natural and Anthropogenic Radionuclides .....	666
19.5.1	Nuclides of importance .....	667
19.5.2	Case studies .....	668
19.6	Sr and Weathering .....	670
19.6.1	Weathering and $^{87}\text{Sr}/^{86}\text{Sr}$ .....	670
19.6.2	Typical $^{87}\text{Sr}/^{86}\text{Sr}$ ratios .....	672
19.6.3	Sr isotopes as tracers of solute sources .....	672

**CHAPTER 20: APPLICATIONS OF URANIUM- AND THORIUM-SERIES RADIONUCLIDES  
IN CATCHMENT HYDROLOGY STUDIES ..... 679**

*T.F. Kraemer and D.P. Genereux*

20.1	Introduction .....	679
20.2	Review of Fundamental Concepts .....	680
20.2.1	Decay chains and radioactive equilibrium .....	680
20.2.2	Physical and chemical processes that redistribute U and Th series radionuclides .....	681
20.3	Radon Techniques in Catchment Hydrology .....	688
20.3.1	General considerations, mixing models .....	688
20.3.2	Mixing model without correction for volatilization .....	689
20.3.3	Mixing model with degassing correction through stagnant film model .....	691
20.3.4	Mixing model with degassing correction through an injected tracer .	695
20.3.5	Mixing model, with partitioning of water inflow into different sources .....	699
20.4	Radium Isotopic Techniques in Catchment Hydrology .....	705
20.4.1	General considerations .....	705
20.4.2	Radium as a tracer for groundwater input to an estuary system ....	705

20.4.3	Use of $^{228}\text{Ra}$ and $^{226}\text{Ra}$ in quantifying groundwater input to a stream: conservative mixing	709
20.4.4	Use of $^{228}\text{Ra}$ and $^{226}\text{Ra}$ in quantifying groundwater input to a stream: non-conservative mixing	713
20.4.5	Use of $^{228}\text{Ra}$ and $^{226}\text{Ra}$ in quantifying three end-member conservative mixing	714
20.4.6	Using $^{224}\text{Ra}$ and $^{226}\text{Ra}$ to determine residence time of water in short-residence time reservoirs	716
20.4.7	Using radium isotopes to identify the source of water issuing from springs	718
20.5	New Research Directions	719

## PART V. SYNTHESIS

<b>CHAPTER 21: MODELING OF ISOTOPES AND HYDROGEOCHEMICAL RESPONSES IN CATCHMENT HYDROLOGY</b>	<b>723</b>	
<i>J.V. Turner and C.J. Barnes</i>		
21.1	Introduction	723
21.1.1	Some definitions and terms	726
21.2	Limitations of the Mass Balance Hydrograph Separation Approach	727
21.2.1	Mass balance hydrograph separation models	727
21.3	Estimation of Transit Times - System Response Functions of Catchments	732
21.3.1	System response functions	732
21.3.2	System response functions based on the IUH	733
21.3.3	Application of system response functions based on the Instantaneous Unit Hydrograph	738
21.3.4	Identifying "old" and "new" water in terms of system response functions	741
21.3.5	Time series approaches to system response functions	742
21.3.6	Kalman filtering and residence times	744
21.4	Comparisons of Models of Isotopic and Chemical Hydrograph Separation	751
21.5	New Research Directions	757
<b>CHAPTER 22: ISOTOPES AS INDICATORS OF ENVIRONMENTAL CHANGE</b>	<b>761</b>	
<i>J.B. Shanley, E. Pendall, C. Kendall, L.R. Stevens, R.L. Michel, P.J. Phillips, R.M. Forester, D.L. Naftz, B. Liu, L. Stern, B.B. Wolfe, C.P. Chamberlain, S.W. Leavitt, T.H.E. Heaton, B. Mayer, L.D. Cecil, W.B. Lyons, B.G. Katz, J.L. Betancourt, D.M. McKnight, J.D. Blum, T.W.D. Edwards, H.R. House, E. Ito, R.O. Aravena and J.F. Whelan</i>		
22.1	Introduction	761
22.1.1	Direct and proxy records of environmental change	762
22.2	Recent Environmental Change Indicators	763
22.2.1	Groundwater dating	763

22.2.2	Direct use of water isotopes to infer recent global change	765
22.2.3	Changes in land use deduced from tracer studies	766
22.2.4	Isotope tracers for tracking migratory patterns of birds	768
22.2.5	Changes in atmospheric deposition	771
22.3	Paleo-Climatic Indicators	776
22.3.1	Groundwater as an archive of paleo-climatic information	776
22.3.2	Continental glaciers	778
22.3.3	Clay minerals, oxides, and hydroxides	780
22.3.4	Pedogenic carbonates	782
22.3.5	Paleoenvironmental reconstruction from stable isotopes in tree rings and plant fossils	785
22.3.6	Lacustrine environments: organics	792
22.3.7	Lacustrine environments: authigenic carbonates	795
22.3.8	Lacustrine environments: ostracodes	799
22.4	New Research Directions	802
22.5	Summary	803

A web page for this book is located at URL <http://wwwrcamnl.wr.usgs.gov/isoig/isopubs/>. This page includes copies of the table of contents and the index, colored versions of selected non-copyrighted figures that can be downloaded for teaching purposes, a list of errata, selected portions of the non-copyrighted chapters and other useful isotope-related information. These listings will be searchable on-line.