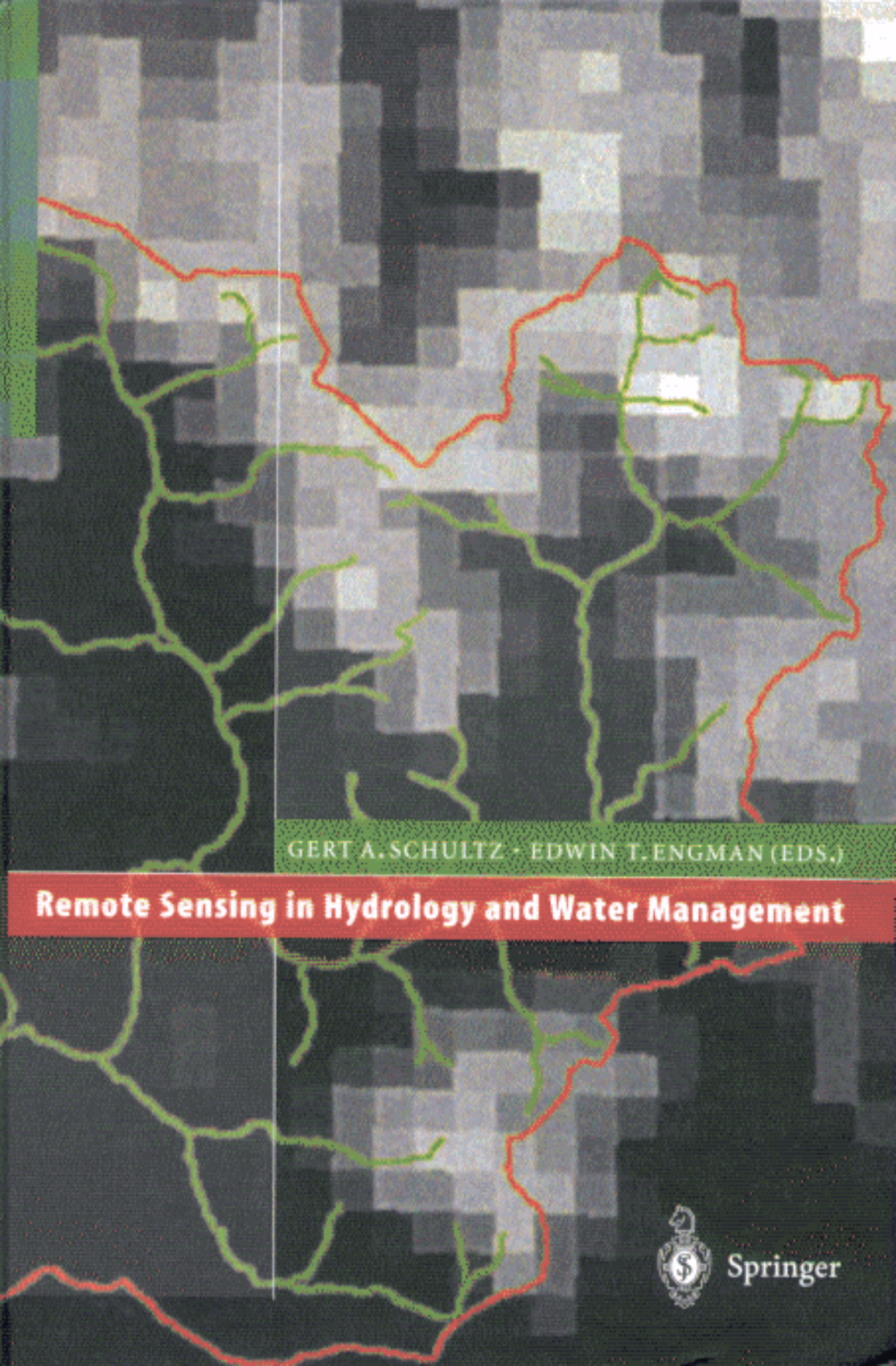




GERT A. SCHULTZ · EDWIN T. ENGMAN (EDS.)

**Remote Sensing in Hydrology and Water Management**



Springer

# Contents

|                                                                                                             |     |
|-------------------------------------------------------------------------------------------------------------|-----|
| <b>Preface</b> .....                                                                                        | V   |
| <b>About the Editors</b> .....                                                                              | VII |
| <b>Authors</b> .....                                                                                        | IX  |
| <b>Section I: Overview and Basic Principles</b> .....                                                       | 1   |
| <b>Chapter 1 Introduction</b> .....                                                                         | 3   |
| 1.1 Introduction.....                                                                                       | 3   |
| 1.2 Remote Sensing Defined.....                                                                             | 3   |
| 1.3 The Nature of Remote Sensing Data.....                                                                  | 4   |
| 1.4 Satellite Systems.....                                                                                  | 6   |
| 1.4.1 Remote Sensing Platforms .....                                                                        | 6   |
| 1.4.2 Remote Sensing Sensors .....                                                                          | 9   |
| 1.4.3 Spatial Resolution .....                                                                              | 10  |
| 1.4.4 Temporal Resolution .....                                                                             | 12  |
| 1.5 Remote Sensing and Hydrology.....                                                                       | 12  |
| 1.6 Structure of the Book.....                                                                              | 13  |
| <b>Chapter 2 Physical Principles and Technical Aspects of Remote Sensing</b> .....                          | 15  |
| 2.1 Introduction.....                                                                                       | 15  |
| 2.2 The Electromagnetic Spectrum and Radiation Laws .....                                                   | 15  |
| 2.3 Atmospheric Propagation .....                                                                           | 21  |
| 2.4 Reflection and Emission Characteristics of Natural Media... ..                                          | 26  |
| 2.5 Sensor Principles .....                                                                                 | 30  |
| 2.6 Summary of Current and Future Earth Observation Missions .....                                          | 37  |
| <b>Chapter 3 Processing Remotely Sensed Data: Hardware and Software Considerations</b> .....                | 41  |
| 3.1 Image Processing System Characteristics .....                                                           | 41  |
| 3.1.1 The Central Processing Unit (CPU): Personal Computers, Workstations and Mainframes .....              | 41  |
| 3.1.2 Number of Analysts on a System and Mode of Operation ... ..                                           | 44  |
| 3.1.3 Serial versus Parallel Image Processing, Arithmetic Coprocessor, and Random Access Memory (RAM) ..... | 44  |
| 3.1.4 Operating System and Software Compilers .....                                                         | 46  |
| 3.1.5 Mass Storage.....                                                                                     | 47  |
| 3.1.6 Screen Display Resolution .....                                                                       | 48  |

|       |                                                                            |    |
|-------|----------------------------------------------------------------------------|----|
| 3.1.7 | Screen Color Resolution .....                                              | 49 |
| 3.1.8 | Image Scanning (Digitization) Considerations.....                          | 49 |
| 3.2   | Image Processing and GIS Software Requirement .....                        | 50 |
| 3.2.1 | Preprocessing.....                                                         | 52 |
| 3.2.2 | Display and Enhancement .....                                              | 52 |
| 3.2.3 | Remote Sensing Information Extraction .....                                | 53 |
| 3.2.4 | Photogrammetric Information Extraction .....                               | 54 |
| 3.2.5 | Metadata and Image/Map Lineage Documentation.....                          | 54 |
| 3.2.6 | Image and Map Cartographic Composition .....                               | 57 |
| 3.2.7 | Geographic Information Systems (GIS) .....                                 | 57 |
| 3.2.8 | Utilities .....                                                            | 57 |
| 3.3   | Commercial and Publicly Available Digital Image<br>Processing Systems..... | 58 |
| 3.4   | Summary .....                                                              | 58 |

|                  |                                                                                            |           |
|------------------|--------------------------------------------------------------------------------------------|-----------|
| <b>Chapter 4</b> | <b>Integration of Remotely Sensed Data into Geographical<br/>Information Systems .....</b> | <b>65</b> |
| 4.1              | Introduction .....                                                                         | 65        |
| 4.2              | General Approach .....                                                                     | 67        |
| 4.2.1            | Raster and Vector Data Structures .....                                                    | 67        |
| 4.2.2            | Current Approaches to the Integration.....                                                 | 70        |
| 4.2.3            | Errors Associated with Geographical Processing .....                                       | 71        |
| 4.3              | Current Applications.....                                                                  | 72        |
| 4.3.1            | Watershed Database Development.....                                                        | 72        |
| 4.3.2            | Integrated Use of Elevation Data .....                                                     | 73        |
| 4.3.3            | Land-use/Land-cover Change Detection.....                                                  | 74        |
| 4.3.4            | Modeling Watershed Runoff.....                                                             | 75        |
| 4.3.5            | Monitoring and Modeling of Water Quality.....                                              | 76        |
| 4.3.6            | Soil Erosion Monitoring.....                                                               | 77        |
| 4.4              | Future Perspectives.....                                                                   | 78        |

|                    |                                                                                  |           |
|--------------------|----------------------------------------------------------------------------------|-----------|
| <b>Section II:</b> | <b>Remote Sensing Application to Hydrologic<br/>Monitoring and Modeling.....</b> | <b>83</b> |
|--------------------|----------------------------------------------------------------------------------|-----------|

|                  |                                                                 |           |
|------------------|-----------------------------------------------------------------|-----------|
| <b>Chapter 5</b> | <b>Remote Sensing in Hydrological Modeling .....</b>            | <b>85</b> |
| 5.1              | Introduction .....                                              | 85        |
| 5.2              | Remote Sensing in Operational Hydrologic Modeling .....         | 87        |
| 5.3              | Remote Sensing in Coupled Water-Energy<br>Balance Modeling..... | 90        |
| 5.4              | Remote Sensing Approach .....                                   | 92        |
| 5.4.1            | Solar radiation .....                                           | 92        |
| 5.4.2            | Downwelling longwave .....                                      | 93        |
| 5.4.3            | Precipitation.....                                              | 94        |
| 5.4.4            | Air Temperature .....                                           | 94        |
| 5.4.5            | Surface Air Humidity.....                                       | 95        |

|     |                                                      |    |
|-----|------------------------------------------------------|----|
| 5.5 | Modeling Example: The Red River Arkansas Basin ..... | 96 |
| 5.6 | Future Directions .....                              | 97 |

|                                          |            |
|------------------------------------------|------------|
| <b>Colour Plates of Chaps. 2-5 .....</b> | <b>103</b> |
|------------------------------------------|------------|

|                  |                                                                                |            |
|------------------|--------------------------------------------------------------------------------|------------|
| <b>Chapter 6</b> | <b>Precipitation .....</b>                                                     | <b>111</b> |
| 6.1              | Introduction .....                                                             | 111        |
| 6.2              | General Approach .....                                                         | 112        |
| 6.2.1            | Ground-based radar .....                                                       | 112        |
| 6.2.2            | Use of visible and infrared satellite data .....                               | 114        |
| 6.2.3            | Use of passive microwave satellite data .....                                  | 114        |
| 6.2.4            | Space-borne radar .....                                                        | 115        |
| 6.3              | Current Techniques .....                                                       | 115        |
| 6.3.1            | Single polarisation radar measurements of rainfall .....                       | 115        |
| 6.3.2            | Measurement of snowfall and hail .....                                         | 118        |
| 6.3.3            | Multi-parameter radar .....                                                    | 120        |
| 6.3.4            | Satellite cloud indexing and life history methods of rainfall estimation ..... | 121        |
| 6.3.5            | Bispectral techniques .....                                                    | 123        |
| 6.3.6            | Passive microwave estimates of rainfall from space .....                       | 124        |
| 6.3.7            | Sampling errors .....                                                          | 126        |
| 6.4              | The potential for improvement .....                                            | 127        |
| 6.4.1            | Current performance levels .....                                               | 127        |
| 6.4.2            | The future .....                                                               | 128        |
| <b>Chapter 7</b> | <b>Land-use and Catchment Characteristics .....</b>                            | <b>133</b> |
| 7.1              | Introduction .....                                                             | 133        |
| 7.2              | Land cover Mapping with Remote Sensing .....                                   | 134        |
| 7.3              | Vegetation Indices .....                                                       | 135        |
| 7.3.1            | Simple Vegetation Indices .....                                                | 136        |
| 7.3.2            | Normalized Difference Vegetation Index (NDVI) .....                            | 138        |
| 7.3.3            | Refined estimates .....                                                        | 139        |
| 7.3.4            | Multi-temporal Vegetation Index .....                                          | 140        |
| 7.4              | Thematic Classification .....                                                  | 140        |
| 7.4.1            | Image Classification Methods .....                                             | 142        |
| 7.4.2            | Maximum Likelihood Classification .....                                        | 145        |
| 7.4.3            | Discussion .....                                                               | 147        |
| 7.4.4            | Probability estimation refinements .....                                       | 147        |
| 7.4.5            | Segmentation .....                                                             | 149        |
| 7.4.6            | Case study in the Pantanal Area, Brazil .....                                  | 150        |
| 7.5              | Radar .....                                                                    | 152        |
| <b>Chapter 8</b> | <b>Evaporation .....</b>                                                       | <b>157</b> |
| 8.1.             | Introduction .....                                                             | 157        |
| 8.1.1            | General .....                                                                  | 157        |
| 8.1.2            | Remote sensing of land evaporation .....                                       | 158        |

|       |                                                                                            |     |
|-------|--------------------------------------------------------------------------------------------|-----|
| 8.2   | Evaporation and radiometric variables .....                                                | 160 |
| 8.2.1 | Potential Evaporation .....                                                                | 160 |
| 8.2.2 | Actual Evaporation .....                                                                   | 162 |
| 8.3   | Remote Sensing of Land Evaporation: Applications and<br>Modelling Approaches .....         | 165 |
| 8.3.1 | General .....                                                                              | 165 |
| 8.3.2 | Linear relationships between evaporation and land surface<br>temperature [1] .....         | 166 |
| 8.3.3 | Improved linear relationships [2] .....                                                    | 167 |
| 8.3.4 | Relationships between evaporation, surface, temperature<br>and spectral indices [3]. ..... | 168 |
| 8.3.5 | Soil Vegetation Atmosphere Transfer<br>(SVAT) models [4]. .....                            | 169 |
| 8.3.6 | Integrated SVAT and Planetary Boundary Layer (PBL)<br>models [5] .....                     | 170 |
| 8.4   | Current trends: improved observations and improved<br>parameterizations .....              | 171 |
| 8.4.1 | Local maximum evaporation<br>and land surface temperature [6] .....                        | 171 |
| 8.4.2 | Improved observation of land surface variables [7] .....                                   | 174 |
| 8.5   | Spatial variability .....                                                                  | 177 |
| 8.6   | Accuracy .....                                                                             | 178 |
| 8.7   | Applications .....                                                                         | 179 |
| 8.8   | Current and Future Observations .....                                                      | 180 |
| 8.9   | Summary and Conclusions .....                                                              | 181 |

|                                          |            |
|------------------------------------------|------------|
| <b>Colour Plates of Chaps. 6-8 .....</b> | <b>189</b> |
|------------------------------------------|------------|

|                  |                                                        |            |
|------------------|--------------------------------------------------------|------------|
| <b>Chapter 9</b> | <b>Soil Moisture .....</b>                             | <b>197</b> |
| 9.1              | Introduction .....                                     | 197        |
| 9.2              | General Approach .....                                 | 198        |
| 9.3              | Sensor-Target Interactions .....                       | 202        |
| 9.4              | Hydrologic Examples .....                              | 209        |
| 9.5              | Future Microwave Remote Sensing of Soil Moisture ..... | 212        |

|                   |                                              |            |
|-------------------|----------------------------------------------|------------|
| <b>Chapter 10</b> | <b>Remote Sensing of Surface Water .....</b> | <b>217</b> |
| 10.1              | Introduction .....                           | 217        |
| 10.2              | Surface Water Detection .....                | 218        |
| 10.3              | Lake and Reservoir Area Estimates .....      | 220        |
| 10.4              | Wetlands .....                               | 223        |
| 10.5              | Lake Levels .....                            | 224        |
| 10.6              | River Levels and Flows .....                 | 226        |
| 10.7              | Flood Extent .....                           | 230        |
| 10.8              | Conclusion .....                             | 233        |

|                                           |                                                                |     |
|-------------------------------------------|----------------------------------------------------------------|-----|
| <b>Chapter 11</b>                         | <b>Snow and Ice</b> .....                                      | 239 |
| 11.1                                      | Role of Snow and Ice .....                                     | 239 |
| 11.2                                      | General Approach .....                                         | 240 |
| 11.2.1                                    | Gamma Radiation .....                                          | 240 |
| 11.2.2                                    | Visible Imagery .....                                          | 242 |
| 11.2.3                                    | Thermal Infrared .....                                         | 244 |
| 11.2.4                                    | Passive and Active Microwave .....                             | 244 |
| 11.2.5                                    | Related Applications .....                                     | 248 |
| 11.3                                      | Current Applications .....                                     | 249 |
| 11.3.1                                    | NOHRSC- Snow Cover and Snow Water<br>Equivalent Products ..... | 249 |
| 11.3.2                                    | Canadian Prairie Snow Water Equivalent Mapping .....           | 250 |
| 11.3.3                                    | Snowmelt Runoff Forecast Operations .....                      | 252 |
| 11.4                                      | Future Directions .....                                        | 255 |
| 11.4.1                                    | Improved Resolution in the Passive Microwave .....             | 255 |
| 11.4.2                                    | Improved Algorithms in the Passive Microwave .....             | 256 |
| 11.4.3                                    | Outlook for Radar Applications .....                           | 256 |
| 11.4.4                                    | Integration of Various Data Types .....                        | 257 |
| <b>Colour Plates of Chaps. 9-11</b> ..... |                                                                | 263 |
| <b>Chapter 12</b>                         | <b>Soil Erosion</b> .....                                      | 271 |
| 12.1                                      | Introduction .....                                             | 271 |
| 12.2                                      | Basis for using Remote Sensing .....                           | 273 |
| 12.3                                      | Applications .....                                             | 274 |
| 12.4                                      | Case Studies .....                                             | 276 |
| 12.4.1                                    | Photointerpretation/Photogrammetry .....                       | 277 |
| 12.4.2                                    | Model/GIS Inputs .....                                         | 279 |
| 12.4.3                                    | Spectral Properties .....                                      | 280 |
| 12.4.4                                    | Topographic Measurements .....                                 | 281 |
| 12.5                                      | Future Directions .....                                        | 282 |
| <b>Chapter 13</b>                         | <b>Water Quality</b> .....                                     | 287 |
| 13.1                                      | Introduction .....                                             | 287 |
| 13.2                                      | Basis for using Remote Sensing .....                           | 288 |
| 13.3                                      | Application .....                                              | 290 |
| 13.4                                      | Case Studies .....                                             | 291 |
| 13.4.1                                    | Suspended Sediments .....                                      | 291 |
| 13.4.2                                    | Chlorophyll .....                                              | 294 |
| 13.4.3                                    | Temperature .....                                              | 297 |
| 13.4.4                                    | Oils .....                                                     | 298 |
| 13.5                                      | Future Directions .....                                        | 299 |
| <b>Chapter 14</b>                         | <b>Groundwater</b> .....                                       | 305 |
| 14.1                                      | Introduction .....                                             | 305 |
| 14.2                                      | Conceptualization of the hydrogeology .....                    | 306 |

|        |                                                         |     |
|--------|---------------------------------------------------------|-----|
| 14.2.1 | The three dimensional hydrogeologic situation . . . . . | 306 |
| 14.2.2 | Groundwater surface. . . . .                            | 309 |
| 14.2.3 | Flow systems . . . . .                                  | 310 |
| 14.3   | Aspects of water budgets . . . . .                      | 312 |
| 14.3.1 | Groundwater irrigation drafts . . . . .                 | 312 |
| 14.3.2 | Recharge. . . . .                                       | 313 |
| 14.4   | Hard rock terrain and lineaments . . . . .              | 319 |
| 14.5   | Groundwater management and conclusions . . . . .        | 321 |
| 14.6   | Conclusions and future perspectives . . . . .           | 322 |

### **Section III: Water Management with the Aid of Remote Sensing Data . . . . . 327**

|                   |                                                                                                      |            |
|-------------------|------------------------------------------------------------------------------------------------------|------------|
| <b>Chapter 15</b> | <b>Introduction to and General Aspects of Water Management with the aid of Remote Sensing. . . .</b> | <b>329</b> |
| 15.1              | Introduction . . . . .                                                                               | 329        |
| 15.2              | Potential of remote sensing in water management. . . . .                                             | 329        |
| 15.2.1            | Surveying and mapping . . . . .                                                                      | 330        |
| 15.2.2            | Spatial analysis and regionalization . . . . .                                                       | 332        |
| 15.2.3            | Monitoring and forecasting . . . . .                                                                 | 332        |
| 15.3              | River basin planning with the aid of remote sensing. . . . .                                         | 334        |
| 15.3.1            | Introduction . . . . .                                                                               | 334        |
| 15.3.2            | Hydrologic monitoring & forecasting . . . . .                                                        | 334        |
| 15.3.3            | Upstream-downstream interrelationships in river basins . . . .                                       | 335        |
| 15.4              | Watershed management with the aid of remote sensing. . . .                                           | 338        |
| 15.4.1            | Introduction . . . . .                                                                               | 338        |
| 15.4.2            | Hydrologic photo-interpretation for watershed management . . . . .                                   | 338        |
| 15.5              | Small-scale water resource development and remote sensing . . . . .                                  | 340        |
| 15.5.1            | Introduction . . . . .                                                                               | 340        |
| 15.5.2            | Runoff water harvesting with the aid of remote sensing. . . .                                        | 340        |
| 15.5.3            | Flood spreading and groundwater recharge . . . . .                                                   | 341        |
| 15.6              | Irrigation water management and remote sensing . . . . .                                             | 341        |
| 15.7              | Decision support systems for water management . . . . .                                              | 342        |
| 15.7.1            | Introduction . . . . .                                                                               | 342        |
| 15.7.2            | Expert and decision support systems . . . . .                                                        | 342        |

### **Colour Plates of Chaps. 12-15 . . . . . 349**

|                   |                                                |            |
|-------------------|------------------------------------------------|------------|
| <b>Chapter 16</b> | <b>Flood Forecasting and Control . . . . .</b> | <b>357</b> |
| 16.1              | Introduction . . . . .                         | 357        |
| 16.2              | General Approach. . . . .                      | 358        |
| 16.2.1            | Modeling Philosophy . . . . .                  | 358        |

|        |                                                                                                         |     |
|--------|---------------------------------------------------------------------------------------------------------|-----|
| 16.2.2 | Remote Sensing Data, Types and Acquisition .....                                                        | 360 |
| 16.2.3 | Determination of Hydro-meteorological Information from Remote Sensing Data. ....                        | 360 |
| 16.2.4 | Transformation of Area Precipitation into a Real-time Forecast of a Runoff Hydrograph .....             | 362 |
| 16.3   | Real-time Flood Control with the Aid of Flood Forecasts Based on Remote Sensing Data – an Example ..... | 365 |
| 16.3.1 | Basic Principle .....                                                                                   | 365 |
| 16.3.2 | Radar Rainfall Measurements in the Günz River Catchment .....                                           | 367 |
| 16.3.3 | Quantitative Precipitation Forecast (QPF) .....                                                         | 368 |
| 16.3.4 | Rainfall-Runoff-Model Application for Flood Forecasting ..                                              | 368 |
| 16.3.5 | Optimum Reservoir Operation Based on Forecast Flood Hydrographs .....                                   | 370 |
| 16.4   | Flood Forecasting and Control in an Urban Environment ..                                                | 372 |
| 16.5   | Future Perspectives .....                                                                               | 375 |

|                   |                                                                         |            |
|-------------------|-------------------------------------------------------------------------|------------|
| <b>Chapter 17</b> | <b>Irrigation and Drainage .....</b>                                    | <b>377</b> |
| 17.1              | Introduction .....                                                      | 377        |
| 17.1.1            | Current non-remote sensing approaches and limitations ....              | 378        |
| 17.1.2            | Reviews of remote sensing applications in irrigation and drainage ..... | 379        |
| 17.2              | General Approach .....                                                  | 380        |
| 17.2.1            | Applications versus Observables and Algorithms .....                    | 380        |
| 17.2.2            | Theory and conceptual approach .....                                    | 380        |
| 17.2.3            | Examples of applications .....                                          | 386        |
| 17.3              | Current Applications .....                                              | 387        |
| 17.3.1            | General .....                                                           | 387        |
| 17.3.2            | High resolution mapping of irrigated lands .....                        | 389        |
| 17.3.3            | Crop water requirements – Visible and Near Infrared .....               | 390        |
| 17.3.4            | Crop water stress – Thermal Infrared .....                              | 391        |
| 17.3.5            | Catchment hydrology .....                                               | 392        |
| 17.3.6            | Detection of saline areas .....                                         | 392        |
| 17.3.7            | Irrigation management .....                                             | 393        |
| 17.4              | Current and future observations .....                                   | 394        |
| 17.5              | Future Directions and Potential .....                                   | 395        |

|                   |                                                                                                               |            |
|-------------------|---------------------------------------------------------------------------------------------------------------|------------|
| <b>Chapter 18</b> | <b>Computation of Hydrological Data for Design of Water Projects in Ungauged River Basins .....</b>           | <b>401</b> |
| 18.1              | Introduction .....                                                                                            | 401        |
| 18.2              | General Approach .....                                                                                        | 403        |
| 18.2.1            | MODUL I: Satellite system, data processing .....                                                              | 403        |
| 18.2.2            | MODUL II: Assessment of the monthly area precipitation on the basis of multi-temporal satellite imagery ..... | 406        |

|                                              |                                                                                                                    |            |
|----------------------------------------------|--------------------------------------------------------------------------------------------------------------------|------------|
| 18.2.3                                       | MODUL III: Estimation of runoff values .....                                                                       | 409        |
| 18.3                                         | Application .....                                                                                                  | 410        |
| 18.3.1                                       | Study area and data used .....                                                                                     | 410        |
| 18.3.2                                       | Assessment of the monthly area precipitation with the aid<br>of multi-temporal B2-Meteosat satellite imagery ..... | 411        |
| 18.3.3                                       | Rainfall – Runoff Model .....                                                                                      | 413        |
| 18.4                                         | Further Applications .....                                                                                         | 414        |
| 18.5                                         | Summary and Discussion .....                                                                                       | 416        |
| <b>Chapter 19</b>                            | <b>Detection of Land Cover Change Tendencies and<br/>their Effect on Water Management .....</b>                    | <b>419</b> |
| 19.1                                         | General Remarks .....                                                                                              | 419        |
| 19.2                                         | Hydrological Modelling and Land Cover Change .....                                                                 | 422        |
| 19.3                                         | A Case Study: Land Use Change Detection by Remote<br>Sensing in the Sauer River Basin, Western Europe .....        | 424        |
| 19.4                                         | Summary .....                                                                                                      | 432        |
| <b>Colour Plates of Chaps. 16-19 .....</b>   |                                                                                                                    | <b>435</b> |
| <b>Section IV: Future Perspectives .....</b> |                                                                                                                    | <b>443</b> |
| <b>Chapter 20</b>                            | <b>Future Perspectives .....</b>                                                                                   | <b>445</b> |
| 20.1                                         | Introduction .....                                                                                                 | 445        |
| 20.2                                         | Status of Hydrologic Research and Modeling .....                                                                   | 446        |
| 20.3                                         | Water Management .....                                                                                             | 448        |
| 20.4                                         | Data Issues in Hydrology<br>and Water Resources Management .....                                                   | 449        |
| 20.5                                         | Intensive Field Campaigns .....                                                                                    | 452        |
| 20.6                                         | Existing Sensors and Platforms .....                                                                               | 453        |
| 20.7                                         | Planned and Proposed Sensors and Platforms .....                                                                   | 454        |
| 20.8                                         | Remote Sensing and Future Needs in Hydrology .....                                                                 | 456        |
| <b>Appendix 20.1</b>                         | <b>Existing and Future Remote Sensing Satellites and<br/>Sensors Relevant to Hydrological Applications .....</b>   | <b>458</b> |
| <b>Appendix 20.2</b>                         | <b>Specification for Sensors Listed in Appendix 20.1 .....</b>                                                     | <b>461</b> |
| <b>List of Acronyms .....</b>                |                                                                                                                    | <b>471</b> |
| <b>Index .....</b>                           |                                                                                                                    | <b>475</b> |