Fluvial Remote Sensing for Science and Management

Patrice E. Carbonneau • Hervé Piégay

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Fluvial Remote Sensing for Science and Management
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## Contents

Series Foreword, xv

Foreword, xvii

List of Contributors, xix

1 Introduction: The Growing Use of Imagery in Fundamental and Applied River Sciences, 1
   Patrice E. Carbonneau and Hervé Piégay
      1.1 Introduction, 1
      1.2 Remote sensing, river sciences and management, 2
         1.2.1 Key concepts in remote sensing, 2
         1.2.2 A short introduction to ‘river friendly’ sensors and platforms, 4
         1.2.3 Cost considerations, 7
      1.3 Evolution of published work in Fluvial Remote Sensing, 8
         1.3.1 Authorships and Journals, 9
         1.3.2 Platforms and Sensors, 9
         1.3.3 Topical Areas, 10
         1.3.4 Spatial and Temporal Resolutions, 14
         1.3.5 Summary, 16
      1.4 Brief outline of the volume, 16
         References, 17

2 Management Applications of Optical Remote Sensing in the Active River Channel, 19
   W. Andrew Marcus, Mark A. Fonstad and Carl J. Legleiter
      2.1 Introduction, 19
      2.2 What can be mapped with optical imagery?, 20
      2.3 Flood extent and discharge, 21
      2.4 Water depth, 22
      2.5 Channel change, 24
      2.6 Turbidity and suspended sediment, 25
      2.7 Bed sediment, 27
      2.8 Biotypes (in-stream habitat units), 29
      2.9 Wood, 31
      2.10 Submerged aquatic vegetation (SAV) and algae, 31
      2.11 Evolving applications, 33
      2.12 Management considerations common to river applications, 33
      2.13 Accuracy, 35
      2.14 Ethical considerations, 36
      2.15 Why use optical remote sensing?, 36
         References, 38
# Contents

3 An Introduction to the Physical Basis for Deriving River Information by Optical Remote Sensing, 43  
*Carl J. Legleiter and Mark A. Fonstad*

- 3.1 Introduction, 43
- 3.2 An overview of radiative transfer in shallow stream channels, 45
  - 3.2.1 Quantifying the light field, 45
  - 3.2.2 Radiative transfer processes along the image chain, 49
- 3.3 Optical characteristics of river channels, 54
  - 3.3.1 Reflectance from the water surface, 55
  - 3.3.2 Optically significant constituents of the water column, 55
  - 3.3.3 Reflectance properties of the streambed and banks, 58
- 3.4 Inferring river channel attributes from remotely sensed data, 60
  - 3.4.1 Spectrally-based bathymetric mapping via band ratios, 60
  - 3.4.2 Relative magnitudes of the components of the at-sensor radiance signal, 61
  - 3.4.3 The role of sensor characteristics, 62
- 3.5 Conclusion, 66
- 3.6 Notation, 67

References, 68

4 Hyperspectral Imagery in Fluvial Environments, 71  
*Mark J. Fonstad*

- 4.1 Introduction, 71
- 4.2 The nature of hyperspectral data, 72
- 4.3 Advantages of hyperspectral imagery, 74
- 4.4 Logistical and optical limitations of hyperspectral imagery, 75
- 4.5 Image processing techniques, 78
- 4.6 Conclusions, 82

Acknowledgments, 82

References, 82

5 Thermal Infrared Remote Sensing of Water Temperature in Riverine Landscapes, 85  
*Rebecca N. Handcock, Christian E. Torgersen, Keith A. Cherkauer, Alan R. Gillespie, Klement Tockner, Russel N. Faux and Jing Tan*

- 5.1 Introduction, 85
- 5.2 State of the art: TIR remote sensing of streams and rivers, 88
- 5.3 Technical background to the TIR remote sensing of water, 91
  - 5.3.1 Remote sensing in the TIR spectrum, 91
  - 5.3.2 The relationship between emissivity and kinetic and radiant temperature, 92
  - 5.3.3 Using Planck’s Law to determine temperature from TIR observations, 93
  - 5.3.4 Processing of TIR image data, 94
  - 5.3.5 Atmospheric correction, 94
  - 5.3.6 Key points, 95
- 5.4 Extracting useful information from TIR images, 96
  - 5.4.1 Calculating a representative water temperature, 96
  - 5.4.2 Accuracy, uncertainty, and scale, 96
  - 5.4.3 The near-bank environment, 97
  - 5.4.4 Key points, 98
5.5 TIR imaging sensors and data sources, 98
  5.5.1 Ground imaging, 98
  5.5.2 Airborne imaging, 98
  5.5.3 Satellite imaging, 101
  5.5.4 Key points, 101
5.6 Validating TIR measurements of rivers, 102
  5.6.1 Timeliness of data, 102
  5.6.2 Sampling site selection, 103
  5.6.3 Thermal stratification and mixing, 104
  5.6.4 Measuring representative temperature, 104
  5.6.5 Key points, 105
5.7 Example 1: Illustrating the necessity of matching the spatial resolution of the TIR imaging device to river width using multi-scale observations of water temperature in the Pacific Northwest (USA), 106
5.8 Example 2: Thermal heterogeneity in river floodplains used to assess habitat diversity, 108
5.9 Summary, 108
Acknowledgements, 109
5.10 Table of abbreviations, 110
References, 110

6 The Use of Radar Imagery in Riverine Flood Inundation Studies, 115
6.1 Introduction, 115
6.2 Microwave imaging of water and flooded land surfaces, 116
  6.2.1 Passive radiometry, 117
  6.2.2 Synthetic Aperture Radar, 117
  6.2.3 SAR interferometry, 119
6.3 The use of SAR imagery to map and monitor river flooding, 120
  6.3.1 Mapping river flood inundation from space, 120
  6.3.2 Sources of flood and water detection errors, 124
  6.3.3 Integration with flood inundation modelling, 129
6.4 Case study examples, 129
  6.4.1 Fuzziness in SAR flood detection to increase confidence in flood model simulations, 129
  6.4.2 Near real-time flood detection in urban and rural areas using high resolution space-borne SAR images, 131
  6.4.3 Multi-temporal SAR images to inform about floodplain dynamics, 133
6.5 Summary and outlook, 135
References, 137

7 Airborne LiDAR Methods Applied to Riverine Environments, 141
Jean-Stéphane Bailly, Paul J. Kinzel, Tristan Allouis, Denis Feurer and Yann Le Coarer
7.1 Introduction: LiDAR definition and history, 141
7.2 Ranging airborne LiDAR physics, 142
  7.2.1 LiDAR for emergent terrestrial surfaces, 142
  7.2.2 LiDAR for aquatic surfaces, 144
7.3 System parameters and capabilities: examples, 146
  7.3.1 Large footprint system: HawkEye II, 146
  7.3.2 Narrow footprint system: EAARL, 147
  7.3.3 Airborne LiDAR capacities for fluvial monitoring: a synthesis, 148
7.4 LiDAR survey design for rivers, 148
  7.4.1 Flight planning and optimising system design, 148
  7.4.2 Geodetic positioning, 150
7.5 River characterisation from LiDAR signals, 150
  7.5.1 Altimetry and topography, 150
  7.5.2 Prospective estimations, 152
7.6 LiDAR experiments on rivers: accuracies, limitations, 153
  7.6.1 LiDAR for river morphology description: the Gardon River case study, 153
  7.6.2 LiDAR and hydraulics: the Platte River experiment, 154
7.7 Conclusion and perspectives: the future for airborne LiDAR on rivers, 158
References, 158

8 Hyperspatial Imagery in Riverine Environments, 163
Patrice E. Carbonneau, Hervé Piégay, Jérôme Lejot, Robert Dunford and Kristell Michel
  8.1 Introduction: The Hyperspatial Perspective, 163
  8.2 Hyperspatial image acquisition, 166
    8.2.1 Platform considerations, 166
    8.2.2 Ground-tethered devices, 166
    8.2.3 Camera considerations, 170
    8.2.4 Logistics and costs, 172
  8.3 Issues, potential problems and plausible solutions, 172
    8.3.1 Georeferencing, 173
    8.3.2 Radiometric normalisation, 176
    8.3.3 Shadow correction, 176
    8.3.4 Image classification, 179
    8.3.5 Data mining and processing, 180
  8.4 From data acquisition to fluvial form and process understanding, 182
    8.4.1 Feature detection with hyperspatial imagery, 182
    8.4.2 Repeated surveys through time, 183
  8.5 Conclusion, 188
Acknowledgements, 189
References, 189

9 Geosalar: Innovative Remote Sensing Methods for Spatially Continuous Mapping of Fluvial Habitat at Riverscape Scale, 193
Normand Bergeron and Patrice E. Carbonneau
  9.1 Introduction, 193
  9.2 Study area and data collection, 194
  9.3 Grain size mapping, 194
    9.3.1 Superficial sand detection, 196
    9.3.2 Airborne grain size measurements, 198
    9.3.3 Riverscape scale grain size profile and fish distribution, 200
    9.3.4 Limitations of airborne grain size mapping, 200
    9.3.5 Example of application of grain size maps and long profiles to salmon habitat modelling, 201
  9.4 Bathymetry mapping, 203
9.5 Further developments in the wake of the Geosalar project, 205

9.5.1 Integrating fluvial remote sensing methods, 205

9.5.2 Habitat data visualisation, 207

9.5.3 Development of in-house airborne imaging capabilities, 208

9.6 Flow velocity: mapping or modelling?, 209

9.7 Future work: Integrating fish exploitation of the riverscape, 211

9.8 Conclusion, 211

Acknowledgements, 212

References, 212

10 Image Utilisation for the Study and Management of Riparian Vegetation: Overview and Applications, 215

Simon Dufour, Etienne Muller, Menno Straatsma and S. Corgne

10.1 Introduction, 215

10.2 Image analysis in riparian vegetation studies: what can we know?, 217

10.2.1 Mapping vegetation types and land cover, 217

10.2.2 Mapping species and individuals, 220

10.2.3 Mapping changes and historical trajectories, 220

10.2.4 Mapping other floodplain characteristics, 220

10.3 Season and scale constraints in riparian vegetation studies, 221

10.3.1 Choosing an appropriate time window for detecting vegetation types, 221

10.3.2 Minimum detectable object size in the riparian zone, 221

10.3.3 Spatial/spectral equivalence for detecting changes, 221

10.4 From scientists’ tools to managers’ choices: what do we want to know? And how do we get it?, 223

10.4.1 Which managers? Which objectives? Which approach?, 224

10.4.2 Limitations of image-based approaches, 224

10.5 Examples of imagery applications and potentials for riparian vegetation study, 226

10.5.1 A low-cost strategy for monitoring changes in a floodplain forest: aerial photographs, 226

10.5.2 Flow resistance and vegetation roughness parametrisation: LiDAR and multispectral imagery, 228

10.5.3 Potential radar data uses for riparian vegetation characterisation, 230

10.6 Perspectives: from images to indicators, automatised and standardised processes, 233

Acknowledgements, 234

References, 234

11 Biophysical Characterisation of Fluvial Corridors at Reach to Network Scales, 241

Hervé Piégay, Adrien Alber, J. Wesley Lauer, Anne-Julia Rollet and Elise Wiederkehr

11.1 Introduction, 241

11.2 What are the raw data available for a biophysical characterisation of fluvial corridors?, 242

11.3 How can we treat the information?, 243

11.3.1 What can we see?, 243

11.3.2 Strategy for exploring spatial information for understanding river form and processes, 245
11.3.3 Example of longitudinal generic parameters treatment using unorthorectified photos, 248
11.3.4 The aggregation/disaggregation procedure applied at a regional network scale, 250
11.4 Detailed examples to illustrate management issues, 253
11.4.1 Retrospective approach on the Ain River: understanding channel changes and providing a sediment budget, 254
11.4.2 The Drôme network: example of up- and downscaling approach using homogeneous geomorphic reaches, 256
11.4.3 Inter-reach comparisons at a network scale, 259
11.5 Limitations and constraints when enlarging scales of interest, 261
11.6 Conclusions, 265
Acknowledgements, 265
References, 266

12 The Role of Remotely Sensed Data in Future Scenario Analyses at a Regional Scale, 271
Stan Gregory, Dave Hulse, Mélanie Bertrand and Doug Oetter
12.1 Introduction, 271
12.1.1 The purposes of scenario-based alternative future analyses, 272
12.1.2 Processes of depicting alternative future scenarios, 272
12.1.3 Methods of employing remotely sensed information in alternative futures, 278
12.1.4 Alternative future scenarios for the Willamette River, Oregon as a case study, 278
12.2 Methods, 279
12.2.1 Ground truthing, 281
12.2.2 Use of remotely sensed data in the larger alternative futures project, 282
12.3 Land use/land cover changes since 1850, 282
12.4 Plan trend 2050 scenario, 283
12.5 Development 2050 scenario, 287
12.6 Conservation 2050 scenario, 287
12.7 Informing decision makers at subbasin extents, 289
12.8 Discussion, 291
Acknowledgements, 294
References, 294

13 The Use of Imagery in Laboratory Experiments, 299
Michal Tal, Philippe Frey, Wonsuck Kim, Eric Lajeunesse, Angela Limare and François Métivier
13.1 Introduction, 299
13.2 Bedload transport, 300
13.2.1 Image-based technique to measure grainsize distribution and sediment discharge, 302
13.2.2 Particle trajectories and velocities using PTV, 304
13.3 Channel morphology and flow dynamics, 306
13.3.1 Experimental deltas, 308
13.3.2 Experimental river channels with riparian vegetation, 309
13.4 Bed topography and flow depth, 312
13.5 Conclusions, 317
14 Ground based LiDAR and its Application to the Characterisation of Fluvial Forms, 323
Andy Large and George Heritage

14.1 Introduction, 323
14.1.1 Terrestrial laser scanning in practice, 324

14.2 Scales of application in studies of river systems, 325
14.2.1 The sub-grain scale, 325
14.2.2 The grain scale, 325
14.2.3 The sub-bar unit scale, 327
14.2.4 In-channel hydraulic unit scale, 329
14.2.5 Micro-topographic roughness units, 330
14.2.6 The bar unit scale, 330
14.2.7 Reach-scale morphological analyses, 332
14.2.8 Terrestrial laser scanning at the landscape scale, 334
14.2.9 Towards a protocol for TLS surveying of fluvial systems, 336

References, 338

15 Applications of Close-range Imagery in River Research, 341
Walter Bertoldi, Hervé Piégay, Thomas Buffin-Bélanger, David Graham and Stephen Rice

15.1 Introduction, 341
15.2 Technologies and practices, 342
15.2.1 Technology, 342
15.2.2 Overview of possible applications, 344

15.3 Post-processing, 347
15.3.1 Analysis of vertical images for particle size, 347
15.3.2 Analysis of vertical images for particle shape, 349
15.3.3 Analysis of oblique ground images, 349

15.4 Application of vertical and oblique close-range imagery to monitor bed features and fluvial processes at different spatial and temporal scales, 350
15.4.1 Vertical ground imagery for characterising grain size, clast morphometry and petrography of particles, 350
15.4.2 Monitoring fluvial processes, 352
15.4.3 Survey of subaerial bank processes, 353
15.4.4 Inundation dynamics of braided rivers, 355
15.4.5 River ice dynamics, 356
15.4.6 Riparian structure and dead wood distributions along river corridors, 359

15.5 Summary of benefits and limitations, 361
15.6 Forthcoming issues for river management, 362

Acknowledgements, 363
References, 363

16 River Monitoring with Ground-based Videography, 367
Bruce J. MacVicar, Alexandre Hauet, Normand Bergeron, Laure Tougne and Imtiaz Ali

16.1 Introduction, 367
18.4 Applications with photo-questionnaires, 412
  18.4.1 From judgment assessment to judgment prediction, 412
  18.4.2 Comparing reactions between scenes and between observers, 415
  18.4.3 Linking judgments to environmental factors, 417
  18.4.4 Modelling and predicting water landscape judgments, 420
  18.4.5 Photographs and landscape perception, a long history of knowledge production, 420

18.5 Conclusions and perspectives, 425
  Acknowledgements, 426
  References, 426

19 Future Prospects and Challenges for River Scientists and Managers, 431
  Patrice E. Carbonneau and Hervé Piégay
  References, 433

Index, 435
Advancing River Restoration and Management

The field of river restoration and management has evolved enormously in recent decades, driven largely by increased recognition of the ecological values, river functions, and ecosystem services. Many conventional river management techniques, emphasizing hard structural controls, have proven difficult to maintain over time, resulting in sometimes spectacular failures, and often degraded river environment. More sustainable results are likely from a holistic framework, which requires viewing the ‘problem’ at a larger catchment scale and involves the application of tools from diverse fields. Success often hinges on understanding the sometimes complex interactions among physical, ecological and social processes.

Thus, effective river restoration and management requires nurturing the interdisciplinary conversation, testing and refining our scientific theories, reducing uncertainties, designing future scenarios for evaluating the best options, and better understanding the divide between nature and culture that conditions human actions. It also implies that scientists better communicate with managers and practitioners, so that new insights from research can guide management, and so that results from implemented projects can in turn, inform research directions.

The series provides a forum for ‘integrative sciences’ to improve rivers. It highlights innovative approaches, from the underlying science, concepts, methodologies, new technologies, and new practices, to help managers and scientists alike improve our understanding of river processes, and to inform our efforts to better steward and restore our fluvial resources for more harmonious coexistence of humans with their fluvial environment.

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Images and maps have provided visual support to fluvial sciences and river management for centuries. Perhaps the earliest case in point, renaissance master Leonardo Da Vinci (1452–1519) frequently used his artistic talents in order to illustrate his scientific observations of fluid motion. His notes, reflections and observations on water, mostly contained in the Codex Leicester (Da Vinci, c1510), contain remarkably accurate drawings of wave erosion and water flow in both meanders and confluences. Da Vinci was also greatly concerned by the control and management of rivers and as a result the Codex Leicester contains detailed observations and drawings of water flowing around man-made obstacles. Most striking to the modern eye is the accuracy of Da Vinci’s technical drawings and illustrations. Flow lines around bridge piers and other obstacles are painstakingly drawn to scale and into patterns giving an impressive level of process representation. This detailed sketching recorded the observations which often provided the foundations for scientific reasoning. In short, Da Vinci used a visual media (i.e. an image) as a tool to encode information on fluvial processes.

Furthermore, Da Vinci’s scientific inquiry was not confined to the small scale observation of local flow phenomena. His illustrations of the Arno River which flows through Florence, demonstrate once again his acute sense of observation. For example, the cover art for this volume shows a sketch of the Arno and Mugnone rivers. To fluvial scientists and practitioners, this early visual representation of a river from an aerial perspective has a few fascinating features. The accurately rendered fluvial forms almost give the viewer the impression of an image rather than a map. Da Vinci clearly has a good understanding of channel features at a range of scales and these were rendered faithfully in his sketches. We can see small scale meanders, confluences and bifurcations. At larger scales, we can see clear distinctions between the main channel, secondary channels and inactive, possibly dry, channels. Furthermore, Da Vinci has clearly defined the boundaries of the braided band thus giving the viewer the impression of three distinct land-cover types in this landscape: the wetted channels, the active braided band and the vegetated area. Whilst it would obviously be exaggerated to consider Da Vinci as a pioneer of remote sensing, his work nevertheless provides one of the earliest and best known examples of visual data (i.e. sketches) used to convey technical information about fluvial landscapes and flow processes with a view towards both fundamental science and management.

Da Vinci relied on his well trained powers of observation in order to faithfully reproduce, among other, fluvial forms and features. However, the invention of photography in the late nineteenth century triggered a fundamental reversal of this process. With the photograph as an acceptable, or at least approximate, representation of geometric reality, the viewer of the image becomes the observer and information about the photographed scene can be acquired without direct physical presence or contact. In short, the photograph becomes a data acquisition method. Furthermore, with the contemporary invention of air travel in the late nineteenth century, it is not surprising that many early aeronauts and photographers collaborated and gave birth to aerial photography. In 1855, Gaspard-Félix Tournachon, most often referred to by his pseudonym ‘Nadar’, patented the concept of using aerial photographs for surveying and mapping. After three years of experimentation, in 1858, Nadar took the very first aerial photograph, a moment which was caricatured by Honoré Baumier in 1863 (Figure 1). Nadar had clearly understood the future potential of imagery as a source of information. Indeed, imagery and remote sensing have now become standardised data acquisition approaches with far reaching applications in all the physical and environmental sciences.

Inspired by these early thinkers who pioneered the use of visual representations in fluvial sciences and mapping, this edited volume will examine the most recent applications and uses of imagery and image-derived information in river sciences and management. Our goal is to present some key highlights of nearly two decades of research during which the use of image data has emerged along with important advances in sciences and technologies which
Figure 1 Caricature by Honoré Daumier of the first aerial photograph taken by Gaspard-Félix Tournachon (Nadar) in 1858.

are fundamentally enhancing our ability to characterise river geometry, sediment calibre, water characteristics, vegetation type, vegetation dynamics, ice dynamics, flooding, organisms, social value, etc and, ultimately, allows managers to provide practical recommendations. Our intended audience is a non-specialist one, this volume seeks to serve as an accessible entry point to both river managers and students who are looking for a condensed reference text capable of answering basic questions and explaining some of the more fundamental concepts. It is our hope that this volume will allow readers to determine if image-based approaches are suitable to their needs and thus encourage them to pursue the wider literature on the topic.

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Introduction: The Growing Use of Imagery in Fundamental and Applied River Sciences

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1.1 Introduction

Earth observation now plays a pivotal role in many aspects of our lives. Indeed, hardly a day goes by without some part of our lives relying on some form of remote sensing. Weather predictions, mapping and high level scientific applications all make intensive use of imagery acquired from satellites, aircraft or ground-based remote sensing platforms. This form of data acquisition which relies on the reflection or emission of radiation on a target surface is now well accepted as a standard approach to data acquisition. However, the fields of river sciences and remote sensing have operated independently during much of their respective histories. Indeed remote sensing practitioners generally consider streams as linear, or perhaps network, entities in the landscape. In contrast, river scientists such as fluvial geomorphologists, lotic and riparian ecologists, with their focus on the internal structure of rivers and the processes which create these structures, often have a much more localised but three dimensional view of river systems. Nevertheless, both modern fluvial geomorphology and ecology are increasingly recognising that we need to reconcile these viewpoints. In a seminal paper, Fausch et al. (2002) discuss the scientific basis for this reconciliation. These authors argue that natural processes, both biotic and abiotic, frequently operate on larger spatial scales and longer time scales than traditional river sciences and management. Consequently, the authors argue that localised, non-continuous, sampling of small scale river processes, forms and biota leads to a fundamental scale mismatch between the processes under scrutiny and our data collection. Fausch et al. (2002) therefore argue that river sciences and management must begin to consider and sample river catchments (i.e. watersheds) at larger scales and that these units must be considered more explicitly as holistic system.

The need to study and sample river catchments as holistic systems naturally leads to the use of remote sensing as a basic methodology. Remotely sensed data and imagery is indeed the only approach which could conceivably give continuous data over entire catchments (Mertes, 2002; Fonstad and Marcus, 2010). However, in the 1990s and early 2000s, existing remote sensing acquisition hardware and analysis methods were neither tailored nor very suitable to the needs and interests of river scientists and managers. Mertes (2002) presented a review of remote sensing in riverine environments at the turn of the century. At that time, any data with sub-metric spatial resolution was considered of ‘microhabitat’ scale. Consequently, riverine features identified by remote sensing in the late twentieth century were generally of hectametric or kilometric scales. However, developments in the early twentieth century proceeded at a rapid pace and our ability to resolve fine details in the landscape has dramatically...
improved in the last decade (see Chapter 8 and Marcus and Fonstad (2008) for a comprehensive review). Therefore, publications on the remote sensing of rivers have dramatically increased and ‘Fluvial Remote Sensing’ (FRS) is emerging as a self-contained sub-discipline of remote sensing and river sciences (Marcus and Fonstad, 2010). Moreover, the technical progress accomplished in the past two decades of research in FRS means that this sub-discipline of remote sensing has now begun to make real contributions to river sciences and management and the appearance of a volume on the topic is therefore timely. Our aim with this edited volume is to provide readers with a minimal background in remote sensing a concise text that will cover the broadest possible range of potential applications of Fluvial Remote Sensing and provide contrasted examples to illustrate the capabilities and the variety of techniques and issues. Readers will notice when consulting the table of contents that we take a very broad view of ‘remote sensing’. In addition to more conventional remote sensing approaches such as satellite imagery, air photography and laser scanning, the volume includes a wider range of applications where image and/or video data is applied to support river science and management. This chapter will set the context of this volume by first giving a very brief introduction to remote sensing and by discussing the evolution of journal publications in fluvial remote sensing approaches and river management. Finally, we will give a brief outline of the volume.

1.2 Remote sensing, river sciences and management

1.2.1 Key concepts in remote sensing

Here we will introduce some key remote sensing concepts which will help us illustrate and contextualise fluvial remote sensing as a sub-discipline. However, this introduction is not meant as a foundation text in remote sensing and we refer the reader in need of some fundamental material to classic remote sensing textbooks such as Lillesand et al. (2008) or Chuvieco and Alfredo (2010).

Remote sensing has a multitude of definitions. In broad terms, ‘remote sensing may be formally defined as the acquisition of information about the state and condition of an object through sensors that are not in physical contact with it’ (Chuvieco and Alfredo, 2010). This type of broad definition does not place any restriction on the type of interactions that occur between the target and the sensor. According to this definition, echo-sounding devices such as sonar which use acoustic energy in order to detect objects in a fluid media such as air or water should be considered as remote sensing. However it should be noted that references to remote sensing usually apply to the collection of information via electromagnetic energy such as visible light, infrared light, active laser pulses, etc. Remote sensing is then generally divided in two broad categories: active or passive remote sensing. This description refers to the source of radiation. Passive remote sensing relies on externally emitted sources of radiation whilst active remote sensing relies on internally generated and emitted radiation. The best-known example of active remote sensing is RADAR (Radio Detection And Ranging) which uses radio waves to establish the position of objects in the vicinity of the sensor. Moreover, lasers have been used in active remote sensing to give birth to LiDAR (Light Detection And Ranging) technology. LiDAR technology is rapidly becoming the method of choice for the generation of topography from ground based and airborne platforms and is the focus of Chapters 7 and 14 of this volume.

The key parameter exploited by active remote sensing has always been the time elapsed between the emission of a radiation pulse and it’s detected return. As a result, active remote sensing uses a narrow and finite portion of the electromagnetic spectrum. For example, typical LiDAR technology uses infrared lasers with a wavelength of 1024 nm and radar relies on radio waves with wavelengths of 1–10 cm. Passive sensors, which rely on an external source of radiation (usually the sun), make a much more comprehensive usage of the electromagnetic spectrum. This is the type of remote sensing which is familiar to all of us because our visual system uses solar radiation to detect features in our surroundings. Table 1.1 presents a simplified form of the electromagnetic spectrum. This table gives the common names and categories of radiation as we move, from left to right, from the very short wavelengths of high energy cosmic radiation to the very long wavelengths of lower energy micro-waves and radio waves. Generally speaking, the majority of passive remote sensing sensor devices applied to earth observation uses radiation in the visible and infrared portions of Table 1.1. Given that the electromagnetic spectrum has a continuous range of frequencies (i.e. radiation wavelength is not intrinsically discreet), their detection and quantification relies on sensors that can detect incident radiation within a specified, finite, range of wavelengths. The most basic example of this would be greyscale (black and white) imagery where the brightness of a point on the photograph is proportional to the total amount of visible
radiation, with frequencies ranging from approximately 0.4 to 0.7 microns, received by the sensor (e.g. the camera film). A further example would be standard colour photography. In this case, it would clearly be impossible to have a near infinite number of detectors each sensitive to a specific wavelength in the continuous visible spectrum. The solution which was therefore adopted in the early days of colour photography was to emulate human vision and to re-create colour by first sampling radiation in three distinct areas of the spectrum: red, green and blue (Lillesand et al., 2008). Within each of these primary colour bands, the total amount of radiation incident upon the sensor is recorded. Therefore for the red band, the sensor detects all the radiation with frequencies between approximately 0.6 and 0.7 microns. For the green band the sensor detects all the radiation from approximately 0.5 and 0.6 microns and for the blue band, detectable wavelengths range from 0.4 to 0.5 microns. It should be noted that the term ‘band’ mentioned earlier is one of the most fundamental in the remote sensing vocabulary. Formally, a ‘spectral band’ is a finite section of the electromagnetic spectrum, recorded and stored in a raster data layer. In the examples above, a greyscale image is a one band image and a colour image is a three band image. The term ‘multispectral’ therefore refers to a remote sensing approach or dataset which has several bands. Strictly speaking, colour photography, with its three bands in red, green and blue, can be considered as multispectral imagery. However, many authors and practitioners reserve the term ‘multispectral’ for datasets which have at least four spectral bands with one of the bands usually covering the infrared portion of the spectrum. It should be noted that the number of available bands is not the only important characteristic of a remotely sensed image. Potential applications of remotely sensed data are often limited and one might even say, defined, by four additional parameters: spectral resolution, spatial resolution, temporal resolution and, to a lesser extent, radiometric resolution.

The concept of spectral resolution is closely related to the concept of a spectral band. It relates to the width, expressed in linear units of radiation wavelength (nm or μm), of the spectral bands of the imaging device. A clear distinction must therefore be made between the number of bands measured by a sensor which determines the range of radiation wavelengths that is sampled and the width (or narrowness) of an individual band which determines the sensors sensitivity to specific spectral features. Arguably the most classic example of the use of spectral features in remote sensing is the detection of vegetation. In healthy green vegetation, chlorophyll absorbs over 90% of incident radiation within the visible spectrum, albeit with a slightly lesser absorption and higher reflection in green wavelengths, which explains the colour of vegetation. However, in the infrared wavelengths, vegetation is a strong reflector. Sensors designed to detect vegetation, such as the classic Thematic Mapper sensor mounted on Landsat satellites, therefore try to exploit these differences by sampling red light (0.63–0.69 μm) which is strongly absorbed by vegetation and near infrared light (0.76–0.90 μm) which is strongly reflected. Note the relatively narrow width, in spectral terms of these bands. Our ability to accurately detect vegetation from remote sensing therefore depends not only on increasing the number of bands beyond the visible spectrum, but also on an improvement of the spectral resolution. If we follow this line of thought to its logical conclusion, we realise that it would be desirable to produce a sensor with a very high number of bands each with a very narrow bandwidth.
Such sensors are called ‘Hyperspectral’ and can have hundreds or even thousands of bands with resolutions as small as 0.002 μm. Whilst such hyperspectral sensors have huge potential, their usage in river sciences has been relatively limited and most of the progress in fluvial remote sensing rests on standard colour imagery with the conventional three bands of Red, Green and Blue (hence the term RGB imagery) which equates to a relatively coarse spectral resolution of approximately 0.2 μm.

One key advantage of widely available colour imagery is its very high spatial resolution. One of the most fundamental descriptors of remote sensing data, spatial resolution refers to the ground footprint of a single image pixel on real ground. This distance is generally quoted as a linear unit with the underlying assumption that the pixels are square. The spatial resolution of a dataset will define the smallest object that can be identified. Whilst there is no absolute rule for the number of pixels required to define a simple object (e.g. a boulder), our experience has shown that a minimum of 5X5 pixels are required in order to get an approximation of the object shape whilst 3X3, or even 2X2, pixels are required to establish presence of an object of undefined shape in the image.

In parallel with spatial resolution, temporal resolution refers to the elapsed time between repeated imagery. Repeated image sampling has been somewhat less exploited in fluvial remote sensing. While studies of large rivers based on satellite imagery have been able to exploit the regular revisit frequency of orbital sensors (Sun et al., 2009; Frankl et al., 2011), airborne data is not acquired with the same regularity and studies reporting change based on airborne data are much less frequent. As a result, substantial progress remains to be made in terms of monitoring rivers and examining changes occurring at the smaller spatial resolutions that can be detected with airborne remote sensing. However, repeated imagery, including video imagery, has been successfully used at smaller scales for laboratory studies (see Chapter 13) and reach based studies (see Chapters 15 and 16). Furthermore, a largely un-exploited archive or terrestrial and airborne archival imagery exists for many parts of the world which does indeed include riverine areas. If issues such as image georeferencing (spatial positioning of the imagery), and image quality can be addressed (see Chapter 8), then these images could provide a very important source of data sometimes dating as far back as the nineteenth century.

The final parameter, radiometric resolution is easily confused with spectral resolution. Here the term ‘radiometric’ refers to the recording of data in the sensors memory. When radiation reaches a device, the intensity of radiation must be converted to some proportional brightness scale which can then be represented on an image. In the case of digital devices, this proportional brightness is termed the Digital Number (DN). The digital number is the dimensionless actual value of the pixel that can be seen if the image is accessed with image processing software. Typically, these pixel values are scaled to increasing powers of 2. For example, standard RGB imagery contains three bands, each of which has pixel values ranging from 0 to 255. These 256 possible values arise from data storage in an ‘8 bit’ binary format meaning that each DN value is coded with 8 binary digits with possible values of 0 or 1 thus leading to $2^8(256)$ possible values for the image pixels. However, more advanced sensors and satellites will frequently use higher ‘bit-depths’ of 11 or 12 bits thus leading to a wider range of 4096 ($2^{12}$) or even 4096 ($2^{12}$) DN values. This higher number of DN values can help in resolving finer differences in image brightness.

In river sciences, radiometric resolution can be an important parameter when trying to measure river properties through the water interface (Legleiter et al., 2009).

In summary, from the point of view of an end-user, the fundamental properties of a remote sensing data acquisition system can be described by four key parameters: Spatial resolution, spectral resolution, temporal resolution and radiometric resolution. Spatial resolution is often considered as the primary parameter as it defines the size of the smallest object which can be resolved on the ground. Spectral resolution can be crucial in identifying certain materials, such as chlorophyll, based on their reflection of light as a function of the wavelength of the incident light. Temporal resolution is obviously crucial in change detection studies. Finally, radiometric resolution, often called ‘bit-depth’, defines the amount of information devoted to the storage of each image pixel. Higher radiometric resolutions allow for the recording of smaller differences in image brightness.

### 1.2.2 A short introduction to ‘river friendly’ sensors and platforms

A remote sensing ‘platform’ is simply the physical support which carries the ‘sensor’ that does the actual data collection. We have illustrated four classic and new platforms in Figure 1.1. This distinction between platform and sensor is not always clear, especially in the field of satellite remote sensing. For example, the TERRA satellite platform carries both the MODIS and ASTER sensor. However, the commercial term ‘QuickBird’ is used to describe both
the satellite and sensor. In the field of airborne remote sensing the distinction is usually clearer since a given sensor can usually be mounted on a range of fixed wing aircraft or helicopters.

Unsurprisingly, there is currently an abundance of remote sensing images and products. Finding a starting point and locating an appropriate data source and/or acquisition method can therefore be quite a daunting process. Here we give a short description of remote sensing data sources most likely to be of use in the context of fluvial sciences and river management. Many river managers are still under the impression that fluvial remote sensing is not an appropriate tool for river environments. This is a reasonable viewpoint if we consider the most classic and widely known remote sensing data: Landsat imagery. With spatial resolutions of typically 15 m or 30 m, Landsat images only sample river outlines accurately for very large rivers. Clearly, such imagery has little to offer a manager or scientist needing to characterise a small stream with widths below 50 m. However, there has been remarkable technological progress in imaging which has now made images with resolutions of less than 1 m available globally. Several satellites now offer image resolutions below 1 m and low altitude airborne colour photography is now capable of resolutions as low as 2–3 cm. The availability of such data, offering a 100-fold improvement in spatial resolution when compared to classic Landsat, has been an important driver of methodological progress in fluvial remote sensing (see Marcus and Fonstad, 2008).

For readers who are unfamiliar with the topic, Table 1.2 gives a very brief summary of a few key satellites and platforms which are likely to be of interest to river scientists and managers. We have also included some older platforms that may be of lesser interest in a modern context but which nevertheless often appear in publications. This list is far from complete or exhaustive. Our aim is merely

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**Figure 1.1** Typical Remote Sensing Platforms. a) Landsat-7 satellite (15m spatial resolution), b) QuickBird-2 satellite (61 cm spatial resolution), c) Full sized fixed wing aircraft operated by the French *Institut Géographique National* (commonly 0.5 m spatial resolution). Copyright IGN – France, d) Ultralight UAS system (1m total wingspan) operated by Durham University, UK.
Table 1.2 Common Satellite/Platforms with key characteristics.

<table>
<thead>
<tr>
<th>Sensor/Platform</th>
<th>Launch Date</th>
<th>Spatial Resolution (at Nadir)</th>
<th>Temporal Resolution</th>
<th>Spectral Bands</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODIS/Terra</td>
<td>Dec. 1999</td>
<td>250 m (bands 1–2) 500 m (bands 3–7) 1000 m (bands 8–36)</td>
<td>16 days</td>
<td>36 bands from the visual to infrared and thermal</td>
</tr>
<tr>
<td>ASTER/Terra</td>
<td>Dec. 1999</td>
<td>15 m (bands 1–3) 40 m (bands 4–9) 90 m (bands 10–14)</td>
<td>16 days</td>
<td>14 bands from the visual to infrared and thermal</td>
</tr>
<tr>
<td>ETM+/Landsat-7</td>
<td>Apr. 1999</td>
<td>15 m Panchromatic 30 m (bands 1–5 and 7) 60 m (band 6)</td>
<td>18 days</td>
<td>8 bands: Panchromatic, 3 visual, 2 infrared, 2 thermal</td>
</tr>
<tr>
<td>SPOT-5</td>
<td>May 2002</td>
<td>2.5 m Panchromatic 10 m (bands 1–3) 20 m (band 4)</td>
<td>2-3 days</td>
<td>5 bands: Panchromatic, 2 visual (no blue), infrared, thermal</td>
</tr>
<tr>
<td>Ikonos</td>
<td>Sept. 1999</td>
<td>82 cm Panchromatic 3.2 m Multispectral</td>
<td>3 days</td>
<td>5 bands: Panchromatic, 3 visual, infrared</td>
</tr>
<tr>
<td>QuickBird</td>
<td>Oct. 2001</td>
<td>65 cm Panchromatic 2.62 m Multispectral</td>
<td>2.5 days</td>
<td>5 bands: Panchromatic, 3 visual, infrared</td>
</tr>
<tr>
<td>WorldView-1</td>
<td>Sept. 2007</td>
<td>50 cm Panchromatic</td>
<td>1.7 days</td>
<td>1 band: Panchromatic</td>
</tr>
<tr>
<td>WorldView-2</td>
<td>Oct. 2009</td>
<td>50 cm Panchromatic 1.85 m Multispectral</td>
<td>1.1 days</td>
<td>9 bands: Panchromatic, 6 visual, 2 infrared, thermal</td>
</tr>
<tr>
<td>GeoEye</td>
<td>Sept. 2008</td>
<td>50 cm Panchromatic 1.65 m Multispectral</td>
<td>2.1 days</td>
<td>5 bands: Panchromatic, 3 visual, infrared</td>
</tr>
<tr>
<td>Air Photography</td>
<td>N.A.</td>
<td>Variable. Typically 2 to 50 cm</td>
<td>≈1 day</td>
<td>Variable. Typically standard colour. Most types of instruments available.</td>
</tr>
<tr>
<td>Unmanned Aerial systems (UAS)</td>
<td>N.A.</td>
<td>Variable. Typically 2 to 50 cm.</td>
<td>&lt;1 day</td>
<td>Variable. Typically small format RGB digital cameras. Other instruments available on large UAS.</td>
</tr>
</tbody>
</table>

to suggest a few data acquisition options and justify these suggestions with the appropriate data characteristics. The first point to note is the variable spatial resolution, for each sensor, when images are acquired in panchromatic mode (i.e. greyscale) and multispectral mode. It should always be remembered that when satellite image vendors quote a sub-metric spatial resolution, they are referring to panchromatic imagery. At the time of writing, no satellite platform in earth orbit can acquire multispectral imagery with sub-metric resolutions. A possible substitute for high resolution imagery is called ‘pan-sharpened’ imagery. In a pan-sharpened image, the sub-metric resolution image is fused with the multispectral images. This transformation uses the brightness values in the panchromatic band to weigh the interpolation of the lower resolution multispectral bands. The result is a multispectral or colour image with the same resolution as that of the panchromatic image. Another interesting point to note about spatial resolutions is the apparent 50 cm limitation which seems to have been reached in the more recent satellites. In fact, the GeoEye in Table 1.2 satellite is capable of producing 41 cm greyscale imagery and the Worldview-2 satellite can acquire at 46 cm. However, US regulations prohibit these companies from delivering data in the public domain with spatial resolutions below 0.5 m and therefore the images are resampled before delivery to the customer. Unfortunately, it seems that for the foreseeable future, satellite image spatial resolutions will be blocked at 50 cm. In terms of temporal resolutions, these satellites can all revisit a site within a few days. From the perspective of fluvial sciences, this makes them well suited to seasonal monitoring. In terms of spectral resolutions, the basic array of bands for a so-called ‘ multispectral’ satellite image has long been four bands in Red, Green, Blue and Near Infrared. Many satellites in Table 1.2 conform to this standard and have three spectral bands in the visible range.
with an additional band in the infrared which is generally intended for vegetation. However, the recently launched WorldView-2 satellite proposes a marked improvement in spectral terms with eight bands with widths of 40 to 70 nm in the visible range with two bands in the near-infrared. This recently available imagery has not yet been applied to small rivers and holds much potential.

For users interested in studying or managing very small rivers with metric scale widths, even the best currently available satellite image may still be insufficient. In such cases, airborne remote sensing should be considered. The final two entries in Table 1.2 are meant to give a broad, preliminary, indication of the potential of airborne remote sensing (see Chapters 2, 5, 7, 8, 9 and 11 for further discussions). Airborne remote sensing is obviously a very wide topical area. Here we present only two broad types of acquisition platforms: air photography from conventional aircraft and Unmanned Aerial systems. Traditional air photography is now widely available from both the private sector and government agencies. In addition to colour imagery, traditional aircraft can be used to mount a range of instruments which have been shown to be useful in river sciences. For example, Fausch et al. (2002) present high resolution temperature acquired from a fixed wing aircraft and Marcus et al. (2003) show how hyperspectral data can provide a rich database of information which significantly surpasses the limits of standard RGB imagery. In terms of spatial resolution, aerial photography generally fills the niche below satellite imagery. The temporal resolution of air photos is obviously not as rigid as that of a satellite which is bound in an elliptical orbit around the earth. In theory, an aircraft can be mobilised very frequently and visit a site at least once a day. However, potential users should be aware that in practice, this is very rarely possible. Government agencies only very rarely commission repeat flights of an area at intervals smaller than one year. Similarly, private sector companies can sometimes have the availability for repeat flights within a year although our experience has been that this is very difficult for a specific rivers owing to cost and logistic constraints. Unmanned Aerial Systems (UAS) can free users from these logistic constraints by giving the opportunity for managers and scientists to operate their own aircraft. UAS exist in a very wide range of sizes and purposes. In fact some UAS, for example the Global Hawk and Ikhana systems operated by NASA, are in essence full sized, pilotless, aircraft. However, of particular interest here is the ever growing range of small, toy-sized, UAS available on the civilian commercial market. These systems are easy to pilot and come equipped with small format digital cameras and onboard navigation hardware which often allows for fully automated flight and data acquisition. These small aircraft can fly at very low altitudes and therefore can deliver very high resolution imagery. Their small size makes them very easy to deploy at high temporal resolutions. At the time of writing, publications using UAS data are relatively rare in river sciences (but see Dunford et al., 2011). However, this new technology is prompting much excitement in the river sciences community and the publication record can be expected to grow in the coming years.

### 1.2.3 Cost considerations

Most users considering remotely sensed data will probably turn to free data sources in the first instance. Classic Landsat data is freely downloadable from the United States Geological Service (USGS) via their EarthExplorer website (earthexplorer.usgs.gov). Whilst the resolution is low, this data can still provide some initial insights for medium to large rivers. For smaller rivers, most users will likely turn to free online mapping services like Google Earth which displays very good quality imagery, often with sub-metric resolutions. Google corporation purchases this imagery from a range of airborne and satellite sources (some in Table 1.2) and makes them freely viewable online. However, users cannot download full, raw, image products from Google Earth. Therefore, in the majority of cases, the purchase of data will still be required. The costs of such purchases are obviously a crucial consideration. Whilst these are quite variable across the full range of data types, sensors and platforms, we give here a basic summary which is not specific to any single company or service provider and which will hopefully provide the reader with some initial estimates.

In the case of satellite imagery, there are two important, broad, distinctions. First, is a new image required? Satellite image providers maintain full archives of all previously acquired images. These archived images are sold at discounted costs which range from 10–20 US$ per km². However, if a new image is required, the purchase of a new acquisition will increase the cost to at least 20–80 US$/km². The second factor in satellite image cost is the level of pre-processing. The cost estimates above are for basic standard imagery. However, image providers offer pre-processing services which range from improved image quality in terms of position, geometry and radiometry to the full production of Digital Terrain Models (DTMs). These levels of processing will obviously increase the cost, sometimes in excess of 100 US$/km². Readers should also note that a minimum area must...
always be purchased. This is typically in excess of 20 km² which therefore places the minimum cost of a single, high resolution, satellite image in the vicinity of 2000 US$.

In the case of airborne imagery, costs are also quite variable. Dugdale et al. (2010) cite a cost of £150/km (approximately 250 US$/km) for the acquisition of 3 cm airborne imagery. This would however be in addition to an initial mobilisation cost required to get the aircraft to the mission locality. Typically, in the case of small rivers with lengths below 100 km and widths below 100 m, surveys of full river lengths in order to acquire sub-decimetric resolution colour imagery will probably cost 10,000 to 25,000 US$. However, many national agencies maintain image archives for their territories. These are generally of a much lower resolution, typically 25–50 cm. However, their cost is much lower. Government agencies, particularly in the US, will often provide these free of charge. Even when not freely available, the cost is roughly 10% of the cost of a new survey. Small UAS are generally affordable for most organisations. Depending on the size, level of automation and imaging equipment of the craft in question, costs can range from roughly 5000 US$ to 30,000 US$. These make them affordable options for ‘do-it-yourself’ remote sensors. However, prospective UAS pilots should take careful notice of national airspace regulations. Airspace regulations in most western nations now have specific regulations pertaining to UAS. The spirit of most UAS airspace usage regulations is that small, light weight, UAS operated in non-urban areas, at low altitudes (below 400 ft or 120 m) and within line of sight of the pilot are allowed. This situation is generally suitable to most river applications thus making UAS a good option for river study and management in the US and Europe. However, we strongly encourage readers to consult specific regulatory agencies before purchasing a UAS since regulations will vary across the globe and may change rather rapidly. Furthermore, many regions of the world do not allow any type of UAS operations. For example, in India, airborne photography, both from UAS and full aircraft, is strictly reserved to military uses. Readers considering airborne photography of any kind should therefore always check the regulatory framework for their intended field site.

1.3 Evolution of published work in Fluvial Remote Sensing

The past decade has clearly seen remarkable contributions to methodological aspects of fluvial remote sensing. As discussed in later chapters of this volume, river scientists now have a wide range of remote sensing and image based methods capable of quantifying the biotic and abiotic aspects of river environments. This progress has been reflected in academic publications and here we focus on a bibliometric survey in order to analyse the evolution of Fluvial Remote Sensing (FRS). The ISI Web of Science (WOS) database was used to provide a summary in international peer-reviewed scientific journals and conferences. Different searches were carried out based on a set of technical key-words, such as ‘Remote sensing’, ‘imagery/image’, ‘photogrammetry/photography’, ‘video’ combined with specific thematic key-words describing our geographical objects such as ‘river’, ‘stream’, ‘fluvial channel’, ‘fluvial geomorphology’, ‘floodplain’ and ‘riparian’. We decided to reject the term ‘river basin’, which we found was used for catchment or regional scale hydrology, an observation in itself. We also rejected the terms ‘video stream’ and ‘image stream’ which are used purely for video technologies. The term ‘channel’ must also be used with caution since it can be used in the purely technical sense of a radiometric channel or video channel. From this request, 244 references are specifically related to our topic. Of the 224 references, 200 have an abstract. In a second search phase, we introduced the terms ‘management’, ‘restoration’, ‘maintenance’, but also ‘planning’. We did the second request on the title for these additional keywords, the others being searched in the topics to reassemble more papers 12 only were then identified.

As a first order analysis, if we consider the pace of publications, we find that 1 to 3 papers were published every year between 1976 and 1996, 7 to 9 papers per year were published between 1997 and 2001, increasing to 11 to 14 per year from 2001 to 2006 and finally surpassing 30 per year since then with a maximum of 37 in 2010. This increase in the number and pace of publications is in itself a good indicator of the accelerating pace of progress in this sub-discipline of remote sensing. In order to pursue