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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 give 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. More recently, 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 its 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

Table 1.1 Simplified Electromagnetic Spectrum table (Modified from Ward et al., 2002).

Wavelength (λ)														
Name	Cosmic Rays	0.4 to 0.7 μm			0.7 to 3 μm	3 to 8 μm	8 to 15 μm	15 μm to 1 mm	1 mm to 1 m					1 m \wedge
	X-Rays	Visible (Optical)			Infrared				Micro-waves					
	Ultraviolet	blue	green	red	near	middle	thermal	far	K-band: 1.1-1.4 cm	X: 2.4-3.75 cm	C: 3.75- 7.5 cm	L: 15-30 cm	Radio	

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 to 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 of 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 2048 (2^{11}) 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

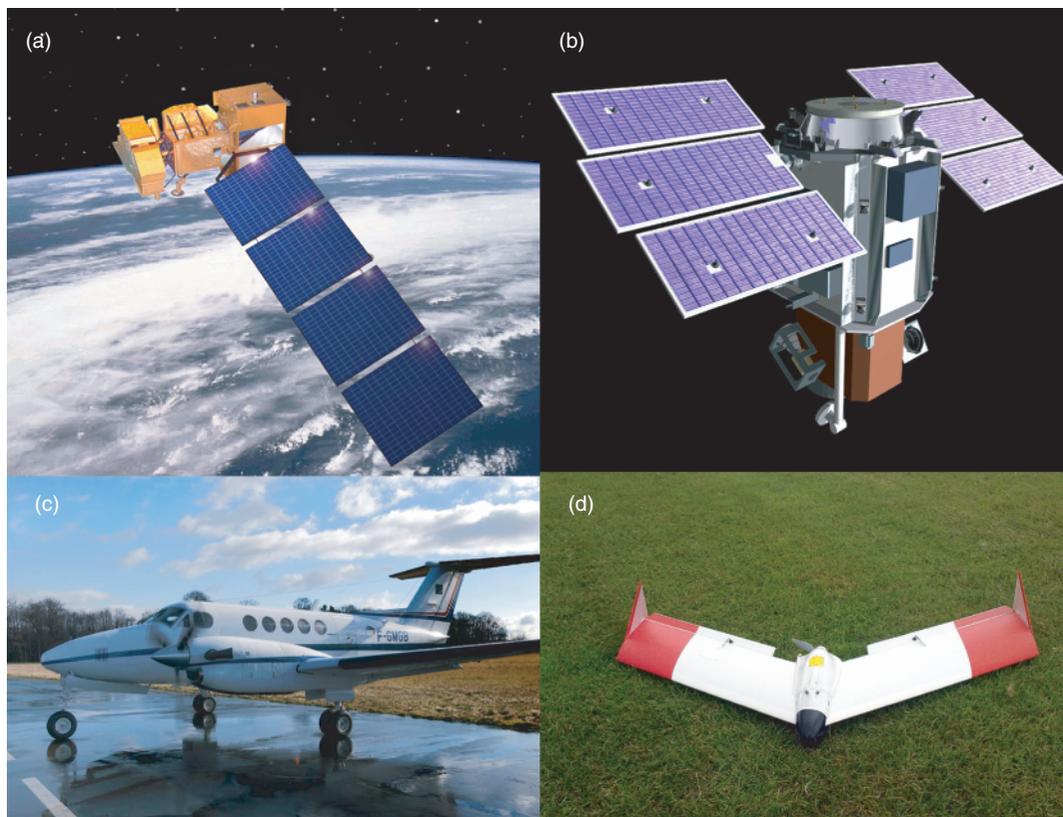


Figure 1.1 Typical Remote Sensing Platforms. a) Landsat-7 satellite (15m spatial resolution), b) QuickBird-2 satellite (61 cm spatial resolution), c) Full sized fixed wing aircraft operated by the French *Institut Géographique National* (commonly 0.5 m spatial resolution). Copyright IGN – France, d)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

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

Table 1.2 Common Satellite/Platforms with key characteristics.

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

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-decimeter 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,¹ 224 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 request² 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

¹Exact request done in May 2011 : Title = (Remote sensing OR image OR imagery OR photogr* OR video) AND Title = (river* OR stream OR streams OR fluvial channel* OR fluvial geomorphology OR floodplain OR riparian) NOT Title = (basin* OR catchment OR watershed OR “video stream*” OR “image stream”) = 333 References listed but only 224 were really in the scope of the discipline.

²Exact request done in August 2011 : Title = (Remote sensing OR imagery OR image OR photogr* OR video) and Topics = (river OR stream OR fluvial) and Topics = (management OR restoration OR maintenance OR planning OR conservation).

the bibliometric analysis in more detail, we considered three elements: authorships and journals, platforms and sensors and topical areas of study.

1.3.1 Authorships and Journals

First authorship is dominated by the USA (36%) and the UK (12%). However, a set of countries are quite well invested in this domain such as Australia (9%), China (9%), France (6%), Canada (6%), Holland (3.6%) and India (4.5%) (Figure 1.2). Many of these countries have active satellite remote sensing programs. If we compare these results to a broad WOS search with the single term ‘rivers’ (>100 000 papers) or ‘river management’ (>15 000 papers), the UK (5.7% and 7.7% of papers respectively), or India (2.5% and 2.0% of papers respectively) are significantly stronger in Fluvial Remote Sensing whereas USA is slightly stronger (31% and 34%) as well as France (5.0% and 4.3%), Australia (4.7 and 8%) and China (11% and 7%), Holland (2.3% and 3.8) and Canada

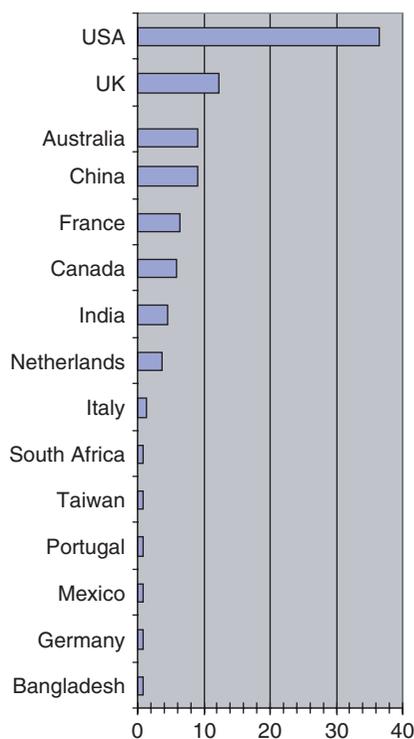


Figure 1.2 Distribution of the manuscripts according to the laboratory citizenship of the first author (in % of the studied papers).

(6.8% and 6.4) are similar. Germany has weak research in this domain compared to its scientific weight in river and river management research (5.2% and 4.8%), similar to Japan (4.4% and 2.3%).

The papers dealing with Fluvial Remote Sensing were published in 91 journals. 81% of these journals only published one or two manuscripts (Figure 1.3). Among the remaining 19%, specialised journals in geomatics and remote sensing such as *International Journal of Remote Sensing* and *Remote Sensing of Environment* are the most popular (respectively 7.5 and 10% of the manuscripts). The thematic journals *Earth Surface Processes and Landforms* and *Geomorphology* are almost as attractive as these specialised journals. They are followed by the *Journal of Hydrology* and the *Journal of the American Water Resources Association*. In the field of ecology, the remote sensing papers are published in a large set of ecological journals none of which is devoted exclusively to remote sensing. Overall, 33% of papers found in our search are published in Geomatics/Remote Sensing Journals, 17% in Ecology/Biology, 16% in Earth Sciences, 13% in Hydrology, 9% in Water Environment, 6% in Ocean Environment, 5% in Environment and 1% in Agriculture.

1.3.2 Platforms and Sensors

Within our search results, papers based on satellite data are slightly more frequent than aerial/airborne data with 34% of papers referring to ‘satellite’ against 27% to ‘aerial/airborne’ (Figure 1.4a). Landsat is the most frequently used satellite platform (21%) following by Terra (16%) and Spot (7.5%). In terms of satellites capable of delivering imagery with spatial resolutions at or below a meter, Quickbird is more popular than Ikonos, but both are still quite infrequently used in the literature (respectively 5.5% and 2% of manuscripts). Envisat and Formosat are cited only in a very few papers. The Shuttle Radar Topography Mission was mentioned in the abstracts of two contributions. The terms ‘UAV’ or ‘drone’ do not appear in any of the abstracts. The terms ‘blimp’, ‘balloon’ and ‘Unmanned’ in one manuscript each and ‘helicopter’ in four of the 200 abstracts.

When considering sensors, we observe a range of equipment used, from spacecraft imagers such as ASTER or MODIS to ground or airborne equipment covering a large part of the electromagnetic spectrum in both passive and active modes (Figure 1.4b). If we combine satellite imagery (both panchromatic and three-band colour), film based archival photography, ground based photography

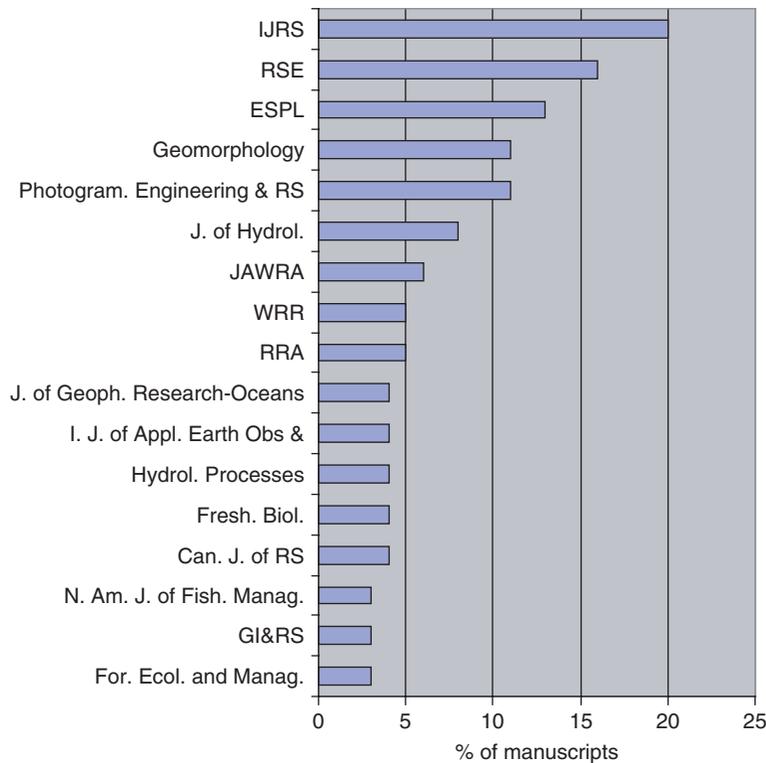


Figure 1.3 Distribution of the manuscripts within the journals having published more than two manuscripts in the WOS (in % of the studied papers).

and contemporary digital airborne photography, we find that the traditional camera (either film or digital) is still the most commonly used sensor (13,5%). LiDAR (Light Detection And Ranging), RADAR and TIR (Thermal InfraRed) sensors are also well cited with respectively 13,5% 11% and 9% of manuscripts. Spaceborne sensors such as ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), MODIS (Moderate Resolution Imaging Spectroradiometer) and MERIS (Medium-spectral Resolution Imaging Spectrometer) are also cited. Airborne hyperspectral imagers such as CASI (Compact Airborne Spectrographic Imager) are less frequently cited (3%). ‘Terrestrial remote sensing’ is also cited with devices such as TLS (Terrestrial Laser Scanning, 0,5%), LSPIV (Large Scale Particle Image Velocimetry, 3,5%) and ground-based video (6%).

We also explored the temporal trend of the platforms/sensors used for the most frequent (Figure 1.5). Two relative references were used, the 15 000 manuscripts focused on river management and stored in the WOS, and the 200 papers studied without distinguishing any method. These two cumulated curves show the WOS database prior to 1990 is not very rich and the steep

trend we observed in recent years is also partly due to the database structure itself. When looking at the relative cumulated curves per year for the different platforms/sensors, two groups can be observed: Pioneer platforms/sensors such as photograph and Infra-Red for which the median year is 2000 and their use seems to decrease a bit after, and new sensors such as TIR (median year 2005), SAR/Radar (median year 2006) but also LiDAR (median year 2008). Airborne/Aerial data, Landsat and video seem to follow the general trend in term of publications. However, Landsat seems more popular in the 1998–2004 period and its relative use is decreasing.

1.3.3 Topical Areas

An examination of the abstracts revealed that FRS is contributing to a large set of topics that we can group into three broad areas (Figure 1.6). First, the drive for a better science base in management decisions has seen remote sensing applied to ecological and habitat studies aiming to identify land-use types, specific habitat types and biotopes (37% of papers). Second, investigations in water sciences which are related to the fields of water

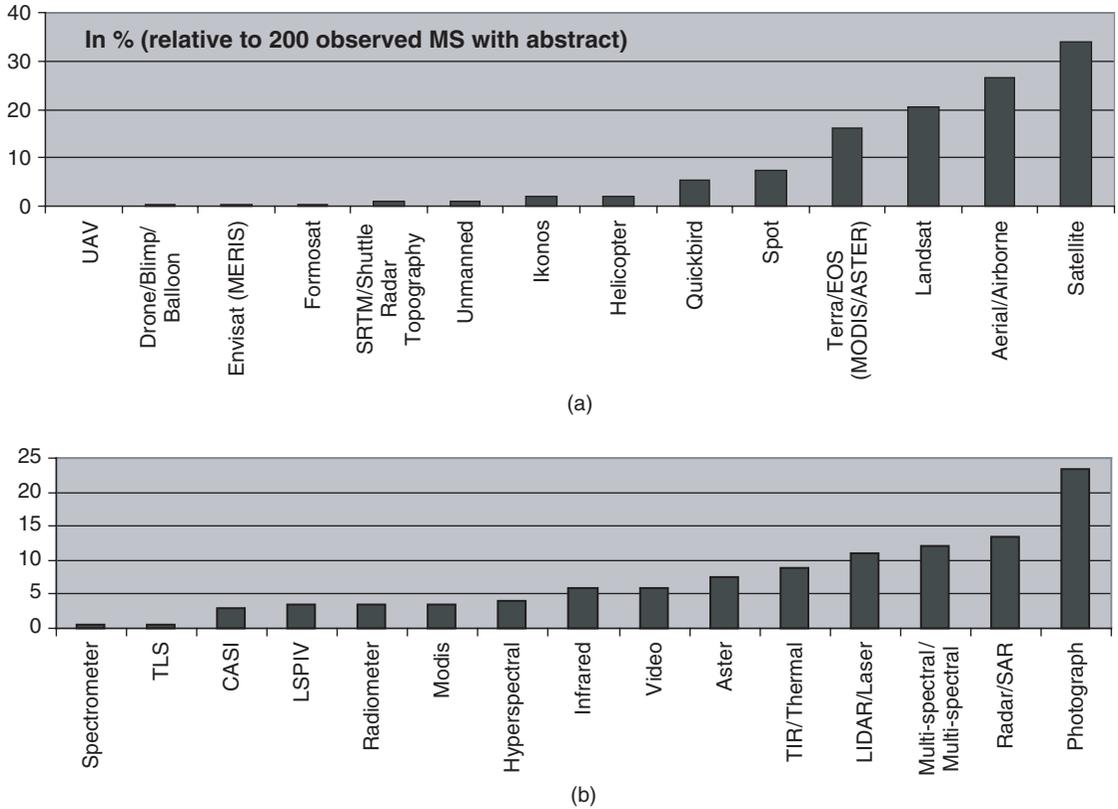


Figure 1.4 Frequency of terms within the abstracts of the 200 manuscripts (in % of the studied manuscripts): a) platforms, b) sensors.

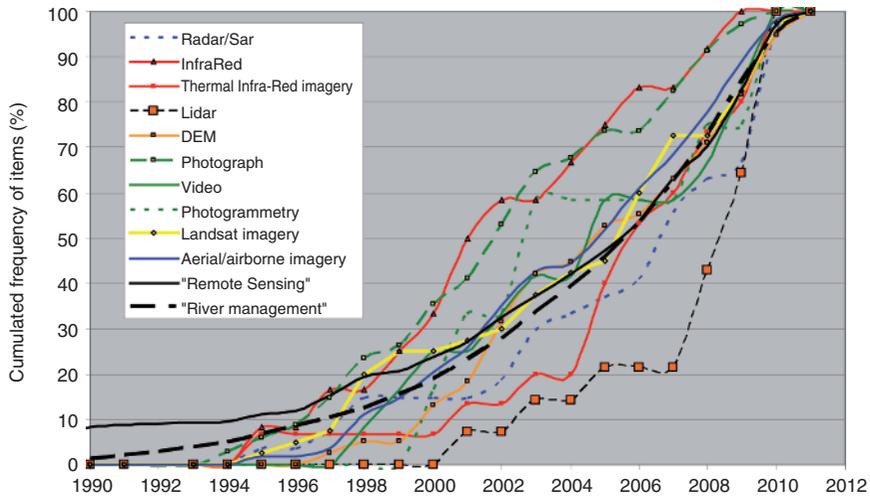


Figure 1.5 Cumulative frequency curve (in % of papers) of each of platforms/sensors cited in the 200 papers of the Web of Science dealing with rivers and remote sensing. We compared the temporal evolution of frequency for the terms “Remote sensing” and “River management” in the 200 studied manuscript within the whole Web of Science dataset.

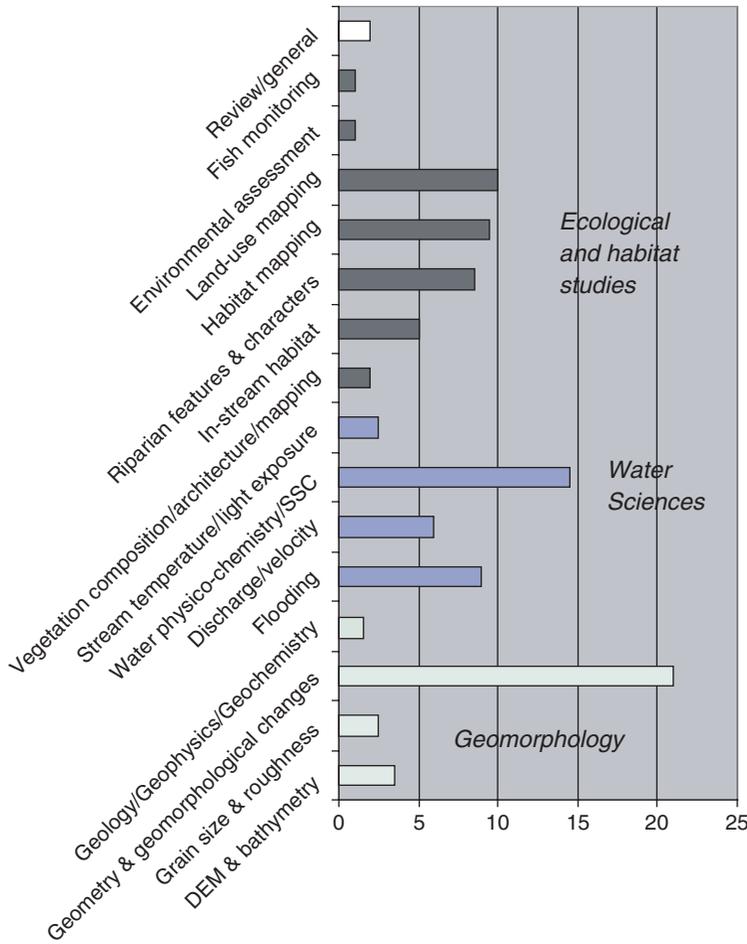


Figure 1.6 Review of abstracts of 203 manuscripts to identify the main topics (in % of the studied manuscripts).

chemistry, hydraulics and hydrology and which study specific topics such as plumes, pollution, suspended sediment concentrations, stream temperature, flooding, discharge and velocity are seeing an increasing dependence on FRS (33.5% of papers). Third, with the aim of improving and often of up-scaling the data acquisition process in traditional fluvial geomorphology, inquiries relating to regional and tectonic settings, bank erosion monitoring and decadal channel shifting, geomorphic changes, channel geometry, bathymetry, grain size, have all seen an increasing use of remote sensing data (27% of papers).

Figure 1.7 presents box and whisker plots showing the publication periods for the five most frequent topics shown on the vertical axis of Figure 1.6. This shows that some of the topics have emerged fairly recently such as SSC & Water Chemistry for which most of the

papers were published between 2008 and 2009 on habitat mapping and riparian features, whereas others are more popular all along the studied period such as flooding and geomorphic changes.

In addition to the timing of publications, we briefly examined the abstract content for these five topics in order to identify the main research thrusts within each area. In the case of habitat mapping, vegetation mapping is by far the most dominant application of remote sensing. Studies range from native vegetation assessment to the identification of invasive species. Satellite platforms are the major source of data but airborne platforms seem increasingly utilised. We also find a few published works using underwater video in order to characterise fish and animal behaviour. However, these studies of fish behaviour and/or habitat are actually rare which indicates

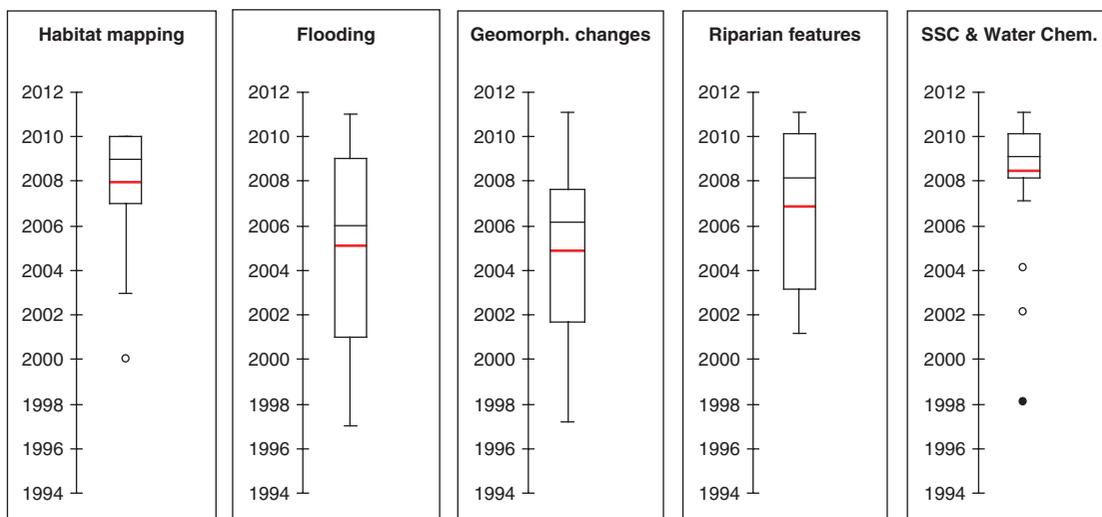


Figure 1.7 Distribution of the occurrence of the five most frequent topics (shown in Figure 1.6) within the set of 200 studied papers. Box plots provide the two deciles and quartiles with a black line indicating the median and the red line showing the average.

that progress remains to be made in the applications of FRS to the mapping and characterisation of stream biota.

Most of the papers dealing with flooding focused on the use of the synthetic aperture radar (which can sense through cloud cover) in order to map flooding extent in near real time at both coarse and fine spatial resolutions. This application uses both spaceborne platforms (ERS-1, RADARSAT-1) and airborne platforms. Additionally, Landsat TM is used to determine inundation from a range of flows because of its temporal capacity to cover areas repeatedly. This topic area also makes heavy use of topographical data derived from remotely sensed sources in order to identify peaks, troughs and slopes in flood affected areas. At large scales, the Shuttle Radar Topography Mission (SRTM) DEM is commonly used. At smaller scales, LiDAR is increasingly used to provide high resolution, high accuracy topographic height and even bathymetry (i.e. water depths). LiDAR also has the advantage of measuring vegetation height, which can be converted to friction coefficients. Generally speaking, these flooding studies employ this range of FRS tools in order to provide baseline data which is then fed into hydraulic and/or hydrologic models.

In the geomorphic change topic, most of the contributions focused on channel changes at a decadal scale based on repeated aerial photos or satellite imagery (e.g. SPOT or Landsat) in order to understand bank or delta erosion, meander migration rates and sediment production.

There is also a good volume of published work on the spatial organisation of fluvial landforms or reaches and the factors controlling them, notably geology, tectonics and riparian vegetation which have often been conducted over very long reaches (catchment and sometimes sub-continental scales). Other papers also explored smaller scale, in-channel morphological changes such as bars, channel branches, considering their sizes, their forms and the associated land cover attributes. At these smaller scales, human pressures such as gravel mining and urbanisation have also been discussed in the literature. In the case of these smaller scale studies, air photo or satellite imagery remains the norm. However, one contribution used Synthetic aperture radar (SAR) imagery for monitoring the changing forms of braided rivers over a short time scale. This is likely a reflection of the technical progress in SAR technology. Finally, fluvial geomorphology seems to be the field where most methodological developments are occurring. Here we find a significant body of published works demonstrating the use of both passive and active remote sensing in order to characterise channel width, channel depth, riparian vegetation and sediment characteristics. In terms of data sources, this area is dominated by standard photography and LiDAR (both terrestrial and airborne).

Abstracts found with the keywords 'Riparian Features' were quite varied in content. However, in common with the habitat mapping topic, vegetation identification

remains as a dominant application of remote sensing. Here we find applications of LiDAR, colour and multi-spectral data aimed at identifying the composition and land-uses of the riparian zones along with their temporal dynamics. Traditional image classification of these datasets remains the principal method. However, a few papers did mention newly developed object-based classification methods. We also find that the scale of the studies in this category varies quite widely from studies focusing on bankside vegetation a few meters or tens of meters away from the channel to studies examining the entire catchment of large rivers.

Studies of river water chemistry and suspended sediment concentrations (SSC) are well established in oceanic sciences. They are also well established in large river science with some early work taking advantage of the Landsat program (Aranuvachapun and Walling, 1988). However, in the context of the smaller, so-called 'normal', rivers which are the focus of this book, remote sensing of water quality publications is scarce. Within our search results, water-quality papers were dominated with estuarine and large river studies at the interface between oceanic and fluvial sciences. The rationale behind most of these studies is to replace expensive and labour intensive ground-based field monitoring with multispectral or hyperspectral remote sensing data in order to perform what is in essence 'remote spectroscopy'. The key focus is the study of river plumes in terms of sediment load

and pollution load. The parameters which are directly measured in these studies are turbidity (i.e. water clarity) and organic matter concentrations (i.e. presence of chlorophyll). These metrics can then be used as proxies for other parameters such as pollution load and salinity. The most commonly used sensors are the ETM+ (Landsat), MODIS and the Advanced Land Imager (ALI) which is a multispectral sensor mounted on NASA's Earth Observation-1 (EO-1) satellite.

1.3.4 Spatial and Temporal Resolutions

Finally, the abstracts were used to examine the range of temporal and spatial resolutions in use within our abstract database (Figure 1.8a). Most of the contributions are based on spatial resolutions of 10–50 m confirming the use of satellite imagery. Coarser resolutions are less frequent. Metric and sub-metric resolution mainly based on airborne imagery are also very common, reaching 25% of papers. Ground-based remote sensing (here we assume decimetric or centimetric resolutions even if not specified in the abstract) is also a field which is well explored within 10% of the contributions. When combining topical areas and the spatial resolutions, a χ^2 test shows they are dependant ($p < 0.0001$) (Table 1.3). Discharge and fish monitoring are based on ground remote-sensing, whereas DEM and bathymetry use very high resolution (>1 m) data. Riparian features and land-use mapping also used very high resolution (1 m) data mainly based

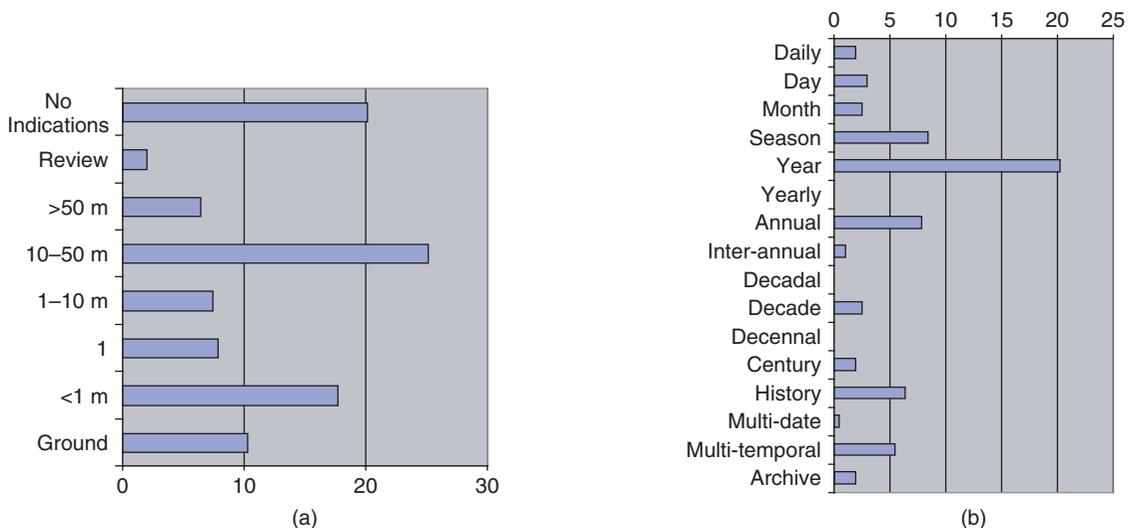


Figure 1.8 Frequency of terms within the abstracts of the 200 manuscripts (in % of the studied manuscripts) dealing with (a) spatial and (b) temporal framework.

Table 1.3 A posterior contribution of each of the cells to the χ^2 test testing the independence between the classes of broad topics and spatial resolution.

Topic	Spatial Resolution					
	Ground	1	<1 m	1–10 m	10–50 m	>50 m
DEM & bathymetry	(+) NS	(-) NS	(+)**	(-) NS	(-) NS	(-) NS
Discharge/velocity	(+)**	(-) NS	(-) NS	(-) NS	(-) NS	(-) NS
Environmental assessment	(-) NS	(-) NS	(-) NS	(-) NS	(+) NS	(-) NS
Fish monitoring	(+)**	(-) NS	(-) NS	(-) NS	(-) NS	(-) NS
Flooding	(-) NS	(-) NS	(+) NS	(-) NS	(+)**	(-) NS
Geometry & geomorphological changes	(-) NS	(-) NS	(+) NS	(-) NS	(+) NS	(+) NS
Grain size & roughness	(+) NS	(+) NS	(+) NS	(-) NS	(-) NS	(-) NS
Habitat mapping	(-) NS	(+) NS	(-) NS	(+)**	(-) NS	(-) NS
Land-use mapping	(-) NS	(+)**	(+) NS	(-) NS	(+) NS	(-) NS
Riparian features & characters	(-) NS	(+)**	(+)**	(+) NS	(-) NS	(-) NS
Stream temperature/light exposure	(-) NS	(-) NS	(+) NS	(+) NS	(-) NS	(-) NS
Vegetation composition/architecture/ mapping	(-) NS	(+) NS	(-) NS	(-) NS	(-) NS	(-) NS
In-stream habitat	(+) NS	(-) NS	(+) NS	(-) NS	(-) NS	(+) NS
Water physico-chemistry/SSC	(-) NS	(-) NS	(-)*	(-) NS	(+) NS	(+)**

(+): Positive association
 (-): Negative association
 NS: not significant at $\alpha = 0.1$
 *: significant at $\alpha = 0.1$
 **: significant at $\alpha = 0.05$
 ***: significant at $\alpha = 0.01$

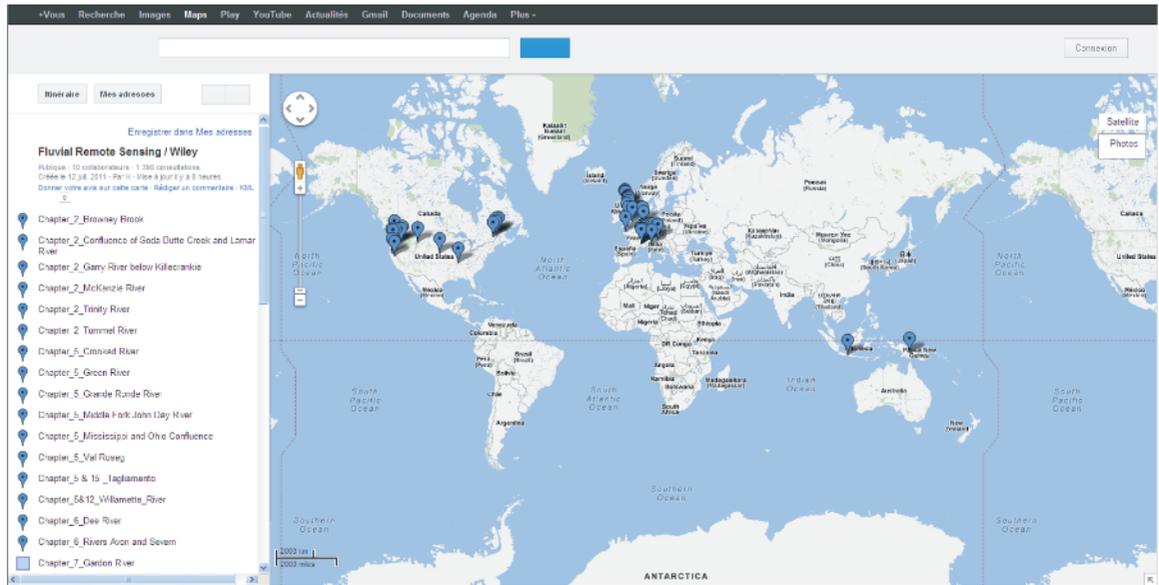


Figure 1.9 Location of the detailed examples shown in the different chapters of the book: public site on Google Earth. Source: <http://maps.google.fr/maps/ms?msid=215028322631048652408.0004a7dd26c4dfd045d2c&msa=0> © 2012 Google.

on high resolution satellite images or airborne photos. Current habitat mapping publications used a lower resolution platform such as Spot or Landsat. Flooding and water physico-chemistry are often based on coarser resolution images.

Temporal resolutions were often difficult to find and/or not explicitly defined in the abstracts. We therefore separated the abstracts into several categories which imply a certain resolution timescale rather than exact quantitative values (Figure 1.8b). The terms ‘year’ and ‘annual’ are the most frequent (respectively 20% and 8%) but ‘early’ or ‘inter-annual’ are less common. The term ‘season’ is quite often cited (8% of MS) as well. ‘Decade’ and ‘century’ but also ‘day’ or ‘daily’ also occurred occasionally. The terms ‘multi-temporal’ or ‘historic’ concerns 5.5 to 6% of MS. Interestingly, we see that 47.5% of papers mention temporal resolution terminology. This obviously shows the importance of monitoring work in remote sensing. However, it also illustrates the importance and persistence of satellite data as a source of data acquisition in river sciences. Despite the lower resolution, the reliable availability of satellite imagery at predictable time intervals is a major advantage which could very well explain the past, current and future importance of satellite data in fluvial remote sensing.

1.3.5 Summary

This survey of published literature in FRS illustrates some key points about this sub-discipline of remote sensing. Our database search revealed that over the last 35 years traditional satellite data was the major data source employed by fluvial remote sensing studies. We found that a surprisingly high proportion of published work used traditional remote sensing data such as Landsat, ASTER and even MODIS (Brodie et al., 2010; Liu et al., 2010; An et al., 2011). The legacy of traditional satellite remote sensing can also be seen in the very high number of publications which focus on vegetation characterisation/quantification (Laba et al., 2010; Bertoldi et al., 2011). This trend has continued well into the twenty-first century with airborne data remaining in second place and, despite being capable of higher spatial resolutions, not yet overtaking spaceborne data in the published literature. The causes for this are difficult to establish with certainty. However, the availability of reliable repeat (multi-temporal) imagery from satellite sources is a likely factor. Furthermore, we believe that the dominance of satellite-based publications also shows that classic river sciences and

management studies have not made heavy use of remote sensing since spaceborne data is rarely suited to the spatial and temporal scales which characterise river processes. In the papers we surveyed, only a small minority examined classic river science topics such as fluvial bedforms and channel topography, sediment calibre and dynamics (especially in the gravel to boulder size range) and river fauna. However, within our search results, we can clearly see the impact of recent published works aimed at developing remote sensing technology and methods which are tailored to river sciences and capable of providing data acquisition strategies that are well suited to river science investigations. Advances in imaging technology which now allow for centimetric imagery from the air (Carbonneau et al., 2004; Forzieri et al., 2010) and decimetric imagery from space (Zhang et al., 2004; Johansen et al., 2010), new LiDAR technology which is customised to river environments (Kinzel et al., 2007) and processing methods designed to extract a range of features of interest to river sciences (Carbonneau, 2005; Jordan and Fonstad, 2005; Buscombe and Masselink, 2009), have all radically improved our capability to characterise the fluvial forms and processes mentioned above. Given time we expect this progress to change the overall profile of publications in fluvial remote sensing. We would therefore hope that an identical bibliometric survey conducted in 2020 would yield a significantly enhanced list of publications where the line between traditional river sciences and traditional remote sensing has become blurred or even invisible.

1.4 Brief outline of the volume

The volume is divided into three main sections. First, we present a series of six chapters with a slightly more theoretical perspective on the ‘Spectrum of Remote Sensing Techniques and their Applications’. Chapter 2 explores the basic rationale for using remote sensing in river environments. Starting from the question of ‘What can we see?’ this chapter explores the possibilities and limitations of Fluvial Remote Sensing. Chapter 3 follows this topic with a discussion on the basic physics which underpins the application of remote sensing to river environments. The following chapters then begin addressing specific elements of technical progress. Chapter 4 discusses hyperspectral (very high spectral resolution) remote sensing, while Chapter 5 deals with thermal imagery, which is clearly of importance in the context

of changing climates and potentially warming rivers. Chapter 6 deals with FRS methods applied to another emerging impact of changing hydrologic cycles: flooding. Chapter 7 deals with LiDAR technology and its specific application to river environments. This first section is followed by a section of five chapters with a more applied perspective and which focuses on 'Hyperspatial to catchment-scale imagery'. Chapter 8 defines and discusses the concept of 'Hyperspatial' imagery. Chapter 9 presents an extensive habitat mapping based on hyperspatial imagery. Chapter 10 examines how high resolution imagery can be used to go beyond classic characterisation and predict the evolution of riparian vegetation. Similarly, Chapter 11 presents image-based characterisation approaches which extend beyond local study areas and can be applied to long reaches or even entire networks. Finally, Chapter 12 examines the uses of remote sensing in predicting the land-use changes of entire catchments (i.e. watersheds). In the third and final section of the book, we examine the increasing use of ground-based (terrestrial) remote sensing methods in river sciences. Chapter 13 considers the uses of image-based data acquisition in indoor flume experiments. Chapter 14 examines the application of ground-based LiDAR, usually called 'Terrestrial Laser Scanners' (TLS) to river sciences. Chapter 15 focuses on oblique and vertical ground-photos which can provide millimetric spatial resolution for grain size or grain morphometry at a very high temporal resolution. These approaches provide powerful tools for small-scale process monitoring. The final three chapters still use imagery as their primary data source but they represent a definite departure from areas which are normally considered as within the remit of remote sensing. Chapter 16 discusses the uses of videography in river monitoring works. Chapter 17 discusses the uses of imagery in the study of small individual lotic organisms. Finally, Chapter 18 examines the use of photo-questionnaires in the assessment of the societal value of rivers and associated restoration works. Practical conclusions close the volume in Chapter 19. This volume therefore introduces the scope of research already achieved and shows that the techniques now available can be the basis for further exciting developments in the next few years ensuring the field of Fluvial Remote Sensing is poised to achieve more significant contributions. Locations of case-studies for the different chapters are also available on line so as to provide opportunities for readers to see in more detail size, geometry and characters of the rivers and field sites discussed in the volume (Figure 1.9).

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