Environmental Science

Joseph L. Awange
John B. Kyalo Kiema

Environmental Geoinformatics

Monitoring and Management

Springer

Environmental Science and Engineering

Environmental Science

Series Editors

For further volumes:
http://www.springer.com/series/3234

Joseph L. Awange · John B. Kyalo Kiema

Environmental Geoinformatics

Monitoring and Management

Springer

Joseph L. Awange
Department of Spatial Sciences
Curtin University
Perth, WA
Australia

Karlsruhe Institute of Technology
Karlsruhe
Germany

Kyoto University
Kyoto
Japan

School of Environment
Maseno University
Kisumu
Kenya

John B. Kyalo Kiema
Department of Geospatial
and Space Technology
University of Nairobi
Nairobi
Kenya

Institut d'Enseignement Supérieur
(INES) - Ruhengeri
Musanze
Rwanda

ISSN 1431-6250
ISBN 978-3-642-34084-0 ISBN 978-3-642-34085-7 (eBook)
DOI 10.1007/978-3-642-34085-7
Springer Heidelberg New York Dordrecht London

Library of Congress Control Number: 2013934385

© Springer-Verlag Berlin Heidelberg 2013
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Foreword

The title and subtitle of this textbook convey a distinct message. Monitoring—the passive part in the subtitle—refers to *observation* and *data acquisition*, whereas management—the active component—stands for *operation* and *performance*. The topic is our environment, which is intimately related to geoinformatics. The overall message is: all the mentioned elements do interact and must not be separated.

There are still other aspects which must not be separated: *theory* and *practice* of geoinformatics. The book presents an excellent balance of both fields. Technology is introduced from the Geodesist's view including; Reference Systems, Positioning Systems, Remote Sensing, Photogrammetry, and Geographic Information Systems. Applications range from Climate, Water, and Land Management to Vegetation, Disaster, and Pollution. Today, many textbooks are written by specialists from these particular fields. However, in the applications there are many common technical elements in space and time, like impact from scale, regionalization, time series, data fusion, visualization, etc.—just to mention but a few. An advanced prospect for environmental management requires system-based thinking and interdisciplinary approaches. Furthermore, technology may be a common denominator for better understanding our environment.

Finally, geoinformatics is a modern tool for location-based decision making. Most decisions in public administration and economy are directly or indirectly related to space. Today, advanced models and digital spatial data may make decisions more transparent than ever before. Very often, in geoprojects a lot of money is involved, and the risk of manipulation in decision making inevitably increases. Quantitative analysis and restitution of the results may, however, reduce this risk.

Both authors, Joseph L. Awange and John B. Kyalo Kiema, are experienced researchers and lecturers with a strong international background acquired from different parts of the world. During research fellowships in Germany, they got the picture that “geodesy” is a global concept beyond measuring just the figure of the Earth.

Germany, January 2013

Prof. Dr.-Ing. Dr.h.c.,
Hans-Peter Bähr
Karlsruhe Institute of Technology

Preface

There is no doubt that today, perhaps more than ever before, humanity faces a myriad of complex and demanding challenges. This has been propelled by the ever increasing global population and intense pressure being exerted on the Earth's resources. The resulting consequences are severe changes in land cover (e.g., forests giving way to settlements), diminishing biodiversity and natural habitats, dwindling fresh water supplies, and the degradation in the quality of the little that is available, and changing weather and climatic patterns, especially global warming with its associated predicted catastrophes such as rising sea level and increased numbers of extreme weather events.

These *human-induced* and *natural impacts* on the environment need to be well understood in order to develop *informed policies*, *decisions*, and *remedial measures* to mitigate current and future negative impacts. This can be achieved through continuous monitoring of the environment to acquire data that can be soundly and rigorously analyzed to provide information about the current state of the environment and its changing patterns, and to enable predictions of possible future impacts. Environmental monitoring techniques that may provide such information are under scrutiny from an increasingly environmentally conscious society that demands the efficient delivery of such information at a minimal cost. In addition, it is the nature of environmental changes that they vary both spatially and temporally, thereby putting pressure on traditional methods of data acquisition, some of which are very labor intensive, such as tracking animals for conservation purposes. With these challenges, conventional monitoring techniques, particularly those that record spatial changes, call for more sophisticated approaches that deliver the necessary information at an affordable cost.

Developing pragmatic and sustainable solutions to address these and many other similar challenges requires the use of geodata and the application of geoinformatics. Geoinformatics, defined by Ehlers (2003) as "the art, science or technology dealing with the acquisition, storage, processing, production, presentation and dissemination of geoinformation", is a multidisciplinary field. It has at its core different technologies that support the acquisition, analysis, and visualization of geodata. The geodata is usually acquired from Earth observation sensors as remotely sensed images, analyzed by geographic information systems (GIS), and visualized on paper or on computer screens. Furthermore, it combines geospatial analysis and modeling, development of geospatial databases, information systems design, human–computer interaction, and both wired and wireless networking technologies. Geoinformatics uses geocomputation and geovisualization for analyzing geoinformation. Typical branches of geoinformatics include: *cartography*, *geodesy*, *geographic information systems*, *global navigation satellite systems* (*GNSS*), *photogrammetry*, *remote sensing*, *and web mapping*.

For example, a typical application of geoinformatics to environmental monitoring and management is the *GNSS-based radio telemetry*, which is a modern method for observing animal movements. This method moves the burden of making observations from the observer (i.e., researcher) to the observed (i.e., animal), and in so doing alleviates the difficulties associated with personal bias, animal reactions to human presence, and animal habits that make most of them secretive and unseen (Cagnacci et al. 2010). The method provides large, continuous, high-frequency data about animal movement, data which, if complemented by other information dealing with animal behavior, physiology, and the environment itself, contributes significantly to our knowledge of the behavior and ecological effects of animals, allowing the promotion of quantitative and mechanistic analysis (Cagnacci et al. 2010).

This book presents the concepts and applications of geoinformatics in environmental monitoring and management. We depart from the 4D to the 5D data paradigm, which defines geodata accurately, consistently, rapidly, and completely, in order to be useful without any restrictions in space, time, or scale to represent a truly global dimension of the digital Earth. The book also features the state-of-the-art discussion of Web GIS and mapping, an invited chapter written by Prof. Bert Veenendaal of the Department of Spatial Sciences, Curtin University (Australia).

The concepts and applications of geoinformatics presented in this book will be of benefit to decision makers across a wide range of fields, including those working in environmental management agencies, in the emergency services, public health and epidemiology, crime mapping, tourism industry, market analysis and e-commerce, or mineral exploration, among many others.

This is a TIGeR publication No 442.

Perth (Australia), Karlsruhe (Germany) Joseph L. Awange
Nairobi (Kenya), Musanze (Rwanda) John B. Kyalo Kiema

References

Cagnacci F, Boitani L, Powell PA, Boyce MS (eds) (2010) Challenges and opportunities of using GPS-based location data in animal ecology. Philos Trans R Soc B 365:2155. doi: 10.1098/rstb.2010.0098

Ehlers M (2003) Geoinformatics and digital earth initiatives: A German perspective. Int J Digit Earth 1(1):17–30

Acknowledgments

Several figures in this book have been generously provided by various authors. In this regard, the first author (Joseph) would like to thank D. Rieser (Graz University of Technology), M. Motagh (GFZ), M. Jia (Geoscience Australia), F. Urbano (RICENRA, Edmund Mach Foundation, Italy), and R. Mikosz (Federal University of Pernambuco, Brazil). Some figures and materials also came from the work undertaken jointly with colleagues B. Heck (Karlsruhe Institute of Technology, Germany), W. Featherstone, M. Kuhn, K. Fleming, and I. Anjasmara (Curtin University), M. Sharifi (Tehran University), A. Hunegnaw (University of Edinburgh), O. Baur (Space Research Institute, Austrian Academy of Science), E. Forootan (Bonn University), J. Wickert, T. Schmidt (GFZ, Germany), J. B. K. Kiema (University of Nairobi), and students N. Wallace, Khandu, G. Schloderer, M. Bingham, and T. Opande. To you all, “arigato gozaimasu” (Japanese for thank you very much). To all his Curtin University 3rd year (Satellite and Space Geodesy unit), and 2nd year (Civil Engineering) students who used materials from the draft book and provided feedback, Joseph would like to say “Danke sehr” (German for thank you very much).

Joseph also wishes to express his sincere thanks to Prof. B. Heck of the Department of Physical Geodesy (Karlsruhe Institute of Technology (KIT), Germany) for hosting him during the period of his Alexander von Humboldt Fellowship (2008–2011) when part of this book was written. In particular, his ideas, suggestions, and motivation on Chaps. 20–22 have enriched the book considerably. Joseph is also grateful to Prof. B. Veenendaal (Head of Department, Spatial Sciences, Curtin University, Australia) for the support and motivation that enabled the preparation of this edition. He also wishes to acknowledge the support of *Curtin Research Fellowship*, while his stay at KIT was supported by a *Alexander von Humboldt's Ludwig Leichhardts Memorial Fellowship*. To all, he says, “ahsante sana” (Swahili for thank you very much). Last, but not least, he wishes to thank his wife Naomi Awange and daughters Lucy and Ruth Awange for their patience and support, especially the hard times they endured when he was away in Germany.

On the other hand, the second author (Kiema) wishes to thank staff and students at the Department of Geospatial and Space Technology, University of Nairobi. In particular, he wishes to acknowledge G. C. Mulaku, R. S. Rostom, J. N. Mwenda,

and S. M. Musyoka for support and motivation, along with D. N. Siriba who graciously proof read this work. He wishes to also express sincere thanks to among others G. Konecny (University of Hannover), S. Murai (University of Tokyo), J. L. Awange (Curtin University), Q. Weng (Indiana State University), E. Nyadimo (Oakar Sevices Ltd., Kenya), B. Kumi-Boateng (University of Mines and Technology, Ghana), G. Eshiamwata (Birdlife International, Kenya), J. M. Mwangi, and M. A. Dangana (University of Nairobi) for material used in the book.

Kiema is also indebted to Prof. H.–P. Bähr of KIT for first, mentorship through the years and secondly, for agreeing to write the foreword for this book. Gratitude is also accorded to the Institut d'Enseignement Supérieur (INES)—Ruhengeri where the second author was stationed for the duration of his sabbatical leave, during which period this monogram was completed. Special regards to Rev. Fr. Dr. F. Hagenimana, Vice Rector Academics at INES for his kind support. Finally, Kiema also wishes to acknowledge his wife Joy and children Abigail and Jayden for their patience and understanding during the long spell when he was away from home.

Contents

Part I Introduction

Part II Environmental Geodesy

Part III Remote Sensing and Photogrammetry

Part IV Geographic Information Systems

Part V Applications to Environmental Monitoring and Management

Part I
Introduction

Chapter 1
Environmental Monitoring and Management

> *"If environmental monitoring is not carried out in a deep and exacting scientific manner, then it is likely that no action will be taken when needed for lack of firm evidence."*
>
> Frank Burden (2002)

1.1 Why Monitor the Environment?

A natural way to begin this monogram is by posing several pertinent questions. Firstly, what exactly does the term "*monitoring*" mean. Furthermore, is monitoring synonymous to measuring or observing? And more specifically, what does it mean within an environmental perspective? *Monitoring* has been defined by James et al. (2003) as observing, detecting, or recording the operation of a system; watching closely for purposes of control; surveillance; keeping track of; checking continually; detecting change. They state that since monitoring implies change, and change implies time, monitoring then means *measuring those things that change in a system over time and space*. It is a process based on *surveying* and *surveillance*, but assumes that there is a specific reason for the collection of data (Spellerberg 2005). A similar definition is provided by Study of Critical Environmental Problems (1970) who states that *monitoring is a systematic observation of parameters related to a specific problem, designed to provide information on the characteristics of the problem and their changes with time*.

Developing the above argument further, surveying entails the *collection* of *quantitative* and *qualitative data* within a specified time frame without having a preconceived idea of what the results would be. Surveillance introduces the concept of time to surveying, leading to the systematic observation of variables and processes, with the aim of producing time series. Monitoring, therefore, is an extension of surveillance, but with a specific purpose in mind. It is thus a systematic observation

J. L. Awange and J. B. Kyalo Kiema, *Environmental Geoinformatics*,
Environmental Science and Engineering, DOI: 10.1007/978-3-642-34085-7_1,

of variables and processes for a specific purpose, such as ascertaining whether a given project is being undertaken according to predefined environmental standards (Finlayson 1996; Spellerberg 2005).

Consequently, the observation and study of the environment is defined as environmental monitoring. This entails objective observations that produce sound data, which in turn produce valuable information that is useful, e.g., in the protection of public water supplies, hazardous, non-hazardous and radioactive waste management, natural resource protection and management, weather forecasting, and global climate change studies (Artiola et al. 2004).

There are various different ways of categorizing monitoring. In one example, Spellerberg (2005) cites the Department of Conservation in New Zealand who recognizes three types of monitoring (*results monitoring*, *outcome monitoring* and *surveillance monitoring*). In yet another example, Spellerberg (2005) outlines four different categories of environmental monitoring based on Vaughan et al. (2001):

(1) *Simple monitoring* records the value of a single variable at one point over time.
(2) *Survey monitoring* examines the current state of environmental conditions in both affected and non-affected areas.
(3) *Surrogate or proxy monitoring* which compensates for the lack of previous monitoring by using surrogate information to infer changes.
(4) *Integrated monitoring* using detailed sets of ecological information.

On the other hand, Downes et al. (2002) classify monitoring into four categories that clarify the objectives of monitoring prior to a specific design. These include the following:

- *Environmental monitoring*. This takes on many forms for many objectives, e.g., those undertaking environmental monitoring might be interested in gaining some indication of the state, as opposed to assessing human impacts upon the environment, of a particular place.
- *Long term monitoring* and *reference site monitoring*. These are forms of environmental state monitoring that are useful in providing a background measure for the long term dynamics of natural systems that may be used to indicate systematic, monotonic, or cyclical changes in the environment at large scales over long time periods. They are relevant in providing frameworks upon which shorter term or localized changes such as those arising from anthropogenic impacts could be measured against.
- *Compliance monitoring*. This seeks to ensure that a stipulated regulation is being followed, e.g., measuring the pollution level of effluent at a given location without bothering with neighboring locations outside of the area of interest. The objective in compliance monitoring is usually to assess whether the level of particular compounds are below critical levels stipulated under some regulatory framework. Compliance monitoring could also be viewed as quality control measures.
- *Impact monitoring*. This is undertaken to assess the human impact upon the natural environment, with the objective of taking remedial measures to prevent or minimize such impacts. This type of monitoring is useful in compliance and impact assessment monitoring.

Within all the above categorization, a framework for designing a monitoring program is essential. As an example, Finlayson (1996) presents a framework that consists of the identification of issues or problems, definition of objectives, formulation of hypothesis, choosing the desired methods and variables to observe, assessment of feasibility and cost effectiveness, conducting pilot studies, collecting samples, analyzing the collected samples, interpreting data and reporting the results, and implementing management actions. A similar model is presented by Maher and Batley as reported in Burden et al. (2002), who point out that good monitoring programs obtain information and are not just data collection exercise and as such should be cost effective, yet provide information and knowledge to inform those commissioning the data collection.

Spellerberg (2005) summarizes the relevance of environmental monitoring as *adaptive management*, which provides a basis for managing data and provides a learning experience from outcomes of operational programs, *environmental planning* as a basis for the better use of land, *monitoring the state of the environment* using organism to monitor pollution and indicate the quality of the environment, *ecological sciences* monitoring as a way of advancing knowledge about the dynamics of the ecosystem, *pest and diseases* monitoring for agriculture and forestry in order to establish effective means of controlling these, and *climate change* to monitor, for example, the effect of global warming.

1.2 Challenges and Practice of Environmental Monitoring

With increasing development and technological advancement in the world and the rapidly changing state of environmental management, the task of monitoring the environment continues to become more important, as noted, e.g., by Burden et al. (2002), who elucidates the role and practice of environmental monitoring. Burden et al. (2002), in realizing the importance that underpins environmental monitoring, present a handbook that guides environmental monitoring of water, soil and sediments, and the atmosphere. Their work also considers chemical, physical and biological monitoring, all aimed at enhancing environmental management. An attempt to address environmental monitoring in an integrated manner is presented, e.g., in Wiersma (2004), while Goldsmith (1991) and Downes et al. (2002) provide thorough overviews of ecological monitoring and conservation.

In most countries, environmental management requires development projects to undertake an Environmental Impact Assessment (EIA) (see Chap. 28), which brings with it the need for baseline survey data that are useful in assisting the prediction of the environmental impacts of a proposed project. The collection of baseline survey data therefore requires some form of monitoring. Downes et al. (2002) put forward the Before-After-Control-Impact (BACI) model, which helps to assess whether a given activity has impacted upon the environment at a given location.

Owing to the increase in human population and the pressure it exerts on the Earth's resources, the planet's environment has been changing at an alarming rate which necessitates monitoring measures to be put in place (Mackenzie 2003). In summary, therefore, environmental monitoring serves *to assess the effectiveness of an environmental legislation or policy*, *to monitor and assess compliance with regulatory statutes established to protect the environment, e.g., monitoring that the effluence from a given factory draining into a given river must be treated to a given standard*, and *for environmental change detection, e.g., vegetation change for the purpose of early warning*.

An example of change monitoring of agricultural land is shown in the photograph in Fig. 1.1, taken at Mt. Kokeby, Australia. In this figure, the vegetation (except salt tolerant fodders) are dying due to the effect of secondary salinity caused by vegetation clearing for farming purposes. The salinity is caused by increased water recharge, which seeped into the ground and caused an upsurge of groundwater (rising to within 1 m of the top soil (i.e., root zone)), dissolving the salt trapped inside the soil and thereby causing the vegetation to die. Monitoring the extent of salinity in this case enables comparisons to be made between the current state (Fig. 1.1) and the baseline data before the salinity effect had a noticeable impact. This can be done by comparing the spatial extent covered by the dying vegetation to that occupied by undisturbed vegetation (baseline data). Geoinformatics provides technologies useful in mapping the spatial boundaries and is thus essential for monitoring changes in agricultural areas thereby assisting in environmental issues.

In 1997, the premier and legally binding protocol on climate change by the United Nation's framework convention on climate change—the Kyoto protocol—was signed (see Sect. 21.5.5). Within its many articles, this protocol outlined measures that were to be taken by signatory countries to reduce the greenhouse gas emissions that are contributing to climate change, e.g., *global warming*. Although political will seems to be wanning in the post Kyoto era, with some of the key players even renegading on their earlier promises, while others have opted out of the framework altogether, global

Fig. 1.1 Effect of secondary salinity at Mt. Kokeby, Australia

warming still remains one of the daunting challenges facing our environment and as a consequence, human society, today. Similarly, the rapid increase in *desertification* on the one hand, and *flooding* on the other, are environmental issues that are of increasing concern globally.

For instance, the damage arising from the torrential rains that caused havoc and destroyed properties in the USA in 1993 is estimated to have been US$15 billion, with 50 people killed and thousands of people evacuated, some for several months (Larson 1996). Today, the threat from torrential rains and flooding still remains real, as was seen in the 1997 El Niño-Southern Oscillation (ENSO) rains that swept away roads and bridges in Kenya, the 2000 Mozambique floods, the 2002 Germany floods, Hurricane Isabel in the US coast in 2003, the flooding in Pakistan in 2010 that displaced millions of people, the 2011 eastern Australian floods that displaced thousand of people and destroyed property estimated at billions of Australian dollars, the Brazilian flash floods that killed more than 500 people, and the 2012 floods in the USA caused by hurricane Candy. Meanwhile, the melting of polar ice and the resulting raising sea level raises concerns for the submersion of beaches and many coastal cities including those already below sea level.

To be able to predict and model these occurrences so as to minimize the negative consequences, such as those indicated by Larson (1996), atmospheric studies must be undertaken with the aim of improving current methods for providing *accurate*, *reliable* and *timely* data. These data are useful in Numerical Weather Prediction (NWP) models for weather forecasting, and climatic models for monitoring climatic changes. In addition, *accurate*, *reliable* and *timely information* on weather is essential for other applications, such as flight navigation, precision agriculture etc.

In practice, data for NWP and climatic models are normally collected using balloon-borne radiosondes, satellites (polar and geostationary) and other sources, e.g., flight data from airplanes. Whereas Mackenzie (2003, p. 94) points out that about 9,500 land-based stations and 7,000 merchant ships at any one time send up weather balloons, Wickert (2002) noted that most of these data cover the northern hemisphere, with the southern hemisphere (especially Africa and South America) lacking adequate data due to financial constraints. The lack of radiosonde data is also noted in the oceanic areas, hence leading to inadequate data for NWP and climatic models.

1.3 Geoinformatics and Environmental Monitoring

To effectively address the diverse challenges typical in environmental monitoring, as outlined in Sect. 1.2, calls for the integration of various multi-disciplinary technologies. In this section, the role of geoinformatics in environmental monitoring is articulated. However, details of various geoinformation technologies are espoused in subsequent chapters. Within the monitoring framework proposed by Finlayson (1996) (see Sect. 1.1), geoinformatics could play a key role by providing efficient methods for measuring and documenting *spatial environmental changes* at local, regional and global scales and over varying temporal scales.

Satellite remote sensing has been extensively applied in monitoring the environment, see e.g., Spitzer (1986), Leimgruber et al. (2005), Dymond (2001) etc. According to Lein (2012), satellite data enjoys a comparative advantage over other methodologies in several ways:

- Large areal coverage;
- Describes a recent historical record dating from the 1970s to present;
- Offers convenient digital storage and retrieval;
- Facilitates objective assessment of environmental conditions; and
- Provides a consistent basis for measurement that permits the analysis of change.

The ability to map and detect environmental changes is key to the successful application of satellite remote sensing in environmental monitoring. Either a *top-down* or *bottom-up* approach can be employed to integrate remote sensing into a monitoring program. Whereas a top-down approach is suitable with low spatial resolution imagery, and is therefore appropriate for monitoring areas of large geographic extent, the bottom-up approach, on the other hand, focuses on regional to local environmental scenarios and relies heavily on input from local stakeholders and/or governmental agencies. To be able to detect changes in remotely sensed imagery, different change detection algorithms ranging from algebraic to classification-based techniques have been developed.

Integrating satellite remote sensing and global navigation satellite systems (GNSS) satellites could be useful in conducting rapid pilot studies such as providing quick and accurate spatial coverage and in recording the locations of the collected samples. These space-based techniques could also play a vital role in implementing management actions and in auditing environmental plans. As an example, for coastal management plans, these technologies could be used to locate areas prone to erosion caused by variations in shoreline position, thereby leading to preventive actions being taken (see, e.g., Goncalves (2010), Goncalves et al. (2012)). For auditing purposes, for example, they could be used to indicate the locations of effluent from a given factory. Such spatial information can then be used to study the ecosystem at that particular location.

To enhance global weather and climatic predictions, current systems have to be complemented by a system that will provide global coverage, and whose signals will be able to penetrate clouds and dust to remote sense the atmosphere. Such a system, already proposed as early as 1965 by Fischbach (1965), and which is currently an active area of research, is the new field of *GNSS-Meteorology*. This involves the use of global positioning system (GPS) satellites to obtain atmospheric profiles of *temperature*, *pressure* and *water vapour/humidity*.

GPS was developed by the US for its military purposes. It is an all weather tool capable of providing three-dimensional positions at any time (Hofman-Wellenhof et al. 2001). At the time of its conception, fewer civilian applications were envisaged. In recent years, however, its use has widened to include, e.g., meteorological and environmental applications such as monitoring of sea level and variation in stored fresh water (Awange et al. 2007; Awange 2012). This wide increase in GPS usage has led to the establishment of other equivalent systems by various nations/group of nations to meet their security and scientific needs.

For example, the European Union (EU) is launching the Galileo satellites, expected to be operational by 2014 or 2015, the Chinese are developing COMPASS (also known as Beidou-2, BD2) that is expected to have 35 satellites, and the Russians are improving upon their GLONASS system by having smaller and more manageable satellites that have now achieved the 24 satellites needed to reach a full operational capability. These constellations of satellites, collectively termed Global Navigation Satellite Systems (GNSS), will provide very useful tools for monitoring the environment. In Chap. 4 a brief overview of the GNSS systems and their future will be presented.

On the other hand, remote sensing is a rapidly advancing field of study that aims at the gathering of environmental data using a wide range of satellite and airborne platforms. When combined with location-based GNSS data, remote sensing contributes enormously to spatio-temporal Earth surface monitoring with a spatial resolution approaching GPS data precision (Urbano et al. 2010). Various forms of remote sensing approaches, e.g., optical (passive), thermal (passive), photogrammetry (passive), LiDAR (Light Detection And Ranging) (active) and microwave (active), see e.g., Lillesand et al. (2010), Richards (1994), Jensen (2005) are available for environmental monitoring.

The importance of remote sensing for environmental applications has been demonstrated through NASA's launch of the Earth Observation Satellites (EOS) 'Terra' and 'Aqua' in 1999 and 2002, respectively, among many others. The objective of the EOS program was to develop the ability to monitor and predict environmental changes that occur both naturally and as a result of human activities through measurements of global and seasonally distributed Earth surface and atmospheric parameters such as land use, land cover, surface wetness, snow and ice cover, surface temperature, clouds, aerosols, fire occurrence, volcanic effects and trace gases (Huete 2004).

The inadequacy in the coverage of radiosonde data, as pointed out at the end of Sect. 1.2, is partly compensated for by the availability of polar and geostationary remote sensing satellite data. Polar orbiting satellites include the US-owned National Ocean and Atmospheric Administration NOAA-14 and NOAA-15 spacecrafts, while examples of geostationary satellites include the US-based Geostationary Operational Environmental Satellite (GEOS) and the European-owned METEOrological SATellite (METEOSAT).

Polar and geostationary satellites, such as the above, provide temperature and water vapour profile measurements. However, they have their own limitations. For high altitude winter conditions, for instance, the use of passive Infra Red (IR) is difficult due to *very cold temperatures*, *common near-surface thermal inversion*, and a *high percentage of ice cloud* coverage that play a role in limiting IR soundings (Melbourne et al. 1994). In volcanic areas, remote sensing satellite measurements are also affected by the presence of dust and aerosol. Large-scale volcanic eruptions normally inject large amounts of aerosols into the lower stratosphere, thus limiting the IR observation of the stratosphere and lower regions.

Coupled with the above technologies for geodata acquisition is geographic information system (GIS). This is a spatial decision support tool comprised of hardware, software, data (which forms the primary component of GIS), human resource, and end users (clients). Until recently, GIS and related technologies such as GPS and remote sensing were largely the domain of a few researchers. Things, however, are changing with the exploitation of these systems for environmental monitoring. For instance, GIS is finding use in environmental applications because (Macarthur 2004):

- Environmental issues are subject to widespread interest and heated debate;
- GIS can handle a large amount of different kinds of data and organize these data into topics or themes that represent the multiple aspect of complex environmental issues; and
- GIS serves as a collaborative tool that promotes interaction.

The important feature of GIS that sets it apart from other information systems, e.g., those used in the financial world that need not or cannot make use of spatial or location-based attributes of the dataset, is its capability to make use of its databases to reference spatial features to locations (longitude, latitude, and altitude), relate these spatial attributes to maps of the region, and to offer spatial integration with other pertinent databases for the region (Taylor et al. 2000). It is in providing these cost effective location-based data for creating and updating GIS databases that GNSS plays a major role. GNSS also provides ground control points for remote sensing techniques that supply geodata to GIS, and the provision of a field mapping tool that enables attributes or features to be directly captured together with positions (see Fig. 2.2, p. 25).

In most text books, e.g., Spellerberg (2005), the most common satellite technique mentioned in environmental monitoring is remote sensing. Several applications have, however, directly reported the direct combination of GIS and GNSS for environmental monitoring, see e.g., Steede-Terry (2000). As an example of the integration of GNSS and GIS, Taylor et al. (2000) discuss the case of monitoring traffic congestion, which has the environmental impact of emitting CO_2 into the atmosphere thus contributing to global warming and increasing fuel consumption. They demonstrate how a GIS-GNSS system can be integrated to provide useful monitoring information, where GNSS provides locations for both static and dynamic recordings of vehicles' positions over time on the one hand. GIS on the other hand plays the role of database integrator by super-positioning separate map layers of the data base, e.g., maps of topography and land use, transport networks, infrastructure, socio-economic and demographic data, traffic flow data, pollution, and environmental impact data (Taylor et al. 2000). However, for such a system to be operationalized, remote sensing would still be required to provide updated map data as shown in Fig. 2.2 (p. 25).

Uriel (1998) discusses the relevance of spatial tools and landscape ecology to emerging infectious diseases and to studies of global change effects on vector-borne diseases, while Bonner et al. (2003) consider the combination of GNSS and GIS geocoding in epidemiological research. Barbari et al. (2006) examined the potential of combining GNSS and GIS to support studies on livestock behaviour in pastures. They illustrated the potential to acquire information useful for cases such as breeding and good environmental management. In another animal behavioural study, Hebblewhite and Haydon (2010) found that the populations of most wide-ranging species move over areas in orders of magnitude larger in scope than could be revealed by traditional methods such as very high frequency (VHF) radio telemetry, and that the advent of GNSS-based radio telemetry offered the possibility of conservation benefits such as harvest management, habitat and movement corridor protection, and trans-boundary collaboration. They present the example of the Serengeti where simple GNSS-based locations over different jurisdictions with different levels of protection highlighted the precarious state of one of the wonders of the world—the Serengeti-Mara wildebeest migration (Hebblewhite and Haydon 2010; Thirgood et al. 2004).

A combination of GNSS and Argos collars have been used by Durner et al. (2009) to contribute to understanding the impact of climate change on polar bears. This is achieved, thanks to GNSS' all-weather continuous observations that permitted year-round observations, revealing the circumpolar nature of polar bear movements, and the details of how sea ice thickness and structure influences polar bear success in hunting their main prey, seals (Hebblewhite and Haydon 2010). In Janssen (2012) an indirect tracking of drop bears using GNSS in presented. The possibility of integrating GNSS spatial data with other data, e.g., from remote sensing satellites, and socio-

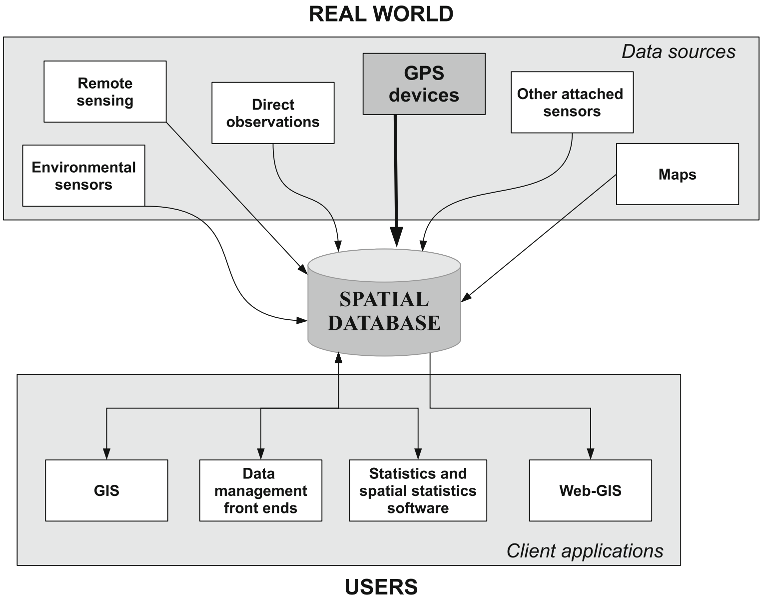

Fig. 1.2 Schema of a possible client/server software system that combines information from several data sources, including core GNSS data, into the central spatial database where it is accessed, locally or remotely, by client applications for manipulation, visualization and analysis. Outputs are stored back in the database. *Source* Urbano et al. (2010)