Environmental Science

Joseph Awange
John Kiema

Environmental Geoinformatics

Extreme Hydro-Climatic and Food Security Challenges: Exploiting the Big Data

Second Edition

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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—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 Awange and John Kiema, 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.

Karlsruhe, Germany
January 2013

Hans-Peter Bähr
Prof. Dr.-Ing. Dr.h.c.
Karlsruhe Institute of Technology (KIT)

Preface to the Second Edition

The main focus of this second edition shifts from monitoring and management to Extreme Hydro-Climatic and Food Security Challenges: Exploiting the "Big Data." Since the writing of the first edition of the book, so much has changed in terms of technology, while the demand for geospatial data has increased with the advent of the "big data era." For instance, the use of laser scanning has advanced so much that it is unavoidable in most environmental monitoring tasks, whereas unmanned aircraft vehicles (UAVs)/drones are emerging as efficient tools that address food security issues among other many contemporary challenges. Furthermore, global navigation satellite systems (GNSS) are now responding to challenges posed by climate change by unraveling the impacts of teleconnection (e.g., ENSO) as well as advancing the use of reflected signals (GNSS reflectometry) to monitor, e.g., soil moisture variations. Indeed, all these are summarized by the explosive use of "big data" in many fields of human endeavor.

Moreover, with the ever-increasing global population, intense pressure is being exerted on the Earth's resources, leading to severe changes in its land cover (e.g., deforestation), diminishing biodiversity and natural habitats, dwindling freshwater supplies, and changing weather and climatic patterns (e.g., global warming, changing sea level). Environmental monitoring techniques that provide such information are under scrutiny from an increasingly environmentally conscious society that demands the efficient delivery of such information at a minimal cost. Environmental changes vary both spatially and temporally, thereby putting pressure on traditional methods of data acquisition, some of which are very labor intensive, such as animal tracking 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. One direction being followed in the development of such techniques involves environmental geoinformatics, which can act as stand-alone method, or to complement traditional methods.

With these in mind, this second edition of the book features five new chapters: light detection and ranging (LiDAR), CORONA historical declassified products, unmanned aircraft vehicles (UAVs), GNSS reflectometry, and GNSS applications to climate variability. Furthermore, various chapters have been updated.

Perth, Australia/Recife, Brazil Joseph Awange
Nairobi, Kenya John Kiema
August 2018

Preface to the First Edition

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 freshwater 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 [2] 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 [1]. 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 [1].

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.

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Perth, Australia/Karlsruhe, Germany — Joseph L. Awange
Nairobi, Kenya/Musanze, Rwanda — John B. Kyalo Kiema
February 2013

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Contents

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 [8]

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. [1] 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 [2]. A similar definition is provided by [3] 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 of variables and processes for a specific purpose, such as ascertaining whether a given project is being undertaken according to predefined environmental standards [2, 4].

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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 [5].

There are various different ways of categorizing monitoring. In one example, Spellerberg [2] 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 [2] outlines four different categories of environmental monitoring based on [6]:

(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. [7] 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 [4] 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 [8], 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 [2] 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. [8], who elucidates the role and practice of environmental monitoring. Burden et al. [8], 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 [9], while Goldsmith [10] and Downes et al. [7] 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. 33), 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. [7] put forward the BACI (Before-After-Control-Impact) 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 [11]. 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 (UNFCCC)—the Kyoto protocol—was signed (see Sect. 25.2.2). Within its many articles, this protocol out-

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