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GIS and remote sensing integration: in search of a definition

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> *Synergy – the bonus that is achieved when things work together harmoniously* – Mark Twain
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> *Wisdom implies a mature integration of appropriate knowledge, a seasoned ability to filter the inessential from the essential* – Deborah Rozman

1.1 Introduction

Ever since its formalism by the NCGIA Initiative-12 in 1990 (Star *et al*., 1991), the move towards 'seamless' and 'hybrid' integration of data, techniques and organization from the geographic information systems (GIS) domain with those from the remote sensing[2] sphere has been arduous, sporadic and irresolute. Few major breakthroughs have materialized other than the establishment of routine data format interchanges, improvements in the efficiency of interoperational relational database systems (Abel *et al*., 1994) and modest advances in the accuracy of object/thematic

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[1] GIS is used both singularly and as a collective throughout this book. GIS is typically defined as 'a computer system for the collection, storage, manipulation, display and management of spatial information'.

[2] Remote sensing predominantly refers to the collection and manipulation of digital satellite imagery.

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identification cross-overs (Shi *et al.*, 1999). More ambitious endeavours to create truly *integrated* geographic information systems (IGIS), sometimes called 'total' integration, seem to have floundered on most of the initial conceptual, technical and institutional obstacles identified by the NCGIA initiative (cf. Ehlers, 1989; Star *et al.*, 1990; Hinton, 1996; Wilkinson, 1996; Mesev, 1997). One could even say that the search for more resolute solutions, such as those related to the object/field dichotomy, analytical interoperability, the close monitoring of error propagation and the compatibility of mutually beneficial research programmes, remains as elusive today as it was in 1990. Admittedly, many proprietary geospatial systems are capable of representing and querying data stored in an increasing number of formats and resolutions, yet computational compatibility is rarely translated to full conceptual, thematic, scale and temporal compatibility. In other words, although technical expediency has facilitated the handling of data from GIS and remote sensing, there is no guarantee that any subsequent computational interaction necessarily results in strong intuitive and theoretical mutual relationships. Total integration may not be a question of whether GIS and remote sensing *can* be integrated, but more of whether they *should* be integrated – and to answer that, some discussion is first required on precisely what integration between GIS and remote sensing actually means.

1.2 In search of a definition

No one definition of integration between GIS and remote sensing exists. Instead, integration has been used to refer indiscriminately to almost any type of connection, ranging from pragmatic computational amalgamation of data to the conceptual understanding of how geographic features are interrelated. Unsurprisingly, an unbounded definition embraces a large and growing body of literature, anything from research on tight, seamless databases, and robust statistical relationships (Zhou, 1989; Smits, 1999), to applications of variable implicitness and unpredictable levels of information exchange (cf. de Brouwer *et al.*, 1990; Janssen *et al.*, 1990; Davis *et al.*, 1991; Chagarlamundi and Ganulf, 1993; Debinski *et al.*, 1999; Driese *et al.*, 2001; Brivio *et al.*, 2002). However, in the search for a narrower definition, any book with the term 'integration', to all intents and purposes, presumes a strict discussion on numerical calculations and complex computational algorithms, especially when the integration is referring to system-based technologies, such as GIS and remote sensing. In this sense, integration may be defined as the establishment of numerical consistency across disparate digital data models and the execution of robust programming algorithms (Archibald, 1987; Brown and Fletcher, 1994; Abel *et al.*, 1994). In addition, emphasis is on computational schemata that ensure either efficient dual operability across software platforms or, preferably, the creation of a hybrid database capable of handling incongruent data at variable resolution, complexity, quality and completeness (Zhou, 1989). Under this definition, the integration of data (the beginnings of data fusion) and algorithms may be numerically and operationally feasible, but it does not necessarily cover the blending of disparate data and algorithms pertinent to information that is explicitly *geographic* in nature. The jump from generic numerical data to geographic data represents more than simply adding a locational dimension. Both the quality and usefulness of spatial data that represent and model the complex real world are intrinsically constrained by three basic cartographic rules: the scale of representation; the generalization of feature delineation; and the semantic description of parcels of the Earth's surface and atmosphere. These three conditioning factors are further intensified by the eternal pursuit for greater accuracy and higher precision when recording the exact locational coordinates of geographic features.

Both GIS and remote sensing are technologies that focus exclusively on geographic data and, as such, both are designed to represent the world's geographic features as reliably and realistically as possible and within the constraints of the three cartographic rules. However, that is where the straightforward comparison ends. Technically and conceptually, each technology[3] is founded on diverging principles, where remote sensing is predominantly a data collection technology, while GIS is one that is principally dedicated to data handling. Remote sensing deals with the more immediate access of primary data at a more continuous scale, collected over extensive areas at rapid temporal frequencies. Digital remotely sensed data records the magnitude of passive and active energy at multiple wavelengths as it interacts with the earth's surface and atmosphere. As such, remotely sensed pixels are a multispectral radiometric vector that represents the continuous nature of the biophysical and anthropogenic landscapes at various levels of spatial, spectral and temporal resolution. The resultant raster image of individual pixels shows how the landscapes would appear from an elevated viewpoint. However, the image does not have an interrelated topology and the pixels are not implicitly related, other than by their positional adjacency. The continuous representation of reality and the lack of a coherent topology invariably limit the extent to which pure thematic information can be extracted, and as such the accuracy of an image is highly unpredictable, both spatially and thematically.

In comparison, data handled by GIS are commonly stored as vector models and represent geographic features as more discrete entities within a structured topology and defined by implicit relationships. As a result, discrete entities are delineated by sharper, crisp boundaries and labelled with less ambiguous thematic descriptions. However, much of the digital spatial data stored in a GIS are derived from external sources, such as analogue maps, ground surveys, global positioning systems (GPS) and, most importantly, remote sensing (Gao, 2002; Xue *et al.*, 2002). Furthermore, remote sensing, in the form of aerial photographs, is also the predominant resource

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[3] GIS and remote sensing are referred to as technologies in this book although the terms 'field' or 'discipline' (as incorporated by GIScience) are sometimes used by other sources to indicate broader theoretical underpinnings.

for producing many of the topographic compilations from which environmental indicators, such as elevation, hydrology and land cover, are digitized into sharp vector boundaries and entered into GIS (Dobson, 1993). More recently, satellite remote sensors with high spatial resolutions of 4 m and finer are also providing valuable input data into many GIS applications, especially for the much neglected field of monitoring urban morphologies, urban pollution and urban growth (Mesev, 2003). The traditional role and reliance on remote sensing as input data for GIS suggests that integration is not new and has existed as long as both technologies (Marble, 1981; Piowowar *et al.*, 1990; Wilkinson, 1996). The three time-honoured ways in which GIS and remote sensing have been integrated are as follows:

- *Remote sensing used to collect data for GIS databases*. This includes the ability to update and validate thematic coverages, using aerial photographs, earth observation satellite sensors, interferometric radar and LiDAR.
- *GIS data used as ancillary information for image processing*. Many techniques exist, such as using vector lines to define boundaries between land covers, providing locational attributes for geo-registration, and aiding classification by selecting purer training samples, weighting discrimination functions and sorting classified pixels (see Hutchinson, 1982; Foody, 1988; Mesev, 1998, 2001).
- *Combined analytical functions*. These include basic spatial queries, the overlay of statistical and thematic attributes from both GIS and remote sensing, using Boolean and fuzzy logic, and the building of multiple-view expert systems.

All three of these traditional means of integration were established well before the NCGIA initiative of 1990. According to the initiative, the next step for greater assimilation between GIS and remote sensing depended on greater computer processing power (Faust *et al.*, 1991), reduction in error propagation (Lunetta *et al.*, 1991), compatibility of data structures (Ehlers *et al.*, 1991), and resolution of many non-analytical institutional impediments, such as data availability, costs, standards and organizational infrastructure (Lauer *et al.*, 1991). Unfortunately, the volume of subsequent research has not matched the same sense of importance and urgency expressed by these and other calls to ensure tighter integration.

1.2.1 Evolutionary integration

For some, complete or total integration between GIS and remote sensing is the ultimate goal. Ehlers *et al.*(1989) proposed three stages in the evolution of integration that focused on the degree of interaction between data models, the level of data exchange, the pursuit of close geometric registration, the matching of cartographic representation, a parallel user interface, and the compatibility of geographic abstraction. The three stages of the evolution are as follows:

- *Stage 1* would focus on the separate but equal development of databases from each technology. Data would be exchanged in predominantly vector format (for GIS) and raster models (for remote sensing) but capable of being simultaneously displayed by overlays. Analysis would be limited to the update of GIS coverages by the positional comparison of thematic attributes generated from classified remotely sensed images; or the use of GIS data for facilitating image georegistration.
- *Stage 2* oversees the continuation of separate databases, but each technology would share a user interface. Data from each technology would be converted to the other through vectorization and rasterization, and the operational rationalization of spatial and temporal attributes.
- *Stage 3* represents the final level of complete or 'total' integration. Essentially, GIS and remote sensing become one indistinguishable system, in which raster and vector data models are handled interchangeably through data uniformity across object-based (GIS data) and field-based (remotely sensed data) geographic representation.

Total integration, although theoretically desirable, is not replicated pragmatically. Instead, much research and applications involving the integration of GIS and remote sensing seems to be adequately completed by stages 1 and 2.

1.2.2 Methodological integration

The three stages in the evolution of integration of data and computational analysis between GIS and remote sensing also presuppose a methodological continuum; generally from loose data coupling to indistinguishable models of representation. However, the continuum is unstructured and integration issues are sporadic and unfocused. Mesev (1997) outlined a logical and structured, yet flexible, framework or schema for the formalization of methodological factors and issues for consideration when tackling integration between GIS and remote sensing. The reasons for designing a formal schema were primarily to define all conceivable steps within a structure that defines data accumulation, processing, and decisions in a general chronological order, and also to promote awareness and stimulate discussion of the many pitfalls surrounding the delicate interface between GIS and remote sensing. Organized into a series of hierarchical levels, the top-down approach of the schema ensures that all methodological issues are addressed at increasing detail. Level 1 contains the broadest set and includes data unity, measurement conformity, positional integrity, statistical relationships, and classification compatibility – as well as integration design with reference to many non-analytical and external factors such as feasibility and cost–benefit studies. At level 2, links between the six level 1 components become more complex, and by level 3 they

Level II	Level III
Data unity (factors that bring together GIS and remotely sensed data)	
Information interchange	Definition of integration, type of information, information harmony (spatial units and attributes)
Data availability	Awareness, publicity, search, data type, age, quality, (access or create)
Data accessibility	Cost, agreements, exchanges, sharing, proprietary, resistance, confidentiality, liability
Data creation	Digitising, scanning, survey information encoding, sampling, data transformation, GPS
Measurement conformity (factors that link GIS and remotely sensed data)	
Data representation	Data structures (vector, raster), data type, level of measurement, field-based vs. object-based modelling, interpolation
Database design	Type (relational, hybrid), schema, data dictionary, implementation (query, testing)
Data transfer	Format, standards, precision, accuracy
Positional integrity (factors that spatially coordinate GIS and remotely sensed data)	
Generalization and scale	Spatial resolution, scale, data reduction and aggregation, scale invariance
Geometric transformation	Rectification, registration, resampling, coordinate system, projection, error evaluation
Statistical relationships (factors that measure links between GIS and remote sensing)	
Vertical	Boolean overlays, fuzzy overlays, dasymetric mapping, areal interpolation, linear and non-linear equations, time series, change detection
Lateral	Spatial searches, proximity analysis, textural properties
Classification compatibility (factors that harmonize information between GIS and remote sensing)	
Semantics	Classification schemata, levels, descriptions, class merging, standardization
Classification	Stage (pre-, during, post-), level (pixel, sub-pixel) type (per-pixel, textural, contextual, neural nets, fuzzy sets), change detection, accuracy assessment

Figure 1.1 Level 3 integration issues

Integration design	
Objectives	Plan of integration, cost/benefit assessment, feasibility, alternatives to integration
Integration specifications	User requirements (intended use, level of training, education), system requirements (hardware, software, computing efficiency)
Decision making	Testing, visualization, ability to replicate integration, decision-support, implementation or advocate alternatives, bidirectional updating and feedback into individual GIS and remote sensing projects

Figure 1.1 (Continued)

increase substantially in number and detail. The relationship between the three levels is a standard hierarchically nested structure; this is where a level 1 component, such as data unity, is divided into a series of level 2 factors, such as information interchange and data availability; and where a level 2 factor such as data availability is divided into level 3 items, such as awareness, publicity, quality, age, etc. (Figure 1.1).

Mesev (1997) only outlines the first three levels (Figure 1.1), but there is no reason why further more refined levels cannot be added. Where schemata have already been documented, for example by Marble (1981) and Davis *et al.*(1991), links between GIS and remote sensing have not been formalized or itemized, and relationships are only presumed. The schema by Mesev (1997) attempts to define the commonest links within a logical structure, and also aims to address direct data coupling, including parallel data acquisition, and analytical operations, with frequent feedback loops and joint decision-making scenarios.

Total integration may be the ultimate goal, yet GIS and remote sensing software have largely retained their independence, even when all technical and methodological issues are sufficiently taken into consideration. For example, there is a conspicuous dearth of literature on total integration in the years since the establishment of the 1990 NCGIA initative. Instead, most studies have tended to focus on the utilization and matching of scale-appropriate thematic information, regardless of source and format (Quattrochi and Goodchild, 1997). Applications spanning both the biophysical and built environments have been facilitated by the expansion in the range of geospatial data, most notably from GPS receivers, and the new breed of remote sensors, such as interferometric synthetic aperture radar (SAR), light detection and ranging (LiDAR), and more recent remote sensors, such as the moderate resolution imaging spectroradiometer (MODIS), the advanced spaceborne thermal emission and reflection radiometer (ASTER), IKONOS and Quickbird.

1.3 Outline of the book

Research and applications throughout this book outline and demonstrate how using data and processing from GIS and remote sensing produces benefits that frequently exceed those from using each technology singularly. Benefits are measured not simply in terms of higher accuracy and greater precision in output, but also on types and levels of information that are otherwise either unavailable or of an inferior quality in one or the other technology.

However, the diverse applications in this book face several common challenges. First, integration can lead to problems of accuracy, uncertainty and scale, which, while affecting any GIS analysis, are often compounded by the integration with remotely sensed data. Chapters 2, 3 and 4 focus almost exclusively on outlining practical solutions for dealing with some of these technical pitfalls. A second major area of concern is the current level of disorganization within GIS and remote sensing technologies. Without a standard method of classifying different operations and data types, it is difficult to develop widely applicable methods of integration. Lack of communication marks a third major obstacle to integration. Chapter 7 notes the need for communication between the remote sensing community and social sciences, while Chapter 9 advocates an exchange of ideas between GIS, remote sensing and the fields of hazard analysis and disaster mitigation. Chapters 6, 8 and 11 showcase the ways in which integration can assist people working in many professions, including urban planning and environmental management. Communication between the academic and professional communities will be an essential factor in the success of integration. Lastly, many of the authors to this book describe their research as a first step towards further integration. They propose better organizational frameworks, more sophisticated applications, and innovative strategies for future interdisciplinary collaboration. Although GIS has long been used to integrate data from various sources, the integration of GIS and remote sensing opens the door to a new world of possibilities.

Chapter 1 attempts to define and conceptualize the rationale, motivation, and expediency behind the integration of data and techniques from the technology of GIS with data and techniques from the technology of remote sensing. It examines whether there is enough scope for overlap and communication and how both technologies have developed concurrently over recent times.

Chapter 2 reiterates the conceptual divisions between GIS and remote sensing and warns of continued *ad hoc* integration if the data integration approach is not replaced by an analysis integration approach based on a taxonomy of system-independent analysis functions. Most existing GIS taxonomies are based on the underlying system and its specific data structure, while various remote sensing systems offer their own unique classification systems. In response, Ehlers proposes an integrated taxonomy based on universal GIS operators and a variety of image processing functions. While somewhat limited, this approach can nevertheless serve as a basis for future progress towards a single, widely applicable, integrated taxonomy for GIS and remote sensing. Another obstacle to total integration is the issue of how to deal with uncertainty. All GIS and remotely sensed data include some level of inaccuracy, but the problem of inaccuracy is compounded when data are transformed from one model of geographic space to another. Ehlers focuses on positional and thematic error, which he identifies as the ‘dominant error sources in the integration of GIS and remote sensing’. To support this, an example of a typical GIS/remote sensing analysis (an inventory of land cover over an administrative area) is used to explore positional and thematic uncertainties, along with discussions on line and point errors, confidence regions for line segments, positional uncertainty of boundaries and area objects, and thematic uncertainties of classified remote sensing images. All of these are combined within the ‘S-band’ model, revealed as a first step towards a more comprehensive model of uncertainty.

Chapter 3 focuses on data fusion, an area of research increasingly prevalent since the inception of ‘telegeoprocessing’, a term referring to the interaction of GIS, distributed computing systems, telecommunications, GPS, etc. Two of the simplest methods of data fusion, already widely used, are remote sensing output to GIS (e.g. the conversion of a remotely sensed image to a GIS layer) and GIS input to remote sensing interpretation algorithms (e.g. the application of GIS data to remotely sensed images). Simple data fusion is currently being used successfully in commercial urban planning products. However, several fundamental problems must be overcome before more sophisticated techniques become prevalent; for example, the establishment of common standards, the use of compatible legends and scales, and the measurement of the degrees of accuracy. Data fusion, the authors assert, is not possible without first being able to compare data and select the most useful for a given project. Gamba and Dell’Acqua note that it is less important to combine original data than it is to derive useful, comparable information from various sources. By extracting comparable information from different sources, it is possible to view a single type of information from multiple perspectives. The authors provide a round-up of recent approaches to data fusion, such as multi-scale analysis, fuzzy logic and non-parametric and knowledge-based techniques, weighing the pros and cons of each. They then propose a method of integrating GIS and remote sensing into a change detection module, specifically to be used to extract features from a remotely sensed image, analyse change in an existing GIS layer, or detect change using both classification and feature extraction.

Chapter 4 centres on the problems that can occur when integrating data from GIS and remote sensing at different scales, using the ‘sampling frame’ and the concept of ‘support’. The sampling framework, defined as the set of all parameters that determine how data are acquired on a property of interest, affects the scale of spatial variation, present in both raster and vector models; while the support – a term derived from geostatistics and encapsulating the size, geometry and orientation of the space over which an observation is defined – can be thought of as a ‘primary scale of measurement’. For instance, variograms and fractal geometry are frequently used to assess the scales of spatial variation in the vector data model, and statistics such as Moran's I and Geary's C can measure spatial autocorrelation – upscaling and downscaling in these allows the size of the support to be altered. Processes can be modelled using spatially distributed dynamic models at appropriate scales; useful when attempting to understand a process better or predict its future behaviour. Atkinson goes on to concentrate on two main types of integration, GIS overlay and remote sensing classification. When combining GIS and remotely sensed data of different scales, degrading the data at finer resolution to match those of the coarser resolution is not always the best choice. It is particularly important to realize that the transformations of data from one form to another impose their own scales. Interpolation techniques, such as IDW and kriging, can be used to transform vector data to raster data, but the smoothing effects of interpolation can produce unwanted consequences. In a discussion of remote sensing land cover classification methods, Atkinson draws attention to problems associated with pixel-based classification, highlighting several advantages of per-parcel classification, soft classification, subpixel allocation and super-resolution mapping. The success of these techniques depends on the scales of measurement, underlying scales of variation, and accurate geometric registration between vector and raster datasets.

Chapter 5 introduces the use of spatial metrics and geostatistics in urban analysis across GIS and remotely sensed data, using techniques such as image interpolation, uncertainty mapping and identification of spatial variability in urban structures. The focus is on land cover and land use, the quintessential dichotomy between biophysical assemblages and anthropogenic exploitation, respectively. Liu and Herold illustrate three empirical studies linking the dichotomy with geostatistics and spatial metrics; the first, classifying images using geostatistics before interpreting the second-order data with spatial metrics; the second, exploring the correlation between population density and urban form; and lastly, reverting to geographically weighted regression to connect urban form and urban growth factors. Overall, these three case studies demonstrate that geostatistics and spatial metrics bring their own strengths and weaknesses to urban analysis.

Chapter 6 illustrates the ways in which GIS and remote sensing can be integrated to reveal spatial characteristics of urban sprawl at the building-unit level. Historically, sprawl research has focused on either demographic-based or physical landscape-based analysis, but concurrent implementation of GIS and remote sensing allows these two branches of investigation to merge. Hasse offers a review of sprawl in the GIS and remote sensing literature, including the variable definitions of sprawl, the concept of smart growth and the analysis of sprawl at the metropolitan and submetropolitan levels. The discussion progresses from simple types of integration (such as land use mapping based on remotely sensed images) to more complicated forms of integration (such as land cover datasets that employ 'land resource impact' indicators). Although geospatial technologies tend to be underused by urban planners and policy makers, Hasse sees great potential for sprawl measurements at the building-unit level, using models that replicate the nested hierarchical structure of urban areas (and may even avoid some of the scale problems mentioned in Chapter 4). The author outlines five geospatial indices of urban sprawl (GIUS) that provide measurements of various forms of sprawl. The five indices are urban density (the amount of land occupied by a housing unit), leap frog (the distance of new housing units to existing housing units), segregated land use (a measurement of land used for similar purposes), highway strip (the amount of land used for strip malls, fast-food restaurants and housing units lining rural highways) and community node inaccessibility (the distance of new housing units to the nearest community centres). The creation of an integrated database could facilitate increasingly sophisticated analyses of building-level urban sprawl.

Chapter 7 reviews a variety of remote sensing applications for urban analysis, but particular emphasis is placed on the estimation of socio-economic information (from remotely sensed images) and the modelling of socio-economic activity (by linking remotely sensed images with GIS data). Various types of socio-economic information can be estimated from remotely sensed images, including population density, employment, gross domestic product and electrical power consumption; and the use of remote sensing allows governments to estimate population in areas where censuses are out of date or unreliable. Population density can be estimated based on types of land use, employment from surface temperature, and GDP and power consumption from nighttime imagery. Furthermore, techniques for population interpolation meld existing population data with additional remote sensing data to create more accurate estimates. Socio-economic indices (e.g. a housing index or quality index) can be created by integrating GIS data with remote sensing data. Wu concludes with a discussion of the advantages and disadvantages of applying remote sensing to urban analysis. Advantages include the frequency with which remotely sensed data can be updated, whilst disadvantages include the lack of dialogue between remote sensing researchers and more traditional social scientists.

Chapter 8 examines the integration of remote sensing, GIS and spatial modelling for sustainable urban planning. It describes historic patterns of urban growth on the outskirts of Atlanta, Georgia, USA, and predicts potential patterns of future development. Using a series of Landsat images of the study area dating from 1973–1999, Yang performs change detection analysis to assess Atlanta's urban expansion, and spatial statistical analysis to identify the forces driving the city's growth. Central to the analyses is the integration of biophysical and socio-economic data at three scales: city, county and census tract. Dynamic spatial modelling is then performed using the SLEUTH urban growth model, with inputs that include remotely sensed and GIS data, such as urban land use, terrain conditions, socio-economic variables and location measures. As a result, the author models two potential scenarios for future urban growth; the first predicts the pattern of urban growth that will occur if current planning strategies remain unchanged and urban sprawl continues unabated, whilst the second scenario predicts the pattern of urban growth that will occur if Atlanta adopts some strategies for 'smart growth' and environmental conservation. This second scenario is favoured because it predicts approximately 50% of the growth that would occur from the first scenario. If geospatial information technology is to be used successfully in sustainable urban planning, Yang asserts that integration is not only desirable, but essential.

Chapter 9 introduces an integrative model for conducting vulnerability analyses – tested on a case study in Los Angeles, California, but remaining portable enough to apply the unique environmental risks and socio-economic context of their study to other places. The authors outline a scenario in which this relationship between the general and the particular is visualized as a hierarchy of nested ‘socio-ecological systems’. Specifically, the model integrates GIS and remote sensing data to predict the effects of hypothetical disasters and to highlight locations that are especially at risk. In their case study, susceptible places or ‘hot-spots’ are identified by a model of urban vulnerability to earthquakes, built on GIS data representing population, building size and geological conditions, as well as remotely sensed imagery used to measure the physical characteristics of the predicted hot-spots. A multiple end-member spectral mixture analysis is used in conjunction with landscape metrics to summarize spatial variation, while census data are used to create an index of wealth for Los Angeles, an index which demonstrates an expected negative correlation between wealth and vulnerability. When constructing their model, Rashed *et al.* borrow techniques from the fields of hazard analysis and disaster management. They argue that future research on GIS and remote sensing integration should be extended beyond the present focus on technological and methodological issues, to include the subject matter and allow its theoretical underlying dynamics to inform the direction of integration.

The last two chapters evaluate the current state of research on environmental applications completed by the mutual interaction of data from GIS and remote sensing. Miller and Rogan in *Chapter 10* focus on biodiversity and ecological representation and analysis, with particular emphasis on species distribution models (SDM) and change detection. In the past, the trend in ecological studies has been to use GIS and remote sensing separately, where GIS functions assist in the calculation of variables pertaining to climate, topography and environmental gradients, while remote sensing contributes information on spectral vegetation indices, structural configuration and land cover classification and change detection. The authors outline how these separate ecological indicators and techniques may be combined within SDM to produce habitat suitability maps, and how levels of biodiversity can be predicted from multiple suitability maps. An early example is the USGS’s Gap Analysis Programme, which combines GIS and remotely sensed data to identify potential problems related to biodiversity and species conservation. A more detailed case study by the authors demonstrates an innovative integrative methodology designed to combine five GIS layers (slope, elevation, aspect, vegetation type, and previous fire) with six spectral variables (Kauth Thomas). The methodology harnesses the logic of a hierarchical classification tree with the descriptive and predictive capabilities of generalized linear and generalized additive models to map land cover change in San Diego County, California. However, the reliability and effectiveness of such multivariate predictor models of species distribution can be improved by research that focuses on the extraction of more continuous spectra-based input data, at variable spatial and temporal scales, within more flexible statistical models.

The environmental theme is continued by the last chapter, *Chapter 11* by Shine and Mesev, which centres on the spatial and temporal role of GIS and remote sensing data for monitoring arid-zone ephemeral wetlands. A longitudinal case study from Mauritania in the Sahel region demonstrates how aerial photography, digital topographic maps, GPS readings and satellite sensor data, in combination, can provide valuable information on the location, size, shape and duration of transitional water bodies. The study is in response to the dearth of consistent digital geospatial information on the extent and quality of natural resources in developing countries – and as such modernized databases built on data from GIS and remote sensing are a vital prerequisite for the evolution of sound environmental management policies. In the Mauritania case study, remotely sensed data collected from the 1950s–1980s are used to compare the changes in size of several ephemeral wetlands, along with more detailed information on wetland characteristics from GPS surveys collected during field visits. The authors herald this integrative monitoring strategy as a model of a methodology that can not only help develop sustainable environmental policies in areas affected by ephemeral wetlands but also be applied to many other natural resources in the developing world.

1.4 Conclusions

Total integration has not yet materialized. With the volume of data available and the ease of exchange through the Internet, perhaps the road to full integration is less a computational bottleneck and more a conceptual disparity. As alluded to earlier, and as will be discussed throughout this book, remote sensing is chiefly designed to collect energy-derived geographic information, while GIS is predominantly a data-handling technology capable of comparing, evaluating, modelling and simulating geographic patterns. Conceptually, this difference is almost unsurmountable, and in any case why seek to completely fuse the two technologies into a single system when they seem to function quite satisfactorily side-by-side? If anything, the notion of total integration should refer to attaining a high level of complementary exchange of information and sharing of data processing, rather than some idealized and ultimately unattainable pursuit for homogeneity of data and the relentless strive for identical algorithms.

Another conceptual divergence and major obstacle to integration is how geographic information is represented. Remote sensors record continuous data representing the interaction of energy with the earth, while GIS is predominantly concerned with much more defined and discrete boundaries between geographic features. These two ‘views’ of reality are conflicting and difficult to operationalize within a single model or system. But these views can be also complementary; they allow the more recent data collected by remote sensors to update and embellish GIS layers, and they allow GIS data to geo-register and help extract information from remotely sensed imagery. Besides, this 'complementary' view is respectful of the fact that most GIS data are derived from remote sensing anyway.

Finally, one further reason for the absence of total integration is expediency. The way many applications 'combine' data from GIS and remote sensing can only best be described as *ad hoc* – not logically and painstakingly within some structured guidelines. Integration to many researchers dealing with geospatial data is *any* process that facilitates the fulfilment of their objectives, regardless of the level of assimilation. So perhaps the definition of integration should remain ambiguous and researchers should instead highlight the strengths of the two individual technologies, rather than strive to attain the redundant and inefficacious goal of absolute amalgamation.

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