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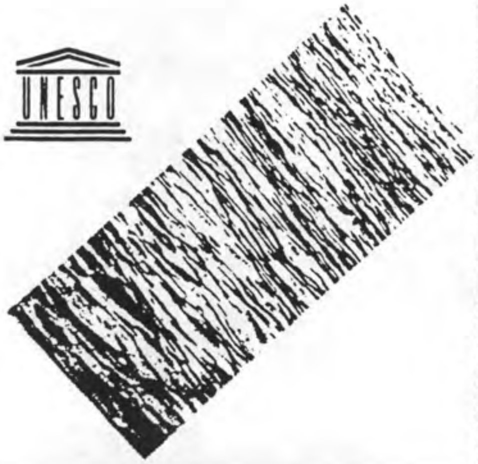
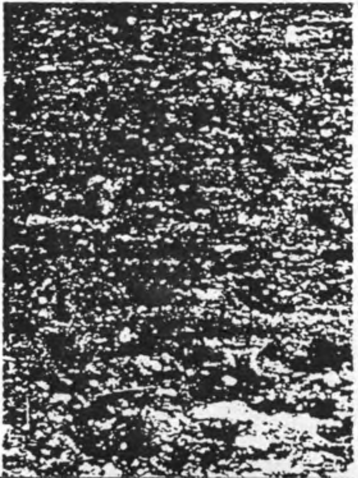
MAB DIGEST 12





UNESCO

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# PREFACE

## About this series...

The MAB Digest Series was launched by UNESCO in 1989. Several types of publications are included: distillations of the substantive findings of MAB activities; overviews of recent, ongoing and planned activities within MAB in particular subject or problem areas; and proposals for new research activities. The target audience varies from one digest to another. Some are designed with planners and policy-makers as the main audience in mind. Others are aimed at collaborators in the MAB Programme. Still others have technical personnel and research workers as the target, irrespective of whether or not they are involved in MAB.

## ... and MAB Digest 12

The purpose of this digest is to provide scientific researchers engaged in activities related to sustainable development with an overview of several data collection and information technologies, including remote sensing, geographical information systems and advanced modeling tools. The primary audience is not the experts and practitioners of the technologies and approaches described in the digest, but rather members of the broader scientific community who might wish to have at hand a synoptic overview of the characteristics and potential of new technologies and their possible application to contemporary research challenges. Particular emphasis is given to remote sensing and geographic information systems.

The digest has been prepared by an *ad hoc* group on Scientific Information for Sustainable Development set up in 1989 by the Scientific Committee on Problems of the Environment (SCOPE), with support from its parent body, the

International Council of Scientific Unions (ICSU), and from the United Nations Development Programme (UNDP), the French Ministry of the Environment and UNESCO. The *ad hoc* group was made-up of seven specialists: John Estes, Manfred Ehlers, Jean-Paul Malingreau, Ian Noble, Jonathan Raper, Jeffrey Star and Jim Weber. An interim report of the group was prepared as background for participants at the International Conference on an Agenda of Science for Environment and Development into the 21st Century (ASCEND-21) organized by ICSU in Vienna in November 1991. This report was also made available to the VIIIth General Assembly of SCOPE held in Seville (Spain) in January 1992. Prior to publication in its present form, the report was subsequently complemented by examples of applying modern technologies to specific issues and geo-ecological situations.

The basic information compiled by the SCOPE group has also been adapted and published in the first half of 1992 as UNESCO Environment and Development Brief 3 entitled *New Technologies: Remote Sensing and Geographic Information Systems*. This 16-page brief for decision-makers was prepared in cooperation with members of an internal UNESCO task force on remote sensing and geographic information systems, led by Robert Missotten of the Division of Earth Sciences. The principal aim of this task force is to promote and where appropriate harmonize the use of new advances in remote sensing and GIS technologies in UNESCO's programmes in such fields as identification and monitoring of natural hazards of geological origin (landslides, mudflows, volcanoes, active faults, etc.), risk managent, mountain hazard mapping, surface and ground water research management, creation of a database on spectral signatures of rocks and soils, ocean observation monitoring and investigations and climate observation, biosphere reserve planning and management, study of archaeological sites, use of computer-based learning modules on the use of remote sensing data in marine applications, and education, training and capacity building.

# CONTENTS

# SUMMARY

*Throughout human history, technology has been a key factor in facilitating and driving change. Today's technologies can create environmental change on spatial and temporal scales never before possible. Yet, the wise application of technologies can also facilitate investigations and lead to a more complete understanding of human impact on the environment. Through appropriate application of remote sensing, geographic information systems and modeling, we can move a significant way towards answering questions concerning the spatial and temporal dimensions of variations in environmental resources. These technologies for data collection, manipulation, analysis and information extraction can be used by the scientific community to: improve our understanding of the global environment; measure, map, monitor and model changes in that environment; and provide decision-makers with the information which they require to summarize the options available to decision-making bodies.*

*Remote sensing is used to gather information from a distance, with sensors recording electro-magnetic energy emitted or reflected from the Earth's surface. Different types of vegetation, soils and other features emit and reflect energy differently. This characteristic makes it possible to measure, map and monitor these features using remote sensing systems. Satellite sensors collect the bulk of remote sensing data at the present time. Most of these data are available in two formats: electronic and analog (i.e. image). Electronic data must generally be enhanced and filtered by a computer and compared with limited 'ground truth' data before they can be used for resource management.*

*Geographic Information Systems can be defined as computer systems for integrating and analysing spatial information in a decision-making context. Recent advances in GIS technology include: new hardware and software for digitizing and managing data, extracting information from complex databases and reproducing maps, making these tools more powerful and easier to use;*

*desk-top work stations, with increased data-processing speed and data storage capabilities; inexpensive plotters, lowering the cost and improving the quality of producing maps, charts and tables; easier to use GIS software; and improved graphics and visualization tools.*

*Models can take many forms and are built for a variety of purposes. A number of factors have restricted the application of models in the management of natural resources, but these problems are being overcome. The tasks required of models are being stated more clearly (e.g. prediction of crop yields, structural changes in vegetation, land suitability) and a suite of successful generic models is being developed in such fields as forest growth, crop trajectories and species ranges.*

*Expert systems (sometimes called knowledge based systems or advisory system) are computer programs able to simulate the problem-solving ability of an expert, and are among the most prominent products of the revival in artificial intelligence research. An expert system can be thought of as a model composed of rules and these rules are often qualitative (e.g. if the amount of monoculture cropping in the district is higher than the norm for the region then...). This is a major area of application in remote sensing where rule based models may assist in the initial classification of images. The other major application of expert systems is in assisting users harness the forces of the very powerful, but complex tools, provided in a comprehensive GIS.*

*These new information technologies have many uses in resource management, and are increasingly being used in combination, as illustrated by examples on land use planning in Senegal, determination of natural hazards risk to agricultural production in Ecuador, crop yield estimation in Italy, and habitat analysis for preservation of species richness in the United States.*

*Key issues in the further use and development of these new information technologies include the question of scale in scientific analysis and policy-making, infrastructural investments for the successful adoption of technologies, accuracy in physical measurement and in interpretation and transformation, standardization of transfer formats for spatial data, timeliness of access to data, trends in technological progress, and clearer and wider understanding of the role of science and technology in human affairs.*

# INTRODUCTION

As scientists we strive constantly to keep abreast of new developments in our areas of specialization. This is not an easy task in today's increasingly information-oriented society. As the rate and volume of output of basic data and research results in our own and cognate fields increase, many of us find it increasingly difficult to follow developments in those fields seeking to improve our understanding of our global resources. Advances in climate and atmospheric modeling, improvements in hydrologic forecasting and our understanding of the carbon cycle are significant. Equally significant are developments in those fields which facilitate the acquisition and analysis of data/information. These are so-called "hi-tech" areas. In recent years there has been an "explosion" in the area of information technologies. These technologies offer the potential to facilitate the conduct of research, resource management and policy decision-making at scales from local to global. The technologies which we believe are critical to improving our understanding of the best paths toward sustainable economic development include: geographic information systems (GIS), remote sensing, and modeling with expert system- and artificial intelligence-assisted methodologies.

## Background

In 1987 the World Commission on Environment and Development published the results of its two years of deliberation in a report entitled "Our Common Future". A key element of this report was its endorsement of the concept of "sustainable development", defined as "development that meets the needs of the present without compromising the ability of future generations to meet them".

To carry out this concept of resource development with due consideration of the mid-term and long-term effects of such development on the environment will require that researchers, planners, and decision-makers have access to unprecedented quantities and types of resource and environmental information. Measurements from specific sites need to be combined with data and information on conditions at other locations. Maps depicting the spatial dimensions of objects and phenomena need to be produced and updated to keep track of (i.e. monitor) changes at varying time intervals. Models depicting the range of alternatives which could result from actions have to be tested.

Many of the systems required to produce these large quantities of data currently exist and data are being collected now. Other advanced data collection systems are currently in the planning and development stages and will produce even larger quantities of data in digital format within the next ten years. Likewise, improved tools for converting these data to relevant environment and resource and policy-oriented information either exist or are in varying stages of development.

As scientists it behoves us to keep abreast of relevant technologies which can enhance our investigations and which can be employed to produce results which are readily understandable by individuals in the resource planning, management and policy areas.

## Purpose of Document

The purpose of this document is to provide scientists, researchers, resource managers and public policy decision-makers engaged in sustainable development activities with an overview of several technologies for data collection, manipulation, analysis and information extraction. Such technologies can be used by the scientific community to improve our understanding of the global environment, measure, map, monitor and model changes in that environment, and provide decision-makers with the information which they require to summarize the options available to decision-making bodies.

A suite of technologies that has the potential to improve our ability to achieve the goal of sustainable development is currently available, yet in differing states of maturity. This suite of technologies includes GIS, remote sensing, and advanced modeling tools. Applications of some of these technologies have expanded rapidly in recent years, while some trace their progression from developments dating back into the last century. Use of these technologies can improve our ability:

- ▼ to acquire measurements of key state variables and images from which spatial information on environmental constituents can be derived;

- to access data we require in our investigations more efficiently;
- to store, retrieve, manipulate and analyze these data more effectively; and
- to provide a wider range of output products to suit user requirements (be the user a scientist, environmental planner, developer or decision-maker).

We are modifying our environment at unprecedented rates and scales. We can, however, debate the specific spatial dimensions, rates and significance of these changes. As humankind has progressed from the Stone Age through the Bronze and Iron Ages to the agricultural and industrial revolutions, technology has been a key factor facilitating change. Today's technologies can create environmental change on spatial and temporal scales never before possible. Yet, the wise application of technologies also offers us the ability to facilitate our investigations and leads to a more complete understanding of human impact on our environment. Through appropriate application of remote sensing, GIS and modeling we can move a significant way towards answering questions concerning the spatial and temporal dimensions of variations in environmental resources.

There are still barriers to the adoption and application of these technologies. These barriers are no longer primarily technical. They are institutional in many cases, sociological in some and legal in others. Some cite the costs: others the time required to learn: others believe that capabilities are still not sufficient for their purposes. These reasons may all be valid. Yet, costs of sharing data and computing today continue to rapidly decrease. Systems are easier to learn, performance is rapidly increasing. What has not been fully realized by the scientific community at large is the scientific and commercial potential of these technologies. Examples of the use of these technologies to enhance the understanding of key science issues exist: several examples are discussed in the body of this document, yet more can and should be done.

We have not even come close, we believe, to exhausting the potential of these technologies. A great deal needs to be done; we have only scratched the surface. What is required is innovative thought and a willingness to work with individuals in cognate fields seeking to achieve the goal of sustainable development. It is our considered opinion that working together we can achieve improved insights, by employing GIS as an integrating resource. Through the use of remote sensing systems, we can begin to collect required data which can either be translated directly into information or input into models which improve our understanding of key environmental processes related to sustainable development.

## What Follows

The following material presents a brief overview of some important data types available to the science community today which could be used as input to sustainable development studies. This is followed by a discussion of the current status of GIS, image processing, modeling, artificial intelligence and expert systems. The paper concludes with a review of some issues involved in the use of these technologies, needs for further research, and trends towards future development.

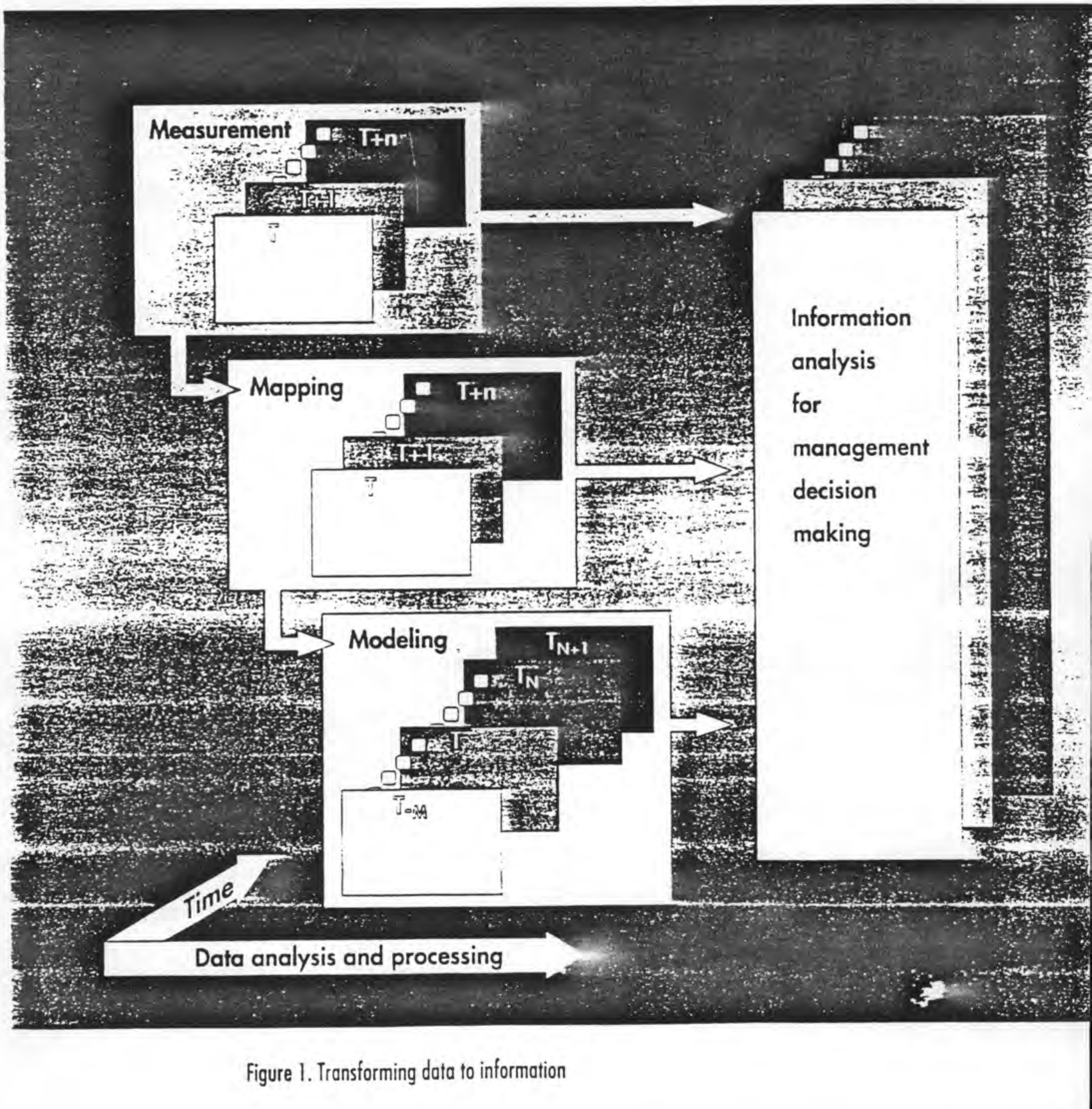


Figure 1. Transforming data to information

# DATA

It is important to understand specific characteristics of data types used in environment and development programmes. Too many of us often accept data at "face value"; often it may be the "only available data." Today, however, the powerful tools we have to collect, integrate, manipulate, and analyze data make it necessary that we understand both the nature and accuracy of our data and its sources as never before, including recognition of the distinction between data and information, and the distinction between spatial and non-spatial data and information.

## Data vs. Information

An essential goal of the use of information systems and models is to convert data into information: converting measurements and observations into knowledge which may be used for evaluating options as a step toward making decisions. As used in this paper, data can be thought of as any input to a process where information is created. As such, measurements could be directly analyzed to provide information, e.g., daily rainfall to produce a monthly mean average for a given location. Measurements could also be used to model a process. The model's output could then be employed as information in a management decision process which would in turn generate other information types (see Fig. 1). In this process of making measurements and observations which will be used to generate information, one must be extremely careful to evaluate the quality and validity of the conversion process. In many instances, the costs of verifying the quality of datasets can be greater than the original costs of acquiring the data.

As a part of our concern to produce high quality data/information upon which decisions on the best paths toward sustainable development can be based, we must distinguish between accuracy and precision, not only in the raw data, but also in the derived information. Accuracy is concerned with fidelity to a standard, and lack of bias. Precision, in contrast, regards the ability to make fine distinctions. For example, one could measure annual rainfall to the nearest 10 centimeters in a simple rain gauge, which might provide highly accurate (or unbiased) data which are rather imprecise. Such imprecision, if inappropriately extrapolated over space and time or across scales, could invalidate the use of these data and lead [illegible] incorrect decisions. On the other hand, use of precise but inaccurate (or biased) data can also create significant problems for management decision-makers.

## Spatial vs. Non-Spatial Data and Information

In applications which involve environmental analysis and sustainable development, we must necessarily consider both spatial and non-spatial data and information. By spatial data, we mean data that can be located on the Earth's surface: a water well, a river, a political or administrative district. By non-spatial data, we include such information as the date that the water well was dug, the pH and temperature of the river at a monitoring station, and the name of the political district. In a variety of applications, the volume of the non-spatial data may be much larger than that of the spatial.

There is a class of non-spatial data associated with spatial datasets as a whole which are called metadata. "Metadata" essentially describe the characteristics of a given data set. Metadata are often described as data about data or data sets. For example, the date at which the dataset was verified for accuracy, and the measurement scale of a dataset (e.g. elevations were recorded in metres, rather than feet) are both forms of metadata. Metadata are often key elements of catalogues which can facilitate access to an understanding of spatial data and information.

In the context of this document, we distinguish two broad classes of spatial data which are commonly used in the analysis of environmental problems and in the consideration of issues related to sustainable development. We discuss these data which come from remote sensing systems separately from those that do not. Remote sensing technology (as described in the following section) provides the means to consistently collect data over large areas of the earth for a number of applications. In addition, there are a variety of other data types and themes described subsequently in this document, some of which may even represent a product derived from the analysis of remotely sensed data that are important input to a wide variety of sustainable development related studies. These sections provide definitions for and examples of data types which are being used within geographic information systems and advanced models to improve our knowledge of the global environment.

# SPATIAL DATA

## Remote Sensing

Since the early days of the various space programmes, there has been an increasing public awareness of the ability of space-derived imagery to capture a sense of our fragile planet. While remote sensing dates from a century before the era of space flight, there is probably no more familiar remote sensing product than the daily view of clouds and weather patterns presented in weather forecasts on the television news programmes in many countries.

### Definition

Remote sensing is the use of systems to gather information on objects and phenomena from a distance. The human eye can be considered a remote sensing system as can an ordinary camera. Yet, contrary to the popular expression, with remote sensing what you get is not necessarily what you see. A great deal of what exists in the world around us cannot be perceived by human sensory organs (see Fig. 2). While one can assume that distance is the major factor limiting human vision, the spectrum of energy we can see with the unaided eye is also an important limitation. The human eye responds to light from only a small portion of the electromagnetic spectrum from blue to red, while energy from gamma rays to radio waves swirl around us unseen. Through the years, however, we have constantly striven to expand our ability to "see" energy fields beyond our direct perception. In this process we have constructed a variety of specialized instruments to record information and present it to us in picture-like forms called images.

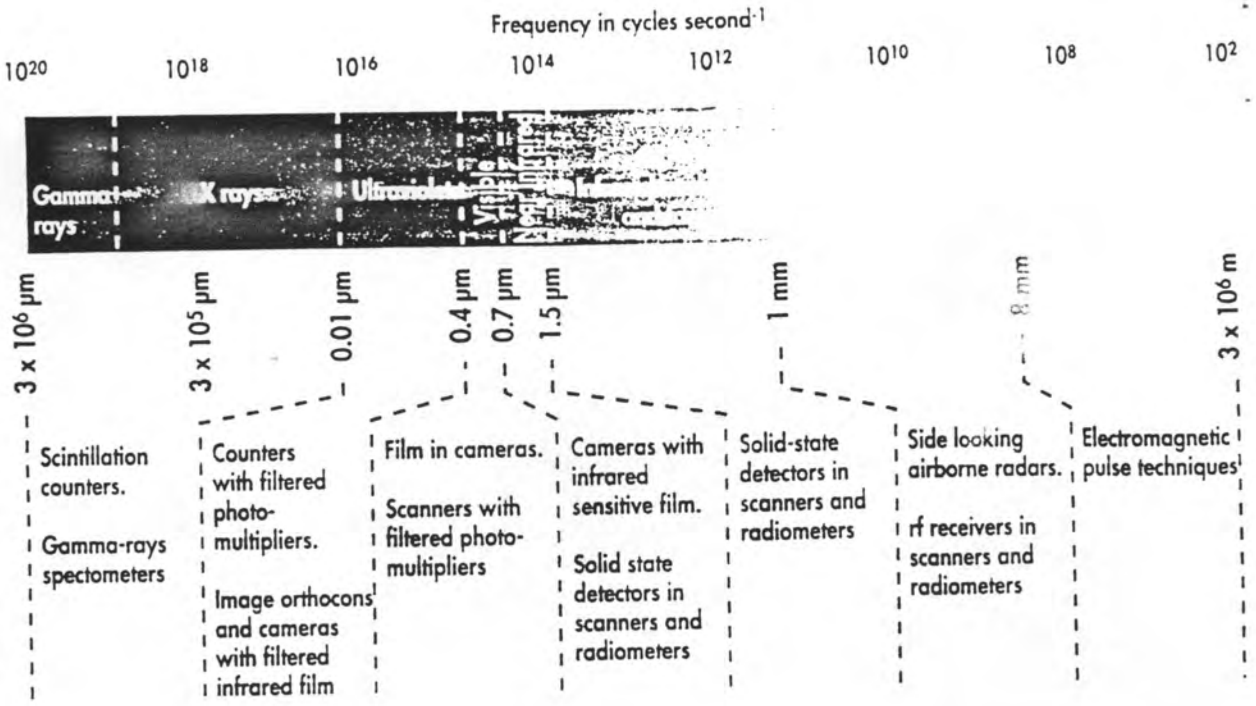
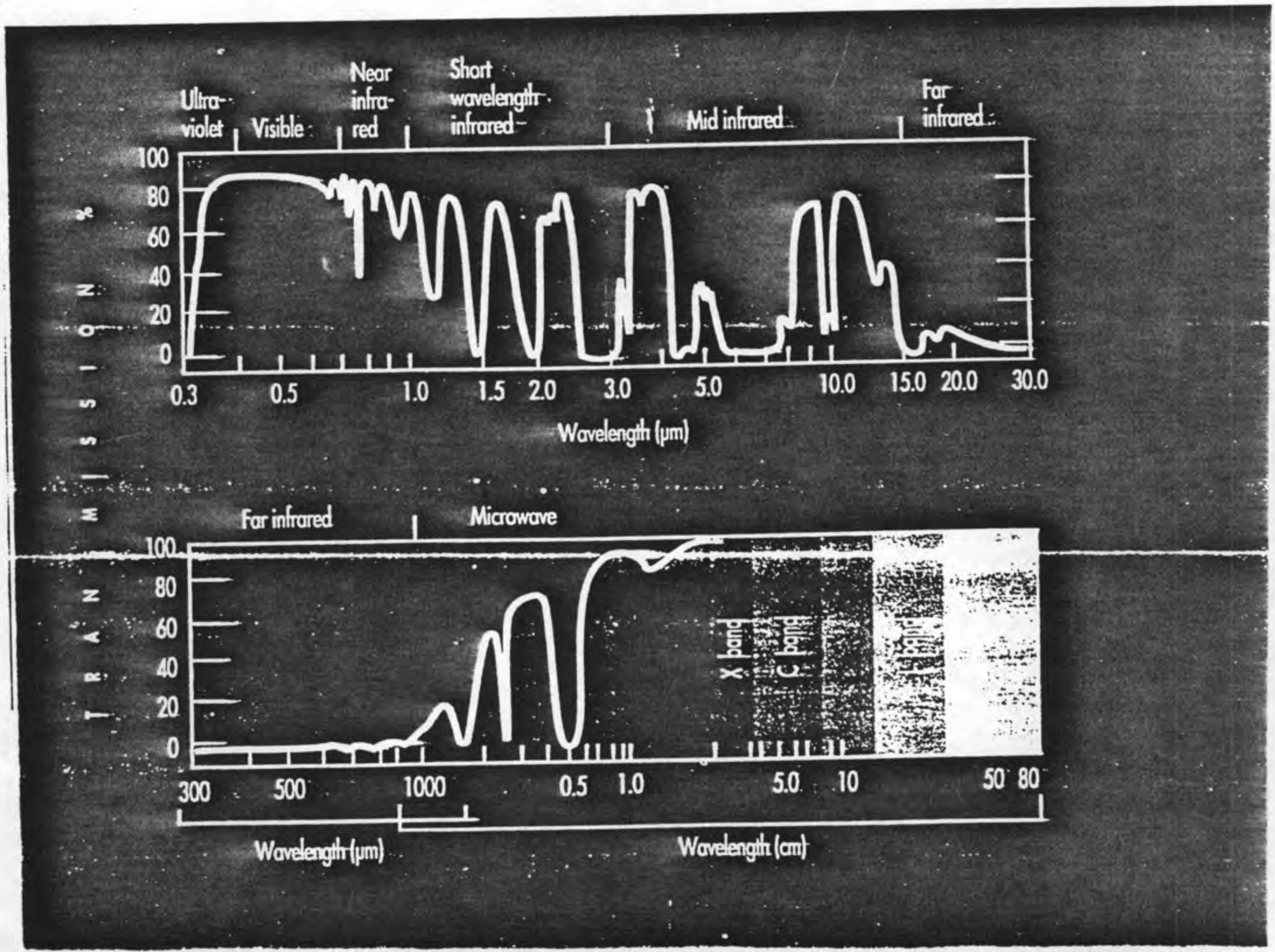


Figure 2. The transmission of electromagnetic energy through the Earth's atmosphere (below) and examples of sensors that image in it (above) (adapted from Estes, 1974)



## Remote Sensing Systems

Today, a wide variety of systems are used to detect energy patterns (see Fig. 2) which provide information about the earth, its atmosphere, oceans, and land surfaces (see Table 1 and Fig. 3).

The bulk of satellite remote sensing data is currently acquired by multispectral scanners and linear array devices in the visible and near infrared positions of the electromagnetic spectrum. These are passive systems recording solar radiation reflected from the earth's surface. Data derived from multispectral scanners provide information on (among other things): vegetation type, distribution and condition; geomorphology; soils; surface waters and river networks.

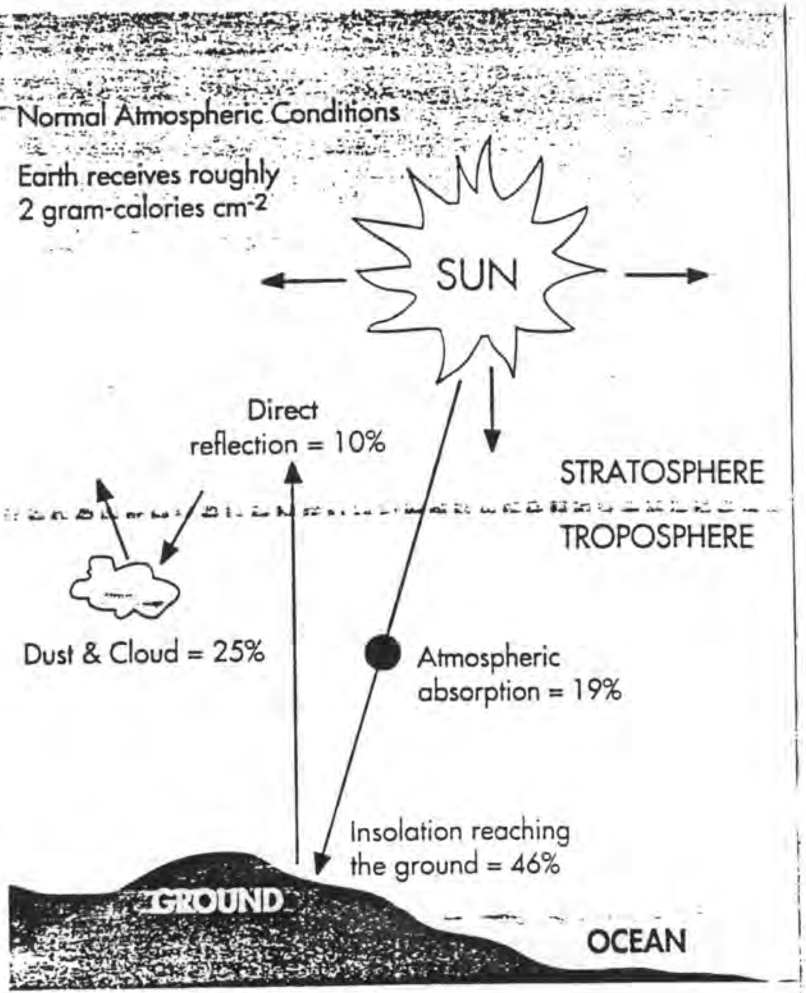


Figure 3. Energy flow model for remote sensing systems

These remote sensor systems can be broadly categorized into active systems and passive systems. A camera is an example of a passive system as its film records light energy reflected from an existing source: the sun (see Fig. 3). Add a flash attachment to the camera and it becomes an active system, since it now provides its own source of illumination. Active microwave (radar) systems are commonly used in geological and hydrological applications.

Active systems in the optical range using laser technologies are being developed for oceanographic and forestry applications. Because active systems do not depend on reflected energy from the sun for image formation they may be able to acquire data during the day or night. In addition, as some microwave radiation is not disturbed by the atmosphere to as great a degree as shorter wavelength energy, radar systems allow data acquisition in cloudy and rainy weather (see Table 1). This ability to operate day or night, and to create images of the surface in spite of cloud cover, makes radar sensors particularly attractive tools for improving our understanding of both tropical and polar areas. Thermal infrared data which represent a record of emitted energy from surfaces have been particularly useful in monitoring fires and in improving our understanding of areas of volcanic and geothermal activity. Surface temperature of the ocean is also

| Spectral region and sensor systems[1] | Approximate wavelength interval (micrometers) | Atmospheric penetration capability[2] | Day-night capability |
|---|---|---|---|
| **Ultraviolet**<br>Optical-mechanical scanners and cameras with film | 0.01 - 0.4 | | day only |
| **Visible**<br>Optical-mechanical scanners with solid-state detectors, conventional cameras with film, and vidicons | 0.4 - 0.7 | H | day only[3] |
| **Reflectance infrared**<br>Conventional cameras with infrared sensitive film, solid-state detectors in scanners and radiometers | 0.7 - 3.5 | H, Sg | day only[3] |
| **Thermal infrared**<br>Solid-state detectors in scanners and radiometers, quantum detectors | 3.5 - $10^3$ | H, S | day or night |
| **Microwave**<br>Scanners, radar and radiometers antennas and circuits | $10^3$ - $10^6$ | H, S, F, R | day or night |

1. System characteristics included are those most commonly employed in resource planning and management applications today.
2. Denotes the atmospheric conditions that can be penetrated by energy in this portion of the electromagnetic spectrum where:
   H = haze; S = smoke; Sg = smog; F = fog or clouds; R = rain.
3. Discounting the use of active optical systems such as flash units, laser line tracers, or light amplification systems.

Table 1. General characteristics of remote sensor systems

related to the dynamics of coastal waters and currents. Over land. plant water stress also induces changes in canopy temperatures which can be detected by thermal sensors. Other remote sensing systems detect the earth's magnetic and gravitational fields; these tools are used extensively in oil and mineral exploration. Figure 4 is an example of imagery of the area around the campus of the University of California. Santa Barbara. from various portions of the electromagnetic spectrum over the same general location. Analyses of such multispectral data can. if properly designed. increase both the quantity and quality of information for given applications.

## Resolution

Resolution is at the core of the successful use of remote sensing data. Yet. resolution is a very difficult concept to understand. Resolution can be measured in line pairs per millimetre or modeled using modulation transfer functions as a tool. Resolution. as typically applied by a user. however normally involves the question "can I identify what I need to identify on this imagery?" Often this involves the use of the term "ground resolved distance" (GRD). GRD is used to describe the smallest object that can be unambiguously identified on the ground given good object to background contrast. Object to background contrast is important here. While it may be possible to see white lines on a black road on one set of images. it may not be possible to see the same size white lines on a concrete stretch of the same road. Resolution is thus dependent upon many things.

Indeed. the level of matching between the spatial. spectral and temporal resolutions of the measurements and the needs of the investigation will condition the usefulness of the derived data/information. Spectral range and resolution as used here refer to the portion of the electromagnetic spectrum which is being used in the measurement. It must be appropriate to the questions being addressed. e.g. thermal range for fire detection. red band for vegetation absorptions. Spatial resolution conditions the level of detail which can be extracted concerning objects in a given scene. As a general rule it must correspond to the size of a typical object which must be separately identified (i.e. a resolution of a metre or less is needed to identify a single tree. while a resolution of 500 m to a kilometre may be enough for studying ocean surface features). A necessary compromise between area to be covered and ground resolution of the measurement must take into account the volume of data which will be generated by. say. a large area coverage - millions of km$^2$ - using high resolution data - 10-30 m (see also Fig. 16. page 60).

Finally. the frequency of the data acquisition must also match the natural frequency of change in the landscape. Daily observations may be needed for an assessment of plant evapotranspiration while observation once every year will be needed for land cover change assessment.

## History of Remote Sensing

The first of what would now be called airborne remotely sensed data were acquired from balloons over Paris in the 1850's. The first pictures were more art and curiosities than data for scientific or resource management. Yet. by the late 1870's. foresters in Germany had begun to use aerial photographs taken from balloons to help manage timber harvests. By the 1920's. dramatic increases in

Figure 4. Four views of the area around the campus of the University of California Santa Barbara: (a) Black and white panchromatic photography

the uses of aerial photography began to occur as individuals with military experience gained during World War I began to apply air photos to peace time uses. Agriculture, water resources, urban and regional planning, civil engineering, soil science, and mineral exploration applications were all pursued. By the 1930's, colour aerial photography was in use, and in the 1950's and 1960's we moved beyond the visible portion of the spectrum to the precursors of the electronic sensor systems of today. Indeed, the term remote sensing was coined in the late 1950's because picture-like images that could not be called photographs anymore were beginning to come into wider use.

Figure 4 (b). Black and white infrared photography

Those who have been involved in the application of remote sensing technology over the years have watched the increasing complexity of sensor systems, data types and the analyses undertaken in employing these data. Figure 5 represents an attempt to illustrate graphically the increasing complexity associated with various aspects of the development of remote sensing. We have progressed to a point where we are employing multisensor data in solving complex problems associated with global surveys.

### Access to Remote Sensing Data

The applications of global satellite coverage move forward rapidly. However, there is still no comprehensive treaty on data gathering which has been ratified

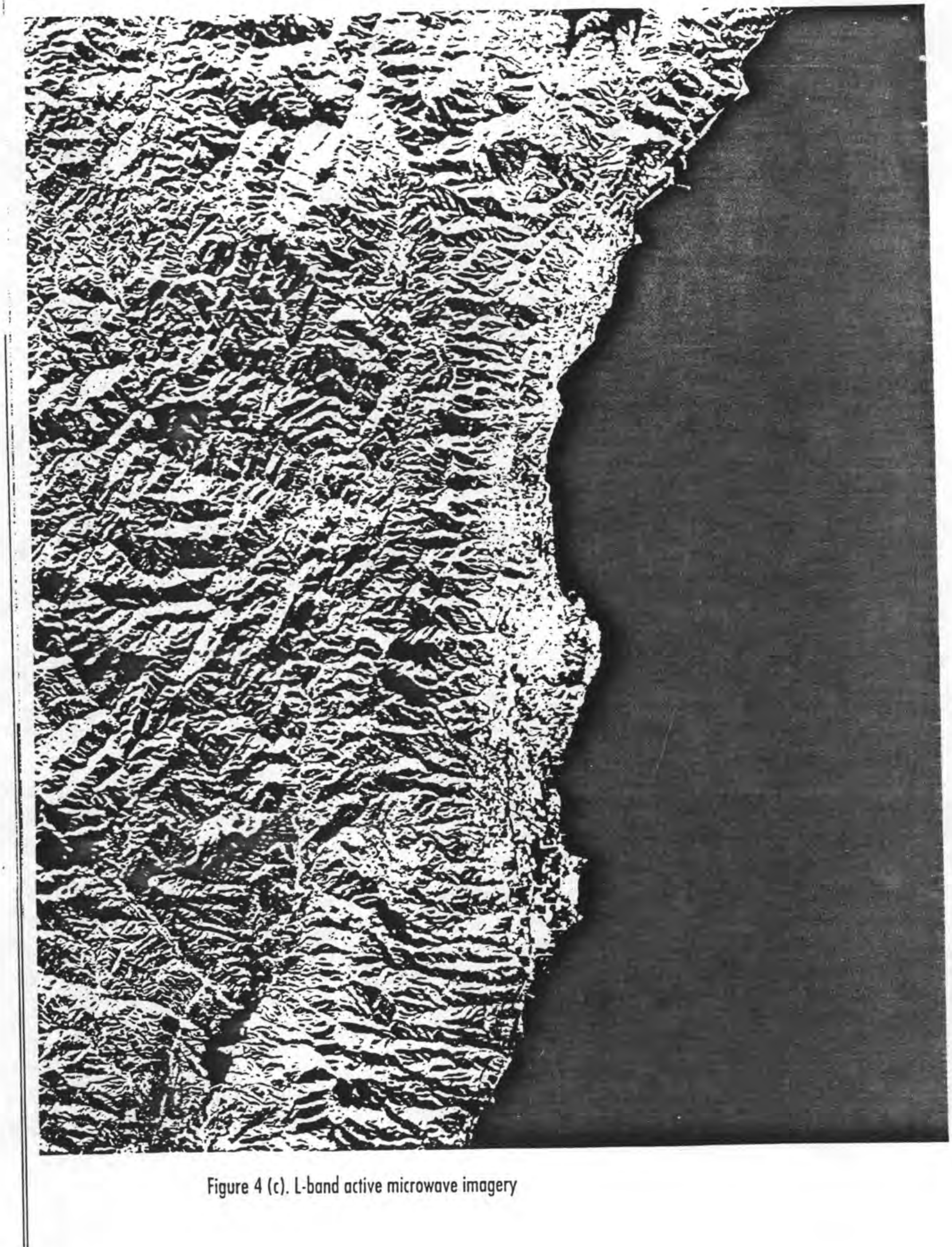


Figure 4 (c). L-band active microwave imagery

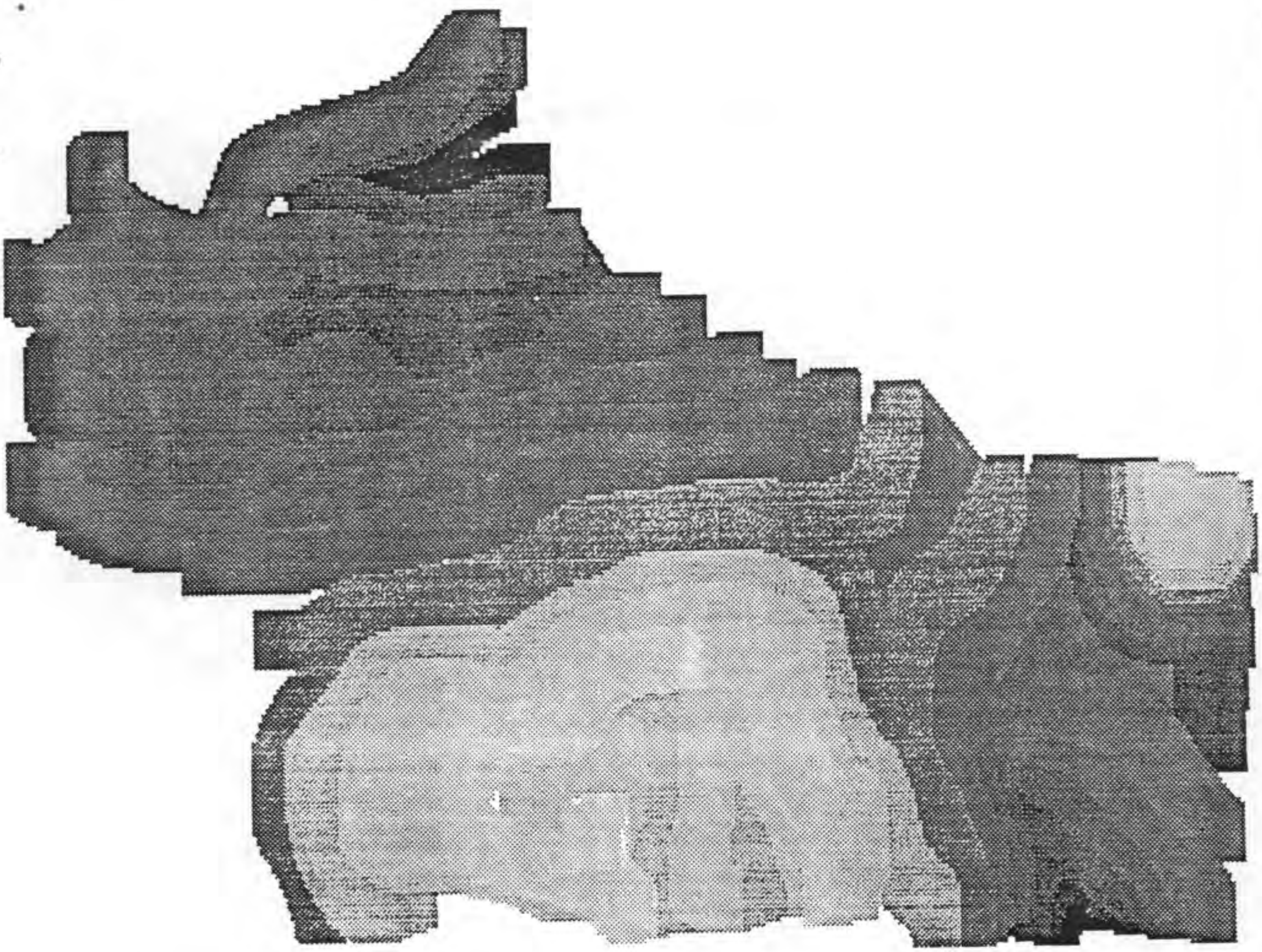


Figure 4 (d). Aero-magnetic survey imagery

Figure 5. Historical development of remote sensing, emphasizing increasing complexity of platforms, systems and tasks

by UN member nations regarding remote sensing from space. The "open skies proposal" first put forward by the United States to the Soviet Union has never been officially adopted. Today the United Nations operates under the 1986 resolution entitled: Principles on Remote Sensing of the Earth from Space. Key points of this resolution include:

- Remote sensing is defined as being for the purpose of improving natural resources management, land use, and the protection of the environment. this excludes surveillance satellites from these principles;
- Worldwide collection and distribution of data is permitted while ensuring that sensed states have access to data of their country;
- Countries operating remote sensing systems bear international responsibilities for their activities, irrespective of whether such activities are carried forward by government agencies or private companies: and
- Further cooperative activities to benefit as many countries as possible are strongly encouraged.

In April 1991, the United Nations went further. Legal aspects related to the application of the principle that the exploration and utilization of outer space would be carried out for the benefit and in the interest of all states, taking into particular account the needs of developing countries, were put forward. The United Nations proposed that states should concentrate their efforts in the following areas among others:

- Continued exchange of information, data, materials and equipment on space science and technology;
- Promotion of easy and low-cost accessibility and availability of remote-sensing data, the ground receiving stations and digital image processing systems; and
- Technical cooperation to promote and facilitate the transfer of technology and expertise in space science and technology, particularly with the developing countries.

Issues of data must certainly continue to be addressed with some urgency. This urgency is driven by the realization that a growing number of operational and research instruments are being planned and that potential users are increasingly faced with difficult questions related to the choice of data sources, the availability of appropriate data, the cost of the required coverage, and the availability of the data in a timely fashion. By the end of this century, we will be receiving terabytes[1] of data daily from space. Indeed, if we examine only the approved and proposed United States missions to the year 2002 these systems alone can

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1. A terabyte ($10^{12}$) of data is the equivalent of a computer tape approximately 5000 km long, given 1992 data storage technology.

| Sensor | Satellite | IFOV | Image size/SWATH | First launch |
|---|---|---|---|---|
| MSS | Landsat | 79 m | 180 km | 1972 |
| TM | Landsat | 30 m | 185 km | 1982 |
| AVHRR | TIROS | 1100 m | 2700 km | 1978 |
| HRV-P | SPOT | 10 m | 60 km | 1986 |
| HRV-XS | SPOT | 20 m | 60 km | 1986 |
| MESSR | MOS | 50 m | 100 km | 1988 |
| SAR | ERS | 30 m | 100 km | 1991 |

Table 2. Examples of current satellite and sensor system parameters

Acronyms for Table 2

| | |
|---|---|
| IFOV | Instantaneous Field of View (resolution) |
| MSS | Multispectral Scanner |
| TM | Thematic Mapper |
| AVHRR | Advanced Very High Resolution Radiometer |
| HRV-P | High Resolution Visible Panchromatic |
| HRV-XS | Multispectral Mode of SPOT Sensor |
| MESSR | Multispectral Electronic Selfscanning Radiometer |
| SAR | Synthetic Aperture Radar |

produce data in the terabyte range (see Tables 2, 3 and 4 and Fig. 6). These data will be of value to earth resource scientists, managers and policy-makers as we attempt to improve our understanding of the factors that sustain life on the earth. They will, for example, help us measure key atmospheric constituents, map land cover, monitor the expansion of agricultural land and model future weather patterns.Such data can provide information which may improve our management of the resources of our earth.

| INSTRUMENT | OBJECTIVES/ MEASUREMENTS |
|---|---|
| **Facility instruments** | |
| AIRS (Atmospheric Infrared Sounder) | Atmospheric temperature and water vapour, cloud properties |
| AMSU-A/B (Advanced Microwave Sounding Units) | Atmospheric temperature; humidity; and water vapour |
| ASTER (Advanced Spaceborne Thermal Emission and Reflectance Radiometer) | Surface temperature and emissivity; stereo imagery; high spatial resolution land cover |
| HIRIS (High Resolution Imaging Spectometer) confirmed for only the 2nd and 3rd EOS-A series platforms | Surface cover; canopy chemistry; snow and soil composition; mineral identification |
| MODIS-N (Moderate Resolution Imaging Spectometer-Nadir) | Surface cover; vegetation index; atmospheric sounding |
| MODIS-T (Moderate Resolution Imaging Spectometer-Tilt) | Ocean colour; multi-angle radiances from land surface moisture; snow and ice cover, cloud water |
| MIMR (Multiband Imaging Microwave Radiometer) European Space Agency | Precipitation; soil moisture; snow and ice cover; cloud water |
| **Principal investigator instruments** | |
| CERES (Clouds and Earth's Radiant Energy System) | Radiation from top of atmosphere to surface; cloud properties |
| EOSP (Earth Observing Scanning Polarimeter) | Polarization for cloud optical thickness and parcticle sizes |
| HiRDLS (High Resolution Dynamics Limb Sounder) conditionally confirmed for flight pending resolution of technical issues | Vertical temperature; gas and aerosol profiles |
| LIS (Lightning Imaging Sensor) | Lightning activity for estimates of precipitation |
| MISR (Multi-Angle Imaging Spectro-Radiometer) | Multi-angle radiances; albedo; atmospheric aerosols |
| MOPITT (Measurement of Pollution in the Troposphere) Canada - confirmed for only the first EOS-A series platform | Vertical profiles of CO and possible CH-4 |
| STIKSCAT (Stick Scatterometer) | Ocean surface wind speed |
| WBDCS (Wide Band Data Collection System) | 7 GHz data uplink capability |

Table 3. EOS-A Series Instruments. The instruments listed were proposed for flight on the EOS-A series platforms

| INSTRUMENT | OBJECTIVES/ MEASUREMENTS |
|---|---|
| **Facility instruments** | |
| ALT (Altimeter) | Sea surface and ice sheet topography |
| GLRS (Geodynamics Laser Ranging System) | Distance measurements to 10 cm -Ice sheet height and slopes |
| LAWS (Laser Atmospheric Wind Sounder) | Direct measurements of tropospheric winds |
| **Principal investigator instruments** | |
| GGI (Gps Geoscience Instrument) | Gps receiver for continuous EOS position accuracy |
| HiRDLS (High Resolution Dynamics Limbs Sounder) | Vertical temperature-gas and aerosol profiles |
| MLS (Microwave Limb Sounder) | Vertical profiles of ozone destroying gas species |
| SAFIRE (Spectroscopy of the Atmosphere using Far Infrared Emission) | Mid-atmosphere ozone and other key chemical species |
| SAGE III (Stratospheric Aerosol and Gas Experiment III) | Vertical profiles of aerosols and gases above the clouds |
| SOLSTICE (Solar Stellar Irradiance Comparison) | Full disc measure of solar ultraviolet irradiance |
| SWIRLS (Stratospheric Wind Infrared Limb Sounder) | Vertical profiles of wind-temperature and $N_2O$ |
| TES (Tropospheric Emission Spectometer) | 3-D profiles of tropospheric gases |
| WBDCS (Wide Band Data Collection System) | 7 GHz data uplink capability |

Table 4. EOS-B Series Earth Science Instruments. The instruments listed are candidates for flight in the EOS-B series

## Other Spatial Data

### Themes

It is well beyond the scope of this paper to provide a description of all spatial data types which could be used in an analysis related to sustainable economic development. What follows are examples of more commonly employed data types. For each of the following commonly-used geographic data, a sample of the derivation of the data is provided.

### Elevation

Data about elevation may be acquired by making measurements at specified locations using Global Positioning Sateliite (GPS) receivers plus conventional surveying techniques. Advance in hardware and software for the satellite-based GPSs have revolutionized the field of geodetic surveying and navigation. It is now possible to precisely determine x-, y-, and z-coordinates of any location on earth using a pocket-size GPS receiver. Combining digital image processing techniques and GPS technology, remotely sensed information can be quickly and accurately related to absolute coordinate systems, thus creating improved and efficient ways for creating topographic information. Elevation data can also be produced using photogrammetric techniques from overlapping pairs of remotely sensed imagery. From these sets of original source data one may derive contour lines for creating printed maps, and regular arrays of estimated elevations through a mathematical interpolation operator. Interferometry using microwave data is also a promising field of research.

### Land Cover, Vegetation and Soils

Data about vegetation and soils may be created through field surveys. These survey datasets may then be used as a sampling frame from which data on vegetation and soil are extrapolated across space by incorporating remotely sensed imagery. Biomass and primary productivity can be derived from such databases using appropriate models.

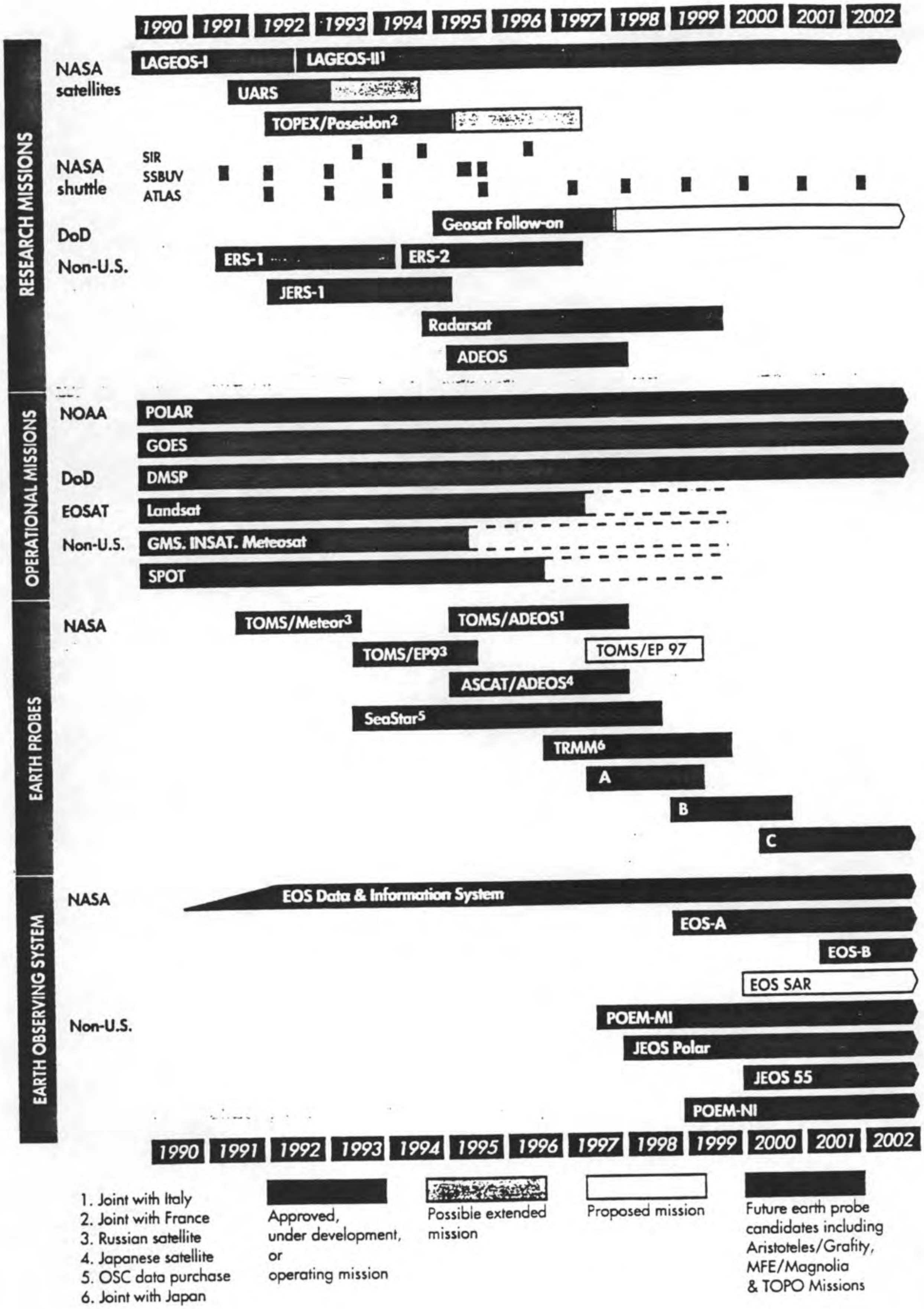
### Land Use

Land use in this context means human interaction with the land. Land uses include transportation, structures, agriculture, urban (residential vs. recreation), utilities. Data concerning human use of the land surface may come from many sources, including tax records from a regional government agency, maps from planning agencies, engineering drawings and databases from civil engineers and architects, and aerial and satellite data coupled with or collected solely by field surveys.

### Meteorology

Data on rainfall, temperature, pressure, humidity and air quality (e.g. percent $NO_2$, $SO_2$, $O_3$) may come from surface, airborne and space borne instruments, mathematically interpolated to derive estimated values where measurements are unavailable.

Figure 6, right. Examples of current satellite missions and those being planned into the next century



1. Joint with Italy
2. Joint with France
3. Russian satellite
4. Japanese satellite
5. OSC data purchase
6. Joint with Japan

### Demographic

Information on the characteristics of people, as a function of their location, is commonly derived from survey data such as a periodic census of the population. These are typically recorded as statistical summaries, aggregated over various spatial scales from parcel to census tract to city, county, state, nation and globe.

### Cadastral

Property ownership. Information about land parcels and their boundaries and characteristics is typically gathered using conventional surveying practices and compiled in analog or digital map format as well as documents created when properties are sold or exchanged.

### Geologic

Lithology of formation and fossil records along with information or structures are often measured at a small number of locations, and spatial patterns in these data are then inferred from ancillary data such as remote sensing observations.

### Hydrologic

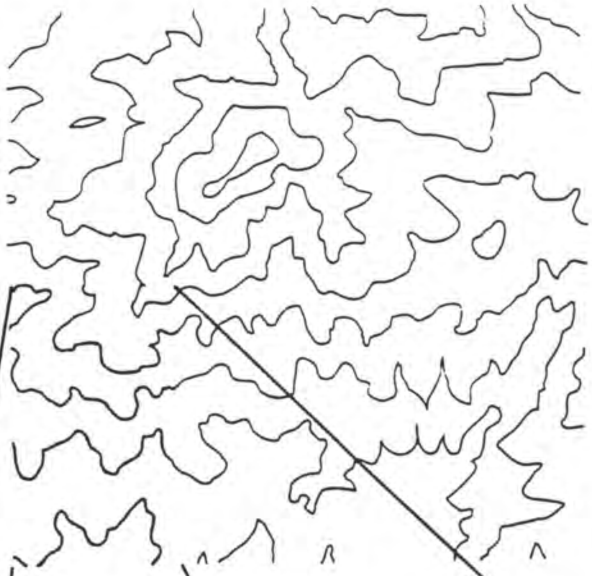
Drainage patterns, flow rates, size of catchments, depth to groundwater. Hydrological data on drainage patterns, flow rates and catchment basins are often derived from ground observations coupled with an analysis of the spatial patterns of lithology and elevation either from existing maps or using remotely sensed data. Data on groundwater are frequently measured at a small number of locations and generalized in space based on correlative information.

## Formats and Structures

For any set of spatial data, there is no single way to record the data values and their variation through space and time. For example, elevation in a region could be recorded as:

- ▼ Contour lines on a map - estimates of the set of locations which correspond to a predetermined list of elevations above datum
- ▼ Entries in a cartographic database - digital data which is designed to store elevation data in a manner which may be used to create printed maps

Figure 7, right. Elevations on a regular grid. The upper portion of the figure shows a set of contour lines from a map, in which locations along a given line are the same elevation above sea level. The array of numbers in the lower portion of the figure represent the estimated elevation at the centre of a set of square raster cells.



| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 83 | 87 | 89 | 85 | 98 | 109 | 113 | 120 | 127 | 133 | 141 | 145 | 154 | 152 | 25 |
| 65 | 73 | 86 | 89 | 98 | 103 | 113 | 118 | 126 | 134 | 142 | 142 | 142 | 142 | 26 |
| 65 | 81 | 89 | 96 | 99 | 107 | 112 | 117 | 125 | 131 | 137 | 136 | 136 | 133 | 27 |
| 80 | 88 | 93 | 99 | 105 | 108 | 110 | 116 | 123 | 126 | 140 | 127 | 124 | 127 | 28 |
| 86 | 92 | 94 | 101 | 105 | 106 | 108 | 112 | 117 | 122 | 122 | 121 | 113 | 113 | 29 |
| 84 | 93 | 95 | 101 | 106 | 106 | 105 | 109 | 116 | 123 | 119 | 117 | 110 | 105 | 30 |
| 81 | 85 | 95 | 95 | 99 | 96 | 97 | 107 | 110 | 114 | 117 | 115 | 105 | 100 | 31 |
| 81 | 54 | 93 | 90 | 93 | 93 | 95 | 101 | 104 | 109 | 105 | 105 | 106 | 97 | 32 |
| 78 | 80 | 84 | 95 | 87 | 85 | 91 | 93 | 95 | 96 | 95 | 94 | 93 | 90 | 33 |
| 69 | 76 | 79 | 80 | 80 | 81 | 85 | 89 | 90 | 90 | 81 | 82 | 81 | 79 | 34 |
| 67 | 67 | 72 | 76 | 77 | 69 | 77 | 81 | 85 | 81 | 75 | 69 | 71 | 66 | 35 |
| 66 | 65 | 66 | 67 | 65 | 67 | 67 | 69 | 77 | 75 | 69 | 66 | 65 | 64 | 36 |
| 63 | 63 | 63 | 62 | 60 | 56 | 60 | 65 | 67 | 65 | 63 | 58 | 53 | 60 | 37 |
| 61 | 61 | 59 | 54 | 49 | 52 | 53 | 60 | 62 | 60 | 54 | 48 | 52 | 57 | 38 |
| 56 | 56 | 51 | 48 | 44 | 46 | 49 | 51 | 55 | 56 | 49 | 46 | 48 | 51 | 39 |
| 48 | 48 | 46 | 38 | 38 | 40 | 44 | 47 | 48 | 47 | 44 | 40 | 44 | 47 | 40 |
| 47 | 45 | 46 | 36 | 36 | 36 | 37 | 44 | 45 | 41 | 36 | 36 | 40 | 44 | 41 |
| 42 | 43 | 36 | 34 | 35 | 34 | 35 | 38 | 38 | 33 | 33 | 33 | 35 | 38 | 42 |
| 34 | 34 | 32 | 32 | 31 | 32 | 32 | 32 | 32 | 30 | 26 | 29 | 32 | 32 | 43 |
| 32 | 32 | 30 | 24 | 24 | 29 | 29 | 29 | 28 | 28 | 21 | 24 | 30 | 31 | 44 |
| 31 | 31 | 27 | 17 | 21 | 22 | 24 | 24 | 21 | 17 | 19 | 16 | 24 | 27 | 45 |
| 28 | 28 | 24 | 17 | 19 | 19 | 19 | 16 | 16 | 15 | 14 | 16 | 20 | 24 | 46 |
| 24 | 23 | 20 | 18 | 17 | 17 | 16 | 16 | 13 | 7 | 0 | 15 | 16 | 20 | 47 |
| 17 | 18 | 16 | 16 | 16 | 16 | 15 | 12 | 6 | 1 | 0 | 12 | 15 | 17 | 48 |

- Values in a raster array - a regular array of adjacent cells where a representative elevation value is stored for each cell: one imagines a sheet of graph paper placed on the earth surface and the elevation at the centre of each cell in the sheet is recorded (see Fig. 7)
- An irregular network - the shape of the earth surface is captured by creating an irregular set of 2-dimensional facets located in 3-dimensional space: where the terrain has little curvature the facets may be large.

The following section provides additional details of some of these alternatives.

In general, printed data such as maps and photographs may be converted to digital databases, albeit with significant costs if high precision is required. Be cautious of cartographic generalization: a map is not reality but a cartographer's representation of reality. Indeed map accuracy and the accuracy which results from integrating or deriving information from the overlay of various maps and or other spatial data types of either known or unknown accuracy is a very active research area with many unresolved questions. However, it should be noted that many users rank currency before accuracy when using maps of various resources. This is often done with the presumption that standard cartographic practice will be followed in creating the map product, and that since use of such products represents the current "state-of-the-practice", decisions made and actions taken will conform to accepted procedures.

# TECHNOLOGIES

In the last decade an important set of new technologies to handle spatial data has developed and matured. Geographic Information Systems (GIS) are an important example of these technologies. The emergence of this suite of new technologies has been made possible by rapid progress in advances in disparate fields. These advances include:

- ▼ the massive increase in the power of computer hardware at a given price:
- ▼ the rapid development in digital spatial data collection technologies, databases, and information systems:
- ▼ the significant developments in the techniques of spatial data modeling and analysis: and,
- ▼ the emergence of highly realistic forms of visualization for spatially distributed phenomena.

Today the technologies resulting from this decade of rapid development offer a means to encapsulate problems with a spatial dimension in models which can represent, as never before, much of the real world's complexity and diversity. These models can then be populated with spatial data so as to incorporate spatial inter-relationships and dynamic behaviour. Such models, once validated, can then be explored by the use of analysis tools. These systems are already being widely used to address many of the challenges associated with finding the optimum path towards sustainable development: however, we believe many more exciting applications for these systems exist.

The material which follows briefly introduces these key technologies, concisely profiling their procedures and potential.

## Geographic Information Systems

Certainly one of the most important technologies for handling environmental data, the Geographic Information System (GIS), is now highly developed and there is a sophisticated market-place where at present over 100 commercial products compete. The last few years have seen an enormous investment in GIS world-wide, ranging from systems which cost less than $200 to those which are implemented on large computers and are accessible via networking across whole organizations. GIS can be defined as "Computer systems for integrating and analyzing spatial information in a decision-making context"

GIS have been described as the "biggest step forward since the introduction of the map". The map is the customary means of communication for observations and analyses of spatial phenomena. The paper map is, however, by definition, a static and interpreted record of a particular phenomena at a given time and place. As such, the traditional map is a useful but limited tool for communicating spatial information. Typically, map users employ paper maps as a backdrop for plotting other kinds of information. As users of spatial data have come to make maps by computers, a shift in the role of the map has become apparent. When stored in a computer, maps take on a new and dynamic form: their content, symbolization and the area covered can now be changed relatively easily and rapidly. For the first time, users of spatial data have truly flexible, interactive access to their data, any part of which can be updated in real time.

It can be argued therefore, that such maps formed within a GIS are better thought of as databases, or collections of information linked by their spatial relationships. In this conception a map can be seen simply as one unique expression of a spatial database, for example, showing the area-by-area values of a spatially varying variable where the categories chosen reflect a spatial model of some kind. In this new spatial data computing environment, the GIS offers new potential for spatial analysis, and is a much more efficient place to "store" spatial information.

The functions of a comprehensive GIS can be traced to a range of early spatial data handling systems which evolved in several related fields such as Automated Cartography (CARTO), Computer Aided Design (CAD), Data Base Management Systems (DBMS), and Image Processing (IMPROC).

A comprehensive GIS today can be defined as the union of the functionality of each of these systems to form a true multi-function, multi-purpose spatial data handling system. The figure (above right) can be used to visualize this development, and to chart the origin and strengths of particular software packages sold as GIS. Depending on the functionality offered, most packages can be plotted on this diagram: many will plot in the overlap of CAD and CARTO, or IMPROC, DBMS and CARTO, but few can actually be placed near the central GIS category when defined in this way (see Fig. 8).

To complete a description of the components of a GIS, it is also necessary to mention: hardware, spatial data and the necessary human skills and management required to operate the system. Estimates of the typical costs of a GIS project

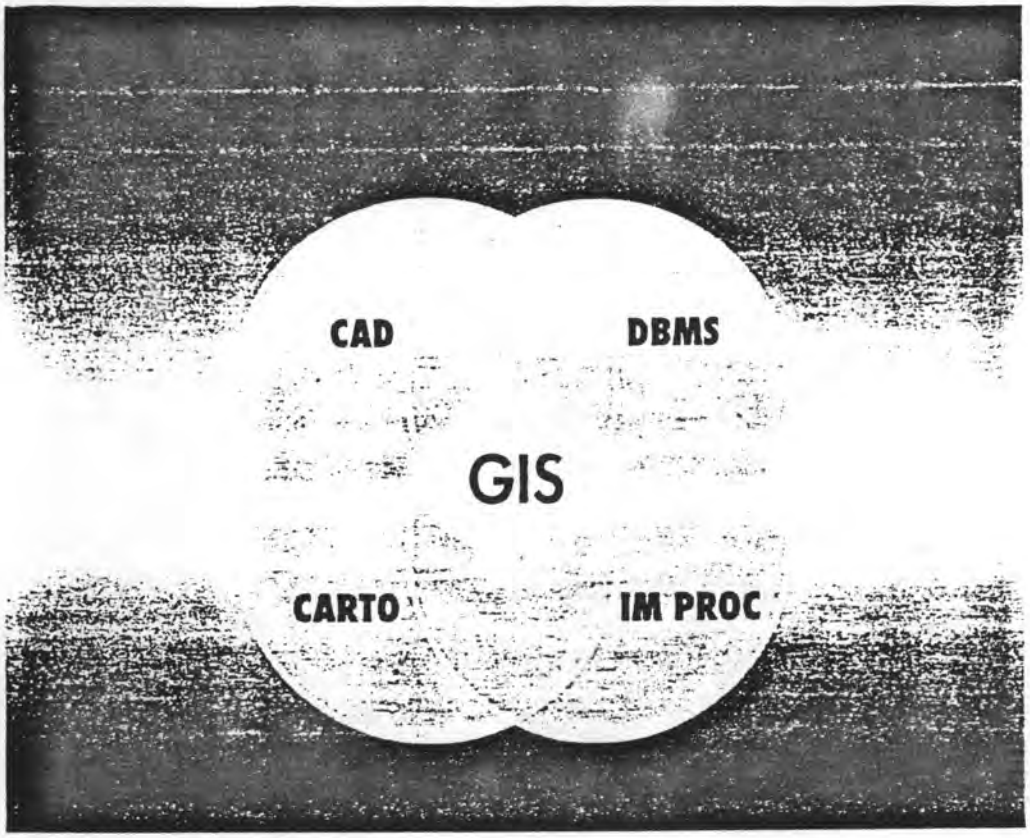


Figure 8. Venn diagram of overlaps in spatial data processing technologies

indicate that hardware and software costs only account for around 20% of total system implementation costs, whereas the staff and data costs associated with database development actually amount to 80% of the total. This implies that the cost of the data and the expertise required to run a GIS are a key part of project costing; and that data and expertise are thus the most important assets for an organization to protect in the long term.

All uses of a GIS should begin with a model of the phenomena under study. These data models may be specified in various ways, for example, as a set of point samples of reality approximated by interlocking regions (whose internal variation may be described by simple functions); or as a set of identified spatial objects which litter the plane. The data models used by GIS are usually "phenomenon-based" using the features in, or derived from, the subjects under study to specify the model used to represent them. The best example of such a data model which uses the object view is the one derived from a topographic map, where a set of features on the landscape such as the coast, rivers, roads and buildings are identified and classified by convention.

To create a computer representation of this model, geometric primitives such as points, lines and areas are typically used as the building blocks for the creation of spatial objects. Such representations are created by first measuring locations using coordinates based on a spatial referencing system: the simplest form is analogous to an x,y graph. This is known as metric information and is stored in the form of characters, numbers and boolean values (true or false).

since the computer cannot handle spatial data types such as lines. To complete the representation, the spatial components of the model must be ordered and indexed to encode spatial inter-relationships (referred to as topological information): this is known as a 'data structure'. The two alternative methods which are most often used to create data structures, are known as the vector and raster approaches.

Vector data structures employ the principles of coordinate fixing as in navigation. A point can be described by its distance along each of two axes of measurement, e.g. north and east, while a line can be described as the shortest straight line distance between two such points – a vector in the mathematical sense. Areas can be represented by any number of lines joined together in a loop and arranged to reflect the specific shape of the area. In all cases, the only information needed is the coordinates in number form, which can easily be stored in the computer and recalled in the right order when needed.

Raster data structures, however, use a different approach altogether, using regular building blocks to build up the shape of a feature on a grid. Using such a grid of very small squares, a point, line or area can be approximated by sets of squares or pixels, the resolution of the representation being directly controlled by the size of the grid squares. In a raster data structure, the computer keeps a record of which pixels have which values and therefore form part of one of the spatial phenomena being represented.

Using one or another of these data structures allows the storage of spatial phenomena in the computer. While raster based systems typically allow for more efficient data storage and retrieval, vector systems offer the potential for more specificity in location when precise coordinates are included. To complete the geographical data base requires the addition of a unique identifier to all the points, lines and areas represented so that they all can be linked to attribute data such as a name or other non-spatial data stored in relation to the spatial data. Many GIS currently in use permit a user to group all geometric and attribute data together for a single subject of study in a single theme such as 'transport' or 'pollution'. This can be implemented as a set of thematic layers in the database (see Fig. 9). The completed database is an integrated spatial and non-spatial information system: however, its potential can only be unlocked by applying spatial tools which operate on this structured spatial data.

Functions available in a typical GIS can easily be framed by the sequence of operations carried out in the creation and analysis of a geographical database. Hence typical operations would include querying the spatial database for given locations or features meeting a particular criteria: analyzing the characteristics of a surface or network: or the integration of spatial data from different sources. These operations offer key advantages in the use of a GIS as they enable the user to examine a model of some spatial phenomena and gain new insights.

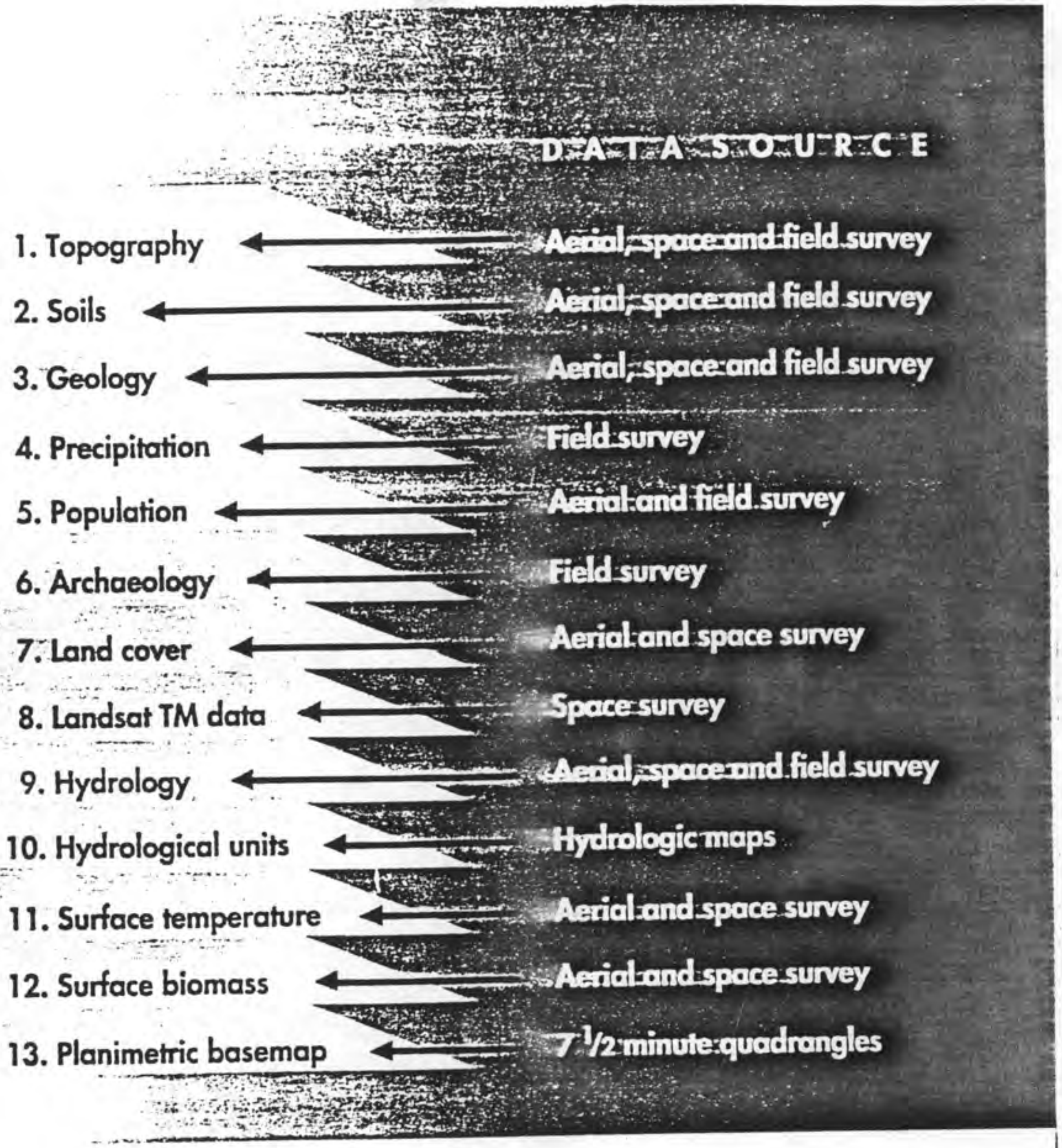


Figure 9. A geographic information system can be conceptualized as a base map by numerous registered overlays. Information in the data base was derived from a variety of sources

## Image Processing

While images from remote sensing systems on platforms from aircraft to satellites may be fascinating, they have to be processed and analyzed to acquire suitable information for applications such as monitoring the paths of severe storms, estimating agricultural yields, and the prediction of runoff from mountain snow packs. We have moved from a reliance on airborne or more recently satellite data alone to accomplish an objective to the use of methodologies which require incorporating remotely sensed data and many other types of information in systems which can examine questions at scales from local to global. The use of geographic information systems has greatly facilitated this trend as seen in

Figure 10. In this progression we have also moved from using remotely sensed data for simple identification of forest species to their application in complex problem solving such as their use in models to estimate runoff from given watersheds within specified time intervals. and the use of this information in the projection of available hydropower generator potential (see Fig. 5. page 25).

In the past. aerial and space photography was primarily analyzed through human photo-interpretation. However. progress in digital data acquisition and computing technologies has led to computer-assisted and interactive digital image analysis systems. As in many other areas. remote sensing applications have benefitted from the explosion of computing capabilities in the past two decades. Where earlier systems required rooms full of computers. technical staff. and custom development of hardware and software. desktop computers and commercial software are now capable of serious project work. Where earlier systems required years of research and development to tailor new tools for users. there are now practical tools for a range of applications.

Digital image processing systems can be seen as an example of a raster-based system where the remote sensing image is tiled into small (normally square) picture elements or **pixels**. Image processing techniques are used in a large number of application areas such as industrial fabrication and control. surveillance systems. television. archiving. and desktop publishing. Specific techniques to process and analyze remotely sensed images include image enhancements (i.e. filtering to smooth images. or contrast stretching). georeferencing and rectification (i.e. registering remotely sensed data with a geographic coordinate system). automated classification and feature extraction for land use mapping/land cover mapping. and change detection and habitat analysis.

In their early stages. digital image processing techniques were primarily concerned with single image evaluation and local applications. and relied to a large degree on algorithms based on statistical and mathematical algorithms or visual analysis. Recently. these techniques have been extended to address topics such as multisensor. multitemporal and multispatial image analyses. integration with geographic information systems. interfacing geoscientific and socio-economic modeling. and the use of expert system technology for knowledge guided image interpretation.

For example. aerial photographs have been in operational use for decades to inventory and manage resources in forestry applications. With the advent of digital photogrammetry. orthoimage maps in digital format are increasingly being used for this purpose. For countries like Canada or Brazil. there is no other way than to rely almost completely on remote sensing and digital image processing techniques to routinely monitor and manage their vast forested areas. Monitoring and quantifying tropical deforestation on a global scale is only now practical with the availability of modern remote sensing techniques. Recently. colour infrared airphotos and scanner images have also been used to analyze and assess vegetation stress. especially for areas affected by acid rain.

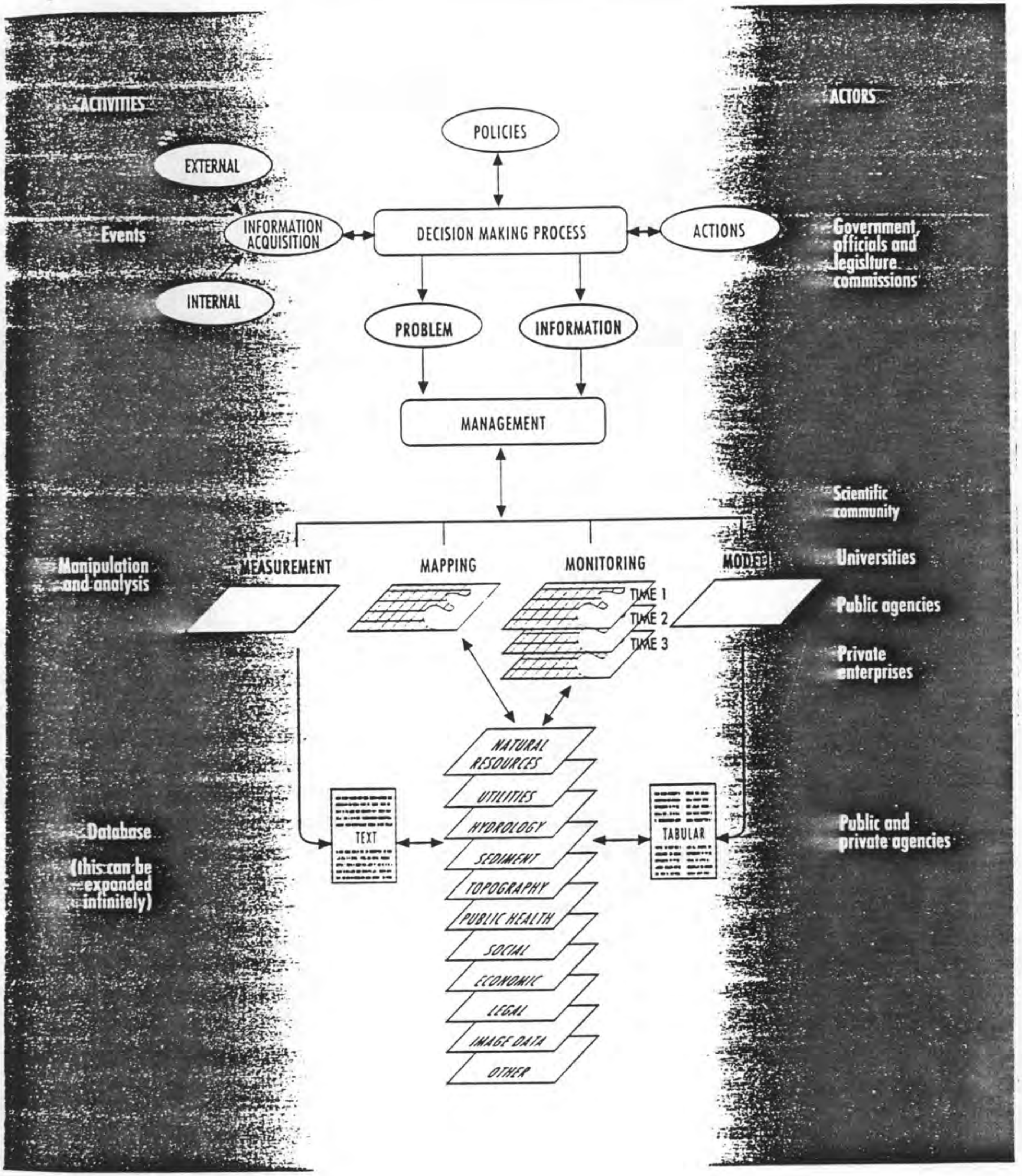


Figure 10. Diagram of a GIS as a decision support system

The critical importance of remote sensing is of course not restricted to one specific application area. The ability to use digital image processing techniques to extract measurements (and as such, spatial information) from remotely sensed data has been used in a number of fields concerned with mapping, monitoring, modeling and managing our environment (see Fig. 10). For example, using sophisticated atmospheric correction models, researchers have been able to relate digital pixel values to energy received from the sun at specific wavelengths at a specific ground location. This has helped users to improve their models describing heat flux at the boundary layer between earth and atmosphere.

How else if not with synoptic remote sensing image data could atmospheric physicists have detected the Antarctic ozone hole or could oceanographers detect and analyze sea surface currents and eddies to assess and refine oceanic global circulation models. It has been shown that ocean colour values as recorded on the Coastal Zone Color Scanner (CZCS) on Nimbus can be correlated with biomass and consequently provide productivity figures for the upper ocean layers.

Using SPOT and Landsat satellite data, GPS measurements, and digital photogrammetric and image processing techniques, digital image maps can be produced for desert areas in the Sahara. For the first time up-to-date, detailed, and accurate maps are available for these areas - a basic requirement for planning and decision-making.

Expert systems are also being developed to improve accuracies of land use/land cover maps. Whereas earlier image analysis techniques were almost solely based on statistical analysis of spectral values at every pixel position, newer developments take into account parameters such as neighbourhood information, texture parameters, or surface shape analysis; researchers are also trying to formalize human interpretation skills into rule-based expert systems in an attempt to improve our ability to extract information from remotely sensed data.

Whereas some of the techniques and interfaces are still in the research and development stage, these interdisciplinary approaches already provide promising tools for efficient storage, query, information extraction and integration of remotely sensed data (see Fig. 11).

## Modeling

Humans have always used models. The first were physical models, ranging from dolls to model boats and gliders. The game *i-go* (*wei-hai*) originated in China before 600 BC as a simulation of the tactics of warfare, and in the Thirteenth century AD data from rain and snow gauges were being conveyed to the controllers of river systems in China to help them predict flood peaks.

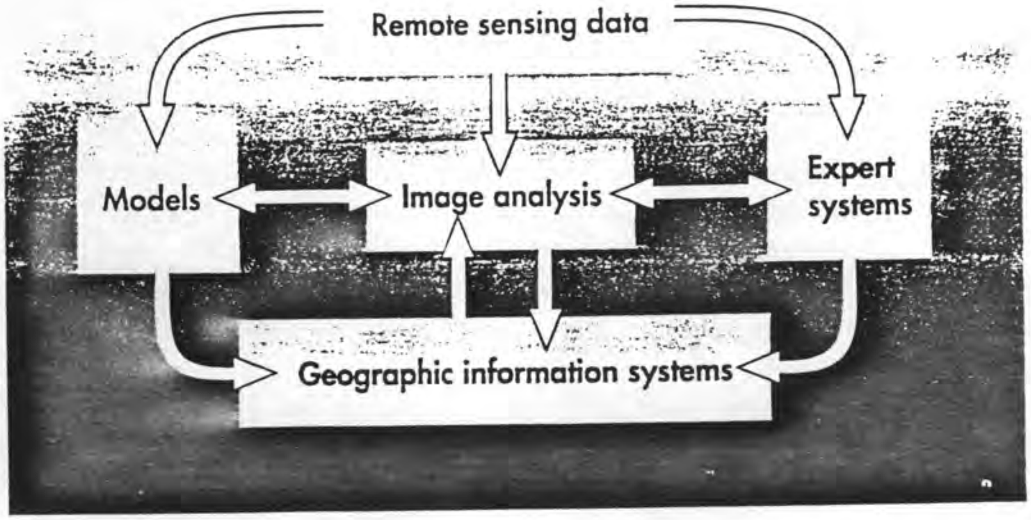


Figure 11. Combining remote sensing and GIS technology into so-called image-integrated GIS (IGIS)

A model is a caricature of reality that emphasizes those parts of a system of most relevance to the user while ignoring those components of less importance. The skill in model building is to decide which detail is essential and which can be omitted.

Models can take many forms. Physical models are widely used in areas of engineering such as fluid dynamics. However, the main types of models relevant to sustainable development are analytical models (i.e. a series of mathematical equations that can be solved) and simulations (i.e. a series of functions expressed as a computer program). Analytical models often oversimplify the system being modeled to achieve a formal mathematical representation, but have the advantage that their behaviour can be efficiently and comprehensively described. Simulation models can capture the complexity of many real systems but always at the risk that a large complex system will be replaced with a large complex model - neither of which can be understood.

Models are built for a variety of purposes. Many are built as experimental tools that explore complex hypotheses about the mechanistic basis of systems. These models are probably better never released from the laboratory, since they often lead to frustration and disillusionment when planners and decision-makers attempt to use them in practice. Here we are more interested in models that can be populated with spatial data and used to explore the complex spatial and dynamic temporal behaviour of systems.

Most models used in resource and environmental management are dynamic models. Dynamic models follow the change through time of particular variables describing a point or points in space or an aggregated area. Examples of dynamic models include models of the yield of a crop, the growth and population dynamics of a forest stand, or the production of a herd of animals grazing a specified field.

A few models predict the changes of variables in space. These are often used in association with spatial databases to predict the values of variables that are difficult to measure by other means. Gradient modeling is perhaps the best known example of these approaches. In gradient modeling the distribution of species or community properties is correlated directly with more readily measurable descriptors such as altitude, aspect, geological substrate and the like. These can then be used to predict among other things the potential distribution of a crop or species of natural vegetation.

There have been very few attempts to combine both model forms of prediction in time and space. The computational demands of such **spatio-temporal** models were once a severe limitation. However, computing power has increased and more efficient computational algorithms are being developed. Some progress is also being made with the automatic simplification of models. Some forms of models can also be used efficiently in standard analytical and optimization packages, thus allowing the user to examine a wide range of options in seeking better management strategies.

An important limitation in developing spatio-temporal models is our inexperience in coupling subsystems of different spatial scales. We have too little experience with this class of models to be certain just which details to include and which to leave out. Mistakes can lead to cumulative errors and spurious chaotic behaviour.

A number of factors have limited the more widespread application of models in the management of natural resources. Most models are built for a particular task, often with the mixed goals of prediction and exploration (or explanation) of the system itself. This means that they are often cumbersome to run and are usable only by the original development team. These problems are being overcome. The tasks required of models are being stated more clearly (e.g. prediction of crop yields, structural changes in vegetation, land suitability). Successful generic models are being developed (e.g. the crop trajectory models of Hall and Badhwar, the JABOWA/FORET suite of forest growth models, BIOCLIM for predicting species ranges) and are currently available in well tested software packages. Also a larger cadre of biologists, agriculturalists, planners and other users with skills in modeling and computing is emerging each day. The users are pushing for more development and better models. This bodes well for further advances in modeling.

## Expert Systems

Expert systems (sometimes called knowledge based systems or advisory systems) are among the most prominent products of artificial intelligence research. An expert system is a computer program designed to simulate the problem solving ability of an expert. The program asks questions and, based on the responses of the user, eventually reaches, or validates, a conclusion and is able to explain how and why it reached that conclusion.

The first expert systems were developed in the late 1960's. Many of these early expert systems were designed to assist in diagnosis of diseases or in identification or classification. A very large literature on the methodology of developing expert systems has been created and there are numerous software packages to assist in the task of building and using expert systems. Much of the theory behind expert systems draws upon the larger debate about artificial intelligence; however, questions about how humans think or whether a particular program does show true "intelligence" are not of prime importance in this area. The goal in developing expert systems should be to design and implement useful advisory systems. What may be of importance are the modes of logic and explanation that people find intuitive so that expert systems can more readily communicate with their users.

The construction of an expert system is a time-consuming process both for the builder (sometimes called the knowledge engineer) and the experts whose experience is being captured. A common fallacy runs, "We don't know enough about this topic to build a **real model** so let's build an expert system". This can be the start of a wasteful process. Expert systems should only be built when human expertise is scarce but available. This expertise may be in the form of a series of rules or empirical relationships, as long as the knowledge encapsulated in these rules or relationships can be communicated in text or pictures. The experts must have the time and willingness to cooperate in the venture. Expert systems work best in diagnostic or classificatory tasks, especially where the understanding of the task is empirical and the input data are "noisy". They also work most effectively within a well prescribed domain. It is very difficult to capture all the pieces of knowledge that go to make up common sense in a widely defined task.

A promising development in the building of expert systems is the application of the techniques of machine learning or rule induction. In developing a quantitative model, a scientist may use statistical software to unravel relations and derive mathematical functions from data. Machine learning plays a similar role in developing expert systems. New algorithms and software packages are becoming available to assist in extracting information from large data sets. The algorithms are especially suitable for handling qualitative relationships between variables and discontinuities within the data. The information is expressed in the form of rules or decision trees.

The field of advisory systems has merged with the more general problem of developing systems of knowledge handling and delivery. This is becoming increasingly important as the quantity of information and the complexity of its interconnectedness increases. Even when information is available electronically, simple searching approaches can still be slow and unsuccessful. The main product in this area is better structured knowledge bases and "intelligent" retrieval systems available on demand and on-site.

Another related area is rule based models and qualitative modeling. An expert system can be thought of as a model composed of rules and these rules are often qualitative (e.g. if the amount of monoculture cropping in the district is higher than the norm for the region, then ...). This is a major area of application in remote sensing where rule based models may assist in the initial classification of images (e.g. if the ratio of Landsat Thematic Mapper bands three and two is low, then the land cover class is water).

Another major application of expert systems is as advisory systems assisting users as they attempt to master the force of the very powerful, but complex, tools provided in a comprehensive GIS (see Fig. 11). Similarly, expert systems can be employed to guide users in the intricacies of reformulating generic models for their particular application, in running the models and in interpreting their models outputs.

The fusion of remote sensing and GIS technology into so called image-integrated GIS (IGIS) is especially seen as one of the key research fields in spatial data handling over the next decade. National and international research programmes are underway to study the degree to which these two technologies can be combined. It is important that advanced expert systems be developed which can aid users as the attempt to understand both the potentials and the pitfalls inherent in the integration of these complex technologies.

# APPLICATIONS AND EXAMPLES

Each of the technologies discussed in this digest – remote sensing, geographic information systems and environmental modeling – has a variety of current applications both within the research as well as the operational resource management communities. More and more often we find, however, that they are combined to greater or lesser degrees depending upon the type of analysis being conducted. Results are available on the use of remote sensing to provide measurements of environmental parameters such as net primary productivity, atmospheric concentrations of ozone, or forest stand densities. The use of Geographic Information Systems for facilities management or locating facilities is also readily documented, as is the use of modeling for the prediction of the economic impacts of development. We have chosen to stress applications that bridge these technologies, in providing a perspective on how integration can achieve synergisms that facilitate our understanding and improve our ability to manage our environmental resources.

The four examples discussed here are drawn from four different regions and concern:

- ▼ Land-Use Planning in Senegal;
- ▼ Crop Yield Estimation in Italy;
- ▼ Habitat Analysis for Preservation of Species Richness in the United States; and
- ▼ Determination of Natural Hazards Risk to Agricultural Production in Ecuador.

The first and fourth application examples are based on work undertaken within the "Monitoring of Tropical Vegetation" and "Tropical Ecosystem Environment Monitoring by Satellite" (TREES) projects of the Joint Research Centre of the Commission of the European Communities (Ispra, Italy). The second example is a joint project of the Department of Agrometeorology of the Region of the Veneto, Italy, and the University of California, Santa Barbara. The third example is based on cooperation among a range of governmental (Federal and State) and non-governmental agencies in the United States[1].

## Land-Use Planning in Senegal

### Introduction

Senegal is experiencing a long-term decline in per capita food production as population growth out-paces agricultural growth. In 1988, Senegal's population was estimated to be 6.9 million. Population is likely to double by 2010. Planners in Senegal face tough land-use decisions. They must weigh the need to increase food production against costs associated with the loss of natural environments to cultivated lands.

### Approach

In 1990, the US Agency for International Development, in contact with Senegalese specialists, sought information on options for increasing rain-fed cereal production in Senegal. The EROS Data Center of the US Geological Survey performed the entire analysis on desk-top and mainframe computers. A GIS was used because of the complex spatial component of the data, the need to integrate numerous natural resource and socio-economic data layers, and the need to analyze a wide range of production scenarios, with the likelihood that these analyses would be repeated in future years. The major cost involved was the time analysts spent entering data and maps defined by the GIS model. All of the data came from existing sources, including maps prepared from LANDSAT remotely sensed images, Senegal's national census, climate data and reports. The GIS contained data on natural resources, climate, demographics, political subdivisions, infrastructure, agricultural production and nutrition. Natural resources data included information on soils, vegetation, land-use and water. Agriculture data covered distribution of cropland, major crops, yields and production figures by crop, the caloric value of the major food crops and land-use rotation practices.

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1. The examples which follow in this section draw on material compiled by the authors for UNESCO Environment and Development Brief 3. This brief, entitled *New Technologies: Remote Sensing and Geographic Information Systems*, was produced as a joint effort by UNESCO and the Scientific Committee on Problems of the Environment (SCOPE). Some support of personnel was also provided by the US National Aeronautics and Space Administration's Earth Science and Applications Division. The 16-page coloured brief was published in mid 1992, and is available in English, French and Spanish from the Bureau for the Coordination of Environment Programmes, UNESCO, 7 place de Fontenoy, 75352 Paris 07 SP (France).

### Results

The analysis concluded that Senegal could significantly increase its production of rain-fed cereals, without extensive costs in terms of natural resources, by applying improved technologies and by expanding cultivation. Specific findings included:

- Existing rain-fed cereals alone could sustain 3.9 million people (56% of the Senegalese population).
- By applying improved agricultural technologies, 5.4 million people (79% of the current population and 37% of the country's projected population for the year 2010) could be sustained from these crops.
- By applying improved agriculture technology and expanding cultivation to potentially arable lands, approximately 7.7 million people (more than the current population and some 56% of the projected population for the year 2010) could be sustained, while preserving some natural vegetation.

This information was used to define two strategic development goals: (1) sustained efforts in family planning; and (2) an increase in crop productivity through the use of new technology in zones of reliable rainfall.

A number of other African countries face the same challenge of increasing food production to feed growing populations. In many cases, the natural resource and socio-economic data needed to carry out GIS analyses similar to the Senegal study are available.

## Estimating Crop Yields in Italy

### Introduction

The Po River Valley of northern Italy is the breadbasket of the country, with crop production in the area exceeding US$ 20 billion per year (see Figs. 12 and 13). The Po River itself forms the southern boundary of the Regione del Veneto (RdV) before it flows into the Adriatic Sea. In 1985, RdV officials became convinced that they would need improved methods for compiling and analyzing agricultural statistics for the Regione in order to make effective agricultural and economic policy decisions in an increasingly complex ecological and economic environment.

### Approach

In 1987, RdV officials instituted a co-operative research programme with the

University of California, Santa Barbara, to develop better crop production estimates. The system that was developed uses digital satellite image data.

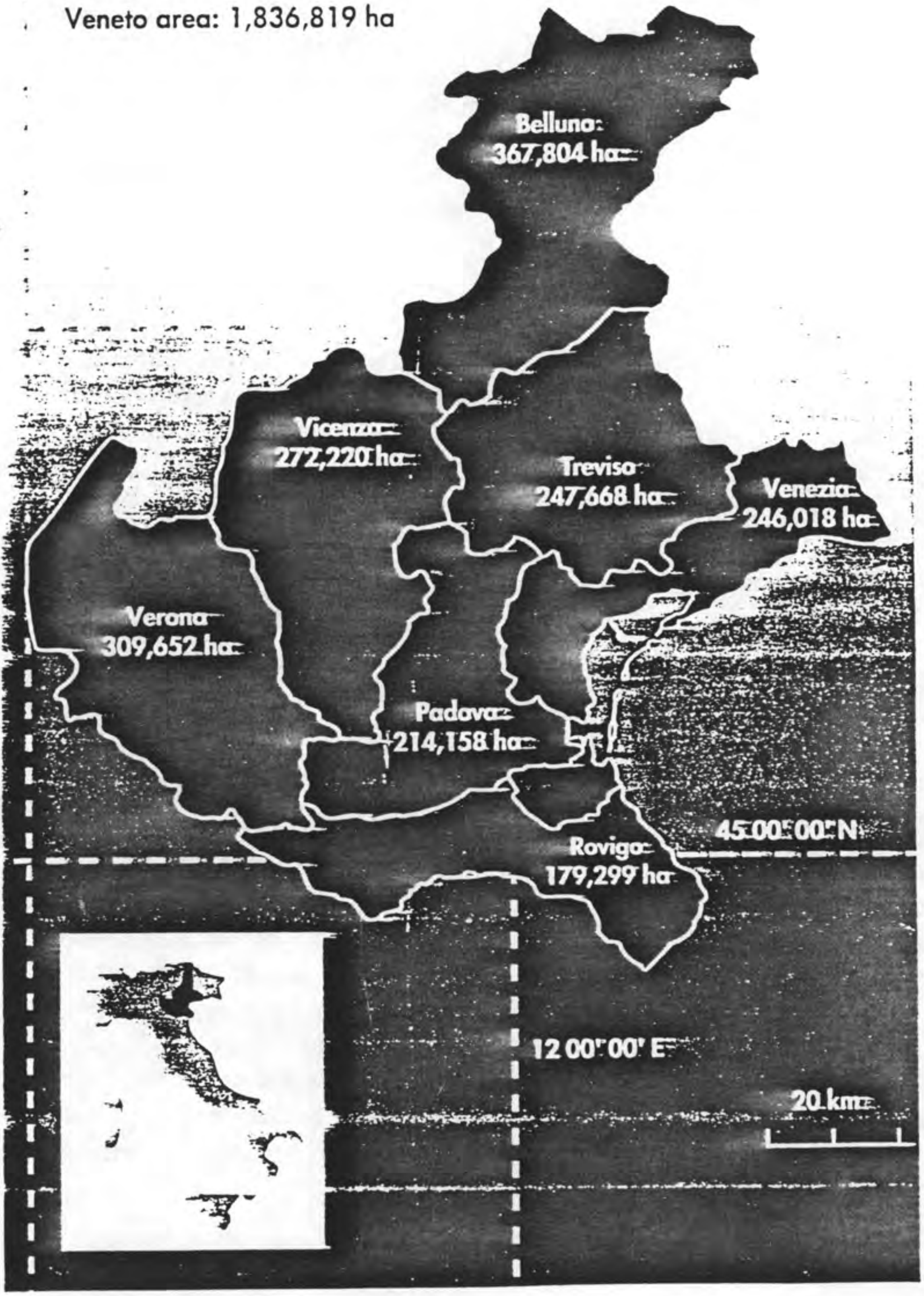


Figure 12. Veneto region and its provinces

cartographic data and environmental data from many other sources as input into a GIS. To produce the crop estimates for the RdV, a minimum of four LANDSAT TM image acquisitions are required per year. The project has made use of commercially available remote sensing and GIS technology. The initial investment for project hardware, software and data input has been in the order of US$ 45,000.

Extensively processed LANDSAT TM data are used to provide primary information on the five most profitable crops grown in the RdV: corn, soybeans, sugar-beet, small grains and orchards. The system also uses meteorological, agronomic, economic and field validation data. The collection of ground truth data represents a significant cost factor in the project.

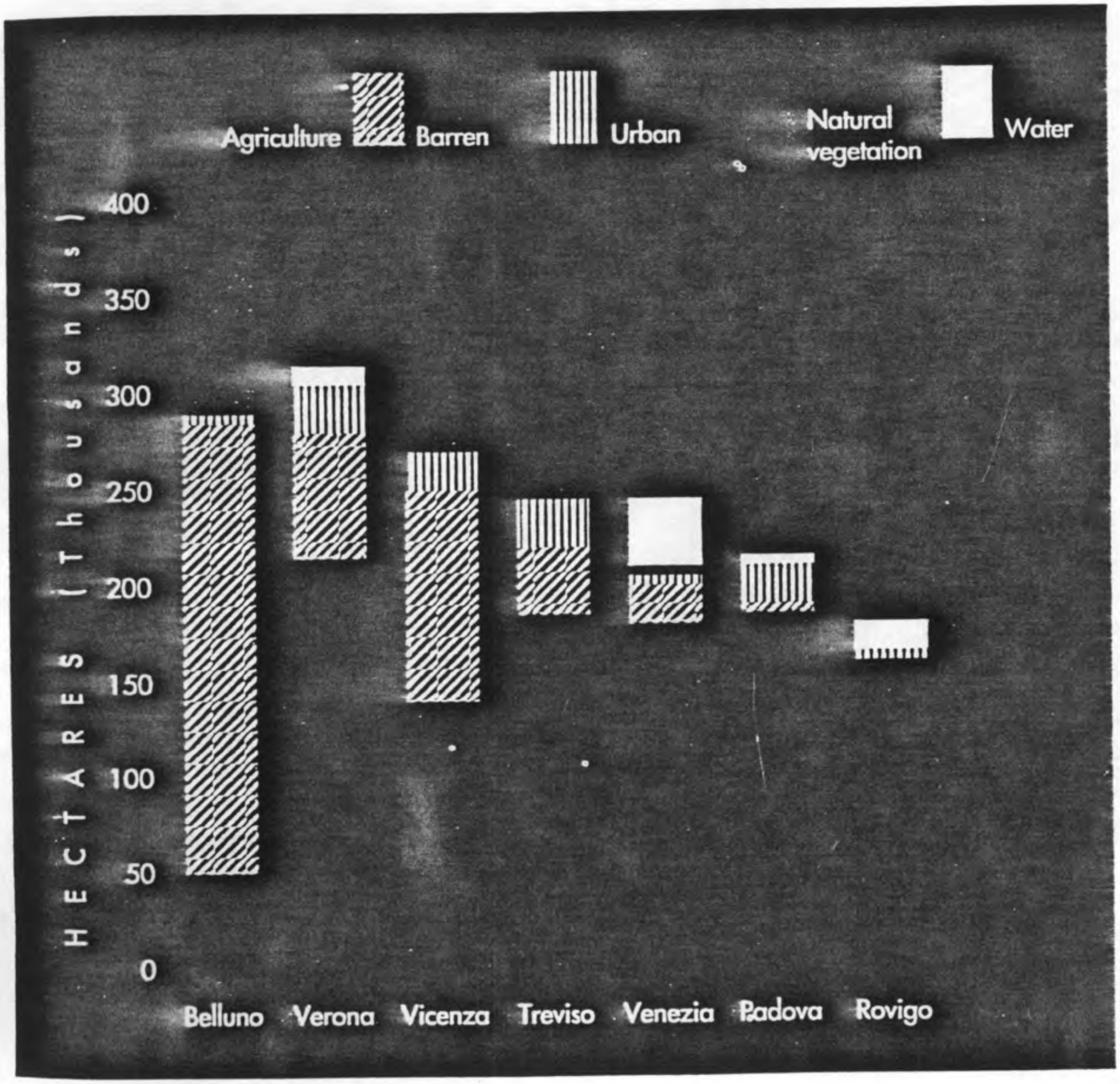


Figure 13. Land use by province

### Results

When completed, the system will provide estimates of the total agricultural area within the RdV that is under cultivation for each of the five major crops. These estimates will be available on a biweekly or monthly basis at 75-95% accuracy.

The information will be used on a regular basis to upgrade region-wide agricultural production forecasts which will become increasingly important as members of the European Community develop closer economic co-operation. In addition, RdV officials will use the system to provide farmers with timely information on crop production, yields and profitability.

Environmental engineers and scientists working with the RdV will also benefit from ready access to accurate spatially referenced information on chemical herbicide, pesticide and fertilizer use within the region. Forecasts of agricultural production are a key economic indicator. GIS using remote sensing data for agricultural monitoring are being developed in a number of countries, including Italy and Egypt, and for regional areas such as the European Community.

In the future, systems like that developed for the RdV are likely to become much more widely used. Their accuracy should continue to increase with experience and as the models they employ are fine-tuned to local conditions.

## Biodiversity/Gap Analyses in the United States

### Introduction

Loss of species has become an issue attracting world-wide attention. Many times, however, we have focused our efforts on individual, highly visible "flagship" species, possibly at the expense of broader issues. Researchers and resource managers are coming to believe that it is more effective and cost efficient to focus on the preservation of intact functioning ecosystems with their myriad species than to continue to practise "emergency room" conservation on one endangered species after another or wait until common species become endangered before acting to protect them.

A challenge to the preservation of biodiversity is to plan future patterns of growth and modifications in land use to insure the survival of remaining biological diversity. This goal will not necessarily be reached by rescuing specific endangered species but by keeping enough of the living world around to supply us with disease-resistant strains of crops, new medicines to fight disease and functioning watersheds that supply water for drinking and for irrigation. Gap analysis is essentially a GIS based approach to facilitate the achievement of these objectives.

Gap analysis places resource managers in a proactive rather than reactive mode in the preservation of biological diversity. Gap analysis builds from a premise that unprotected species and communities represent "gaps" in our conservation safety net.

## Approach

Work in Hawaii demonstrates the potential of gap analysis in assisting decision-makers in their efforts to preserve diversity. This work involved cooperation by the United States Fish and Wildlife Service (USFWS) and the Hawaii Department of Land and Natural Resources. Other cooperating groups included private citizens. the Sierra Club. Hawaii Audubon Society. Conservation Council. Wildlife Federation. and the Nature Conservancy.

In the summer of 1975. ornithologists in Hawaii were asked to identify the best area in the islands for an endangered forest bird reserve. Hawaiian ornithologists could not provide an adequate answer that would convince decision-makers to commit funds for the acquisition of the preserve. While there were several locations where endangered species were known to occur. there were far larger areas where there was no species distribution information.

To correct this situation. the Hawaii Forest bird survey was begun in 1976. During the survey. 538 biologists and technicians surveyed 9940 stations and counted nearly 135.000 birds. These studies were conducted along 1401 km of transects systematically distributed over the forested areas of five islands. In assessing the need for new preserves. the first step was to plot species richness for endangered forest birds on each island. The next step was to overlay on this base map a map of existing reserves (see Fig. 14). In doing this simple GIS analysis it was obvious that despite the large surface areas set ,aside on both Maui and Hawaii. there was little overlap with the ranges of endangered species. Prior to establishing reserve boundaries. research and management biologists carefully reviewed the floral and faunal distribution and abundance data. Reserve designs were developed and forwarded to the US Fish and Wildlife Service personnel. based on a number of factors including: the distribution of current and potential habitats. future land-uses in the general region. information on the prevalence and abundance of suspected limiting factors. and the need for a minimum viable size for the species of concern.

## Results

To date five reserves have been established on various islands at a total cost of more than forty million dollars. An example from the big islands of Hawaii is illustrative of the process. After analysis of the map of species richness overlain by the existing reserves, it was found that the largest numbers and highest densities of endangered forest birds occurred in the Hakalau Forest, in an area of privately owned parcel on the mid elevation slopes of Mauna Kea. Densities of the more common birds at Hakalau were among the highest in the state. The area also included the habitat of the endangered Hawaii hoary bat and a number of rare and endemic plants including several species considered for the endangered list.

After a thorough review of the project and a complete public review of the proposed refuge boundaries and alternatives for accomplishing habitat protection goals, the director of USFWS approved the acquisition of some 113,360 ha of privately owned land in the Hakalau region. Individuals associated with this project credit the graphic depictions presented in maps (such as that shown in Fig. 14), for helping to convince their management of the need for new reserves.

Such reserves are needed in many areas of the world. Wise use of the products of gap analysis is one way we may be able to reduce the projected losses in plant and animal species. By the year 2000, every state in the United States is now scheduled to complete a statewide gap analysis.

## Risk Assessment in Ecuador

### Introduction

Ecuador's agricultural sector, which provides a high percentage of the country's Gross National Product (GNP), is vulnerable to natural hazards, particularly floods and droughts. During 1982-83, floods caused losses of more than US$ 110 million in damage to crops and the country's agricultural infrastructure.

By 1990, Ecuador's Ministry of Agriculture had become increasingly concerned about the frequency and extent to which natural hazards were affecting agricultural production and related income, employment and investment. Although officials were aware of the problem, they did not know which roads and other facilities used for agricultural distribution were most vulnerable to hazards or where the government should implement mitigation measures to protect sectoral income, employment and investment.

### Approach

From the outset, it was clear an automated system was required because of the sheer number of variables and quantity of data to be analyzed. In 1991, with

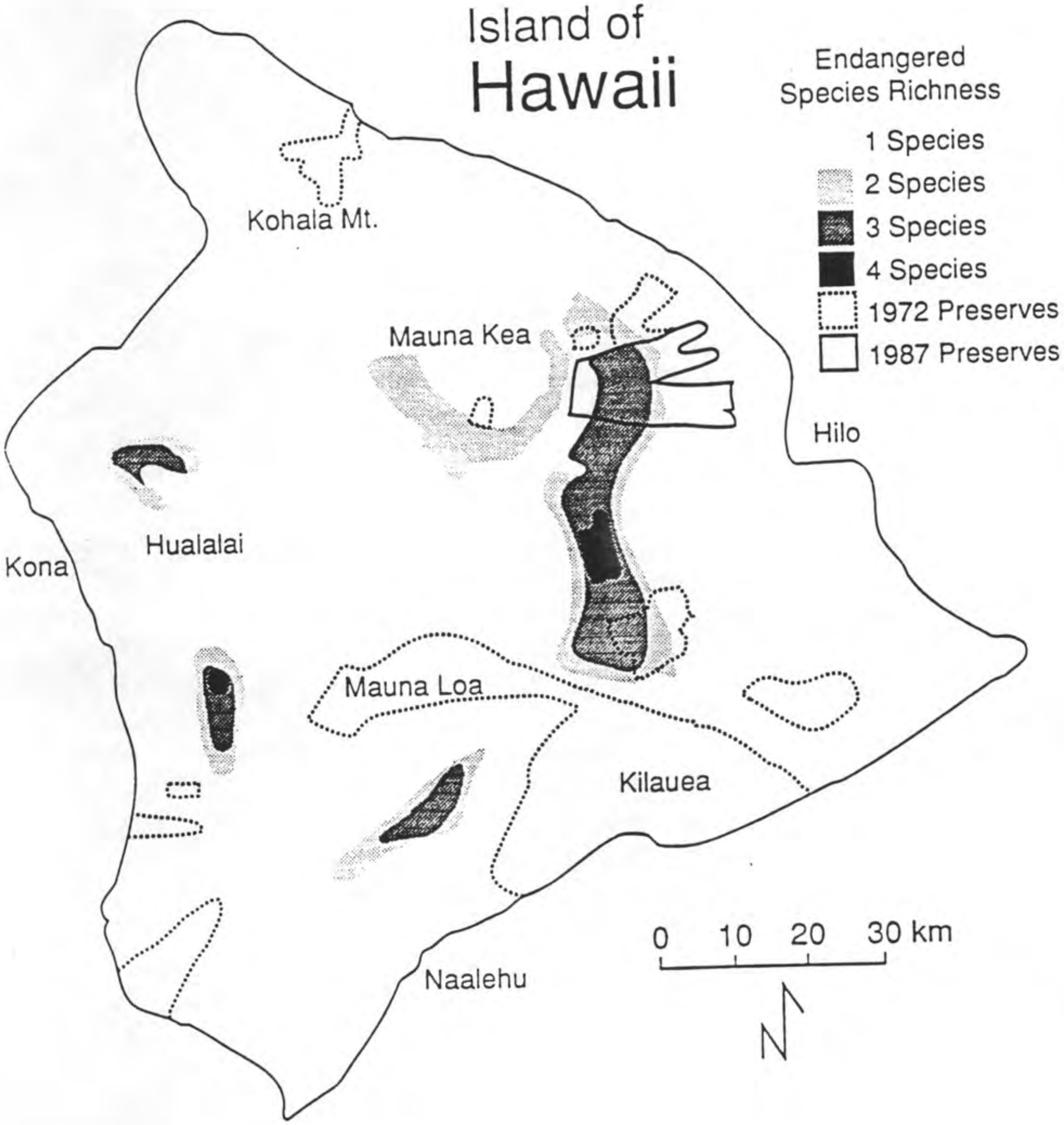


Figure 14. Distribution of the endangered forest birds and preserves on the Island of Hawaii in 1987, showing the extent of the preserves in 1972 and the new preserve on the eastern slopes of Mauna Kea

support from the Department of Regional Development and Environment and the Organization of American States. the Government acquired a desk-top GIS work station and spreadsheet software to analyze data for Ecuador's 20 provinces. For each province. the GIS combined data on 26 production systems. 14 crops and related infrastructures - storage facilities. irrigation systems. road networks - with data on droughts. erosion. volcanoes. floods. landslides and seismic hazards. Data on five economic indicators - income. employment. foreign exchange earnings. investment and food security - were also introduced into the system.

### Results

The analysis performed on this database identified 49 critical situations that required action to mitigate hazard vulnerability. including the following:

- ▼ Erosion hazards were likely to damage a potato-growing area that. at the time of the study. accounted for 43% of the national income from potato production. and 40% of the employment and 80% of the income in one province (Carchi).
- ▼ Flood hazards in one province (Guayas). and erosion hazards in another (Tungurahua). posed the greatest threat to agricultural employment in Ecuador.
- ▼ Drought impacts on banana production in El Oro province posed the greatest threat to Ecuador's foreign exchange earnings from agriculture.

Based on this information. the Ministry prepared a US$ 317.000 technical cooperation proposal which several agencies are now evaluating to finance activities to reduce the risks to agricultural production from natural hazards. In addition. the Ministry formulated new investment policies and technical assistance activities in the agricultural sector. Since natural hazards pose a major threat to the agricultural sector in many Latin American countries. analyses similar to this one could be used throughout the region based on GIS technology.

# ISSUES, NEEDS AND TRENDS

A growing number of uses of the technologies discussed in this digest have achieved either acceptance within various areas of the scientific community or operational status within resource management agencies and the commercial arena. This does not mean that there are not issues yet to be addressed and research needed. The trends, however, are very positive and these technology trends will, we feel, continue to enable even more scientific utilization of these technologies. In this closing section, we address some of the key issues in the future development and application of data collection and information technologies including the role of the scientist in the development and wise use of these technologies.

## Scales

Issues related to the use of information systems technologies for the studies of sustainable development cannot be dissociated from the question of scale. Indeed, scientific analyses and policy making processes are intimately linked to the level of organization to which they apply (see Fig. 15).

Concerns with the Earth systems and with linkages between its parts require that analyses be made at global levels and that actions be taken under the umbrella of international agreements (i.e. Montreal Protocol, IPCC, IGBP, etc.). Regional questions arising in the framework of transport of water, gases, pollutants or of intercountry agreements with respect to resource exploitation or population policies (multinational watershed plans, forest concessions, migration, etc.) are most often examined at supra-national scales despite territorial divisions of authority and irrespective of competences. Local needs for information about resources are more directly linked to well identified projects and the definition of precise courses of action. At each scale, requirements for data and information will be very specific. Clearly, if the examination of the factors that enhance sustainable development by their very nature integrates economic, political, institutional, legal, ethical and ecological considerations, then the relative importance of each of those factors will vary according to the adopted perspective. The perspectives of the individual – planners, resource managers, policy-makers – are coloured by the acculturation processes operating in the nations and regions involved. The role of science and technology will, similarly, assume a variable importance depending on local, national, regional and global imperatives.

The question of scale also bears heavily upon the resolution or "grain" of the analysis and thus of the necessary data sets required to accomplish adequately a given task. As a rule, local investigations will need finer resolution data than a scientist, resource manager, or policy maker involved in a global analysis. Furthermore, although rapid advances are being made in this area, technology and limitations in our current ability to handle large amounts of data still prevent the systematic application of higher resolution observations and analyses to large regions, continents, hemispheres and the entire globe. However, there may be specific needs to dissociate scale and resolution when, for example, a highly accurate measurement of a specific chemical compound must be obtained over a large area (ozone, pollutant, etc.). Thus, today, information technologies must still be managed through a set of compromises between scale and detail, and utilize data structures and algorithms which facilitate flexibility in analyses.

A major advantage of the new information technologies is that the same techniques and instruments can, within some limits, work at different scales which can be "nested" into each other (see Fig. 16). This provides new opportunities for examining specific problems "across scales": a local analysis may thus be easily set in a more regional context and, vice-versa, regional or continental issues can be substantiated using linked local analyses. Together, GIS, remote sensing and advanced modeling offer a means to extend significantly the breadth and depth of considerations brought into the decision-making process.

## Infrastructure

Infrastructural investments represent a key element in the successful adoption of new information technologies. Such investments, which can be made at different levels of sophistication, are needed to facilitate access to the tools, networks, systems and concepts discussed in this digest. Again, apart from obvious financial considerations, the scale of concern and the nature of the problem to be

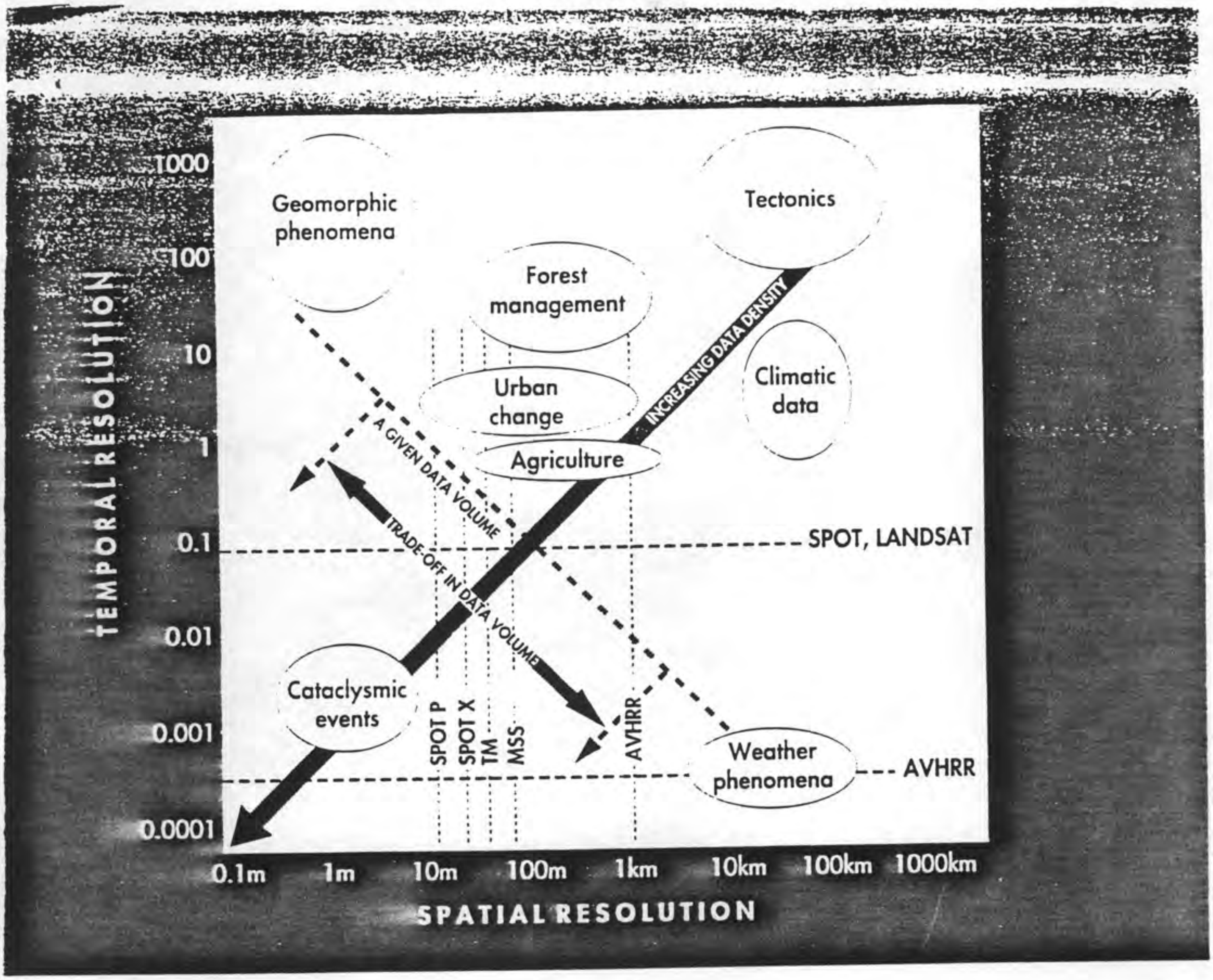


Figure 15. The spatial and temporal scales of various environmental phenomena

tackled will govern the choice of technologies acquired by institutions. Essentially, investments in informatics are needed to acquire, display and analyze data coming from sources as varied as satellite sensors, existing maps, field surveys, statistical tables .

The rapid advance of computing capabilities over the last two decades has greatly facilitated access to the new information technologies. Desktop computers and commercial software are now available to support most types of project work. High data rate communications networks are becoming more common. Yet, training, maintenance and updating of the hardware and software require careful consideration as they involve recurring costs not always readily available in institutions. Until a few years ago, the balance of investments was heavily slanted towards the purchase of basic hardware and software. Data acquisition and training now represent the bulk of the necessary investments involved in

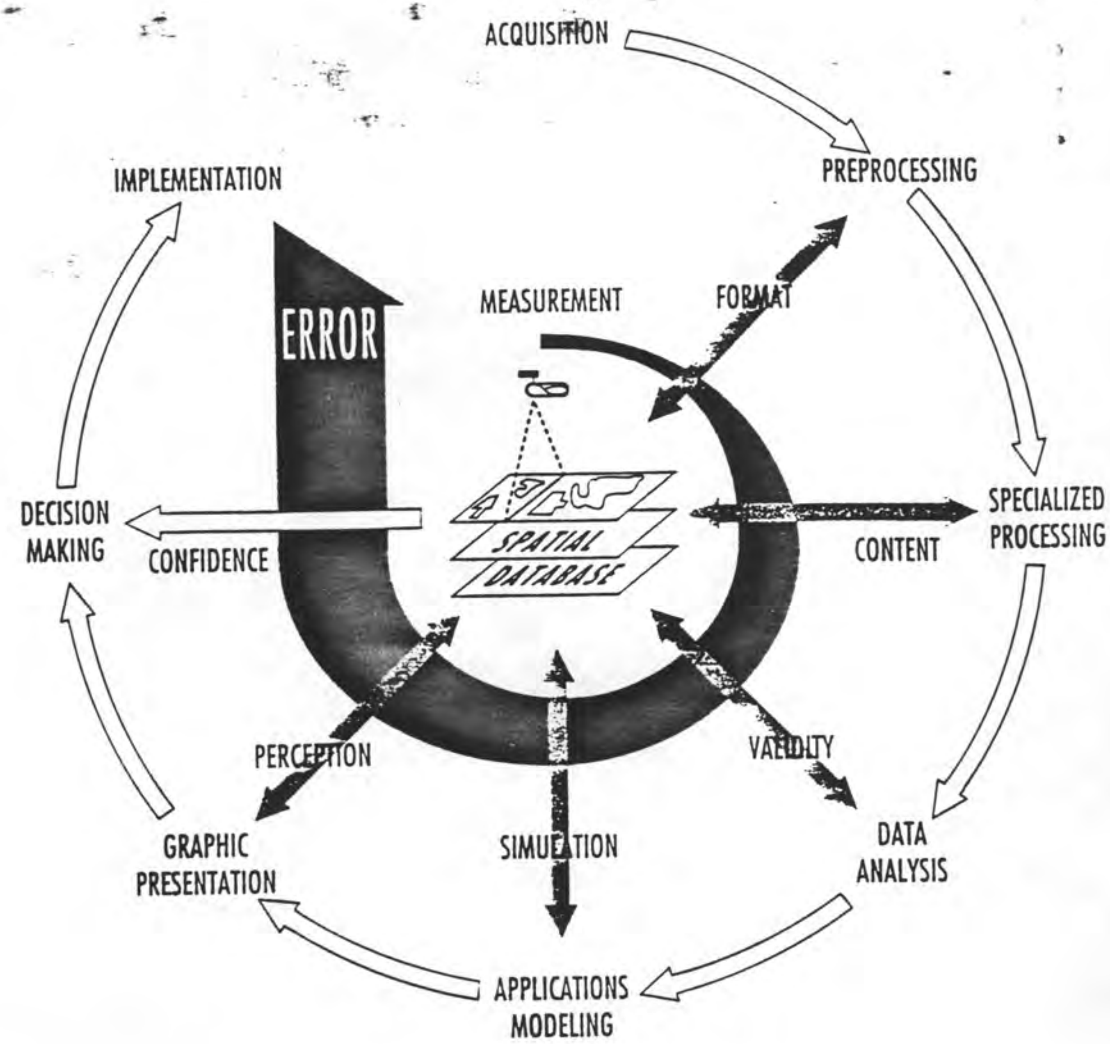


Figure 16. Nested scales of observation. Sample designs employing this concept are being used to effectively extrapolate field data across space

**Measurement**
- Precision of measurement
- Density of observations
- Observer bias
- Completeness

**Validity**
- Relevance
- Statistical significance
- Data mixing constraints

**Format**
- Digital representation
- Geometric registration
- Interpolation/extrapolation
- Normalization

**Simulation**
- Simplification
- Sub-grid scale processes
- Bifurcation

**Confidence**
- Sensitivity of objective functions
- Undue trust in technology

**Content**
- Mathematical logic
- Spatial convolution
- Classification system
- Subjectivity

**Perception**
- Readability
- Appropriate projection
- Interpretation

implementing the technologies discussed here. Training is particularly important within the context of the needs of both the scientific and operational applications of these technologies. As both remote sensing and GIS software systems become more sophisticated, the need to understand their potential increases, even as attempts are made to make these systems less user hostile. Yet, institutions which must do such training are faced with the complex issues related to maintaining state of the art capabilities in areas of rapidly advancing technologies.

## Accuracy

In remote sensing, two components of the accuracy evaluation can be identified. The first one is related to the physical measurement itself, such as the one made by a satellite sensor recording the radiation reflected from the earth surface. The second refers to the accuracy of interpretation or transformation of such physical measurements into information related to either features or processes on the ground. Obviously, both the physical measurements and the derived information are linked. Yet, different types of research are required to improve our knowledge of these processes. Methodological developments in image analysis try to improve constantly the accuracy of interpretation. This accuracy depends, however, upon the type of information sought. For example, land cover maps can generally be produced with an accuracy of more than 90%. National assessments of forest changes can be produced with similar accuracy.

Error assessment still represents a major research item in the development and application of the GIS technology. Data used in GIS-based analyses typically must be collected from a variety of sources. Each of these data products will have been compiled to address specific and perhaps conflicting goals with respect to locational and thematic accuracy. Methods must be developed to assess the uncertainty, or error, associated with specific types of data products. Furthermore, a sophisticated understanding must be developed for the accumulation of various types of error as multiple data sources are combined into information products (see Fig. 17). What one must constantly strive to ensure is that the accuracy improves with respect to traditional field methods of data collection.

## Standards

Standards are needed for the transfer of spatial data in electronic form. As currently structured, spatial data sets typically carry an unacceptable overhead

LEVEL I: **Global AVHRR**
*Resolution: 1.1 km*

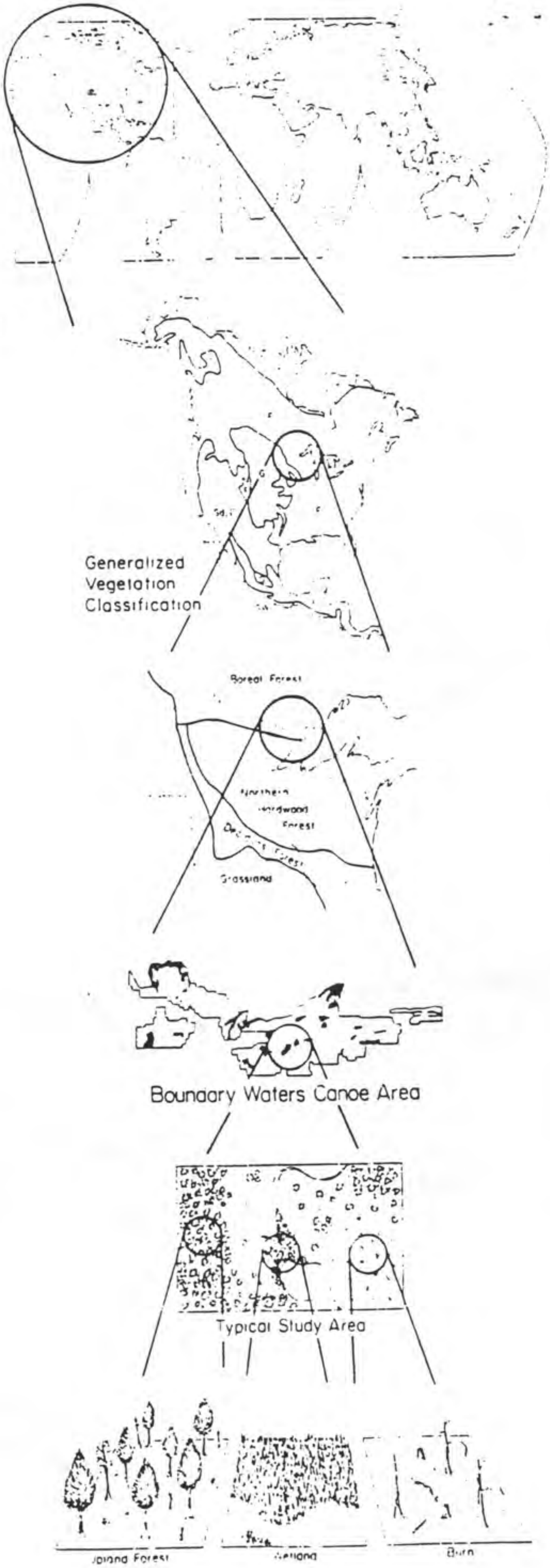
LEVEL II: **CONTINENTAL AVHRR**
Landsat multispectral scanner
*Resolution: 1.1 km - 80 m*

LEVEL III: **BIOME**
Landsat multispectral scanner
thematic mapper
*Resolution: 80m - 30m*

LEVEL IV: **REGION**
Thematic mapper high altitude
aircraft
*Resolution: 30m - 3m+*

LEVEL V: **PLOT**
High and low altitude aircraft
*Resolution: 3m+ - 1m+*

LEVEL VI: **SAMPLE SITE**
Surface measurements
and observations



when rapid error-free exchange between users is needed. More research is required here to facilitate distributed cooperative scientific investigations and sharing of data and information. Standardization of spatial data transfer formats will further encourage the combined use of remote sensing and GIS data sets. Finally, although the problems of operating in heterogeneous computing environments remain, this issue is being seriously addressed by major hardware suppliers. It is our belief that problems currently associated with the exchange of data and processing between different vendor systems will be substantially mitigated within the next few years.

## Timeliness

Timeliness of access to data is a crucial characteristic of an information system. Requirements will obviously vary from one application to another (see Fig. 15). Crop monitoring or a search for locust breeding grounds will lead to more stringent temporal requirements than a general land use survey. Measurements of flooded surfaces will require more frequent data than a national forest inventory. In its early stages, remote sensing may have appeared to respond slowly to operational needs, and requirements of agencies, institutions and commercial enterprises. Today, advances in communication or in real-time local satellite data acquisition are constantly improving the potential for the "real enough time" use of these data. Commercialization of portions of the remote sensing sector has also contributed to improve the timeliness of data access even if the pricing structure currently applied to data by the commercial sector may strongly limit access to data for many applications. The problem of data dissemination is thus seen as two-fold: on the one hand, it is up to the users to make sure that communication channels with data sources are optimized for their specific needs. On the other hand, it is also the responsibility of nations and agencies which hold the key to satellite systems and data archives to reduce as much as possible policy or practical restrictions to timely data access.

Another aspect of timeliness in producing the required analyses for sustainable development necessitates the mastering of techniques. This leads us to emphasize the need for the training of scientists and technicians able to cope with evolving technologies. This can also be seen as an infrastructure issue.

Figure 17 (Left). Accumulation of error in an integrated remote sensing / GIS processing flow

## Technology Trends

Information technologies of the kind proposed in this digest may appear to many as being intensively "high-tech" driven. Human ingenuity can thus be seen as applied first to the design of instruments and tools and less to the nurturing of skills and know-how to use them. The trend is clear and field practitioners may quickly feel overtaken by events. Such general feelings of incapacity to keep up with advances, let alone master their application, can only be mitigated by a major and concerted educational and developmental effort to reverse the current state of affairs. At this stage, it may not be so much the technology that is wanting, but perhaps more our ability to put it properly to work.

The situation is further compounded by constant changes in the technical base. Current trends in the three major technology areas discussed here (Remote sensing, GIS and modeling) are summarized in Table 5. Techniques in these three areas have amply demonstrated their capability to aid researchers and resource managers as they monitor the earth surface, detect changes, and measure and evaluate trends. The combination of these technologies represent a powerful means of verifying that environmental commitments made with respect to the conservation of resources have been met. Whether we like it or not, those techniques offer a possible verification mechanism for holding nations accountable to those commitments. The quality of international data which can help chart the path toward sustainable development is a shared responsibility which requires the free circulation of information. This topic and these technologies have far-reaching scientific, social, economic, political and ethical implications.

## Role of Scientists

It is important that the role of science and technology in human affairs be more widely known and better understood. A corollary to that statement is that the scientific community holds a special responsibility for communicating what the business of science is about, and keeping up with advances in a wide variety of fields of investigation. Currently, the data and information technologies discussed in this digest are little known and, to date, are truly understood by a relatively small number of scientists. Cross disciplinary approaches are, as a rule, not directly appealing to more classically trained scientists. This ignorance of the capability and limitations of tools by the broader scientific and resource management community is often the source of undue scepticism or excessive optimism with respect to reality. The scientific community involved in various elements of sustainable development has, therefore, the particular responsibility

### Remote sensing

- Exponential increase in the quantity of data and range of data types being produced by earth observing satellites;
- Increase in the spatial, spectral and temporal resolution and in the precision of the recording of such data;
- Significant improvements in our capacity to store and manipulate the large data sets thus being produced;
- Growing availability of local satellite data receiving stations and of global communication networks; and,
- Increasing sophistication of software package to analyze remotely sensed data, thus creating increased demand for user training.

### GIS

- Increasing availability of digital datasets;
- Increasing system processing power and software functionality;
- Initial awareness of the costs and benefits of GIS technology for update of large spatial datasets;
- Increasing concern regarding issues of accuracy and precision; and,
- Improvement in user interfaces to GIS.

### Modeling

- Increasing availability of generic models known to be effective for specific problems over a wide range of regions;
- Increasing use of qualitative models. and models mixing rules and functional relationships;
- The embedding of models and comprehensive GIS in decision support systems; and,
- Use of expert systems to aid users in gaining the full power of such integrated systems.

Table 5. Current trends in remote sensing. GIS and modeling

to significantly upgrade its familiarity with techniques which have been shown to be most efficient and effective in collecting, organizing and applying appropriate data to a particular field of investigation. One might even venture to say that the problems of development and environment will increasingly become so intractable that their resolution will necessitate the integration and the use of science and technology at scales which, as yet, have received little consideration. The scientific community has an additional role to play in making sure that these techniques are properly tuned and adjusted to problems of sustainable development at all scales. Finally, scientists must endeavour, as a community, to steer advanced technology programmes of the future in directions which truly serve human needs.

With such a perspective, technology transfer assumes a particular significance. Indeed, information systems tools now permit significant decentralization in the data analysis and decision-making process. Technological advances are not reserved to a particular country or a specific class of scientists any more: they are increasingly within the reach of individual scientists or institutions around the globe. A true contribution by the world scientific community to sustainable development objectives would thus derive, among others, from improvements in the accessibility of those techniques discussed herein to the globally distributed science community as a whole. In return, familiarization of scientists and technicians with a diversity of scientific concerns and field situations can only work toward improving the appropriateness of proposed technical alternatives to the solution of problems arising out of our attempt to achieve the goal of sustainable development.