CHAPTER 4

REMOTE SENSING IN NATURAL HAZARD ASSESSMENTS

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SUMMARY

This chapter provides planners with an overview of remote sensing technologies and their general application in natural hazard assessments. Characteristics of both aerial and satellite remote sensing techniques and the role remote sensing can play in detecting and mitigating several natural hazards are highlighted.

One of the most important tools available to the regional planner is the remote sensing of the environment. Not only is it very useful in the planning process in general, but it is also valuable in detecting and mapping many types of natural hazards when, as is often the case, detailed descriptions of their effects do not exist. If susceptibility to natural hazards can be identified in the early stages of an integrated development planning study, measures can be introduced to reduce the social and economic impacts of potential disasters.

All natural hazards are amenable in some degree to study by remote sensing because nearly all geologic, hydrologic, and atmospheric phenomena that create hazardous situations are recurring events or processes that leave evidence of their previous occurrence. This evidence can be recorded, analyzed, and integrated into the planning process.

Most remote sensing studies concerned with natural hazards have been about an area's vulnerability to a disaster, the monitoring of events which could precipitate a disaster, and the magnitude, extent and duration of a disaster. This chapter tells planners what types of remote sensing information are suitable for identifying and assessing particular natural hazards and where to look for it.

Since the existing remote sensing information may be inadequate for a planning task or phase, this chapter also provides guidelines on selecting and acquiring the appropriate data. Only those sensor systems that are deemed capable of making a insignificant contribution to the development planning process are discussed, with their specific applications to the assessment of each of several natural hazards. It is assumed that planners and other readers are already familiar with basic remote sensing technology and vocabulary. If further details of techniques and/or applications are required, near state-of-the-art information is available in Sabins (1986), Lillesand and Kiefer (1987), and ASP (1983). An excellent overview of satellite imaging systems and disaster management can be found in Richards (1982).

While both aerial and satellite remote sensing techniques are presented, emphasis is placed on satellite-derived sensing because the data provide the synoptic view required by the broad scale of integrated development planning studies. Aerial remote sensing data are useful to natural hazard management for focusing on priority areas, verifying small-scale data interpretations, and providing information about features that are too small for detection by satellite imagery, but extensive aerial surveys commonly exceed the budget constraints of a planning study and may also provide more information than is necessary, particularly during the early stages of the study.

A. Overview of Important Remote Sensing Attributes

Effective utilization of remote sensing data depends on the ability of the user to be accurate and consistent when interpreting photographs, images, graphs, or statistics derived from remote sensing sources. While most planners have been introduced to photo and image interpretation in their formal training, the best use of the data usually requires analysis by people with experience in landform analysis, such as geologists, physical geographers, foresters, etc. A relatively small investment in the services of an experienced interpreter may avoid needless delays and inappropriate use of remote sensing data. Whether or not the planner does his own interpretation, he should have a working knowledge of remote sensing techniques and the capability to assess the validity of an interpretation, as well as the ability to use the derived information.

The factors that determine the utility of remote sensing data in natural hazard assessments are scale, resolution, and tonal or color contrast. Other factors

DEFINITIONS

Instruments which record electromagnetic radiation emitted or reflected from the earth can be mounted on aircraft or satellites. The former are called aerial or airborne remote sensors and the latter, satellite or spaceborne remote sensors. These instruments record data using optical, electro-optical, optical mechanical, or electronic devices. In this chapter, visual displays analogous to photographs, made with such processes as radar and thermal infrared scanning and produced on a medium other than film, are referred to by the general terms "image" or "imagery".

include area of coverage, frequency, and data cost and availability.

1. SCALE

The scale to which a photograph or image can be enlarged, with or without optical or computer enhancement, determines in what phase of the development planning study this information should be used. Presentations at scales of 1:500,000 or smaller are useful during the Preliminary Mission and certainly in Phase I, Development Diagnosis, when more detail is not necessary Imagery at a scale of 1:250.000 or larger is required during the project formulation and feasibility study activities of Phase II when detail is more important and where certain, but less obvious, aspects of natural hazards must be defined. Frequently it is possible to detect natural hazard phenomena on a small scale photograph or image, but it is impossible to annotate it without enlargement to larger scales. Thus, it is necessary to use imagery at scales commensurate with the levels of detail required for the particular stage of the study, as well as the size of the study area itself. In addition, the larger the areal extent of change associated with a natural event, the more useful satellite imagery becomes.

2. RESOLUTION

Scale is meaningless in the absence of adequate spatial resolution, the capability of distinguishing closely spaced objects on an image or a photograph. Image resolution is determined by the size and number of picture elements or pixels used to form an image. The smaller the pixel size, the greater the resolution. In photography, resolution is limited primarily by the film grain size, but lenses and other technical considerations play important roles.

In both cases, imagery and photography, separability between adjacent features plays a very important part in the identification process. Enlargements of photography or imagery cannot improve resolution but only the working space for the interpretation.

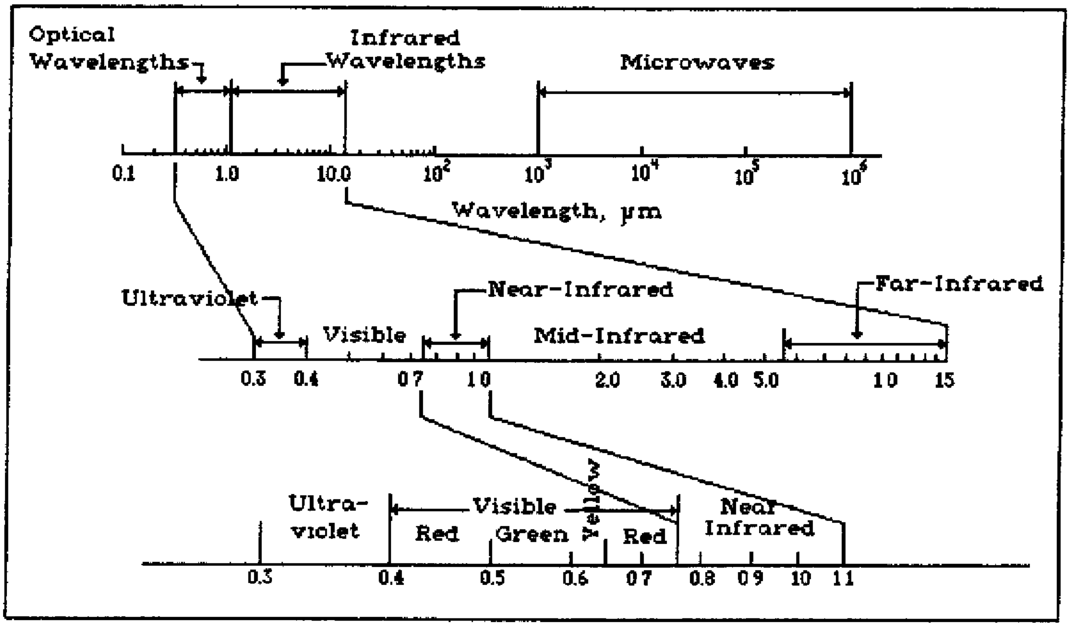
Spectral resolution also needs to be taken into consideration when selecting the type of data since different sensors are designed to cover different spectral regions. Spectral resolution refers to the band range or band width offered by the sensor. Figure 4-1 shows the spectral regions most commonly used in remote sensing. Most natural disasters involve spectral changes. Floods lead to significant spectral changes whereas earthquakes lead to little spectral variation due to less spectral contrast in relation to non-affected areas.

3. IMAGE CONTRAST

The contrast between features on an image or photograph is a function of the sensor's ability to record the tonal or spectral content of the scene. Different spectral bands of sensing systems may exhibit strong or weak contrasts depending on the regions covered on the electro-magnetic spectrum and the surface viewed. For example, a given band may show little contrast between vegetation types in a forest environment but may show strong contrasts between rock types in an arid area. Hazardous areas such as earthquake fault zones or areas susceptible to landslides may be too small for some sensors, e.g., Advanced Very High Resolution Radiometer (AVHRR) imagery, but may be readily visible on imagery produced by other sensor systems, e.g., Landsat Thematic Mapper (TM). The heavily vegetated and cloud-covered terrain of tropical Latin America and the Caribbean is among the most difficult to interpret geologically, but expert interpreters can detect many

Figure 4-1

ELECTROMAGNETIC REGIONS MOST COMMONLY USED IN REMOTE SENSING



natural hazards through physiographic analysis of radar data which can penetrate clouds.

When an image does not provide the detail, resolution, or contrast that is needed, there are several options available. Since the identification of all desired features by interpretation from one sensor is not always possible, a second, completely different type of sensor, or even a combination of sensors, may be needed. Digital data can be enhanced and/or manipulated by using techniques such as contrast stretching, false color composites, principal component analysis, filtering, and supervised and unsupervised classifications.

4. TIME FRAME

The temporal occurrences of natural events will also affect the utility of remotely sensed data. Certain sensors can detect a phenomenon quite readily although their repeat coverage is every 16 days (Landsat). A flood could easily occur and recede within this time frame. On the other hand, desertification of an area can be a long process and the utility of remotely sensed data could be great for monitoring these changes. Events which are seasonal, predictable, or highly correlated with other events are more likely to benefit from imagery than events which occur randomly such as earthquakes or tsunamis (see Chapters 8-12).

5. REMOTE SENSING IMAGES AND MAPS

To derive the most benefit from the use of available remote sensing data, the planners should use all supporting information on the study area (see Appendix A). Maps are particularly helpful in interpreting remote sensing data. Topographic maps are foremost among maps which help clarify many terrain recognition ambiguities found on remote sensing images. Geological maps bring attention to formations conducive to particular types of hazards. This knowledge can assist in localization and the systematic search for these hazards. Soils maps can serve a similar purpose, but to a lesser extent. Finally, vegetation and land-use maps can provide information on the moisture content, underlying geologic formations, and types of soils present.

In summary, remote sensing imagery should be regarded as data available to assist the planner in the assessment of natural resource and natural hazard information throughout the development of a planning study. The meaning and value of remote sensing data is enhanced through skilled interpretation used in conjunction with conventionally mapped information and ground-collected data.

6. OUTPUT FORMATS

Output formats consist of different ways in which remote sensing data can be presented. Photographic data are usually used in a film positive format or as a photographic print. Film data and photographic prints can be scanned and converted into digital data by being recorded on a computer compatible tape (CCT). The main advantage of digital data is the fact that they can be quantified and manipulated using various image processing techniques. Satellite or other images recorded on a CCT can be presented in a film positive format or photographed directly from the display monitor.

B. Aerial Remote Sensing

Aerial remote sensing is the process of recording information, such as photographs and images, from sensors on aircraft. Available airborne systems include aerial cameras, multispectral scanners, thermal infrared (IR) scanners, passive microwave imaging radiometers, and side-looking airborne radars (SLAR) The systems offering the most practical and useful data in the context of integrated development planning and natural hazard assessments are aerial cameras, multispectral scanners, and thermal IR scanners and SLAR. This section describes the characteristics of the photography or imagery obtained from these three systems.

Availability of aerial remote sensing imagery varies for the type of data required Aerial photography is readily available for many areas of study in most parts of the world, although in some instances it must be declassified for non-military use by the government of the country involved in the study. Radar imagery is also frequently classified.

Acquisition of infrared (IR) and radar data is more complex than aerial photography, although for a large area, radar may be less expensive than photography. Due to the specialized systems and operators required to produce IR and SLAR imagery, such data are usually available only from a limited number of organizations which either own or lease the systems. The cost to mobilize aircraft, equipment, and crews is high, but the cost of data coverage per line kilometer or per unit area can be reasonable if the area to be flown is large.

In addition to the type, availability, and cost of data, the planner should consider the conditions under which the acquisition of the appropriate data is taking place. Each sensor type has an optimum time of day, season, and/or table of appropriate conditions under which the best results are obtained. Also, to establish the current status of a hazard such as a volcano's activity, the interpretation of thermal IR imagery must be made close to the time of acquisition, and anomalies should be checked out immediately to determine the magnitude of temperatures that correlate with them. Currently obtained data, flown under similar instrument, weather, and terrain conditions, may be used to compare temporal variations of the hazard In this way thermal pattern changes may be determined.

Thermal IR imagery information is the most transitory of any sensor data. There is a procession of changes in the thermal contrasts between the different materials on the ground, both terrain and vegetation. The transitions occur over daily and seasonal cycles and are modified considerably by the weather, soil, climate, relief, slope direction, and land-use practices. In spite of these masking variations, the thermal contrasts resulting from volcanic and geothermal activity can be interpreted by an experienced thermal IR interpreter.

The primary utility of SLAR imagery is in the interpretation of the relatively unchangeable elements of basic geologic structure and geomorphologic conditions. As a result, it is useful in studying many features related to natural hazards. Special SLAR image data acquisition is not normally feasible in a planning study budget, but previous coverage of the study area may be available. If it does exist, it should be sought and used to its fullest extent.

Both IR and SLAR imagery can be used in a stereoscopic mode but only where adjacent flight lines overlay. Since distortion due to air turbulence and/or differential altitude occurs during the raster-like development of each image as the aircraft moves forward, the stereoscopic model is imperfect. Despite these distortions the stereoscopic dimension is definitely an asset in helping to define natural hazards.

1. AERIAL PHOTOGRAPHY

Of all the sensors, aerial photography gives the closest representation to what the human eye sees in terms of wavelength response, resolution, perspective, stereoscopic viewing, and tonal or color values. The interpreter familiar with photographs can easily interpret these scenes, whereas other sensors, such as thermal IR scanners and SLAR systems, produce imagery whose appearance and physical basis is completely foreign to the inexperienced eye. Aerial photographs are probably the remote sensing data source with which the planner is most familiar (OAS, 1969).

a. Scales and Wavelengths

The most useful scales for aerial photographs range from 1:5,000 to 1:120,000. The need for reconnaissance type of information over large areas limits the use of photographs to the scales of 1:40,000 or less.

Photography is limited to the optical wavelengths which are composed of ultraviolet (UV), visible, and near-IR portions of the electromagnetic spectrum (see Figure 4-1). The first and last of these portions are recoverable on film under special film-filter conditions. The near-IR wavelengths are the reflective part of the larger infrared portion, which also includes emitted or thermal wavelengths.

b. Type of Film

Aerial photography may be obtained using black and white film, the least expensive medium, or with conventional color or color IR film. The type of film that should be used depends on its utility for a particular terrain being studied and the cost of the film. The speed of the film is also an important factor: the slower color films may not be used where the terrain is too dark, such as areas of ubiquitous heavy vegetation or predominantly dark rocks.

The two general types of black and white films used most frequently are the panchromatic and IR-sensitive films. Panchromatic films, which are negative materials having the same approximate range of light sensitivity as the human eye, are regarded as the standard film for aerial photography It is the least expensive medium for aerial mapping and photo interpretation, but it may not be the logical choice for a given study area.

Black and white IR-sensitive film, although not commonly used, is a better choice for the penetration of strong haze and/or lush vegetation in humid tropical areas. It renders surface water, moisture, and vegetation contrasts much better than the standard film, and, as a result, can be an effective tool in regional planning and natural hazard assessments in humid tropical areas. There is, however, a diminution of detail in shadowed areas since scattered cooler light (blue end) is filtered out.

In high relief areas, it is best to shoot close to mid-day using IR films. In areas of low relief, photographs should be taken when the sun is low on the horizon (10° to 30°), causing shadows on the fine-textured surface. Low-sun-angle photography (LSAP) emphasizes textural characteristics of particular rock types, discontinuities, and the linear topographic features associated with faults and fractures. Vegetation types, both natural and cultivated, can also be defined to a large extent on a textural basis, and this may provide further information on the terrain. Almost any state-of-the-art aerial camera can capture LSAP using panchromatic or red-filtered infrared film.

The use of color films for natural hazard assessment takes various forms: negative film from which positive color prints are made, and positive transparencies, including color slides. To a limited extent, the negative films can be printed to emphasize certain colors and offer the ease of handling of prints. They do not have, however, the sharpness and dynamic color range of the positive transparencies, which are significantly better for interpretation purposes.

There are two major spectral types of color film: the natural or conventional color film, which covers the visible spectrum, and color IR film (green through near IR). The former is available as a negative (print) film and positive transparency, and the latter is available only as a positive transparency.

The IR color film response is superior to that of natural color films for a number of reasons. First, the yellow filter required for its proper use eliminates blue light that is preferentially scattered by the atmosphere. Eliminating much of the scattering greatly improves the contrast. Second, the differences in reflectance within vegetation types, soils, and rocks are commonly greater in the photographic IR component of this film. Third, the absorption of infrared and much of the red wavelengths by water enables a clearer definition of bodies of water and areas of moisture content. And fourth, the diminution of scattered light in shadowed areas enhances relief detail, thus improving the interpretation of the geomorphology. In view of these attributes, color IR film is preferred if color aerial photography is desired for humid tropical climates.

2. RADAR

Radar differs from aerial photography as an aerial remote sensor. Unlike photography, which is a passive sensor system using the natural reflection from the sun, radar is an active sensor that produces its own illumination. Radar illuminates the terrain and then receives and arranges these reflective signals into an image that can be evaluated. These images appear similar to black and white photographs. The best use of airborne radar imagery in the development planning process and natural hazard assessments is the identification of geologic and geomorphologic characteristics. Radar imagery, like photography, presents variations in tone, texture, shape, and pattern that signify variations in surface features and structures. Of these elements, tonal variations which occur in conventional aerial photographs are the same as the eye sees. The tonal variations, which occur in radar images and appear as unfamiliar properties, are the result of the interaction of the radar signal with the terrain and vegetation. Just as it is not essential to fully understand the optical theory and processes involved with photography to be able to use aerial photographs, it is also possible to use radar images without a thorough understanding of electromagnetic radiation.

However, an interpreter needs to know something about how the image is formed in order to interpret it correctly and to appreciate fully the potential and limitations of radar. A skilled interpreter need only become familiar with the parameters that control radar return, understand their effect on the return signal, and recognize the effect of the side-looking configuration of the sensor on the geometry of the return signal.

Many useful radar images have been acquired in X-band, K-band, and Ka-band wavelengths (see Figure 4-2). However, X-band airborne radar systems are currently the most commonly offered by commercial contractors. In this band-width there are two basic types of systems: real aperture radar (RAR) and synthetic aperture radar (SAR). Real aperture or "brute force" radar uses an antenna of the maximum practical length to produce a narrow angular beam width in the azimuth (flight line) direction. The longer the antenna, the narrower the azimuth beam. A typical length is 4.5m, which approaches a maximum practical size for aircraft. For this reason the SAR was developed. The SAR is capable of achieving higher resolution without a physically large antenna through complex electronic processing of the radar signal.

The resulting resolution, coupled with the small scales at which images can be acquired, makes radar more suitable than photographic surveys for covering large areas. While RAR has a simple design and does not require sophisticated data recording and processing, its resolution in the range direction is relatively limited in comparison with the SAR of the same waveband. SAR maintains its high resolution in the range direction at long distances as well as its azimuth resolution. Resolution with SAR approaches 10m in azimuth and range.

3. THERMAL INFRARED SCANNERS

An airborne electro-optical scanner using a semiconductor detector sensitive to the thermal IR part of the spectrum is the best way to produce imagery that defines the thermal pattern of the terrain. Alternative methods using a television-like presentation have inadequate spatial resolution and thus cannot be

Figure 4-2

RADAR WAVELENGTH AND FREQUENCIES USED IN REMOTE SENSING FOR AIRCRAFT RADAR SYSTEMS

Band Designation[a/]	Wavelength (cm)	Frequency (v), GHz (10^9 cycles/sec^{-1})
Ka (0.86cm)	0.8 to 1.1	40.0 to 26.5
K	1.1 to 1.7	26.5 to 18.0
Ku	1.7 to 2.4	18.0 to 12.5
X (3.0cm, 3.2cm)	2.4 to 3.8	12.5 to 8.0
C	3.8 to 7.5	8.0 to 4.0
S	7.5 to 15.0	4.0 to 2.0
L (23.5cm, 25.0cm)	15.0 to 30.0	2.0 to 1.0
P	30.0 to 100.0	1.0 to 0.3

[a/] Wavelengths commonly used in imaging radars are shown in parentheses.

Source: Sabins, Floyd F., Jr Remote Sensing: Principles and Interpretation
(New York, W H Freeman, 1986)

used effectively from aircraft altitudes. They also lack adequate thermal resolution.

Spatial resolution in scanners decreases with altitude above the terrain. Most commercial thermal infrared systems have spatial resolutions which provide for 2m to 2.5m resolution per 1,000m altitude at the nadir point (the point in the ground vertically below the camera) of the scan. Increasing the altitude above terrain to 2,000m would produce 4m to 5m spatial resolution.

Commonly, the 3.0µm to 5.5µm band provides the best information for "hot" objects (active volcanic vents, hot springs, etc.), while the 8.0µm to 14.0µm band provides the best information for features that are at ambient or cooler temperatures (flooding streams under canopies, warm springs, etc). Frequently in studies involving IR surveys both bands are used to provide simultaneous imagery.

Properties of the airborne IR scanner system indicate that its practical use is restricted to the lower altitudes (under 3,000m) and, consequently, to relatively smaller areas than either radar or aerial photography. In natural hazard assessments, its best use would be in areas that are known or suspected to be areas of volcanism or where abnormal moisture conditions indicate dangerous situations. The latter may include, for example, trapping of water along active faults, or in back of landslide slumps, or moisture conditions associated with karst terrain.

IR scanning systems have drawbacks, but their unique capability of thermal imaging is unsurpassed. In addition, they can provide critical information for relatively small areas once specific hazard-prone areas have been identified.

4. ADVANTAGES AND LIMITATIONS OF PHOTOGRAPHY, RADAR, AND THERMAL IR SCANNERS

a. Photography and Radar

Both aerial photography and radar have advantages and limitations. Photography cannot be used at any time in any weather as can radar. Radar can map thousands of square miles per hour at geometric accuracies conforming to national mapping standards. An area can be surveyed much more rapidly by radar than by aerial photography, and the final product provides an excellent synoptic view. Distance can be measured more accurately on radar than photography, and maps as large as 1:24,000 scale have been produced experimentally. The RADAM project of Brazil covered the country completely at a scale of 1:250,000. On the other hand, photography at the same scale shows considerably more detail, and it provides an excellent stereoscopic model for interpretation purposes in contrast to a more limited, but still useful, model obtained from radar. Aerial photography has the advantage of offering instantaneous scene exposures, superior resolution, ease of handling, and stereoscopic capability.

b. Thermal IR Scanners

Airborne electro-optical scanners, in general, can cover the electromagnetic spectrum using semiconductor electronic sensors from the UV through the visible and near IR into the thermal IR range of the spectrum. The utility of the UV spectrum in natural hazard and resource investigations has yet to be demonstrated, particularly when the image is degraded due to intense scattering of its rays. Scanners in the visible range are useful, especially when two or more wavebands are algebraically combined or manipulated.

Scanning imagery, because of its technique of recording a raster on film or tape, produces inherent distortions in the final built-up image scene. The lateral distortion from the flight line is reasonably corrected in the scanner system. Along the flight line, however, the rapid changes of altitude above the terrain during the formation of one scene from many scan lines produces many distortions. The persistent movement of the aircraft on three axes with limited stabilization presents the same problem. These distortions result in images that are difficult to interpret and whose location is difficult to identify, especially in mountainous and/or forested terrains. Despite these deficiencies, scanning from aircraft continues to be a very valuable method of obtaining thermal infrared imagery with reasonable spatial and thermal resolution.

In summary, aerial remote sensing provides information from aerial photographic cameras, side-looking radar, and thermal imaging scanners that is unsurpassed in resolution in their respective coverage within the electromagnetic spectrum. These systems produce imagery that ranges from the familiar visible spectrum to the unfamiliar infrared and microwave radar (short radio) spectra. This information can be used in conjunction with conventional maps of all kinds to enhance the data available to the planner.

C. Satellite Remote Sensing

This section describes several satellite remote sensing systems which can be used to integrate natural hazard assessments into development planning studies. These systems are: Landsat, SPOT satellite (Système Probatoire pour l'Observation de la Terre), satellite radar systems, Advanced Very High Resolution Radiometer (AVHRR) on NOAA-10 and 11 satellites, metric camera, large format camera (LFC), and Sojuzkarta. Remote sensing from satellite vehicles has become increasingly important following the successful launch of the Landsat 1 satellite (formerly ERTS-1) in 1972. Since then many satellites with remote sensing capabilities have been developed and used successfully.

The Landsat multispectral scanner (MSS) provided the first practical imagery in four different spectral bands from space. The characteristics of this and other Landsat sensors are summarized in Figure 4-3. The accompanying return beam vidicon (RBV) sensor on this and subsequent satellites of this series were never noticed by scientists and planners like the MSS. The broad areal coverage of the Landsat sensors and the others that have followed, together with the capability to process the sensor data digitally, has made the satellite-derived data useful to regional planners and others interested in natural hazard assessments. The synoptic view of lands targeted for development can be imaged in an instant of time. Satellite imagery can provide a continuity of viewing conditions for large areas that is not possible on aerial photographic mosaics.

In addition to MSS, other satellite-borne sensors warrant discussion since they are potential tools for assessing natural hazards Each sensor has its advantages and limitations in coverage of areas of interest and its resolution capability to define certain types of hazards. Some sensors are experimental, and provide limited areal coverage and lack temporal continuity. However, where coverage is available for a study area, the sensor data should be used in conjunction with existing data derived from Landsat or SPOT The data derived can produce an inexpensive synergistic effect by combining data from more than one part of the spectrum, and are well worth the relatively small expense.

Ideally, it would be desirable to use a "multi-stage" approach to the natural resource and natural hazard assessments. This would involve using aerial photography and ground checks to establish more detailed knowledge of sample or representational sites. This may then be extrapolated over a larger area using Landsat or other satellite-derived data. Figure 4-3 shows the needed imagery characteristics for the assessment of various natural hazards--earthquakes, volcanic eruptions, landslides, tsunamis, desertification, floods, and hurricanes--for purposes of planning and mitigation. The characteristics of applicable satellite sensing technologies are described below.

1. LANDSAT

Since the Landsat series of satellites have been operational for a long period of time, there is a very large data base available, both in areal coverage and in repetitive coverage, through different seasons and during periods of natural disasters. Landsat MSS coverage exists from 1972 to the present in four spectral bands at 80m resolution. The thematic mapper (TM) was introduced on Landsat 4 in 1982, with seven spectral bands, six of them with 30m resolution and one in the thermal IR range with 120m resolution (see Figure 4-3).

Sensor data are digitally transmitted to ground stations in various parts of the world where they are recorded on magnetic tapes and preprocessed to improve their radiometric, atmospheric, and geometric fidelity. Ground receiving stations that cover Latin America and the Caribbean are in California, Maryland, Brazil, and Argentina. Distribution centers for Landsat sensor imagery are listed in the box below.

Although none of the existing satellites and their sensors has been designed solely for the purpose of observing natural hazards, the variety of spectral bands in visible and near IR range of the Landsat MSS, and TM and the SPOT HRV sensors provide adequate spectral coverage and allow computer enhancement of the data for this purpose. Repetitive or multitemporal coverage is justified on the basis of the need to study various dynamic phenomena whose changes can be identified over time. These include natural hazard events, changing land use-patterns, and hydrologic and geologic aspects of a study area.

The use of Landsat MSS and TM imagery in natural resource evaluations and natural hazard assessments is facilitated by the temporal aspect of available imagery. Temporal composites from two or more different image dates allow the recognition of hazard-related features that have changed, such as alteration of floodplains or stream channels and large debris slides, and to some extent, early recognition of disasters that evolve over time, such as drought or desertification. Chapter 8 has a detailed discussion of the use of Landsat sensors in flood hazard assessments. Specific manipulation and combination of the MSS or TM tape data of various bands of the same scene can increase the utility of the data.

Three-dimensional analysis, or stereoscopy, is essentially missing on the MSS and TM data. With MSS on Landsat 1, 2, and 3, there is an 18-day cycle, and sidelap is 14 percent at the equator, increasing poleward to 34 percent at latitude 40 and to 70 percent at polar latitudes. (Sidelap is the amount of overlapping of adjacent image coverage.) On Landsat 4 and 5, a lower altitude and a 16-day cycle with wider spacing results in only 7.6 percent sidelap at the equator and negligible increase toward the poles for both MSS and TM data. Unfortunately, the areas at

Figure 4-3

CHARACTERISTICS OF LANDSAT SENSORS

SENSOR[a]	LANDSAT PLATFORM	SPECTRAL BANDS AND RANGE (micrometers)		ALTITUDE (km)	RESOLUTION (m)	IMAGE SIZE (km)	COVERAGE REPEAT
RBV	1,2,3	PAN	0 505-0.750	920	79x59 [d]	185x185 [d]	every 18 days
		1 [b]	0.475-0.575		30x30 [e]	99x99 [e]	
		2 [c]	0.580-0.680				
		3 [c]	0.690-0 830				
MSS	1,2,3,4,5	4 (green)	0.5- 0.6 [f]	920 [g]	79x57 [g]	185x185 [f]	every 18 days [g]
		5 (red)	0.6- 0.7	705 [h]	60x60 [h]	185x170 [g]	every 16 days [h]
		6 (near IR)	0.7- 0.8		237x237 [i]		
		7 (near IR)	0 8- 1.1				
		8 (thermal)	10.4-12 6 [b]				
TM	4,5	1	0 45-0.52	705	28 5x28.5 [k]	85x170	every 16 days
		2	0.52-0 60		120x120 [l]		
		3	0.63-0.69				
		4	0.76-0.90				
		5	1.55-1.75				
		6	10.40-12.50 [j]				
		7	2.08-2.35				

[a] RVB, Return Beam Vidicon; MSS, Multispectral Scanner; TM, Thematic Mapper; IR, Infrared.
[b] Panchromatic and Landsat 3 only
[c] Bands 1,2,3 on Landsat 1 and 2 only
[d] Landsat 1 and 2
[e] Landsat 3
[f] Also called bands 1 to 4 on Landsat 4 and 5
[g] Landsat 1 to 3
[h] Landsat 4 and 5
[i] Band 8 on Landsat 3
[j] Thermal
[k] Bands 1 to 5 and 7
[l] Band 6 only

Source' Adapted from Budge, T. A Directory of Major Sensors and Their Parameters (Albuquerque, New Mexico: Technology Application Center, University of New Mexico, 1988).

the lower latitudes where our interests lie have the minimal stereoscopic coverage.

If the terrain is flat with little relief, the little stereoscopic sidelap present would not be effective. In areas of rugged terrain, any small stereoscopic coverage would be welcome, especially if it fell within a critical part of a project area.

The return beam vidicon (RBV) is a framing camera system that operates as an instant television camera. It has not enjoyed the same popularity as the MSS, even though it provides useful information. Landsat 1 and 2 carried three RBVs that recorded green, red, and solar IR images of the same scene as the MSS did. They were capable of producing color IR images of 80m resolution, the same as the MSS, but were decidedly inferior due to technical problems. Landsat 3 carried an RBV system that acquired single black and white images in quadrants of the MSS scene in the 0.50μm to 0.75μm waveband, a spectral response from the green through red. The ground resolution was 40m, much better than the existing MSS and the earlier RBV resolution, enabling the recognition of natural hazard evidence of smaller scale.

The broad response of the RBV, however, did not enhance any particular feature or differentiate vegetation or rocks as well as the MSS bands. Its advantage lay primarily in providing higher spatial resolution for larger scale mapping of spectrally detectable features. In this regard it complemented the lower resolution MSS data which covered the same area. The RBV system was dispensed with entirely on

SOURCES FOR LANDSAT IMAGERY

Argentina
Established: November 1980
Reception: MSS
Distribution Center:
Comisión Nacional de Investigaciones Espaciales
Centro de Procesamiento
Avenida Dorrego 4010
1425 Buenos Aires, Argentina
Telephone: 722-5108; Telex: 17511 LANBA AR

Brazil
Established: May 1974
Reception and Processing: MSS and TM
Distribution Center:
INPE-DGI
Caixa Postal 01, Cachoeira Paulista, SP
CEP 12630, Sao Paulo, Brazil
Telephone: (125) 611507; PBX: (125) 611377
Telex: 1233562 INPE BR

United States
Established: July 1972
Reception and Processing: MSS and TM
Distribution Center:
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4300 Forbes Blvd., Lanham, Maryland 20706
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Landsat 4 and 5, leaving only the MSS and TM sensors. The former was included to continue the temporal library with that type of sensor data and their 80m spatial resolution. The TM, with a 30m resolution, negated any requirement for the ineffective and little-used RBV system. Despite its absence on Landsat 4 and 5, RBV data of certain heavily vegetated tropical areas may be the only available source of data with adequate resolution for temporal comparison with later TM data.

The thermal IR portion of the TM was originally placed in the 10.4μm to 12.5μm spectral window where the earth's radiant energy is so low that a large detector is required. This resulted in a 120m ground resolution cell which generalized thermal detail, limiting its value for detecting the subtle and finely detailed geothermal changes associated with volcanic activity. The thermal resolution is 0.5° K (degrees Kelvin), which by airborne IR scanner standards (0.1° K or smaller), is poor. The best possible application in natural hazard assessments may be in active floodplain delineation and perhaps as a crude index to regional volcanic activity. The thermal infrared band (band 8) in Landsat 3 (10.4μm - 12.5μm with 240m spatial resolution) never worked properly and is, therefore, of no consequence for the applications discussed here. The blue-green band (0.45μm - 0.52μm) in the TM system (band 1) is unique among sensors aboard natural/resource-oriented satellites. The reason that this band has not been a part of the spectrum sought from satellites is the severe scattering of the blue light, which can badly degrade the image contrast where there is high humidity and/or high aerosol content in the atmosphere. However, in water, blue light has the best penetration capability in the visible spectrum.

In clear, sediment-free waters it can define sea bottoms to depths of 30 or more meters, depending primarily on the angle of incidence of the sun's illumination and the reflectance of the bottom. This property is useful for determining offshore slope conditions relevant to potential tsunami run-up.

SATELLITE REMOTE SENSING: APPROXIMATE COSTS OF BASIC DATA ACQUISITION (CCTs, June 1989)

System	Cost per km^2
Landsat MSS	US$.02
Landsat TM	US$.11
SPOT	US$.47 - .61

Figure 4-4

CHARACTERISTICS OF SPOT SENSORS

SPOT SENSOR: MULTISPECTRAL HIGH-RESOLUTION VISIBLE (HRV)

Band	Wavelength (μm)	Resolution (m)	Image Format
XS1	0.50-0.59	20	60km swath with vertical viewing angle and up to 80km with +/- 27° viewing angle from vertical
XS2	0.61-0.68	20	
XS3	0.79-0.89	20	

SPOT SENSOR: PANCHROMATIC HIGH-RESOLUTION VISIBLE (HRV-P)

Band	Wavelength (μm)	Resolution (m)	Image Format
P	0.51-0.73	10	60km swath with vertical viewing angle and up to 80km with +/- 27° viewing angle from vertical