2. SPOT

The SPOT satellite with its High Resolution Visible (HRV) sensors is similar in many respects to the Landsat satellite with its MSS and TM sensors. The HRV multispectral sensor (XS) ranges from the green wavelength into the near IR. The HRV-XS coverage is in three spectral bands rather than the four found in the MSS, but with much higher spatial resolution (20m versus 80m), although it covers only about 1/9 of the area covered by a Landsat scene. Additionally, SPOT carries a panchromatic sensor (HRV-P) which covers the green through red portions of the visible spectrum in a single band with 10m resolution. Both HRV sensors cover a 60km swath along the orbit path. It is possible to obtain simultaneous side-by-side coverage from each sensor, producing a 117km swath width, although this capability has not been frequently used. Figure 4-4 above summarizes the characteristics of SPOT sensors and their image formats.

The SPOT sensors have the unique capability of being pointable, 27 degrees to the left or right of the orbital track. This feature allows for repeated off-nadir viewing of the same ground swath, producing image stereopairs. The base-height ratios range from 0.75 at the equator to 0.50 at the mid-latitudes. This provides a strong vertical exaggeration. This third dimension,

SOURCES OF SPOT IMAGERY

ARGENTINA:
Comisión Nacional de Investigaciones
Espaciales (CNIE)
Av. del Libertador 1513
Vicente López 1638
Buenos Aires, Argentina

BOLIVIA:
CIASER
Casilla de Correo 2729
La Paz, Bolivia

BRAZIL:
SENSORA
Rua Bertolomeu Portela, 25 S/Lojas
Botafogo, Rio de Janeiro CEP 2290, Brazil

CHILE:
S.A.F.
Casilla 67 Correo Los Cerillos
Santiago de Chile

MEXICO:
INEGI
San Antonio Abad 124
Mexico City, 8 D.F.,

PERU:
ONERN
355 calle 17, Urb. El Palomar, San Isidro
Lima, Peru

UNITED STATES:
SPOT Image Corporation
1897 Preston White Drive
Reston, Virginia 22091-4326, U.S.A.
Telephone: (703) 620-2200

VENEZUELA:
CPDI
Edo. Miranda Apartado 40200
Caracas, Venezuela 1040 A

if it is available for a particular study area, together with the higher image resolution, can make SPOT's sensors superior to those of Landsat if greater spectral resolution is not required. The sources for SPOT data are listed in the box above.

3. SATELLITE RADAR SYSTEMS

There is considerable radar coverage throughout the world, and more space-derived radar data can be expected in the future.

The family of space radars stems from the Seasat (U.S A.) radar, which was a synthetic aperture system that was especially designed for studying the ocean surface. In this capacity it had a large (70° average) depression angle to study the relatively flat ocean surface For this reason Seasat's usefulness for imaging land extended to those land areas of low relief During its short life in 1978, it managed to acquire a large amount of data from Western Europe, North and Central America, and the Caribbean.

Seasat was followed by Space Shuttle imaging radars SIR-A and SIR-B. Data from these radars was obtained from Space Shuttle flights in 1981 and 1984. Their characteristics along with those of Seasat are shown in Figure 4-5. SIR-A and SIR-B provided greater worldwide coverage, including large parts of Latin America, because the image data were recorded on board the Space Shuttle rather than telemetered to a limited number of receiving stations within range of the spacecraft, as was the case with the unmanned Seasat radar satellite

Figure 4-5

CHARACTERISTICS OF SEASAT, SIR-A, AND SIR-B SYSTEMS

Characteristics	Seasat(1978)	SIR-A(1981)	SIR-B(1984)
Repeat Coverage	irregular, northern hemisphere	little to none	little to none
Resolution	25x25m	40x40m	25x(17-58)m
Wavelength (23.5cm)	L-band	L-band	L-band
Latitude coverage	72°N-72°S	50°N-35°S	58°N-58°S
Altitude	790km	250km	225km
Image-swath width	100km	50km	40km

Source: Adapted from Budge, T. A Directory of Major Sensors and Their Parameters (Albuquerque, New Mexico. Technology Application Center, 1988).

SOURCES OF SATELLITE RADAR IMAGERY

SIR-A and SIR-B:
National Space Science Center
World Data Center A for Rockets and Satellites
Code 601
NASA/Goddard Space Flight Center
Greenbelt. Maryland 20771, U.S.A.
Telephone: (301) 286-6695

Seasat:
NOAA, National Environmental Satellite Data and Information Service
World Weather Building, Room 100
Washington, D.C. 20233, U.S.A.
Telephone· (301) 763-8111

The long wavelengths of these radar systems permit potential subsurface penetration between 2m and 3m in extremely dry sand (Schaber et al., 1986). There may be areas of hyperaridity in South America that may permit this type of penetration. This property may have some application to natural hazard assessment that is not readily apparent, as well as to integrated development planning studies. The problem seems to be that while significant amount of radar coverage is available, much has yet to be acquired where needed.

The SIR series of radar data acquisition is expected to continue with SIR-C in the future. Other radar sensors will be placed into orbit soon: Canada's Radarsat, a C-band (6.0cm) radar designed to provide worldwide stereoscopic coverage, is planned for the 1990s; the European Space Agency expects to launch a C-band synthetic aperture radar aboard the Earth Resources Satellite (ERS) in 1990; and Japan will launch an L-band imaging radar satellite in 1991. Thus, it can be expected that more radar imagery is forthcoming which will provide additional tools for natural hazard assessment.

4. AVHRR

The Advanced Very High Resolution Radiometer (AVHRR) on board the NOAA-7 through 11 satellites would not normally be considered useful for natural hazard assessments on the basis of its low resolution (1.1km at nadir) alone. However, its large swath width of 2253km provides daily (day and night) coverage of the inhabited parts of the earth (see Figure 4-6). The near-nadir viewing repeat cycle is nine days, but the same area is still viewable from different angles within the swath from space. This results in complicated radiometric and geometric comparisons between different dates of data acquisition.

This scanning radiometer has 5 bands, which include band 1 (green to red), band 2 (red to reflected IR), band 3 (middle IR), band 4 (thermal IR), and band 5. The most useful bands are the thermal IR bands 4 and 5 particularly where moisture or ice is involved These have been successfully used to delineate flooded areas using temporal analysis techniques within 48 hours following a major flood event (Wiesnet and Deutsch, 1986). The thermal resolution in these bands is better than the Landsat TM thermal band 6 but with a significant trade-off loss in spatial resolution (1.1km versus 120m, respectively).

5. METRIC CAMERA

The metric camera was an experiment on the STS-9/Spacelab 1 Mission in 1983 to determine whether topographic and thematic maps at medium scales (1:50,000 to 1:250,000) could be compiled from mapping camera images taken from orbital altitudes. Due to a late November launch date, illumination conditions were poor over many of the candidate target areas. As a result, slower shutter speeds had to be used than were planned, causing some image

Figure 4-6

AVHRR CHARACTERISTICS

Platform: NOAA satellites (formerly Tiros)

Spectral bands	Tiros-N	NOAA-6,8,10	NOAA-7,9,d,H,I,J
1	0.55 - 0.90	0.58-0.68	0.58 -0.68
2	0.725- 1.00	0.725-1.00	0.725-1.00
3	3.55 - 3.93	3.55-3.93	3.55 -3.93
4	10.50 -11.50	10.50-11.50	10.30-11.30
5	none	none	11.50-12.50

Altitude: 833-870km
Resolution: Large Area Coverage (LAC) 1km
Global Area Coverage (GAC): 4km
Image size: 2253 km swath
Repeat coverage: Daily, worldwide

SOURCE OF AVHRR IMAGERY

Satellite Data Services Division
NOAA/NESDIS/NCDC
World Weather Building, Room 100
Washington, D.C. 20233, U.S.A.
Telephone: (301) 763-8111

SOURCE OF METRIC CAMERA PHOTOGRAPHY

Deutsche Forschungs- und Versuchsanstalt für
Luft- und Raumfahrt e.V. (DFVLR)
Oberpfaffenhofen
D-8031 Wessling
Federal Republic of Germany

smear. Nevertheless, high quality images with a photographic ground resolution of about 20m were obtained on a 23cm x 23cm format panchromatic and color IR film. Analysis has shown that these images may be used for mapping at a scale of 1:100,000. On this mission, despite the fact that many problems were encountered, an area of more than 11 million km^2 was covered. Plans are now underway to modify the camera to compensate for forward image motion and to refly it. It is expected that a ground resolution of about 10m would be obtained, permitting maps with a scale as large as 1:50,000 (Schroeder, 1986)

Ground coverage of 190km x 190km per photograph frame was obtained using a 305mm lens from an altitude of 250km, yielding an image scale of 1:820,000. Overlap of 60 to 80 percent, obtained for topographic mapping purposes, is of great value in interpretation for natural hazards. The high resolution and stereocoverage make this photographic sensor system a potentially useful tool when sufficiently enlarged.

Five lines of metric camera photography cover parts of Latin America, and with resumption of the U.S. Space Shuttle program, additional high quality space photographs of areas of interest may become available.

6. LARGE FORMAT CAMERA

The large format camera (LFC) photography was obtained during a Space Shuttle flight in October 1984. The term "large format" refers to the 23cm by 46cm film size, which was oriented with the longer dimension in the line of flight. LFC acquired 1,520 black and white, 320 normal color, and 320 IR color photographs, covering many areas within Latin America and the Caribbean. The scale of the photographs ranges from 1:213,000 to 1:783,000 depending on the altitude of the Space Shuttle, which varied between 239km and 370km. The swath covered a range between 179km and 277km, and each frame covered between 360km and 558km in the flight direction. Forward overlap up to 80 percent was obtained, allowing vertical exaggerations of 2.0, 4 0, 6.0, and 7.8 times in the stereomodels. Most photographs were taken with 60 percent overlap, which provided 4 times vertical exaggeration and an excellent stereomodel. The spatial resolution was about 3m for the black and white film and about 10m for the color IR film.

The availability of this excellent stereophotography, which can be enlarged ten times or more with little loss of image quality, is limited to certain areas covered by the ground track of the Space Shuttle. Some of this coverage includes clouds or heavy haze, but despite the limitations of coverage and occasional poor quality, the existing photography should be examined for its possible use in any regional natural hazards assessment and planning study.

Given the range of tools available for aerial and satellite remote sensing, their applications vary based on the advantages and limitations of each. The planner can regard each of these as a potential source of information to enhance natural resource evaluation and natural hazard assessment. The next section covers some of the applications of photographs and images in natural hazard assessments.

7. SOJUZKARTA

Sojuzkarta satellite data consist of photographs taken with the KFA-1000 and KM-4 camera Computer compatible tapes (CCTs) for digital image processing are not available, although it is possible to convert the data into digital format by using a scanner Photographs obtained through the KFK-1000 camera have 5m resolution in the panchromatic mode and 10m resolution in the color mode; scales range from 1:220,000 to 1:280,000. KM-4 photography has a 6m resolution and is available at scales of 1:650,000 and 1:1,500,000. Applications of this sensor to natural hazard studies are likely to be in desertification monitoring, flood hazard and floodplain, and landslides studies.

SOURCES OF LFC PHOTOGRAPHY

Chicago Aerial Survey, Inc.
LFC Department
2140 Wolf Road
Des Plaines, Illinois 60018, U.S.A.

Martel Laboratories
7100 30th Avenue North
St. Petersburg, Florida 33710, U.S.A.

U.S. Geological Survey
EROS Data Center
Sioux Falls, South Dakota 57198, U.S.A.

D. Applications of Remote Sensing Technology to Natural Hazard Assessments

For purposes of assessing natural hazards in the context of integrated development planning studies, it is not necessary to have real-time or near real-time remote sensing imagery. What is required is the ability to define areas of potential exposure to natural hazards by identifying their occurrence or conditions under which they are likely to occur and to identify mechanisms to prevent or mitigate the effects of those hazards. This section considers the practical detectability by remote sensing technology of the potential for floods, hurricanes, earthquakes, volcanic eruptions and related hazards, and landslides. It will become evident that some of these hazards are interrelated, e.g., floods and hurricanes, earthquakes, volcanoes and landslides.

The ability to identify these natural hazards or their potential for occurring depends on the resolution of the image, the acquisition scale of the sensor data, the working scale, scenes free of clouds and heavy haze, and adequate textural and tonal or color contrast. The availability of stereomodels of the scene being studied can greatly enhance the interpretation Figure 4-7 displays satellite remote sensing attributes to be taken into consideration for the assessment of various hazards.

After a hazard is identified, formulating appropriate mitigation measures and developing response plans may require different remote sensing data sets This additional remote sensing data needed are most likely to include greater detail of the infrastructure, e.g., roads and facilities This may have to be derived from aerial photography.

1. FLOODS

Floods are the most common of natural hazards that can affect people, infrastructure, and the natural environment. They can occur in many ways and in many environments Riverine floods, the most prevalent, are due to heavy, prolonged rainfall, rapid snowmelt in upstream watersheds, or the regular spring thaw. Other floods are caused by extremely heavy rainfall occurring over a short period in relatively flat terrain, the backup of estuaries due to high tides coinciding with storm surges, dam failures, dam overtopping due to landslides into a reservoir, and seiche and wind tide effects in large lakes. Occasionally an eruption on a glacier or snow-covered volcanic peak can cause a flood or a mudflow in which the terrain is radically changed and any agrarian development is totally destroyed, frequently with much loss of life. See Chapter 8 for a more detailed discussion of flood hazards and Chapter 11 for a discussion of floods and mudflows associated with volcanic eruptions.

It is impossible to define the entire flood potential in a given area. However, given the best remote sensing data for the situation and a competent interpreter, the evidence for potential flood situations can be found or inferred. The most obvious evidence of a major flood potential, outside of historical evidence, is identification of floodplain or flood-prone areas which are generally recognizable on remote sensing imagery. The most valuable application of remote sensing to flood hazard assessments, then, is in the mapping of areas susceptible to flooding.

Synoptic satellite sensor coverage of a planning study area is the practical alternative to aerial photography because of cost and time factors. The application of Landsat MSS imagery to floodplain or

Figure 4-7

SATELLITE IMAGERY APPLIED TO NATURAL HAZARD ASSESSMENTS

	EARTHQUAKES	VOLCANIC ERUPTION	LANDSLIDES	TSUNAMI	DESERTIFICATION	FLOODS	HURRICANES
INFORMATION TO BE OBTAINED	Land-use maps, geological maps	Maps of areas vulnerable to lava flows, ash fall, debris fall and fires	Slope maps, slopes stability, elevation, geology, soil type, areas of standing water, land-use maps	Bathymetric/ topographic maps	Land-use maps, soil moisture content, crop condition and natural vegetation	Floodplain delineation maps, land-use classification, historical data, soil cover and soil moisture	Land-use maps
SPECTRAL BAND	Visible and near IR	Visible, near IR and thermal IR	Visible	Visible, including blue and near IR	Visible, near IR, and microwave	Near IR, thermal IR and microwave	Visible and near IR
SPATIAL RESOLUTION	20-80m	30-80m	10-30m	30m	80m-1km	20m (for cultural features); 30-80m (for land use); 1km (for snow cover and soil moisture)	20m (for cultural features); 30-80m (for land use)
AREAL COVERAGE	Large area	Large area	Large area	Large coastal area	Large regional area	Large regional area	Large area
ALL WEATHER CAPABILITY	No	No	No	No	No	No	No
SYNOPTIC VIEW	Yes	Yes	Yes	Yes	Yes	Yes	Yes
STEREO CAPABILITY	Yes	Yes	Yes	Yes	No	Yes	No
FREQUENCY OF OBSERVATIONS FOR PLANNING STUDY USE	1 to 5 years	1 to 5 years	1 to 5 years	1 to 5 years	Monthly	Seasonal (except weekly for snow cover and soil moisture)	Yearly

Source: Adapted from Richards, P.B. The Utility of Landsat-D and other Satellite Imaging Systems in Disaster Management (Washington, DC: Naval Research Laboratory, 1986).

flood-prone area delineation has already been demonstrated by comparing pre-flood scenes with scenes obtained at the height of the flood, using Landsat MSS band 7 (near IR) images in a color additive viewer (Deutsch et al., 1973). This temporal comparison can now be done pixel by pixel in a computer. Landsat TM, with its greater spatial resolution than MSS data (30m versus 80m) and its additional spectral coverage (7 bands versus 4 bands), can be used for more detailed mapping of floodplains and flood-prone areas on larger scale maps of 1:50,000 or greater. TM data have been used for discriminating land cover classification (Kerber et al., 1985) and to provide useful input to flood forecasting and flood damage models for urban and agricultural areas (Gervin et al., 1985).

This approach to floodplain delineation does have its limitations. The area of potential flooding delineated in this manner may represent a flood level that exceeds an acceptable degree of loss. Also, no floods may have occurred during the period of the sensor operation. In this case, indirect indicators of flood susceptibility are used. A more detailed discussion of flood susceptibility and the use of Landsat imagery can be found in Chapter 8. Landsat and presumably similar satellite data floodplain indicators are listed in Figure 4-8.

There are large parts of tropical humid ecosystems where adequate Landsat or other similar imagery is not available due to cloud coverage or heavy haze. In some instances the heavy tropical vegetation masks many geomorphic features so obvious in drier climates. In this case the use of available radar imagery from space or previously acquired from an aircraft survey is desirable. The radar imagery, which has a resolution comparable to Landsat TM and SPOT from both space and sub-orbital altitudes, can satisfactorily penetrate the clouded sky and define many floodplain features. Moisture on the ground noticeably affects the radar return and, together with the textural variations emphasized by the sensor, makes radar a potentially desirable tool for flood and floodplain mapping.

2. HURRICANES

To mitigate the impact of hurricanes, the planner needs to know the frequency of storms of given intensity in the study area, to what extent these storms could affect people and structures, and what sub-areas would be most affected such as low-lying coastal, estuarine, and riverine areas threatened by flooding and storm surge. See Chapter 12 for a more detailed discussion of hurricanes and coastal areas.

The determination of past hurricane paths for the region can be derived from remote sensing data from the U.S. National Oceanographic and Atmospheric Administration (NOAA) satellite sensors designed and operated for meteorological purposes. These data are already plotted by meteorological organizations in the U.S.A. and other countries where hurricanes are a threat. For plotting new data, the best sensor is the

Figure 4-8

LANDSAT FLOODPLAIN INDICATORS

- Upland physiography
- Watershed characteristics such as shape, drainage, and density
- Degree of abandonment of natural levees
- Occurrence of stabilized sand dunes on river terraces
- Channel configuration and fluvial geomorphic characteristics
- Backswamp areas
- Soil-moisture availability (also a short term indicator of flood susceptibility)
- Variations in soil characteristics
- Variations in vegetation characteristics
- Land use boundaries
- Flood alleviation measures for agricultural development on the floodplain

Source: Adapted from Rango, A. and Anderson, A.T. "Flood Hazard Studies in the Mississippi River Basin Using Remote Sensing" in Water Resources Bulletin, vol. 10, 1974.

AVHRR which, with its 2,700km swath, makes coverage twice a day, and has appropriate resolution. The red band is useful for defining daytime clouds and vegetation, while the thermal IR band (10.50μm to 11.50μm) is useful for both daytime and nighttime cloud observations

The AVHRR is not useful in other aspects of hurricane contingency planning due to its limited spatial resolution. These planning needs require higher resolution available from other satellite sensors. If imagery of areas inundated by floods, hurricane storms, or other storms is obtained with any sensor immediately after the event, it should be used, of course, regardless of its resolution. Any such information that is obtained in a timely fashion should be used to delineate the problem areas since their definition is more exact than can be interpreted from higher resolution data obtained during a non-flood period.

Predicting areas of potential inundation along coasts and inland can be achieved using topographic maps with scales as large as 1:12,500. When such maps are not available, remote sensing techniques can be used. In areas with a distinct wet and dry season, it is desirable to obtain information for the wet season from Landsat or comparable imagery in the near IR bands, or use a color IR composite made from Landsat MSS or TM imagery or from SPOT HRV imagery. These image products can be used to identify the moisture-saturated areas susceptible to flooding as well as the higher and drier ground for potential evacuation areas. Likewise, consideration of development plans in view of this potential natural hazard can proceed in a way similar to that for areas prone to flood hazards. For flood hazard assessments, radar imagery from space or aircraft could be used (if available) in lieu of the Landsat MSS imagery. Since there is a general lack of relief in low-lying coastal areas and estuarine areas, stereoscopy would not normally play an important role in this situation. However, stereoscopic viewing even without significant relief enhancement can still reinforce the details of the scene, although at considerably greater cost.

The development planner also needs to consider the additional feature of a hurricane--its high winds. In identifying measures to mitigate wind effects, the planner may consider the type of crops grown, if an agricultural development is being planned, and the design and construction materials used in buildings.

3. EARTHQUAKES

The planning of development in earthquake-prone areas is laden with problems. There are large human settlements already located in earthquake/prone areas. As with other geologic hazards, the frequency of occurrence can fall in cycles of decades or centuries. Earthquakes are particularly difficult to predict at this time. Thus, mitigation emphasis is on land use planning (non-intensive uses in most hazardous areas), on building strength and integrity, on response planning, and on incorporating mitigation measures into reconstruction efforts. The main problem is the identification of the earthquake damage-prone zones (see Chapter 11 for detailed discussion of earthquakes and their assessment). While in most areas of great earthquake activity some seismic information is available, it may not be sufficient for planning purposes. Remote sensing techniques and resulting data interpretation can play a role in providing additional information.

Tectonic activity is the main cause of destructive earthquakes, followed by earthquakes associated with volcanic activity. Where the history of earthquakes due to seismic activity is present in an area, the faults associated with the activity can frequently be identified on satellite imagery. Where volcanic-related earthquakes occur, the source is generally not as obvious: it may be due to movement on a fault near the surface or deep within the earth, to caldera collapse, or to magma movement within the volcanic conduit

In order to identify earthquake hazards it is necessary to have the expertise to recognize them and then determine the correct remote sensing tools to best delimit them. Landsat imagery has been effectively and widely used for this purpose since it is less expensive and more readily available than other remote sensing data. Airborne radar mosaics have been successfully used for the delineation of fault zones. Generally, two mosaics can be made of an area: one with the far range portion of the SLAR and the other with the near range portion. The former is best used in areas of low relief where the relief needs to be enhanced, and the latter in areas of high relief where the shadow effect is not needed or may be detrimental to the image.

Radar is applicable to delineate unconsolidated deposits sitting on fault zones--upon which most of the destruction occurs--to identify areas where an earthquake can trigger landslides. This is best accomplished on stereomodels using adjoining and overlapping radar flight lines. Conventional aerial photography, in black and white or color, would also work well for this purpose.

An alternative, which is adequate but not as good as using radar and aerial photography, is to use multispectral imagery obtained from the Landsat TM and/or MSS or SPOT HRV sensors. Color IR composites or straight near-IR imagery from these sensors at scales up to about 1:100,000 can be used to define active surface fault zones, but not as efficiently as with the radar images. The distinction between bedrock versus unconsolidated materials and the areas of potential landslide hazards can be defined but, again, only if stereocoverage is available. SPOT sensors can provide this capability.

While radar imagery is an ideal data source, available coverage is extremely limited, and contracting airborne radar is usually prohibitively expensive Landsat TM and MSS are the most practical data source, simply because of its availability, and both provide sufficient resolution for regional planning studies.

4. VOLCANIC ERUPTIONS AND RELATED HAZARDS

Many hazards are associated with the conditions brought about by volcanic activity. Active volcanoes pose hazards which include the immediate release of expelled ash, lava, pyroclastic flows, and/or poisonous hot gases; volcanic earthquakes; and the danger of mudflows and floods resulting from the rapid melting of snow and ice surrounding the vent during eruption. Some secondary hazards may threaten during volcanic activity or during periods of dormancy These include landslides due to unstable accumulations of tephra, which may be triggered by heavy rains or by earthquakes. A more detailed discussion of volcanic hazards and their assessment can be found in Chapter 11.

Each volcano has its own particular behavior within a framework of given magmatic and tectonic settings. Prediction of a volcano's behavior is extremely difficult, and the best evidence for the frequency of activity and its severity is the recorded history of eruptions. Imminent eruptions are now best recognized by on-site seismic monitoring. Some classifications distinguish between active, inactive, dormant, and extinct volcanoes. But since some of the most catastrophic eruptions have come from "extinct" volcanoes, many volcanologists have abandoned such a classification, settling for a simple distinction between short-term and long-term periodicity.

Gawarecki et al. (1965) first detected volcanic heat from satellite remote sensing using thermal IR imagery from the high resolution IR radiometer (HRIR) Remote sensing data interpretation can lead to the recognition of past catastrophic events associated with recently active volcanoes (recently in the geologic sense), as in the Andes and the Lesser Antilles. This information together with the available historical data can be used as the basis of assessing the risks of an area with potential volcano-related hazards.

The varied nature and sizes of volcanic hazards require the use of various types of sensors from both satellites and aircraft. The relatively small area involved with volcanoes should encourage the use of aerial photography in their analysis. Panchromatic black and white stereo aerial coverage at scales between 1:25,000 to 1:60,000 is usually adequate to recognize and map geomorphic evidence of recent activity and associated hazards. Color and color IR photography may be useful in determining the possible effects of volcanic activity on nearby vegetation, but the slower film speed, lower resolution, and high cost diminish much of any advantage they provide.

The airborne thermal IR scanner is probably the most valuable tool in surveying the geothermal state of a volcano. The heat within a volcano and underlying it and its movement are amenable to detection. Because of the rapid decrease in resolution with increasing altitude (about 2m per 1,000m) the surveys need to be made at low altitudes under 2,000m.

An IR pattern of geothermal heat in the vicinity of a volcano is an indication of thermal activity which many inactive volcanoes display Many volcanoes thought to be extinct may have to be reclassified if aerial IR surveys discover any abnormally high IR emissions from either the summit craters or the flanks. Changes in thermal patterns can be obtained for a volcano only through periodic aerial IR surveys taken under similar conditions of data acquisition. The temperature and gas emission changes, however, can be monitored on the ground at ideal locations identified on the thermal imagery, making periodic overflights unnecessary. Continuous electronic monitoring of these stations is possible by transmission through a geostationary data relay satellite, another phase of remote sensing.

The thermal IR bands of the satellite sensors now available have inadequate spatial and thermal resolution to be of any significant value to detect the dynamic change in volcanic geothermal activity. In addition to sensing geothermal heat, however, other remote sensing techniques are useful in preparing volcanic hazard zonation maps and in mitigating volcanic hazards. Mitigation techniques requiring photo interpretation and topographic maps include predicting the path of potential mudflows or lava flows and restricting development in those areas.

5. LANDSLIDES

Landslides, or mass movements of rock and unconsolidated materials such as soil, mud, and volcanic debris, are much more common than is generally perceived by the public. Many are aware of the catastrophic landslides, but few are aware that small slides are of continuous concern to those involved in the design and construction business. These professionals can often exacerbate the problem of landsliding through poor planning, design, or construction practices. Frequently, the engineer and builder are also forced into difficult construction or development situations as a result of ignoring the potential landslide hazard This can be avoided if there is early recognition of the hazard and there is effective consultation between planners and the construction team prior to detailed development planning. See Chapter 10 for a more detailed discussion of landslide hazards and their assessment.

The mass movement of bedrock and unconsolidated materials results in different types of slides, magnitudes, and rates of movement. An area with a potential landslide hazard usually has some evidence of previous occurrences, if not some historical record. Unfortunately, some types of landslides, particularly those of small size, cannot be delineated on remote sensing imagery or through aerial photography. Usually the scars of the larger slides are evident and, although the smaller slide features may not be individually discerned, the overall rough appearance of a particular slope can suggest that mass movement occurred. If a fairly accurate geologic map is available at a reasonable scale (1:50,000 or larger) rock types and/or formations susceptible to landslides may be examined for evidence of movement. An example of this would be finding a shale in a steeper than usual slope environment, implying the strong possibility of a landslide history. An examination of stream traces frequently shows deflections of the bed course due to landslides. If one can separate out the tectonically controlled stream segments, those deflections due to slides or slumps often become evident.

Typical features that signify the occurrence of landslides include chaotic blocks of bedrock whose only source appears to be upslope; crescentic scarps or scars whose horns point downward on a normal-looking slope; abnormal bulges with disturbed vegetation at the base of the slope; large intact beds of competent sedimentary or other layered rock displaced down dip with no obvious tectonic relationship; and mudflow tongues stretching outward from the base of an obviously eroded scar of relatively unconsolidated material. A good understanding of the structural geology of the study area frequently places these superficial anomalies into perspective. As discussed in Chapter 10, the susceptibility to landslides is relative to the area. Landslides can occur on gentle slopes as well as on steep slopes, depending on landscape characteristics.

Most landslide discussions do not address the problem of sinkholes, which are a form of circular collapse landslides. The karstic areas in which they occur are easy to identify even on some satellite imagery (MSS, TM, SPOT, etc.) due to their pitted appearance and evidence of the essentially internal drainage. Despite the obvious occurrence of many sinkholes, many individual small sinkholes are subtle and not easily recognized. These are frequently the sites of collapse and subsequent damage to any overlying structure when ground water is removed to satisfy development needs, which results in lowering the water table and undermining the stability of the land.

The spatial resolution required for the recognition of most large landslide features is about 10m (Richards, 1982). However, the recognition depends to a great extent on the ability and experience of the interpreter and is enhanced by the availability of stereoscopic coverage, which can be expensive to acquire Stereoscopic coverage and the resolution requirements preclude use of most satellite-borne sensor imagery, although large block landslides can be detected on Landsat MSS and TM imagery.

Given the spatial resolution requirement, SPOT HRV-P (panchromatic mode) imagery can be useful with its 10m resolution. Its broad band coverage, however, is not conducive to providing adequate contrast in scenes involving heavily vegetated tropics, where most of the potential hazards occur. Ameliorating this factor slightly is the availability of stereocoverage. It is important to understand that this is specifically programmed for the SPOT satellite and that stereocoverage is not normally acquired during sensor operation.

Detection of landslide features is more easily achieved using airborne sensors. Aerial photography with its normal stereoscopic coverage is the best sensor system with which to define landslides, both large and small. Aerial photographic scales as small as 1:60,000 can be used. Black and white panchromatic or IR films are adequate in most cases, but color IR may prove better in some instances. The IR-sensitive emulsions, as stated earlier, eliminate much of the haze found in the humid tropics. The open water or other moisture in back of recent slump features stands out as an anomaly in the aerial IR stereomodel, either in black and white or color. The color IR photography might, in some rare cases, show the stress on the vegetation caused by recent movement. If the scales are large enough, tree deformation caused by progressive tilting of the slope of the soil might also be detected.

A more sensitive detector of moisture associated with landslides is the thermal IR scanner. This sensor is particularly useful in locating seepage areas that lubricate slides. It is particularly effective during the night, when there is a maximum temperature difference between the terrain and the effluent ground water. Despite its utility many factors rule out the widespread use of the thermal IR scanner. These factors include the low altitude required for reasonable spatial resolution, the large number of flight lines required for the large area involved, and the geometrical distortions inherent in the system. If the terrain to be interpreted has some relief and is nondescript, these distortions become an even greater problem when the data are interpreted by making the location of features very difficult.

SLAR, especially the X-band synthetic aperture radar with its nominal 10m resolution, can be marginally useful in a stereo mode because of its ability to define some larger textures related to landslides. In some cloud-prone environments radar may be the only sensor that can provide interpretable information.

6. DESERTIFICATION

Desertification occurs when an ecosystem experiences a diminution or loss of productivity. This process can have a natural and an anthropic component, which may reinforce each other, creating a synergetic effect (see Chapter 9). The degree of desertification risk is directly related to certain natural conditions such as climate, topography, natural vegetation, soil, and hydrology, as well as to the intensity and type of anthropic activity in the area. Desertification is among the most serious problems of the region. This trend indicates the increasing need to consider desertification processes in integrated development planning studies. Remote sensing, both spaceborne and airborne, provides valuable tools for evaluating areas subject to desertification. Film transparencies, photographs, and digital data can be used for the purpose of locating, assessing, and monitoring deterioration of natural conditions in a given area. Information about these conditions can be obtained from direct measurements or inferred from indicators (keys to the recognition of a desertification process).

In order to describe, evaluate, and decide about the type of action to be taken, the following issues should be addressed:

- Location: involves the identification of areas that are currently undergoing desertification and areas expected to be exposed to the forces that can lead to deterioration.

- Assessment: involves the identification and quantification of vegetative cover types, soils, land forms, and land-use change patterns. Vulnerability to change, rate of change, and direction of change in desertification patterns can be studied through this assessment.

- Monitoring· accomplished by detecting and measuring changes in landscape characteristics over a period of time. Comparisons are made between present conditions and previously observed conditions for the purpose of recording the reduction in biological productivity.

Chapter 9 presents an initial assessment technique utilizing information commonly available in the early integrated development planning stages. For a more detailed approach, four sets of data should be taken into consideration for a desertification study of a given area: a set taken at the end of the humid season, a set taken at the end of the last dry season, and the same two seasons taken five or ten years earlier (López Ocaña, 1989). Data selection for a given area will be directly related to the desired amount of detail, size of the area, required degree of precision and accuracy, and available time frame.

Large-scale aerial photography provides a great amount of detail for this type of study. Systematic reconnaissance flights can be used for environmental monitoring and resource assessment. Radar sensors and infrared scanners may be used to monitor soil moisture and other desertification indicators. However, acquisition of this type of data is costly and time consuming.

The use of satellite imagery is recommended during the first stages of a detailed desertification study since it offers an overview of the entire region. Computer enhancements, false color composites, and classifications can offer useful information. Optical enhancements can be performed, but these lack the quantitative control available through an automated approach. Statistical data obtained from a quantitative analysis through the use of a geographic information system (GIS--see Chapter 5) can be expressed as a histogram, a graph, a table, or a new image.

AVHRR imagery is commercially available and has been used for vegetation change studies. Ground resolution of 1 to 4 km represents some limitation in making large continental area studies. Other studies have used Nimbus data to delineate moisture patterns and vegetation boundaries. Geostationary Operational Environmental Satellite (GOES) data have been used effectively to locate and measure dust plumes; and Seasat SAR imagery has been applied in the delineation of large dune morphology.

Landsat MSS and TM and SPOT data have proven to be useful and cost effective for regional assessments. Landsat transparencies of bands 5 and

7 have been used to monitor superficial changes in areas undergoing desertification, and to map present water bodies and former drainage systems. Temporal tonal variations on Landsat MSS have been correlated with variations on the field. Movement of sand-dune belts has been detected using Landsat with a multitemporal approach. Albedo changes in arid terrains have been calculated using Landsat digital data: phenomena that tend to lower productivity (increased erosion, loss of vegetation density, deposition of eolic sedimentation) also tend to appear brighter on the image. On the contrary, phenomena that tend to increase productivity (increased vegetation, soil moisture), tend to darken the land. In this way, brightness variations can be detected in an area over a period of time. These data can also be calibrated with ground data collected from the areas where change has occurred.

Aerial and space remote sensing provide valuable tools for desertification studies, although, as for any other natural hazard related study, they must be combined with ground-collected data The use of remote sensing methods should minimize the need for ground data, therefore saving time and resulting quite inexpensive per unit of data. The combination of remotely sensed and ground-collected data can then, provide the basis for the assessment.

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