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# An Assessment of Remote Sensing Applications in Hydrologic Engineering

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The current status of techniques, limitations, and applications of remote sensing to hydrologic problems of rainfall estimation, snow cover monitoring, water quality monitoring, and hydrologic modeling and runoff computation was reviewed. Tabulated data for twenty-nine remote sensors indicated for each sensor the resolution range, spectral interval, spacecraft or aircraft that sensor has or could be flow on, and the major hydrologic parameters that could be measured on infrared. The thirteen hydrologic parameters listed were: surface temperature, cloud cover, atmospheric liquid water content, snow cover, water equivalent of snow pack, vegetation, land use, soil moisture, short wave radiation in radiation budget, long wave radiation in radiation budget, water bodies configuration, soil types, and basin area. Each sensor was capable of measuring from one to none of theses parameters. The capability of remote sensing to gather regional scale synoptic information offers the potential of greatly enhancing watershed modeling.

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# FOREWORD

Modern detailed hydrologic analysis required for planning and operation of water resources systems increasingly requires both regional scale and detailed levels of information. In particular, watershed modelling with digital computers, places a premium upon general characterizations of watersheds so that "parameters" can be determined and adjusted by a rational process. The capability of remote sensing to gather regional scale synoptic information offers the potential of greatly enhancing watershed modelling.

This research note reports the findings of Robert H. Burgy and V. Ralph Algazi, Associates, of Davis, California, in assessing the potential of remote sensing applications in hydrologic engineering. The study was supported by Contract No. DACW05-74-C-0034 (amended) from The Hydrologic Engineering Center, Corps of Engineers, U. S. Army.

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# An Assessment of Remote Sensing Applications in Hydrologic Engineering

## I. Introduction

This assessment was undertaken with the following broad objectives.

1. To review the current status of remote sensing technology in relation to hydrologic applications.

2. To analyze selected applications to identify potential remote sensing research needs for the Hydrologic Engineering Center.

As work progressed, the investigators have become more familiar with the specific interests and emphasis of HEC and with the approach and techniques used by the Center in the solution of hydrologic engineering problems. Thus, this final report reflects our awareness of HEC interests and objectives, but it also includes a fairly broad, partly tutorial presentation of Remote Sensing. The intent is to provide a rounded view of techniques, limitations and applications of Remote Sensing, in addition to an assessment of its applicability to the perceived research needs of HEC.

This study and assessment is quite timely since after 10 or 15 years of preliminary work, the field of Remote Sensing has reached a substantial level of maturity and sophistication. Considerable interest, substantial results and large amounts of data have also resulted from the ERTS-1 investigations which originated with the launch of the ERTS-1 Satellite in July 1972.

Remote Sensing is very much an interdisciplinary field, drawing upon a wide range of scientific, technical and technological resources. In the preparation of this report we have drawn upon our own special field of knowledge as it applies to Remote Sensing and on information available in the open scientific and technical literature or in specialized technical reports. Specific references and general sources of information for Remote Sensing are given at the end of the report.

## II. The Approach and Sensors of Remote Sensing

In the study and control of their physical environment, scientists and engineers rely on a broad range of physical principles and techniques to identify and quantify attributes of physical objects. In many situations identification and quantification of attributes can be performed remotely by electromagnetic sensing. The attributes that can be sensed remotely by electromagnetic radiation are spatial distribution (shape and texture), spectral distribution (color), polarization and temporal variations. Since people are sensitive to electromagnetic radiation through their sense of sight, remote sensing has always been used by man in interacting with his environment. Quite recently, considerable emphasis has been given to the systematic exploitation of the whole spectrum of electromagnetic radiation from physical objects, whether directly perceived by man or not, and to Remote Sensing on a large geographic scale through the use of aircraft and satellites. In a large measure a compromise has to be achieved between the detail and accuracy required in the study of the physical environment and the geographic extent (or number of measurements) which can reasonably be performed. The promise of Remote Sensing is that it opens new possibilities as to the spatial scale and geographic extent which can be sensed and thus studied or monitored with some limited accuracy.

To use the Remote Sensing of electromagnetic radiation for the study of the Earth, one has to determine in some way whether for the problem at hand there are actually usable corresponding changes in the electromagnetic radiation. An obvious method of long standing consists of taking aerial photographs either in black and white or natural color (using 3 spectral bands which match the sensitivity of the color receptors in the human eye) and to observe intensity variations or color variations. Texture, shape, lines, colors, etc., can then be interpreted by a human observer in a meaningful way. This is still a very useful, inexpensive and convenient approach for many problems.

If one wishes to examine the electromagnetic spectrum outside the visible range or more finely or more precisely within the visible spectrum, one has to resort in general to non-photographic means.

By using specialized sensors one can study in fine detail the whole range of the electromagnetic spectrum from the ultraviolet to microwaves. The basic problem then is to determine whether different objects of interest have sufficiently different spectral properties to permit reliable identification within acceptable errors by Remote Sensing. Different basic properties of materials can be studied in different areas of the electromagnetic spectrum. In the region between 0.32 - 4.0 microns (which includes the visible spectrum) one observes primarily the spectral reflectance of direct and scattered solar radiation. Spectral radiations arise from selective absorption (by chlorophyll, pigments, liquid water, etc.) and scattering. In the 4.5 - 15 micron region, one observes thermal emission originating at the surface of solids and liquids. In the microwave region 1 - 300 mm one also observes thermal emissions which are now influenced by substantial emissivity variations of natural surfaces. This makes passive microwave images to some extent dependent on subsurface effects.

Radar, which provides its own illumination, operates in wavelengths varying from centimeters to meters and measures the scattered signal. Here again substantial subsurface effects may be sensed by radar.

To systematically exploit these general properties in applications, one may study the electromagnetic radiation which emanates from objects of interest in the laboratory, under controlled conditions, or in the field under natural conditions. Consider for instance the curves of Figure 1, obtained in May 1969 using sensors in 9 distinct spectral bands. The spectral reflectance of cotton, sorghum, soil and water was recorded in each spectral band. The curves of reflectance versus wavelength, is called the spectral signature of the natural object. The fact that these signatures are different for different objects indicates that they may be discriminated by Remote Sensing. Further work using these signatures may indicate the minimum number of sensors and the corresponding spectral bands needed to do the job of discrimination.

Thus for each field of application there are some preferred spectral bands for remote sensing and some minimal requirements. Since the same sensors are used for several applications, some sort of compromise on the sensors' characteristics is generally needed.

The physical sensors being used vary as to type, achievable spatial resolution, sensitivity, linearity, dynamic range, spectral range, etc.

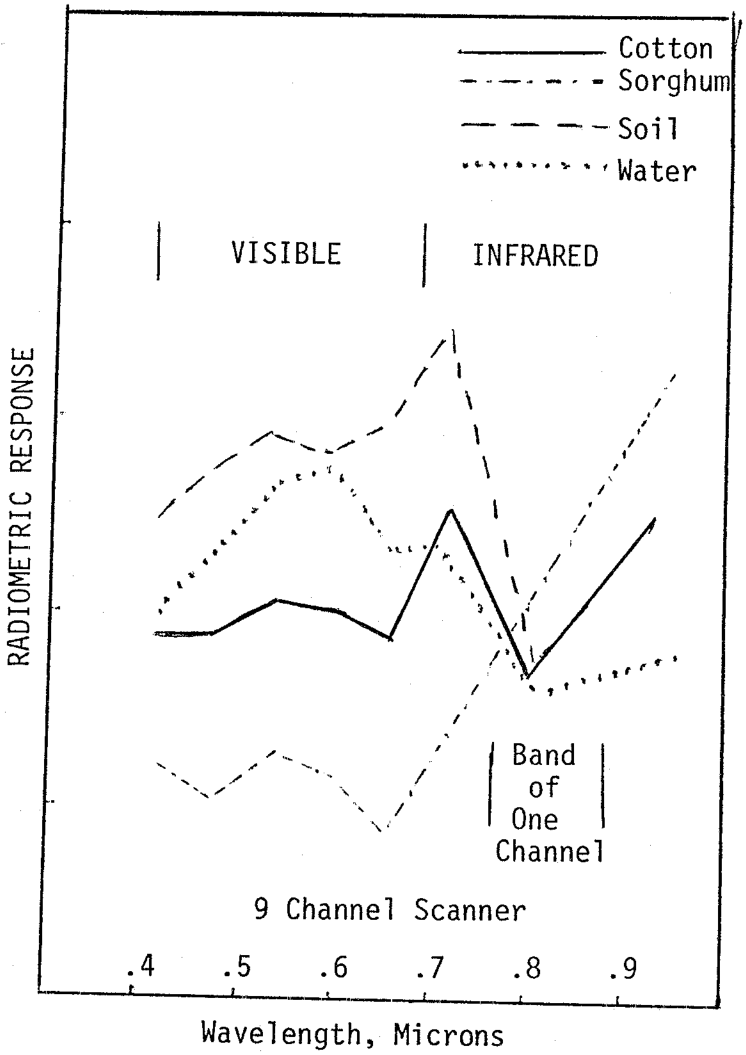

Figure 2. Examples of Spectral Signatures
(from USDA, SWC Report 431, June 1972)

The principal types of sensors and some of their characteristics are listed below.

Optical-mechanical Scanner

An optical-mechanical scanner is an electromagnetic radiation detector (radiometer) whose narrow field of view is systematically scanned over the scene by moving optical components. Where used in an aircraft or satellite the forward motion of the platform provides one of the directions of scan and a mirror moving from side to side provides the second direction of scan. An array of detectors can be used to cover a number of spectral bands at once. The spectral range from 0.3 to 15 microns can be covered by such scanners. A multispectral scanner is flown in the ERTS-1 satellite and MSS data was used to generate the images included in this report. The radiometric quality of these sensors is generally good and of considerable value in applications and quantitative analysis. To make use of the spectral signature of natural objects one has to be able to locate a given object within several spectral images. Image registration is the name given to the process of bringing multispectral images into spatial correspondence. Image registration is quite easy for MSS data.

## Photography

Photography with silver halide film can be used in the spectral range from 0.3 to 0.9 microns. The near infrared band, from 0.7 to 0.9 microns is covered in commercially available aerial infrared film. The advantages of photography are high resolution, convenience for human interpreters, inexpensive and widely available equipment and techniques. The spectral range however is limited and recovery of film from a satellite may be a problem. Quantitative work may be limited by a generally poor and inconsistent radiometric quality.

## T.V. Sensors

An image (snapshot) of the Earth, taken through a spectral filter, is formed on a photocathode or on a two dimensional array of sensors and transmitted to the ground in the form of an electrical signal. A 4000 line resolution has been achieved and available spectral bands extend into the near infrared. The radiometric quality of the data is intermediate between those of optical-mechanical scanners and of photography. Image registration from spectral band to spectral band is generally difficult and not very good.

### Microwave Radiometry

These sensors are similar to thermal infrared sensors of scanners except for the wavelength range covered (1 - 300 mm). They sense temperature and temperature gradients, can measure temperature and other properties of clouds and fog (although they do penetrate clouds and rain). The microwave radiometer is a passive, all weather sensor and is capable of measuring temperature, pressure, wind and cloud density profiles in the atmosphere. The spatial resolution which can be achieved is limited and depends on the wavelength and on the size of the antennas.

### Radar

These "active" systems are also all weather sensors in the wavelength range from 1 cm to 1 m but they generally require a substantial transmitted power of several hundred watts. Good resolution radar images have been obtained from aircraft, but none have been obtained from space at this time.

This brief description of sensors and their properties can be used in the interpretation of the Survey of Remote Sensors collected in Table 1. Note that the resolution range indicated for each sensor is dependent on the altitude of the satellite as well as on inherent properties of the sensors.

|  | Resolution Range | Spectral Interval (microns) | Spacecraft or Aircraft | Major Hydrologic Parameters Which Can be Measured Or Inferred** |
|---|---|---|---|---|
| 1. Television & Photographic Cameras |  |  |  |  |
| AVCS | .3 - 2.0 n.m. | 0.45 - 0.65 | Meteorological Sats. | 2,4,7,11,13 |
| APT | 1.7 - 3.4 n.m. | 0.45 - 0.65 | Meteorological Sats. | 2,4,7,11,13 |
| IDCS | 1.7 - 3.4 n.m. | 0.4 - 0.7 | Meteorological Sats. | 2,4,7,11,13 |
| Multispectral Photographic Facility (EREP) | 100 ft. | 0.4 - 0.9 at 0.1 intervals | SKYLAB-A | 2,4,6,7,11,12,13 |
| Multispectral Terrain Photography Exp. | 280 ft. | 0.48 - 0.9 | APOLLO 9 | 2,4,5,7,11,12,13 |
| RBV | 200 ft. | 0.475-0.830 (3 chan.) | ERTS-1 & B | 2,4,6,7,11,12,13 |
| Spin-Scan Cloud Cover Camera (Monochromatic) | 2.5 n.m. | 0.475-0.630 | ATS 1 | 2,4,7,11,13 |
| Vidicon Camera System | .15-1.5 n.m. | 0.4 -0.65 | Met. Satellites | 2,4,7,11,13 |
| Spin-Scan Cloud Cover Camera (Color) | 2.0 n.m. | 0.390- .700 | ATS 3 | 2,4,7,11,12,13 |
| 2. Spectrometers |  |  |  |  |
| Mapping Microwave Spectrometer* | 100 n.m. | 5.47 - 13.5 mm | NIMBUS F | 3,4,5,8 |

*As of this date instrument has not been flown on spacecraft.

**1. Surface Temperature
2. Cloud Cover
3. Atmospheric Liquid Water Content
4. Snow Cover
5. Water Equivalent of Snowpack
6. Vegetation
7. Land Use
8. Soil Moisture
9. Short Wave Radiation in Radiation Budget
10. Long Wave Radiation in Radiation Budget
11. Water Bodies Configuration
12. Soil Types
13. Basin Area

Table 1

Survey of Remote Sensors and Their Applicability in Determination of Hydrologic Parameters

Table 1 - continued

| | Resolution Range | Spectral Interval (microns) | Spacecraft or Aircraft | Major Hydrologic Parameters Which Can be Measured Or Inferred** |
|---|---|---|---|---|
| 3. Radiometers | | | | |
| Experimental 24-channel Multispectral Scanners* | 0.1146° Ang Res. | 0.34 - 13 | C-130 A/C | 1,2,4,6,7,9,10 |
| Earth Radiation Budget* | 0.25° Ang. Res. | 0.2 - 40 | NIMBUS-F | 9,10 |
| Electrical Scanning Microwave Radiometer | 13 n.m. | 19.35 GHz | Nimbus 5 | 3,4,5,8 |
| Electrically Scanning Microwave Radiometer* | 8 n.m. | 37 GHz | NIMBUS-F | 3,4,5,8 |
| EREP Multispectral Scanner* | 130 - 260 ft. | 0.41 - 12.5 | SKYLAB-A | 1,2,4,6,7,8,10 |
| High Resolution Infrared Radiometer | 9 n.m. | 3.4 - 4.2 | Nimbus 1,2 | 1,2,4 |
| High Resolution Infrared Radiometer | 5 n.m. | 0.7 - 1.1,<br>3.4 - 4.2 | Nimbus 3 | 1,2,4,8 |
| L-Band Radiometer* | 63 n.m. | 1.4 - 1.427 GHz | SKYLAB-A | |
| Medium Resolution Infrared Radiometer | 29 n.m. | 0.2 - 30 (5 chan.) | Nimbus 2,3 | 5,10 |
| Medium Resolution Radiometer | 35 n. miles | 0.25 - 30 | TIROS | 9,10 |
| Microwave Radiometer/ Scatterometer and Altimeter* | 6 n. miles | 13.9 GHz | SKYLAB-A | |
| Multi-Spectral Scanner | 200 ft. | 015 - 1.1(4 chan.) | ERTS-1 & B | 2,4,6,7,8,9,11,12,13 |
| Nimbus E Microwave Spectrometer | 100 n. miles | 0.456 - 1.35 m | Nimbus 5 | 3 |
| Passive Microwave Imaging System* | 300 ft. | 10.69 - 150 MHz | NP3A A/C | 3,5,6,8 |
| Surface Composition Mapping Radiometer | 1.35 n.m. | 0.7-1.4, 8.3-9.3,<br>10.2-11.2 | Nimbus 5 | 1,2,4,6,11,13 |
| Temperature Humidity Infrared Radiometer | 4.2 n.m.,<br>12.6 n.m. | 10.5-12.5,<br>6.5-7.0 | Nimbus 4,5 | 1,2,4 |
| Very High Resolution Radiometer* | 8 n.m. | 0.55-0.75,<br>10.5-12.5 | ATS-F | 1,2,4 |
| Very High Resolution Radiometer | .5 n.m. | 0.6-0.7,<br>10.5-12.5 | NOAA-2 | 1,2,4 |
| Visible Infrared Spin Scan Radiometer* | .5 n.m., 5 n.m. | 0.55-0.7,<br>10.5-12.6 | SMS-A | 1,2,4 |

## III. The Techniques and Problems of Remote Sensing

A. Introduction. In this section we present a fairly short discussion of the techniques which have been found useful in Remote Sensing and of the problems and limitations which are inherent to the use of Remote Sensing. At the end of this section we shall present some schematic diagrams on the data flow and the data handling and processing steps which are commonly followed in applications.

As one proceeds from the theoretical or laboratory stage of measuring the electromagnetic radiation properties of natural objects to a field situation one meets a number of problems and practical limitations.

These can be best understood by referring to the diagram of Figure 2. Figure 2 shows a number of unwanted or uncontrolled parameters which modify the attributes of the physical object under study so that the acquired data may differ in significant ways from the ideal. Given these difficulties one has to assess, for each application, whether these unwanted effects are limiting and whether corrective action is possible or needed. The major undesirable effects are the atmospheric absorption which is very significant in parts of the spectrum, the limited resolution which blurs and mixes the spectral radiation from a number of adjacent objects, the errors in radiometric values recorded which make analysis and discrimination difficult or impossible, and the geometric inaccuracies limiting the ability to bring images in registration or in concordance with maps. A significant additional problem is related to the amount of data which has to be manipulated, quantified and analyzed before useful information can be extracted. We shall describe more extensively these problems in relation

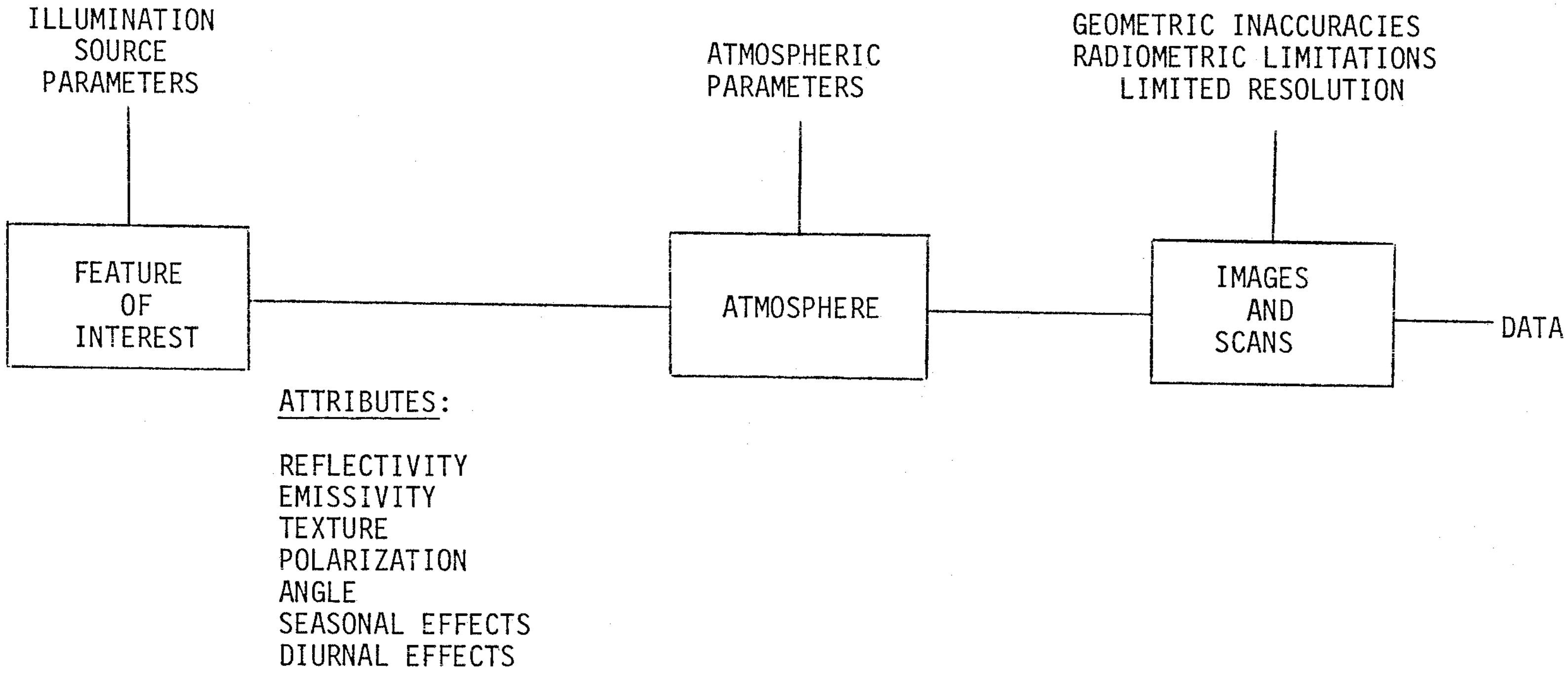

Figure 2: UNWANTED OR UNCONTROLLED PARAMETERS IN REMOTE SENSING

to the techniques used to solve them. We now consider in turn the principal techniques for the processing of remote sensing data with emphasis on computer techniques.

B. Digitization of Images. The digitization, that is to say the process of converting continuous values such as position or radiometric value into numbers, is commonly used for images and for maps.

The digitization and recording of x,y coordinates can be used for mensuration and quantification of areas. An example of such a need is the delineation of the basins and subbasins in the modeling of watershed. This delineation seems easier by far to do by a human working on a photograph or a map than automatically by computation. Thus, it seems quite useful to superimpose on remote sensing imagery a schematic delineation of watersheds and basins done by a human observer. The specific equipment for this task consists of a digitization tablet which senses the position of a marker or hand held cursor and enters the corresponding coordinates.

The digitization of radiometric value is also very useful for quantitative work. If the remote sensing data available is in the form of multispectral photographs the film density can be transformed into an electrical signal and then digitized. These digitized images can then be further processed in one of the several ways described later in this report. The physical devices which digitize photographs measure the electromagnetic radiation (light intensity) transmitted by a photographic transparency or reflected from a print. These devices have therefore some similarity of principle with the remote sensors discussed in the previous section. One thus finds electro-mechanical scanners or TV type imaging systems to perform the densitometry and digitization of images.

C. Geometric Manipulation and Geometric Correction of Images. In applications, one may be interested in geometric manipulations and corrections for several reasons. The three most common reasons are:

1. Change of Scale. Once data and images have been acquired by a set of sensors, some specific application may have resolution requirements which match poorly the available data. One can easily degrade the resolution by smoothing the data spatially or discarding part of the data by decimation of the points. For instance, in the image* of Figure 3 which shows a substantial portion of the San Francisco Bay, only one half of the original data points, both in the vertical or horizontal directions have been preserved. At the other extreme, one may obtain a resolution somewhat better than what is provided by the sensors, by numerical interpolation between adjacent, recorded radiometric values. For instance Figure 4 shows a picture of Castro Valley consisting of 256 x 256 radiometric values (picture elements or pels) recorded by an ERTS scanner in band 5 (0.5 - 0.6 micron). In Figure 5 we have taken a portion of the same data, consisting of 128 x 128 pels, and by interpolation generated a 256 x 256 pel image. By comparing Figure 4 and 5 we observe a significant improvement in apparent resolution. However, this approach has definite limit and the example given is probably close to the best that can be done to increase resolution by processing.

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*All illustrations in this report are generated from digital ERTS-1 MSS data, ID. 1291-18182.

Figure 3. Southern Tip of San Francisco Bay.

Figure 4. Castro Valley 256 x 256 pel.

Figure 5. Castro Valley 128 x 128 with Interpolation.

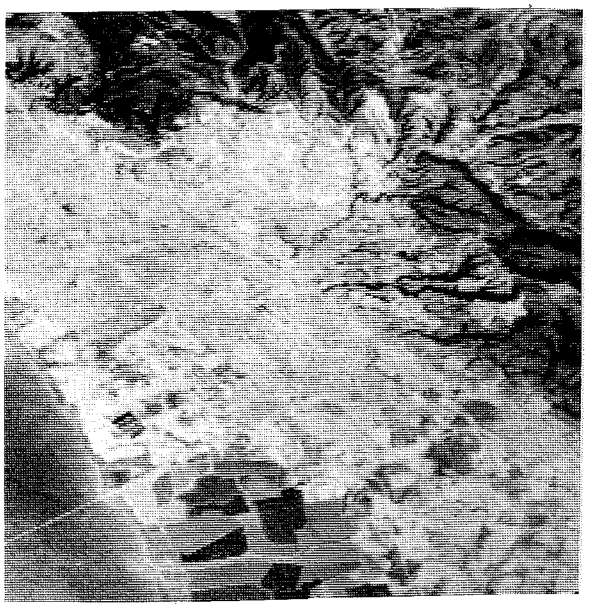

Figure 6. Castro Valley No Geometric Correction.

2. Scene Registrations: We recall that registration refers to the ability to superimpose the same point on two images of a scene. Good scene registration is necessary in order to use the multispectral response of objects or to incorporate data obtained at different times.

In a multispectral scanner, in which data is obtained from the same point on the ground at the same time in several spectral bands, registration is excellent. On photographs, careful processing is needed and registration marks are commonly provided to ease the task of bringing data in registration. In data acquired at different times, the problem of registration may be substantial for any of the sensor types.

3. Location Correction: Most often, one wishes to locate a point in an image with respect to geographic coordinates so as to make the data compatible with maps. What can be achieved in reducing location and registration errors by processing is illustrated in Table 2 which summarizes results for the ERTS-1 sensors.

ERTS-1 SATELLITE (ALTITUDE: 900-950 Km)
SYSTEM GEOMETRIC ACCURACY (METERS RMS)

| | LOCATION | | SCENE REGISTRATION | |
|---|---|---|---|---|
| | RBV | MSS | RBV | MSS |
| SENSOR OUTPUT | 3700 | 3700 | 2100 | 20 |
| BULK PRODUCTS | | | | |
| 9 1/2 IN. POSITIVE TRANSPARENCE | 1000 | 1000 | 325 | 145 |
| CTT (DIGITAL TAPE) | 2300 | 2300 | 2100 | 20 |
| PRECISION PRODUCTS | | | | |
| 9 1/2 IN. POSITIVE TRANSPARENCY | 90 | 240 | 105 | 105 |
| CTT | 80 | 235 | 100 | 125 |

RBV: Return Beam Vidicon (TV Camera)
MSS: Multispectral Scanner (4 Spectral Bands)

TABLE 2

According to the application, the geometric correction performed does not have to be very sophisticated. For instance, we show in Figure 6 the direct display of the ERTS-1 data from which the image of Figure 4 was obtained. Two types of corrections have been applied to obtain the image of Figure 4 from the data shown in Figure 6. Firstly, a significant difference in the spacing of the horizontal and vertical elements was corrected. Secondly, a skew in the data of approximately 3° was removed. We believe that such fairly simple geometric corrections are probably adequate for most applications in hydrology.

D. Information Extraction. Once, for a specific application, remote sensing data has been acquired at suitable times and scales; and has been geometrically corrected, the problem remains to extract useful information from that data. What is useful information depends of course on the application. To be specific, consider the three parameters of common interest in hydrologic engineering shown in Table 3.

| PARAMETER NAME | DEFINITION | QUANTIFICATION |
|---|---|---|
| Impervious Surface Fraction | Fraction of total watershed area covered by paving, rooftops, etc., whose run-off contributes directly to a stream. | Estimated from remotely derived images. Usually zero for rural areas except where there are large areas of exposed rock. In urban areas, related to land use. |
| Water Surface Fraction | Fraction of total watershed area covered by water surfaces at normal low flow. | Estimated from remotely derived images. Water has a low reflectance in the infrared. |
| Vegetative Interception Maximum Rate | Maximum rate of rainfall interception by watershed vegetation. | Estimated from land cover, derived from image. Value assigned is 0.10 for grassland, 0.15 for moderate forest, 0.20 for heavy forest. |

Table 3. Relation of parameters of hydrologic models to remotely sensed observables (Examples)

From this table one can infer some of the processing steps which may allow quantification of the parameter of interest. For instance, in order to determine the vegetative interception maximum rate, the classification of the watershed into grassland, moderate forest, heavy forest and the determination of the area in each class are needed. The theoretical spectral signatures of these vegetative covers may or may not be known. In any case, the recorded imagery may have been degraded by the unwanted and uncontrolled parameters shown in Figure 2. Further, the classification into heavy or moderate forest may not be well characterized in terms of spectral signatures since different tree species may have different spectral responses.

The practical question is then what is there actually in the recorded data which correlates to the vegetation types and the classification of interest. Two broad classes of techniques have been found useful.

1. Techniques which assist an observer in decision making:
    - False color presentation
    - Image enhancement
    - Multispectral combinations
2. Techniques in automatic decision making:
    - Empirical signature analysis
    - Training sets and decision rules
    - Automatic classification

We shall characterize these two classes of techniques broadly as image enhancement and automatic classification.

## I. Image Enhancement

At this time, machines cannot match man's capability in the many areas of decision making which involve judgement, experience, training, the interpretation of ambiguous data, etc. Even for cases in which a machine can reasonably do the task, it may do so very awkwardly and at a very high cost. An example to the point is the delineation of watersheds which a trained person can do very rapidly from a topographic map and that a computer would handle with difficulty. An example of such delineation for the Castro Valley watershed is shown in Figure 11.

For remote sensing data, in which images are generated from the radiometric values recorded, there are two types of difficulties which need to be overcome before an interpreter can use the data. First, the range of radiometric values displayed as an image may be so narrow that the observer cannot perceive much information at all in the images. This is generally the case for the standard black and white and color composite photographic products generated from ERTS-1 data and distributed by NASA. The second difficulty is that there may be too much data. For data recorded in up to 3 spectral bands, false color displays are used which assign one color to each of the spectral bands. For instance, NASA's standard color composite assigns bands 4, 5 and 7 to blue, green and red respectively. More than 3 spectral bands may be involved. ERTS-1 has four and some other multispectral scanners go up to 9, 16 or even more spectral bands.

These two difficulties can be alleviated by fairly simple computer processing. For instance, contract stretching, that is to say, increasing the dynamic range of the recorded data before display, is a useful technique which makes perceptible to an observer the recorded data. A more systematic and rational approach can be used for this problem by taking into account the properties of human vision and the statistics of the data to be displayed (Algazi, 1973a). For the problem of too much data one can also use multispectral combination of the data so that a human observer can perceive and comprehend all the data pertinent to a specific application. Heuristically, this can be done because the data recorded in many spectral bands is highly correlated from band to band, so that little new data is provided by additional spectral bands after the first few. Thus most of the significant information can be represented into a few equivalent data sets by digitally combining multispectral data. This approach is discussed by Algazi (1973b) and illustrated in some of the following figures. First note that the photographs of Figures 4, 5, and 6 have already been enhanced to make the data perceptible. In Figure 7 we show a color composite of the south portion of the San Francisco Bay. The spectral bands used were Band 4 (0.4 - 0.5 micron) Band 5 (0.5 - 0.6 micron), Band 7 (0.8 - 1.1 micron) each globally enhanced by taking into account the statistics of the radiometric values recorded in each spectral band. Significant information is displayed but if one is interested, for instance, in the study of Castro Valley, the image is obviously inadequate. In Figure 8 we have focused attention more specifically on Castro Valley and since most of the image is now occupied by data of interest it is possible to perceive some additional details.

If we are interested in the urban areas we can selectively enhance the image using only the statistics of urban areas. This has been done and is displayed in Figure 9. Finally, since data was recorded in 4 spectral bands, it is possible to combine these 4 spectral bands into a single color composite by linear combinations of the multispectral data. The results of that type of processing is shown in Figure 10. Note that by focusing attention in the urban areas we bring out considerably more information in those areas but we have destroyed information in the vegetated areas shown in red. To facilitate the interpretation of Figures 8, 9 and 10 we in Figure 11 a portion of 1:2400 map of Castro Valley. In order to illustrate the use of such enhanced images we show in Figure 12 a map illustrating the land use/ crop type delineation for San Joaquin County as drawn by photo interpreters using a July 1972 ERTS composite image. Also shown are lines flown at low altitude to gather reliable calibration data for the prupose of evaluation of the significance of the delineations (Thorley, et. al., 1973). Class 1 is broadly related to urban areas, class 2 to rangeland, class 3 to grapes, etc.

Another use of image enhancement is as an exploratory tool, whenever it is uncertain that useful information is in fact contained in the remote sensing data. Assume for instance that one perceives a substantial amount of information in terms of lines and colors in enhanced images, but that its interpretation is not obvious. By the study of such an image in detail in conjunction with a map showing actual information on the ground (ground truth) and possibly low altitude aerial photographs, one may infer meaningful associations to shapes and colors displayed.

Figure 7. San Francisco Bay Enhanced Color Composite, 3 Bands

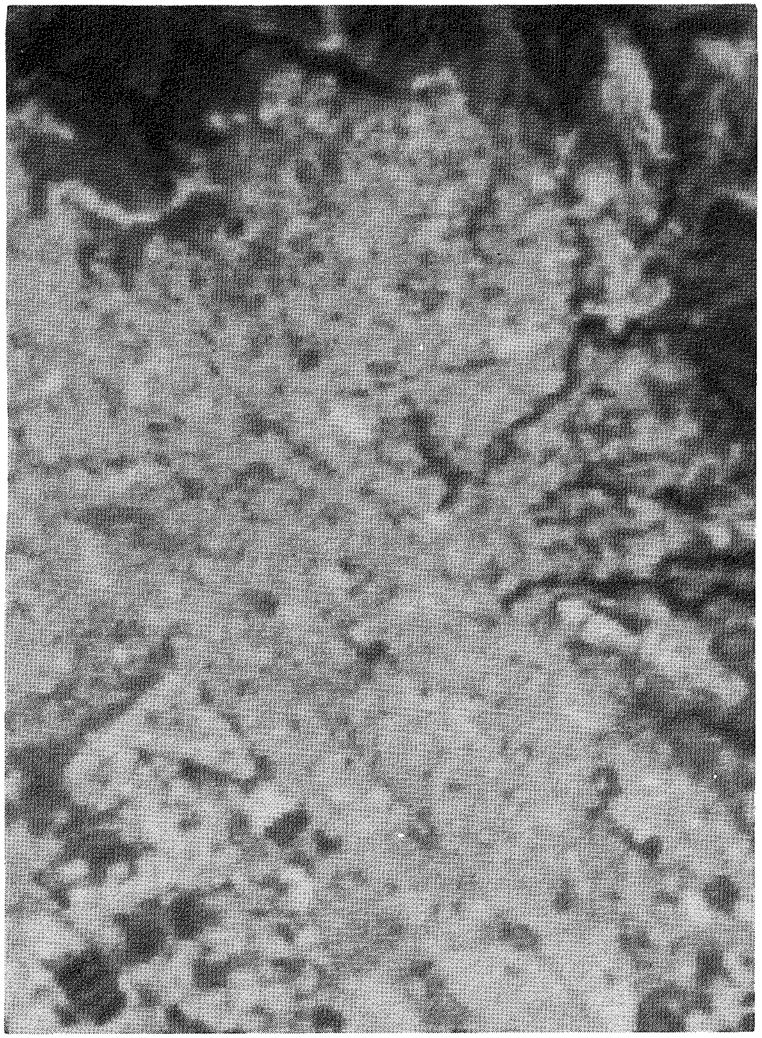

Figure 8. Castro Valley Enhanced 3 Bands

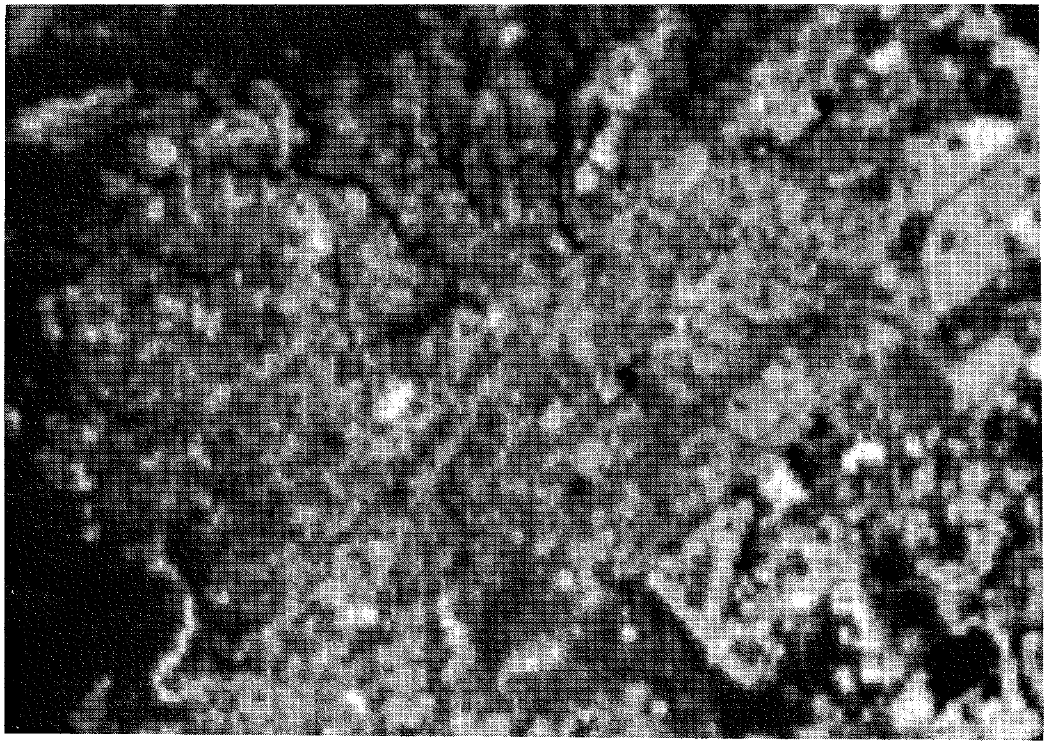

Figure 9. Castro Valley
Enhanced Urban 3 Bands

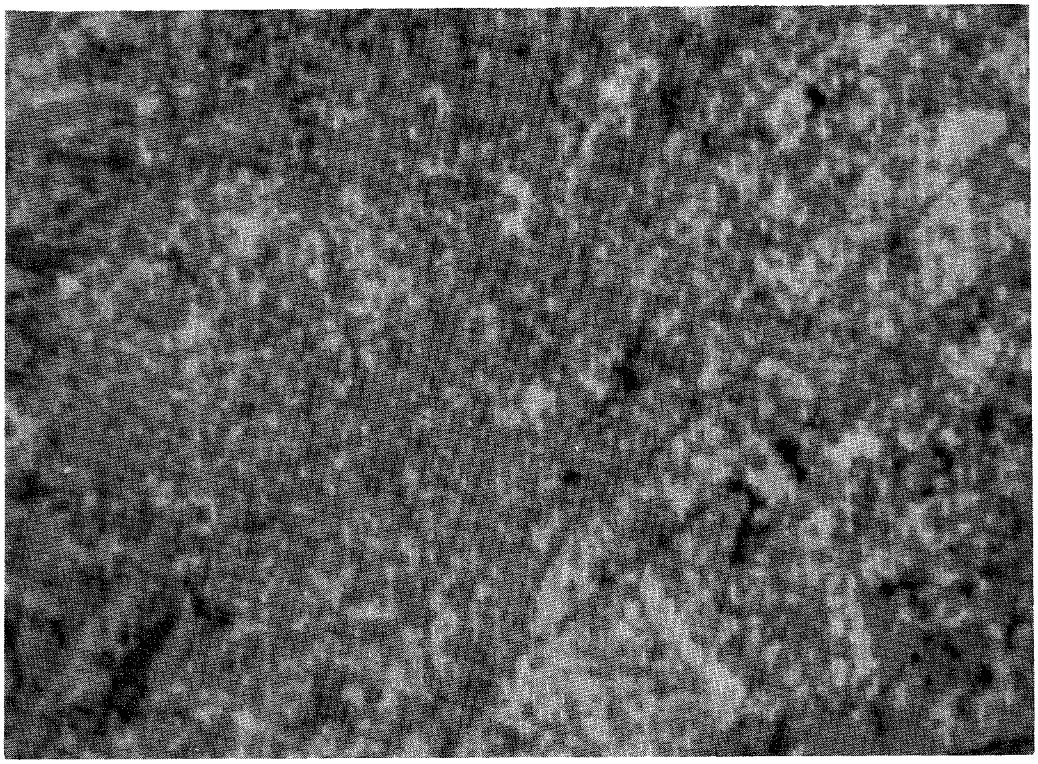

Figure 10. Castro Valley
Enhanced Urban, 4 Bands

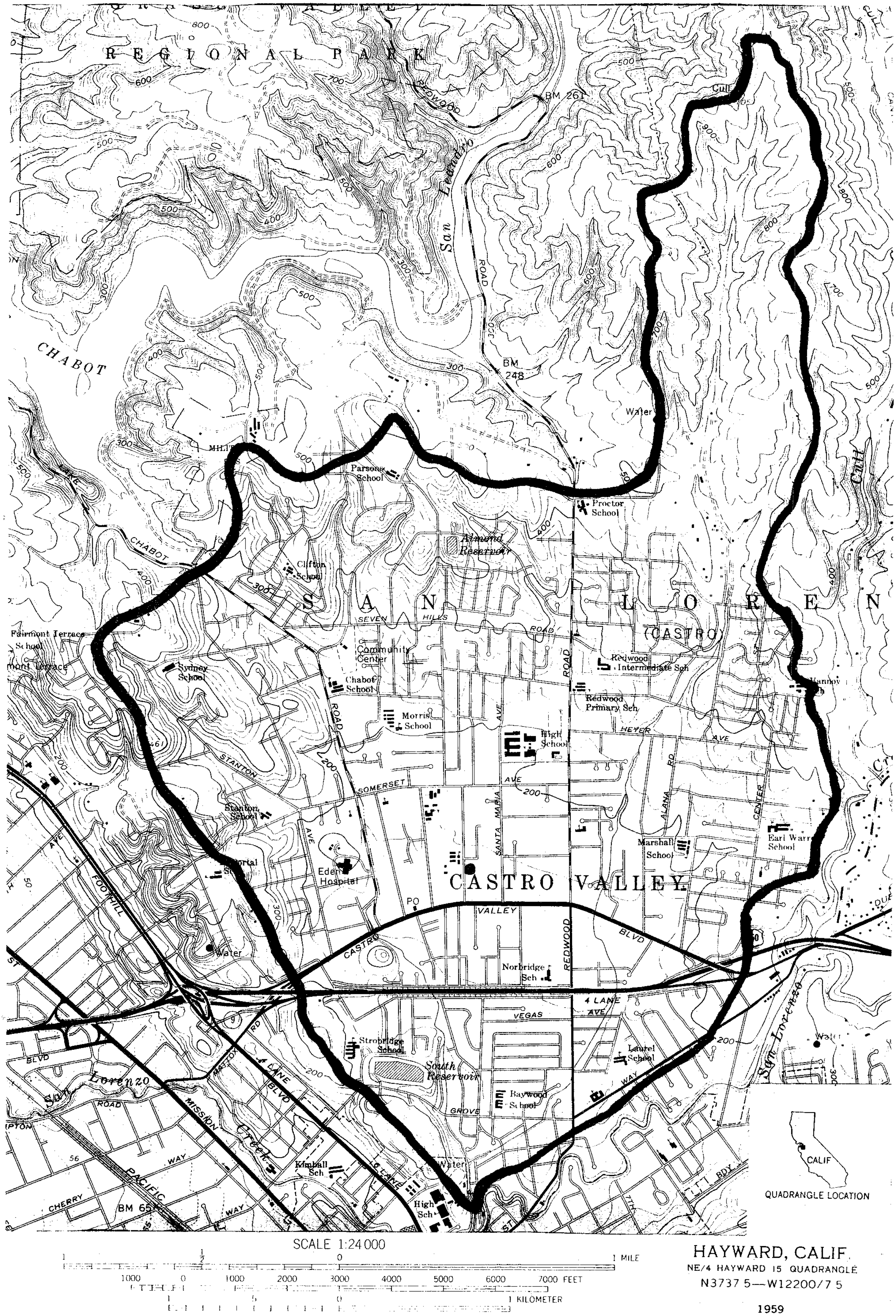
REGIONAL PARK
CHABOT
San Leandro
REDWOOD ROAD
BM 261
BM 248
Water
Parsons School
Proctor School
Almond Reservoir
Clifton School
SAN LORENZO
(CASTRO)
SEVEN HILLS ROAD
Fairmont Terrace School
Community Center
Redwood Intermediate Sch
Sydney School
Chabot School
Redwood Primary Sch
Morris School
High School
HEYER AVE
STANTON
SOMERSET AVE
SANTA MARIA AVE
ALANA RD
CENTER
Stanton School
Marshall School
Earl Warren School
Eden Hospital
CASTRO VALLEY
CASTRO VALLEY BLVD
Norbridge Sch
FOOTHILL
4 LANE AVE
VEGAS
Strobridge School
South Reservoir
Laurel School
Baywood School
GROVE
San Lorenzo Creek
MISSION BLVD
Kimball Sch
High Sch
CHERRY
PACIFIC
BM 65
QUADRANGLE LOCATION
CALIF
SCALE 1:24000
1 MILE
7000 FEET
1 KILOMETER
HAYWARD, CALIF.
NE/4 HAYWARD 15' QUADRANGLE
N3737.5—W12200/7.5
1959
CONTOUR INTERVAL 20 FEET
DOTTED LINES REPRESENT 5-FOOT CONTOURS
DATUM IS MEAN SEA LEVEL

Figure 11.

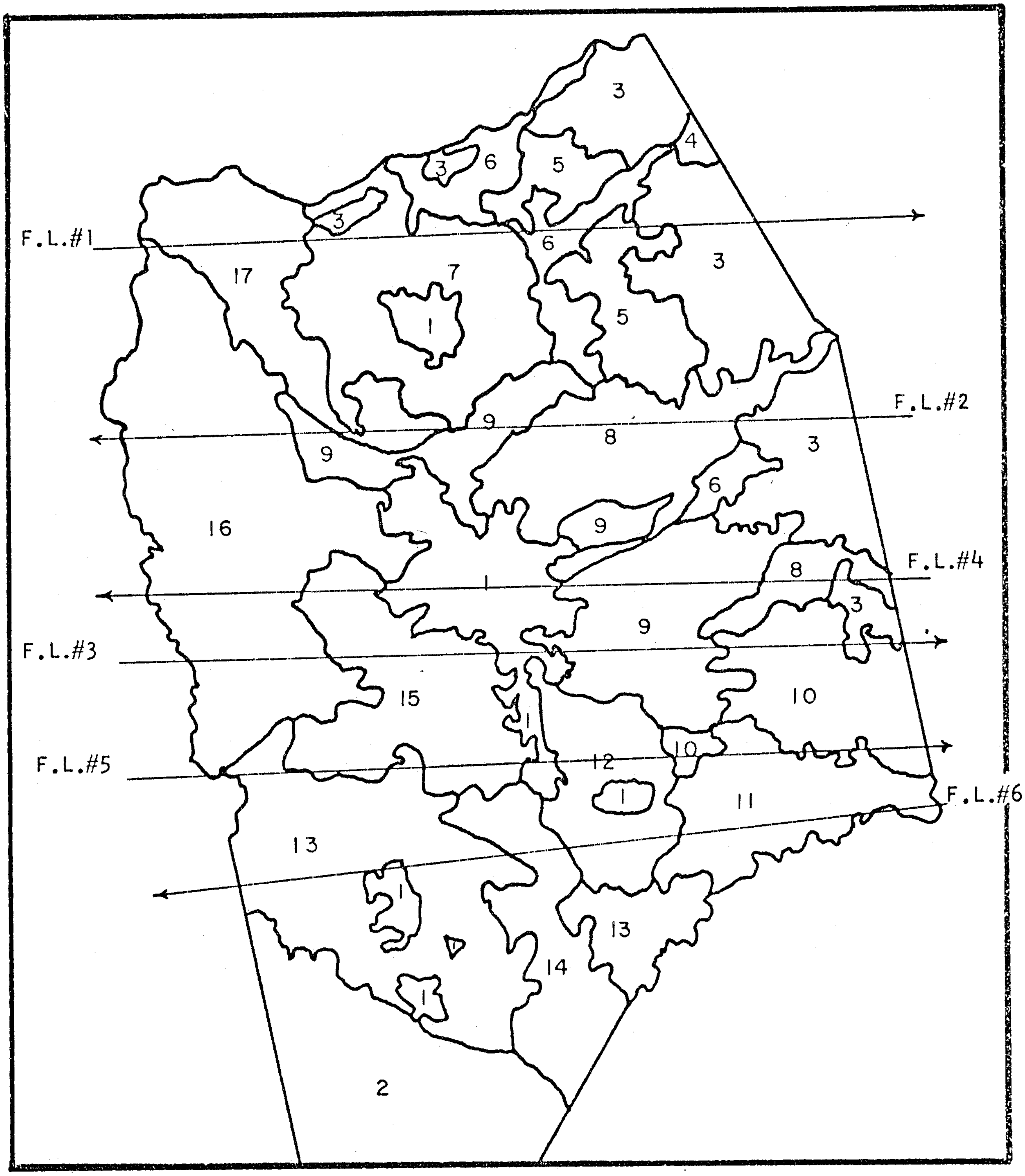

Figure 12. This map illustrates the land use/crop type strata delineations for San Joaquin County as drawn by photo interpreters using the July, 1972 ERTS color composite image. It also shows the lines flown at low altitude to gather "ground truth" for purposes of evaluating the significance of these strata and the strata delineated on January 1973 ERTS color composite.

## 2. Automatic Classification

The purpose of automatic classification is to exploit the spectral signatures (and possibly the texture) of features and classes of interest, such as vegetation types, and to provide, without human intervention, an estimate of the areas belonging to each class. Here again, the spectral signature obtained in the laboratory may not be directly usable because of extraneous effects and unknown parameters which affect the data under field conditions. The most common practical approach is then to use ground truth. Sample areas of each of the classes to be discriminated are localized in the ground by field crews or by low flying aircraft.

Each of these sample areas is identified in the remote sensing data and then an empirical signature analysis for each of the classes is performed. In each of the spectral bands and for each of the classes, the recorded radiometric values will not be unique generally and will have instead a distribution of possible values. Thus, for each spectral band one can obtain a histogram of radiometric values for each of the classes. If, for two classes, the corresponding histograms in some spectral band have very little overlap then the two classes can be distinguished on the basis of the radiometric values recorded in the band. Since data is recorded in several spectral bands, multidimensional histograms can be generated for each of the classes. If one thinks of radiometric values in one spectral band as a point on a line, then a set of values recorded in N spectral bands can be thought of as a point in an N-dimensional space. Thus, each class will have some statistical distribution in this N-dimensional signature space. If the histograms of distinct classes form distinct clusters of points in the N-dimensional signature space, then automatic classification can be done successfully. The process of statistical evaluation of signatures and implementation in an automatic classifier is shown in Figure 13. Among the questions of concern in the implementation of automatic classifiers is the speed of computation, which is tied to the number of spectral bands used and the specific algorithms implemented.

The result of an automatic classification scheme is illustrated in Figure 14 which refers to the Bucks Lake region in the Feather River watershed (Krumpe, et. al., 1973). An automatic classification of wildlands vegetation was performed and compared to ground truth, acquired here by high flight imagery and ground crews. Eight classes were allowed for (one is called "other resources"). The matrix of results, called confusion matrix, shows which percentage of each resources type was properly classified and which are confused with one another. For instance, hardwood class FH was properly classified 84 percent of the time, classified as chaparral 21 percent of the time and classified as exposed soil and rock 4 percent of the time.

This short survey of the processing techniques found most useful in remote sensing applications allows a discussion of the normal flow of data and of the processing steps involved in the use of remote sensing data.

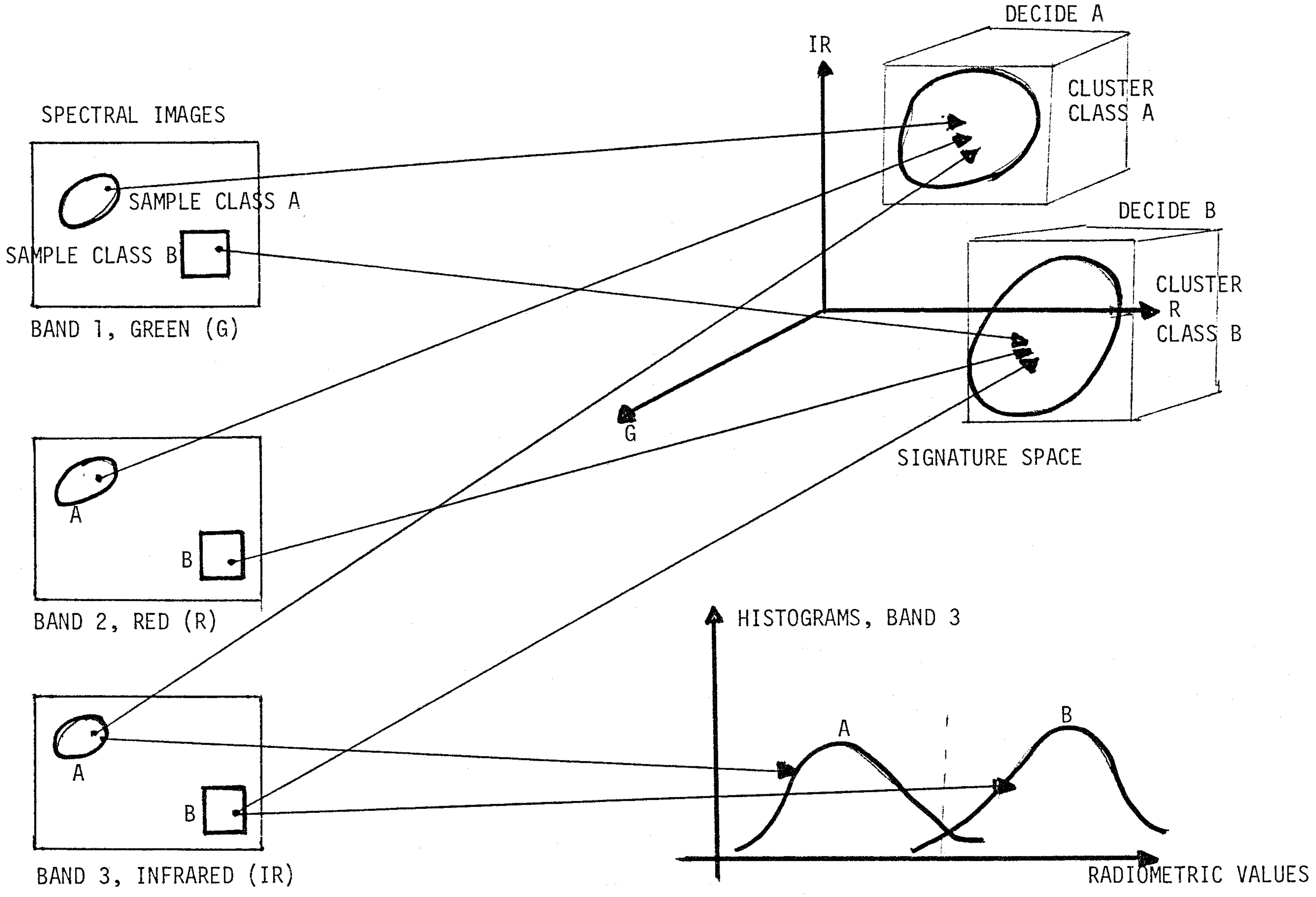

Figure 13. Empirical Signature Analysis, Automatic Classification

| | AB | VW | K | FH | X | T | NR |
|---|---|---|---|---|---|---|---|
| AB | 96 | 1 | 0 | 4 | 0 | 0 | 1 |
| VW | 0 | 72 | 0 | 14 | 0 | 7 | 7 |
| K | 14 | 0 | 48 | 13 | 0 | 1 | 23 |
| FH | 13 | 1 | 2 | 75 | 0 | 4 | 6 |
| X | 0 | 0 | 0 | 0 | 100 | 0 | 0 |
| T | 13 | 13 | 0 | 44 | 0 | 31 | 0 |
| NR | 16 | 9 | 3 | 6 | 0 | 6 | 59 |

OVERALL PERCENT CORRECT = 79

AB = Commercial conifer consisting of pure fir and mixed conifer stands
VW = Exposed soil and rock
K = Chaparral species in mixed and pure stands
FH = Hardwoods including Oak and riparian
X = Water
T = Chaparral lands converted to conifer plantations
NR = Grasslands and wet meadows
* = Other resource types

Figure 14. Example of automatic classification using ERTS-1 data.

## E. Data Processing and Information Flow in Remote Sensing.

From the foregoing, the reader should have obtained an overview of the principles, techniques and technology of remote sensing. We now incorporate individual steps and techniques into a logical sequence of operations to be performed from the acquisition of data to the estimate of physical parameters or decision making. Figure 15 shows a fairly typical situation in which common sensors are used for many distinct applications such as in the case of the ERTS-1 satellite. The diagram would be considerably simpler in the case of a small aircraft flying for a specific mission, since all processing would be done by each user on the ground. The box labelled Data Information Extraction in Figure 15 can in turn be expanded as shown in Figure 16. The diagram could be reduced and becomes very simple if the extraction of information is done by a photo interpreter working on photographs. A typical digital image processing facility which is allowed to perform the most sophisticated tasks is shown in Figure 17.

The data can be entered in digital form as digital tape or in photographic form and digitized by a scanner. Statistical analysis and processing are performed digitally. The output can be viewed directly as a color display by using color television equipment or photographed from a high precision, high resolution cathode ray tube oscilloscope. Tables and graphs can be printed or plotted by using standard computer peripherals.

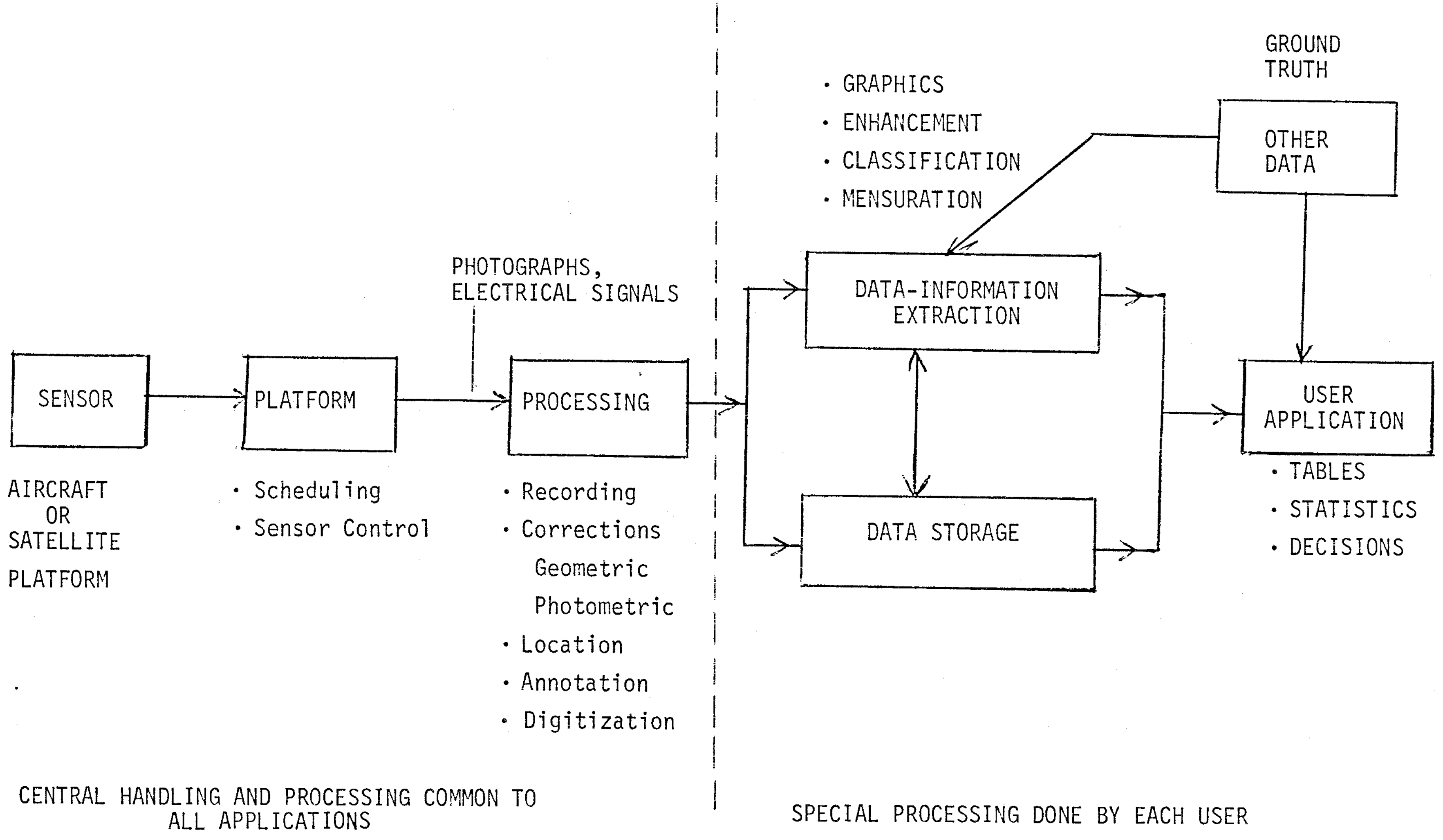

Figure 15: DIAGRAM OF DATA FLOW AND DATA PROCESSING IN REMOTE SENSING

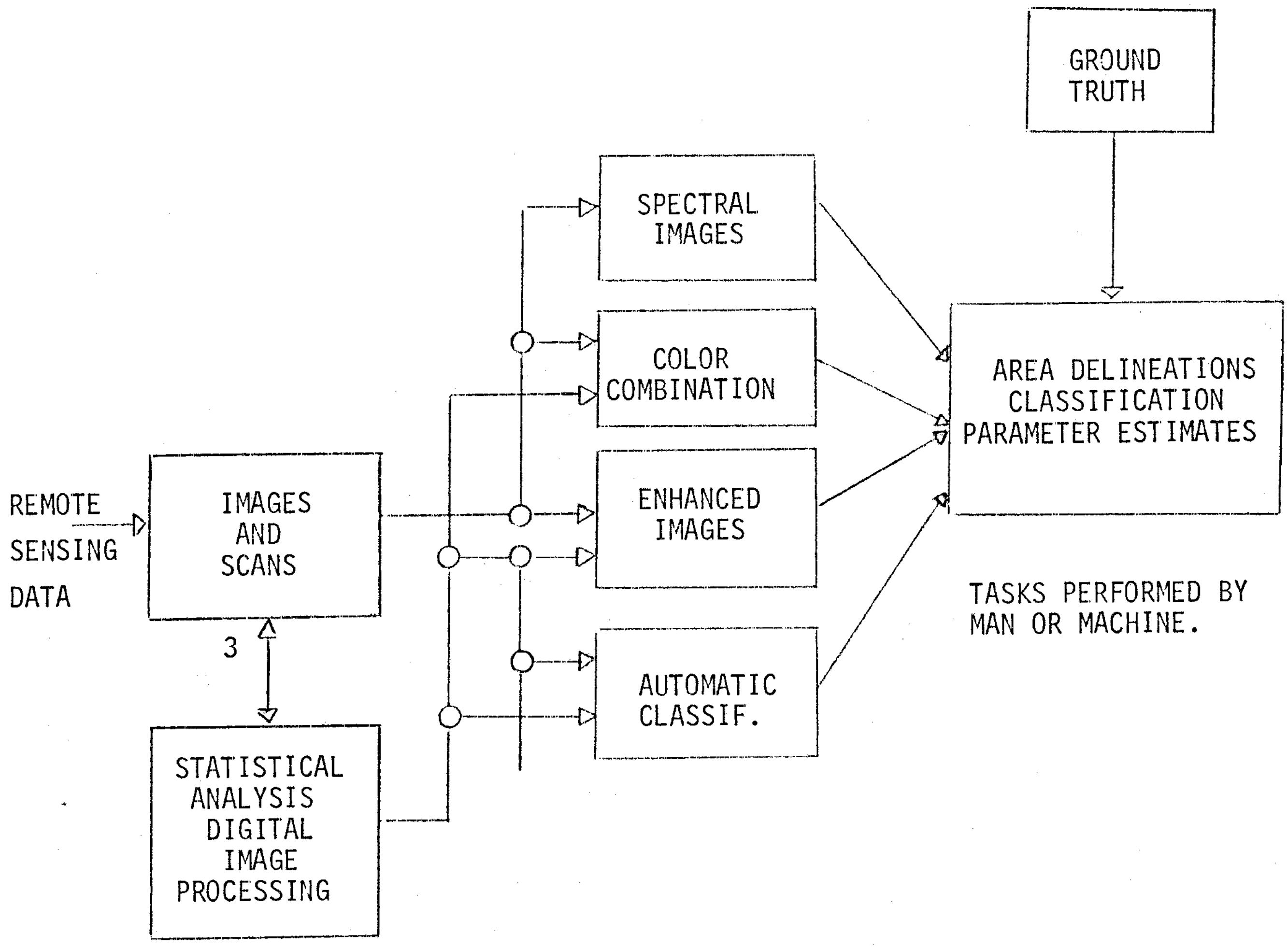

Figure 16: INFORMATION EXTRACTION

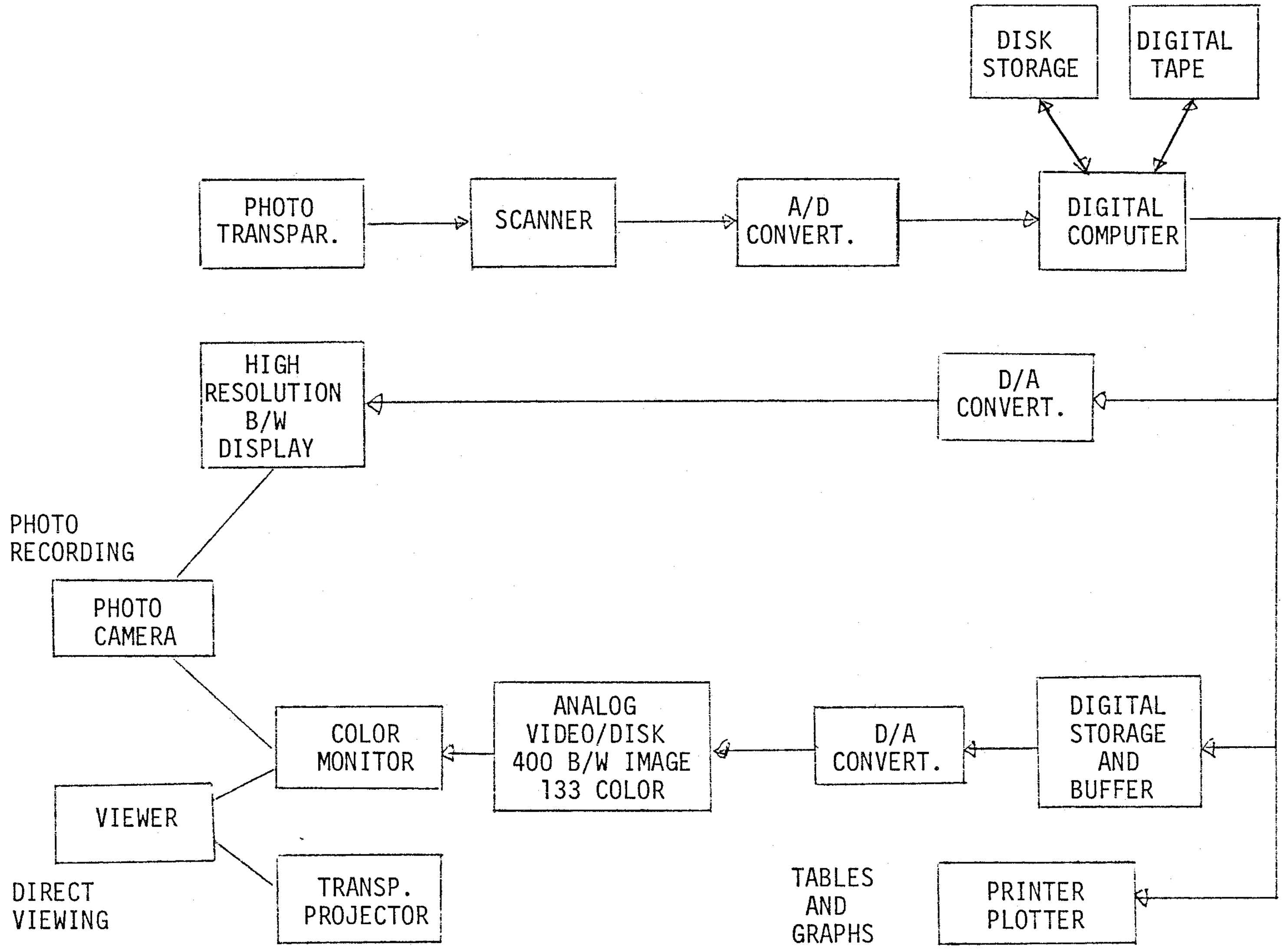

Figure 17. TYPICAL DIGITAL IMAGE PROCESSING FACILITY

## IV. Applications of Remote Sensing To Water Resources

In this section we discuss some of the applications of the tools and techniques of remote sensing to water resources monitoring. An overview of recent advances has been presented by Salomonson (1974). Our emphasis here is different and reflects the interests of HEC. We shall survey rapidly some of the work and the results in four distinct areas of application of remote sensing:

1. Rainfall estimation
2. Snow cover monitoring
3. Water quality monitoring
4. Hydrologic modeling and runoff computation

The work reviewed ranges from quite basic in the study of physical mechanisms of reflection absorption and scattering of electromagnetic radiation, to very applied, in use of estimated parameters for operational use. We shall principally emphasize results with actual or potential engineering applications.

In most cases the work being surveyed has made use of remote sensing data acquired by multipurpose sensors and some of the conclusions reached may be constrained by operational conditions of the satellite doing the remote sensing. Whenever possible we have acknowledged that fact in the specific applications. It is worthwhile however to enumerate the limitations and constraints of remote sensing as it applied to hydrologic problems.

1. Feature and parameter of interest not correlated with remote sensing observables. Among these are most of the hydraulics parameters and many subsurface parameters. Microwaves show promise for subsurface parameters but no results are available.

2. Limited resolution of remote sensors. This does not seem to be a fundamental constraint for most of the problems of interest in hydrology. However, satellite data is currently of insufficient resolution for urban watershed studies. Some of the work reported used low resolution data.

3. Frequency of coverage. This is currently a serious limitation in the use of existing satellites in real time problems in hydrology. Aircraft are not so limited. Evolution of the remote sensing technology seems to indicate that future satellites will also overcome this problem in many areas of the United States. The 18 days repeat cycle of ERTS-1 has constrained some of the application work reported.

4. Cloud cover. In some problems in hydrology one is concerned with monitoring the watershed parameters on a continuing basis. Thus, a cloud cover will render ineffective all sensors in the visible and infrared portions of the electromagnetic spectrum. Again, microwave techniques show promise and will probably be tried in the future.

5. Technical limitations. In some cases it is clear that the workers, by choice or by necessity, have chosen fairly primitive data processing techniques and their results may be limited by that constraint. It is difficult to assess what difference more sophisticated data processing techniques would have made in the solution of the same problem.

## A. Rainfall Estimation

In view of the complexity of rainfall patterns, the major advantage gained from satellite observations is the large spatial domain sensed from space geostationary satellites. In the future we may be able to obtain data on an almost global basis every 20 to 30 minutes. With visual and infrared sensors, near-global coverage is possible on a practically continuous day and night basis. Experiments have been done in which visible or infrared characteristics of clouds, as seen by sensors on satellite platforms, are classified and measured. The sensors do not see rain directly; neither do they respond selectively to the liquid and frozen drops to which the longer wavelength meteorological radar are sensitive.

### Areal Statistics Approach

These attempts to estimate precipitation from satellite pictures depend upon empirically established relationships between cloud categories and gage-measured precipitation. Follansbee (1973) monitors the rain-producing clouds--cumulonimbus, nimbostratus, and cumulus congestus--to the exclusion of the others. The method is simple: for each cloud type the ratio of cloud area to total area is multiplied by an empirical coefficient. These products are summed to obtain an average 24-hourly rainfall over the whole area. A 24-hour small-area estimate of rainfall can succeed only if the clouds seen in the satellite photograph are either representative or are the dominant cloud modes for the period. Under certain circumstances, the method is remarkably successful.

The same type of areal statistics approach has been developed and tested independently by Davis, Wiegman, and Serebreny (1971). Their goal was to objectively estimate total precipitation, including snow, for the Flathead River drainage basin in Western Montana. Data for the initial phase of their program consisted of daily precipitation from 17 basin stations and once-daily ESSA pictures, which were interpolated to give twice-daily cloud patterns. Each 12-hour period was assigned to one of nine cloud categories (including clear) based on satellite cloud characteristics. Daily total precipitation, weighted according to topography was used to determine average 12-hourly precipitation for each cloud type. Two periods, October-Decenter and April-June, were processed separately. Cloud type precipitation coefficients matched well, the largest difference in coefficients being 0.11 inch (25%), with an average difference of 0.02 inch. Verification for the spring period and extension of the method to two adjacent drainage basins was accomplished using 1970 daytime ESSA and NOAA visible images and nighttime Nimbus 4 window channel infrared images (Davis and Weigman, 1973). Total observed and estimated precipitation at the end of the 2 1/2 month test period were substantially in agreement, the differences being from 5% to 15% of the total observed precipitation. However, errors on shorter time intervals were considerably higher.

## Brightness Techniques

Several scientists have experimented with brightness as a key variable in the estimation of convective precipitation. Martin and Suomi (1971, 1972) tested the effectiveness of brightness enhancement as a technique for isolating areas of deep convection from background cloudiness in cloud clusters. Comparisons of brightness contoured ATS 3 images mapped to radar images showed that ". . . very bright regions of the ATS image correlate well with large radar echoes," and therefore, "properly enhanced ATS pictures isolate areas of deep convection."

Difficulties in using this method are that the change with time of cloud systems need to be taken into account and thus continuous coverage may be needed.

## Infrared Technique

A method which uses High Resolution Infrared (HRIR) satellite data was developed by Scherer and Hudlow (1971). Estimates whithin a factor of 2 of radar estimates have been obtained in some examples. Radar senses, within certain limitations, liquid water in the atmosphere. It has become fairly common practice to rely on quantitative radar precipitation estimates. Ground truth data is in existence and has been gathered by the Experimental Meteorology Laboratory (1972) in Southern Florida. For two months during the summer of 1972, the echo intensity of returns from two radars operating at 10 cm wavelength were recorded, as well as the raingage outputs from 40 recording raingages. ATS 3 satellite images were also gathered at the same time. Work is continuing under the sponsorship of NOAA in the evaluation of satellite rainfall estimation methods, as correlated with raingage and radar data. It seems likely that in the near future, rainfall estimates obtained by remote sensing will be available to complement standard raingage measurements in hydrologic applications.

## B. Snow Cover Monitoring

Several questions relative to snow cover and snowmelt are of interest to hydrologists:

The water content and the wetness of the snow packs in basins and watersheds and the seasonal and daily average basinwide snowmelt: Satellites have been used successfully to quantify some observables related to these primary objectives of hydrology in the monitoring of snow. For meterological satellites, this work has now been carried out for more than a decade.

In mountainous areas snow can be identified reliably because the drainage and terrain patterns are clear and stable, and thus the area of snow cover can be accurately located and measured; but very little data can be obtained on snow depth.

More recent satellites with higher resolution and infrared channels provide additional information to aid snow surveys. Increased resolution permits more accurate location of mountain snowlines. Because the near-infrared reflectivity of water is very low, wet snow can be identified by comparing visible and near-infrared images (Strong, et.al., 1971). Repetitive coverage can be used to differentiate clouds from snow because clouds move, but snow patterns are relatively fixed in position. In order to suppress clouds, digitized images from several days may be composited retaining only the minimum brightness value at each map position.

A number of workers are now exploring the usefulness of the improved imagery of the ERTS-1 satellite to measure snowcovered areas and the snowline altitude.

Barnes (1973) has reported results from the Central Arizona Mountains and the Southern Sierra Nevadas in California. Other preliminary work has been done in Switzerland (Haefner, et. al., 1973) and in Norway (Odegaard, et. al. 1974). Areal extend is determined in both cases from ERTS-1 data. Wiesnet et McGinnis (1973) compares ERTS-1 data with NOAA-2 VHRR (Very High Resolution Radiometer) and obtains useful comparable estimates of aeral extent of snow using either satellite. By recording runoff, Odegaard constructed a curve of inflow into reservoirs vs. percent of snow cover (during the snow melt season). No data is available on the usefulness of such a curve. All ERTS-1 investigators seem to concur that even for the limited task of mapping areal extent it is difficult to develop a complete automated system. Problems exist because of mountain shadows, exposure and steepness of slopes, time variations of radiometric values and forest masking of the snow cover.

Present observational systems do not, and cannot, supply the hydrologist with the snow cover data he needs for operational purposes. This has been principally to do with the spectral range of currently operational satellites. Among techniques that have been explored is the measurement of passive terrestial gamma radiation by aircraft (Peck, et. al., 1971). Promising results are obtained on snow water equivalent as determined by the corresponding attenuation of gamma ray radiation. The approach is limited to low flying aircraft.

Meir, et. al. (1971) has studies passive microwave techniques which may have the greatest potential for use in an operational snow survey satellite. Controlled experiments on the ground and from aircraft indicate that snow can be easily distinguished by its characteristic microwave radiation from most other land surface materials. The microwave emission from snow depends primarily on snow wetness, depth and density. Temperature, surface roughness, slope or terrain roughness, and the character of the underlying material appear generally to be of secondary importance. Thus, at this time, a limited amount of information on snow cover is available by remote sensing. For the future, operational use in this important area of application may result in the incorporation of currently available data into suitable models or in the launch of more specialized and suitable satellites to cover the microwave range.

## C. Water Quality Monitoring

The monitoring of water quality by remote sensing techniques has attracted considerable attention because of the increasing interest in water quality or water pollution and because of the difficulty of performing measurements over extensive areas by conventional means. Strandberg (1966) in some early work, classified the various types of water pollution and discussed the use of aerial methods and photography in the detection of sources of pollution. More recently, technical work has been done in the monitoring of sediments, either as carried by streams and rivers (Yarger, et. al., 1973), or in shallow bodies of water and tidal estuaries (Brown, et. al., 1973, Williamson, et. al., 1973, Klemas, et. al., 1973). The conclusions of these studies are that a ERTS type satellite is a suitable platform for observing suspended sediment patterns in water masses over large areas and for deducing gross current circulation patterns. Quantitative determination of suspended sediment load has also been done with some success (Yarger, et. al., 1973) in concentrations up to 1000 ppm. The detection of chlorophyll and algae is also possible. Quantitative work of engineering significance is hampered by effects of variation in illumination (sun angle for instance) by atmospheric selective attenuation and by the shallow penetration of water bodies by electromagnetic radiation. Very promising results have also been obtained in monitoring thermal discharges into water using the thermal infrared bands (Whipple, 1973) of up to 14 and 20 micron wavelength. Differences of 1°C are easily mapped and can be used with a mapping of water circulation data in the siting of generating plants and in thermal pollution monitoring (Borgese, et. al., 1973, Stingelin, et. al., 1973). Surface pollutants such as oil slicks can also be detected and monitored by remote sensing (Vizy, 1974).

Because of the scarcity of currently available monitoring of water quality, monitoring systems using a dense waterborne set of sensors have also been proposed (Pitchai, et. al., 1972). One would expect that in the future a rational design would involve a combination of onsite sensors (ground truth) and of remote sensing data.

### D. Hydrologic Modeling and Runoff Computation

There is very little reported work which considers directly the utilization of remote sensing data in watershed simulation models or in the empirical correlation of remote sensing data to runoff characteristics of watersheds.

Still, there is interest in the subject and considerable expectation of a successful and economically important application for remote sensing technology (Castruccio, 1974). Castruccio bases his expectation in good part on the work of Blanchard (1973). Blanchard uses the rainfall-runoff model of the Soil Conservation Service of the USDA. For a single event, the relation between rainfall P and runoff Q is modeled as

$$Q = \frac{(P - .2S)^2}{(P + .8S)}$$

with

$$S = \frac{1000}{CN} - 10$$

P and Q are in inches, CN is a dimensionless coefficient related to the hydrologic condition of the watershed, principally the soils. Thus, to predict Q, given P, one requires the knowledge of CN for the watershed. For a first group of gaged watersheds, Blanchard uses measured rainfall and runoff to compute CN. He then develops an empirical correlation between computed CN and parameters of remote sensing data acquired by ERTS-1. He found that correlation exists, using ERTS dry dormant scenes, between average values of MSS responses and runoff coefficients. He then uses the empirical relation between remote sensing observables and CN to predict CN on a new group of watersheds. Predictions of CN based on remote sensing data are significantly more accurate than the handbook hand calculations.

For watersheds with a significant vegetation cover, the technique is not successful because the remote sensing data is then principally dependent on vegetation rather than soils. Blanchard* indicates success in the extension of his work to the use of microwave passive sensing. Details are not available at this time.

The use of this technique to engineering problems is expected to be in the design of reservoirs and flood detention structures in the vicinity of ungaged watersheds in arid parts of the United States such as the southwest.

Ambaruch and Simmons (Ambaruch, et. al., 1973) of IBM proposed a systematic study of the use of remote sensing in watershed models. They based their study on a modification of the Stanford Watershed Model IV which includes a set of optimization routines. Preliminary work on the calibration phase of the project has been conducted using the data from watersheds in the Tennessee Valley. They examined the accuracy of the watershed model in simulating observed flows and carried out an analysis of the sensitivity of the model to the change of watershed parameters. They also discuss the anticipated remote sensing and ground truth requirements of their study. These requirements were informative and have been reproduced in Table 4. No information is available on the success and results of Ambaruch and Simmons' work after this preliminary phase.

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*Private Communication.

| WATERSHED CHARACTER-ISTICS | BASIN TOPO. | STREAM NETWORK | LAND COVER (Vegetation) | SOIL TYPE | SOIL DEPTH | CHANNEL AND FLOOD PLAIN TOPOGRAPHY | PRECIPITATION |
|---|---|---|---|---|---|---|---|
| REQUIRED RESOLUTION (METERS) | 30 | 15 | 90 | 30 | N/A | 3 | |
| SENSOR SYSTEM | Color Photos | Color Photos | Color Photos | Multispectral Scanner | Ground Survey | Ground Survey | Precipitation Gauges (Radar Potential) |
| SENSOR LOCATION | High Flying Aircraft | High Flying Aircraft | Low Earth Orbit | High Flying Aircraft | Ground | Ground or Very Low Flying Aircraft | Ground |

Table 4. Remote Sensing Requirements for Watershed Models, from Ambaruch, et. al, 1973.

Work has also been underway for the past year on the incorporation of remote sensing data into watershed models as a part of the University of California project "An Integrated Study in the State of California Using Remote Sensing Data" sponsored by NASA. This work, for specificity, reflects the operational and planning needs of the Department of Water Resources of the State of California as they relate to the California State Water Project.

Some investigation of the models used by the Department of Water Resources has been done: the River Forecast Center hydrologic model (RFC model, also known as the Sacramento model) and the California Cooperative Snow Surveys model (CCSS model) for the computation of runoff due to snowmelt. From this preliminary work and from conversations with personnel of the Department of Water Resources, a set of immediate, intermediate and long range objectives for the use of remote sensing data have been developed. At the present time, attention is focused on the monitoring of the snow cover and on the estimation of the evapotransporation potential of watersheds. Only partial results are available at this time.

A considerable amount of work has been done on areas which provide background and supporting information in the modeling of watersheds.

Work in engineering geology using ERTS data, thermal infrared sensors and radar imagery has been carried out by the Corps of Engineers and private corporations in the study of soils, geologic structures and faults. Concentrated and well documented work has been done on the classification of vegetation by remote sensing. In particular, we already mentioned the vegetation mapping in the wildlands (Krumpke, et. al., 1973) which has relevance to watershed modeling.

Land use and mapping using remote sensing has been carried out intensively since the launch of the ERTS-1 satellite, in which 10 or 12 categories are classified.* Of particular interest is the monitoring of the growth of urban areas quickly and efficiently over large areas.

## V. Identification of Future Remote Sensing Research in Hydrologic Engineering

The assessment of remote sensing applications in the general categories of hydrology and for the specific missions of the HEC has been the key objective in this study. One special task undertaken is the identification of needed research emphasis for the immediate future.

Current work of the Center indicates a major use of modeling techniques for the solution of operational and planning problems in the analysis of hydrologic systems, reservoir system analysis, quantity and quality of runoff from urban areas, water quality in rivers and lakes, river hydraulics and sediment movement in rivers.

In its planning analysis function the Center is concerned with the development of systems analysis procedures for application to water resources planning. The planning process is based on the extension of the experience acquired in the use of operational models and computer programs developed and maintained by HEC. Thus, a continuous link is provided from the models and programs in operational use to the planning and analysis of future projects.

At present, five fully operational hydrologic modeling programs have been developed and tested. These models and programs list as follows:

| | | |
|---|---|---|
| HEC | 1 | Flood Hydrograph Package |
| HEC | 2 | Water Surface Profiles |
| HEC | 3 | Reservoir System Analysis |

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*See the Proceedings of the ERTS-1 Symposium for details.

HEC 4 Monthly Streamflow Simulation
HEC 5 Reservoir System Operation for Flood Control

In addition, a new package called STORM, dealing with urban runoff phenomena is being tested for adoption.

These models and programs have generally evolved to their present status after lengthy experimentation, trial and use. The models and program packages incorporate physically-based components of the hydrologic system, such as the loss-rate computation in the Flood Hydrograph Package. That component in turn, uses physical parameters and constants determined empirically to fit recorded input-output relationships.

Remote sensing is a means of measurement or estimation of physical properties and physical conditions at and near the earth surface. For remote sensing to be a useful new tool in hydrologic engineering, therefore, the major and anticipated value will be in quantifying physically-based parameters.

In the short term, remote sensing utilization in hydrologic engineering can fit quite closely with current programs, models and practices of HEC. The objectives one can hope to achieve are:

a. To estimate the physical parameters used in modeling more accurately than currently;

b. to substitute a readily obtained physical value for the "default" values often used in models;

c. to indicate ways of incorporating remote sensing data by which the operational use of HEC models may be made more convenient or faster; and

d. to point out some areas in which physically-based data might replace empirical non-physical parameters in models, thus increasing the confidence placed in the results of simulation.

Two specific research projects which could be carried out with existing or readily available remote sensing data are outlined below:

Basin Modeling and Streamflow Forecasting: A Remote Sensing Case Study as applied to the simulation of the hydrologic response of a specific watershed using the HEC-1 Program Package.

The HEC-1 is a versatile, widely used package that is employed in the simulation of the hydrologic response of a watershed to specific storms. Some watersheds where the model has been used have been covered by the satellite ERTS-1, and where the physical size of all sub-basins is compatible with the limited resolution of the sensors (200 ft.). A case study is suggested in which: all simulation data is available; extensive remote sensing data is at hand; specific physical and non-physical parameters in the sub-basins are estimated or optimized to fit observed data. The purpose of the study would be to:

1. Examine the methods needed to enter remote sensing data on the watersheds into a form suitable for HEC-1 use. This has principally to do with the digitizing of parameters such as area with the least geometric correction, to make it useful for the purpose.

2. To examine the correlation of observed images to the hydrologic parameters assigned to each basin. This might require processing, combination and enhancement of imagery to make correlation more apparent. If warranted after a preliminary look, a statistical study would quantify the correlation of hydrologic parameters to observables.

3. To use as extensively as possible, non-optimized hydrologic parameters derived from remote sensing data into HEC-1 to assess the merit of using physically based data directly.

4. To combine the results of 1, 2, and 3 above with current practices in the use of HEC-1 to suggest procedures which would incorporate remote sensing data operationally and to assess such procedures as to speed, convenience, cost, etc.

The major advantage of such a study lies in the fact that much work is already done if one can use an already tried watershed subject.

### Urban Runoff Studies

The Corps of Engineers are involved in urban runoff studies on an increasing basis, resulting in the development of the computer program called STORM for the computation of runoff, runoff quality and treatment, storage and overflow of runoff in an urban watershed. The purpose of the program is to estimate the quantity and quality of urban runoff and of overflows to receiving waters for hypothetical storage and treatment rate. Although the program is intended as a planning and design took, the model which it implements has several components and parameters based on physical characteristics and which may be potentially correlated with remote sensing observations. These include: watershed areas, land use group, percent of area in various land use groups, percent of imperviousness in the group, coefficient of runoff in pervious areas and in impervious areas in each group.

Other parameters important in water quality modeling may also be correlated to remote sensing data.

A case study to determine the use of remote sensing data in this new subject seems desirable. Since data for the Castro Valley area has been acquired it is presumed that site might be best for the study. Satellite remote sensing resolutions are too great for this study and therefore, some imagery would need to be acquired.

The purpose of the study would be to:

1. Delineate land use, estimate acreages by remote sensing, and compare with ground truth. Remote sensing may be an effective means of surveying urban watersheds.

2. Undertake correlation study of STORM parameters with observed and classified land use groups.

3. Examine procedures which combine remote sensing data and the STORM program to compute runoff and quality and compare to measured values.

4. To gain insight into the importance of physical parameters in urban runoff studies.

Other areas of research which show promise may require a longer lead time because adequate remote sensing data and hydrologic models are lacking. In the area of remote sensing the increase use and availability of infrared and microwave sensing should have a significant effect on the range of hydrologic applications of remote sensing. One such application of specific interest to HEC is in real-time operation and management of reservoirs, in which the ability to sense watersheds and hydrologic parameters in spite of cloud cover is important.

Longer range applications of remote sensing may also result from a re-examination of the models currently used by hydrologists. A case to the point is in the work of Blanchard discussed earlier in which an empirical correspondence was discovered between remote sensing data and runoff, through a simple model. A more systematic examination of the reasons for this success may lead to a model directly based on remote sensing observables, which would be of interest in a preliminary planning stage, in the case of ungaged watersheds. In summary, we have now available, in remote sensing data, new information of such a nature and extent that a significant long range impact will occur in hydrologic engineering. Remote sensing will complement the sophisticated engineering practices which in their current state have to circumvent nonexisting physical data. How this long range impact will manifest itself in detail is not easy to see, but we believe that a step by step incorporation into existing engineering practice will allow the understanding and confidence on which long term progress is based.

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## Sources of Information on Remote Sensing Applications

Since remote sensing is a new and interdisciplinary field, the information available is scattered among journals, proceedings of conferences and symposia, etc. We list some of these sources of information.

Journals: Most have infrequent publications in the field.

--Remote Sensing.

--American Society of Photogrammetry

Photogrammetric Engineering

--Inst. of Elect. and Electronic Engineers (IEEE)

Proceedings

Transactions on Geoscience and Electronics

Transactions on System Science and Cybernetics

--Am. Soc. Civil Engineers (ASCE)

Journal, Surveying and Mapping Division

--Am. Institute of Aeronautics and Astronautics

--Am. Geological Institute

Conferences and Symposia

--Ann Arbor, Michigan: Interm. Symposium on Remote Sensing of the Environment (since 1962)

--Tullahoma, Tennessee. Annual Remote Sensing Conference (since 1972)

--NASA Sponsored Symposia. There have been 3 ERTS related symposia. Other conference proceedings and remote sensing technical publications are available from NASA.

--Seminar on "Operational Remote Sensing", Houston, Texas, February 1972.

--AWRA Symposium on "Remote Sensing and Water Resources Management", 1973.

--Symposium on Manag. and Utilization of Remote Sensing Data, Sioux Falls, South Dakota, 1973.

## U.S. Laboratories Active in Remote Sensing

--Laboratory for Applications of Remote Sensing (LARS), Purdue University.

--Environmental Research Institute of Michigan (ERIM)

--Center for Remote Sensing Research, University of California, Berkeley.

--Jet Propulsion Laboratory, California Institute of Technology.

--Stanford Research Institute.

--Kansas Center for Remote Sensing (KRES), University of Kansas.