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Detecting Landfill Leachate Contamination Using Remote Sensors

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DETECTING LANDFILL LEACHATE CONTAMINATION USING REMOTE SENSORS

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FOREWORD

Protection of the environment requires effective regulatory actions that are based on sound technical and scientific information. This information must include the quantitative description and linking of pollutant sources, transport mechanisms, interactions, and resulting effects on man and his environment. Because of the complexities involved, assessment of specific pollutants in the environment requires a total systems approach that transcends the media of air, water, and land. The Environmental Monitoring and Support Laboratory-Las Vegas contributes to the formation and enhancement of a sound monitoring data base for exposure assessment through programs designed to:

- develop and optimize systems and strategies for monitoring pollutants and their impact on the environment

- demonstrate new monitoring systems and technologies by applying them to fulfill special monitoring needs of the Agency's operating programs

This report describes the use of aerial photography and multispectral scanners for detecting environmental anomalies that may indicate contamination of ground and surface waters from landfill leachate. Such remote sensing techniques can provide perspective and cost effectiveness not always available with other investigative techniques for monitoring landfills for environmental impact. The report can be used by novice and experienced individuals alike to plan and guide selection of sensors and data collection and analysis procedures. Governmental and commercial agencies should find it useful in considering and managing landfill monitoring activities.

George B. Morgan
Director
Environmental Monitoring and Support Laboratory
Las Vegas

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SECTION 1

INTRODUCTION

Remote sensing as a means for identifying contamination of ground and surface water by landfill leachate has potential for a wide range of applications. Most of these applications can be grouped as some type of regulatory monitoring. This term needs to be defined very broadly, however, to encompass a range of applications from a local environmental group's study of a single landfill through a state or federal program of conformance monitoring. The objective of regulatory monitoring is to ascertain whether a particular landfill or other waste disposal site is contributing to ground or surface water pollution by leachate. Since regulatory monitoring is basically an adversary relationship, there may be need for additional verification of contamination by specific sampling and testing of water bodies suspected of being contaminated.

A second general area of applications is in control monitoring where the objective is to define what would otherwise be unknown sites of pollution. Control monitoring would usually be done for an owner/operator group or its agent and would be justified as the most effective or least-cost method for gathering information on leachate contamination. Unlike regulatory monitoring which applies only to existing disposal sites, control monitoring is an appropriate part of the design and development activities for a landfill. As such, the limit of control monitoring would be the use of remote sensing data in site evaluation prior to development.

The amount of leachate produced at a particular waste disposal site, and the subsequent distribution of the leachate on and off the site, depend on a wide range of site-specific characteristics. The nature of the waste material, as well as many design and management procedures, can influence the quantity of leachate produced and its distributuion; but the two most important characteristics of the site are the climate and geological setting. In some areas there is little if any potential for leachate production from waste disposal. Here there may be little need or justification for monitoring using remote sensors. In humid areas of moderate to heavy rainfall, on the other hand, most land disposal areas will produce leachate. Depending upon the effectiveness of leachate control systems, the impact on ground and surface water quality can range from none to very severe.

Compared with alternatives, remote sensing methods have the potential to monitor the impact of leachate on ground and surface water quality at lower cost and increased convenience. Remote sensing will often be only a part of the total pollution evaluation procedure, however. On-site sampling for verification will usually be appropriate or necessary.

An advantage of the remote sensing approach is in the complete areal coverage provided. Leachate contamination of surface water near the land disposal site can usually be identified by almost any monitoring approach; but contamination away from the site, especially if this is associated with subsurface flow of groundwater, often goes undetected. Remote sensing has particular application to this problem, both in regulatory and control monitoring.

The objective of this report is to describe a remote sensing approach for detecting contamination of ground and surface waters by landfill leachate. The report addresses a number of specific elements of a remote sensing application as well as the overall methodology. Among the topics covered, Section 5, are:

a) leachate indicators for sensing
b) spatial and temporal aspects of leachate detection
c) sensor evaluation and selection
d) flight parameters and mission design
e) analysis and interpretation of remotely sensed data

In Section 6 a group of illustrations of remote sensing applications to detect leachate is presented. These illustrations are taken from the data collected during a research program of remote sensing missions supported by the National Aeronautics and Space Administration (NASA) and the Environmental Protection Agency (EPA). Preliminary funding of this research program were reported by Sangrey et al., (1976). The research program flights were conducted over a group of approximately twenty landfills representing a broad range of management and geological settings. All of the study sites were from the same general climatological setting, however, which was typical of the humid northeastern United States. Although all of the illustrations are from this type of area, the report has been prepared for general application regardless of climate or geological conditions.

The conclusions and recommendations for establishing a remote sensing monitoring program are presented in Sections 3 and 4.

SECTION 2

SUMMARY

A methodology for using remote sensing to detect landfill leachate contamination of ground and surface water is described. The problem is addressed without regard to specific geographical or climatological regions.

Among the topics covered are leachate indicators, spatial and temporal aspects of leachate detection, sensor selection, flight design and data interpretation. Specific methodologies for using remote sensing to detect leachate under various situations are described. These range from survey monitoring of individual landfills to comprehensive programs for regulatory monitoring of many landfills.

Data from a field research and demonstration project are used to illustrate the use of remote sensors to detect leachate.

SECTION 3

CONCLUSIONS

Remote sensing systems can be effective in detecting contamination of ground and surface waters by leachate. The major advantages are the lower cost and increased convenience and effectiveness of remote sensing techniques compared with alternatives.

Several direct or indirect characteristics of leachate pollution serve as the best indicators for detection if they can be related spatially to the landfill. These include wetness, gaps in a vegetative or snow cover, and other spectrally reflective or emissive anomalies from water, soil, rock, vegetation or snow.

Spatial, spectral as well as temporal characteristics of leachate contamination influence the selection of a particular sensor and the design and flight parameters for a mission. Aerial photography at a scale of 1:5,000 or larger is recommended for most monitoring programs, although a variety of film-filter combinations might be used. Pre-dawn, thermal infrared coverage may be a useful complement to the photographic data.

Certain temporal factors such as time of day, season of the year and climate are important elements in design of a remote sensing program to detect leachate.

The specific objective of a monitoring program, the number of sites to be studied, and the intended use of the acquired information all influence the specific elements of a monitoring program. From the standpoint of cost effectiveness, the most important application of remote sensing is to provide an indication of where to look for leachate contamination. Ground sampling and analysis will usually be necessary to confirm the condition.

SECTION 4

RECOMMENDATIONS

The following recommendations are made for implementing a remote sensing monitoring program to detect leachate contamination of ground and surface water.

Leachate Indicators for Sensing

From among a large group of potential indicators of leachate contamination, several are most important in detection using remote sensors. Leachate contamination is most consistently evidenced by the occurrence of either gaps or wetness on the ground surface. Gaps in snow or vegetative cover can be closely associated with a landfill or at some distance. They are usually caused by wetness, toxicity or heat.

As with gaps, wetness patterns can radiate from the landfill or occur in isolated spots at various distances away from the disposal area.

Spectral anomalies from conditions such as uniquely colored water or vegetation have potential for use in detecting leachate but are not as consistent indicators as gaps or wetness. Similarly, stressed vegetation and thermal anomalies have some particular usefulness but not as a consistent indicator.

Sensors

The most generally applicable sensor for detecting leachate contamination is aerial photography at a scale of 1:5,000 or larger. Several film formats can be used in different situations ranging from 35 mm to 23 by 23 cm. Cartographic quality mapping cameras may not be required for leachate monitoring programs, but can provide higher quality imagery than others.

A variety of film-filter combinations could be used to detect leachate, with ultraviolet, visible and near-infrared spectral wavelengths potentially useful for detecting certain indicators. Conventional color film, color infrared film and panchromatic film with spectral filters could be used. Color infrared film is the most generally applicable if only one camera is available.

Multispectral scanners could be used in place of photographic systems, but this is probably not a least cost or most effective sensor. Thermal infrared scanners may have practical applications in selected cases where the leachate is significantly hotter than other water bodies. Thermal scanner data should be collected during pre-dawn periods to maximize contrast of the target.

Scale and Flight Parameters

The photographic scale of 1:5,000 should permit detection of leachate contamination features of about one meter in minimum dimension. The necessary flying height above ground and the areal coverage will vary with camera focal length. Larger film formats are clearly preferred for major monitoring programs.

Photographic sensing for leachate should be conducted with high sun angles to minimize shadows and to maximize the amount of reflectance.

Flight parameters for a thermal scanner should be selected for a target as small as one-half meter in size and with a net temperature difference of approximately 3°C compared with the background. Thermal scanner missions should be flown in pre-dawn periods.

Temporal Aspects

There is a clear advantage to conducting a leachate detection program during certain seasons of the year; in general, when there is a maximum production of leachate and a minimum of interference from other surface features such as vegetation or heavy snow. Since weather and climate are the major determinants of leachate production for a particular landfill design, the greatest potential for detection is during wet periods, with dry and frozen periods having the least potential.

The ideal season will depend on the climate and location. In temperate humid areas, the best time for a sensing program will usually be early spring, prior to heavy vegetation. In warmer southern areas, midwinter may be best; while in dry arid regions, there may be no appreciable potential for detecting leachate because little or none is produced.

Thermal scanners may be particularly effective in winter.

Analysis of Data

Photographic transparencies or prints can be analyzed individually or in pairs if stereoscopic coverage is available. Magnification, especially through variable magnification stereoscopes, is desirable.

Several enhancement procedures can be used with photographic film data, including density slicing, additive color viewing, and subtractive color viewing with diazo. In general, the more costly computer analysis procedures will not necessarily provide a proportional increase in information.

Detection Methodology

The specific objective of a remote sensing program will determine the most appropriate detection methodology. Two cases can be defined. One is typical of regulatory monitoring where a general survey of a large number of waste disposal sites is conducted to evaluate conformance to regulations. The major elements in this type of methodology are:

Step 1. Obtain topographic maps which locate landfills to be monitored.

Step 2. Fly 1:5,000 scale, aerial photographic coverage of each landfill using film-filter combinations which record ultraviolet, blue, green, red, and near-infrared radiation.

Alternative A

Step 3A. Analyze photographs to identify the most probable locations of leachate breakout or contamination.

Step 4A. Field check these most probable locations.

Step 5A. Take appropriate action based on verification of leachate contamination.

Alternative B

Step 3B. Fly pre-dawn thermal infrared scanner coverage of all landfills.

Step 4B. Analyze thermal and photographic data.

Step 5B. (see Step 4A).

Step 6B. (see Step 5A).

Alternative C

Step 3C. (see Step 3A).

Step 4C. Based on the photographic analysis, select landfills to be overflown with pre-dawn thermal infrared scanner coverage. Conduct this sensing at a dry or frozen, low vegetation period to maximize effectiveness of this sensor. Field check <u>other</u> landfills as outlined in Steps 4A and 5A.

Step 5C. (see Step 4B).

Step 6C. (see Step 4A).

Step 7C. (see Step 5A).

The second general type of detection methodology applies to comprehensive control monitoring. The major elements in this type of monitoring are:

Step 1. Obtain all available background information on the landfill site, including topographic, soil and geologic maps and reports.

Step 2. Obtain aerial coverage of the undeveloped landfill site and coverage flown periodically during the development of the site.

Step 3. Analyze available aerial coverage, together with background information, to identify the most probable locations of leachate breakout or contamination.

Step 4. Field check the landfill site(s), concentrating on those locations identified in Step 3.

Step 5. Fly new aerial photographic coverage of the landfills using one or more film-filter combinations which are appropriate for the expected spectral leachate indicators.

Step 6. Analyze the new photographs, together with the other aerial and background data, to identify to most probable locations of leachate breakout or contamination.

Step 7. Field check the landfill site(s).

Step 8. Upon verification of leachate contamination, plan remedial measures.

(Steps 9 through 12 are optional extensions)

Step 9. Fly pre-dawn, thermal infrared coverage of the landfills.

Step 10. Analyze the thermal infrared data, together with all photographic and background data, to identify any additional locations of suspected leachate breakout or contamination.

Step 11. Field check any new locations of suspected leachate.

Step 12. If required, modify planned remedial measures.

SECTION 5

REMOTE SENSING OF LEACHATE

5.1 AN INTRODUCTION TO LAND DISPOSAL OF SOLID WASTE

Landfilling is a common and appropriate means for disposing of a wide variety of solid waste. Materials commonly placed in a landfill include municipal and industrial solid waste, construction and demolition debris, sludges and dredging spoil as well as many unique substances peculiar to certain locations. The major advantages of landfill disposal methods are low cost, convenience and a lack of acceptable alternatives. Among the major disadvantages is the production of leachate with potential for contamination of ground and surface water. Other methods of land disposal of solid waste, including open dumping, may also develop leachate and, in most cases, the methodology presented in this manual can be applied in these situations as well.

Leachate, as used in this report, is an extremely variable liquid constituent of landfill or other waste disposal (EPA, 1975). Leachates can be characterized by their physical, chemical or biological properties, Table 5.1. However, it is important to appreciate that the variability of leachate is dependent upon the specific organic and inorganic substances dissolved in the leachate at a particular time and place. To a large degree the particular characteristics of a leachate depend on the source material at the land disposal site. The characteristics of a leachate change, however. There is a general tendency to change with time or age of the landfill and there may also be a significant seasonal change or fluctuation, Figure 5.1.

Leachates can be positively controlled at the site of land disposal, or they can flow from the site as part of the ground and surface water regime. The extent to which leachate becomes an unacceptable pollutant of ground or surface water is primarily dependent upon the quantity of leachate and the effectiveness of various attenuation mechanisms, including dilution, decomposition and several fixation mechanisms, particularly in the soil (Roberts et al., 1976). In most cases it is not only leachate but also leachate-contaminated waters which are the objective of a monitoring program.

To provide a basis for considering the application of remote sensing technology to monitoring leachate it is appropriate to illustrate how and where leachate is produced, Figure 5.2. The amount of leachate produced by direct decomposition of wastes is usually insignificant. Most leachate is produced when water flows through the waste either as a result of infiltration of precipitation or through irrigation from ground or surface waters. Unless a control system is used, leachate will exit a landfill in several ways. Surface runoff is often contaminated by leachate, as illustrated in Figure 5.2. Seeps from the side or toe of a landfill are also common and are a major source of contamination in surface waters. Groundwater is contaminated by leachate when

TABLE 5.1. LEACHATE INDICATORS

Physical	Chemical		Biological
	ORGANIC	INORGANIC	
Appearance	Phenols	Total Bicarbonate Solids (TSS, TDS)	Biochemical Oxygen Demand (BOD)
pH	Chemical Oxygen Demand (COD)	Volatile Solids	Coliform Bacteria (Total, fecal; fecal streptococcus)
Oxidation-Reduction Potential	Total Organic Carbon (TOC)	Chloride	Standard Plate Count
Conductivity	Volatile Acids	Sulfate	
Color	Tannins, Lignins	Phosphate	
Turbidity	Organic-N	Alkalinity and Acidity	
Temperature	Ether Soluble (oil & grease)	Nitrate-N	
Odor	MBAS	Nitrite-N	
	Organic Functional Groups as Required	Ammonia-N	
	Chlorinated Hydrocarbons	Sodium	
		Potassium	
		Calcium	
		Magnesium	
		Hardness	
		Heavy Metals (Pb, Cu, Ni, Cr, Zn, Cd, Fe, Mn, Si, Hg, As, Se, Ba, Ag)	
		Cyanide	
		Fluoride	

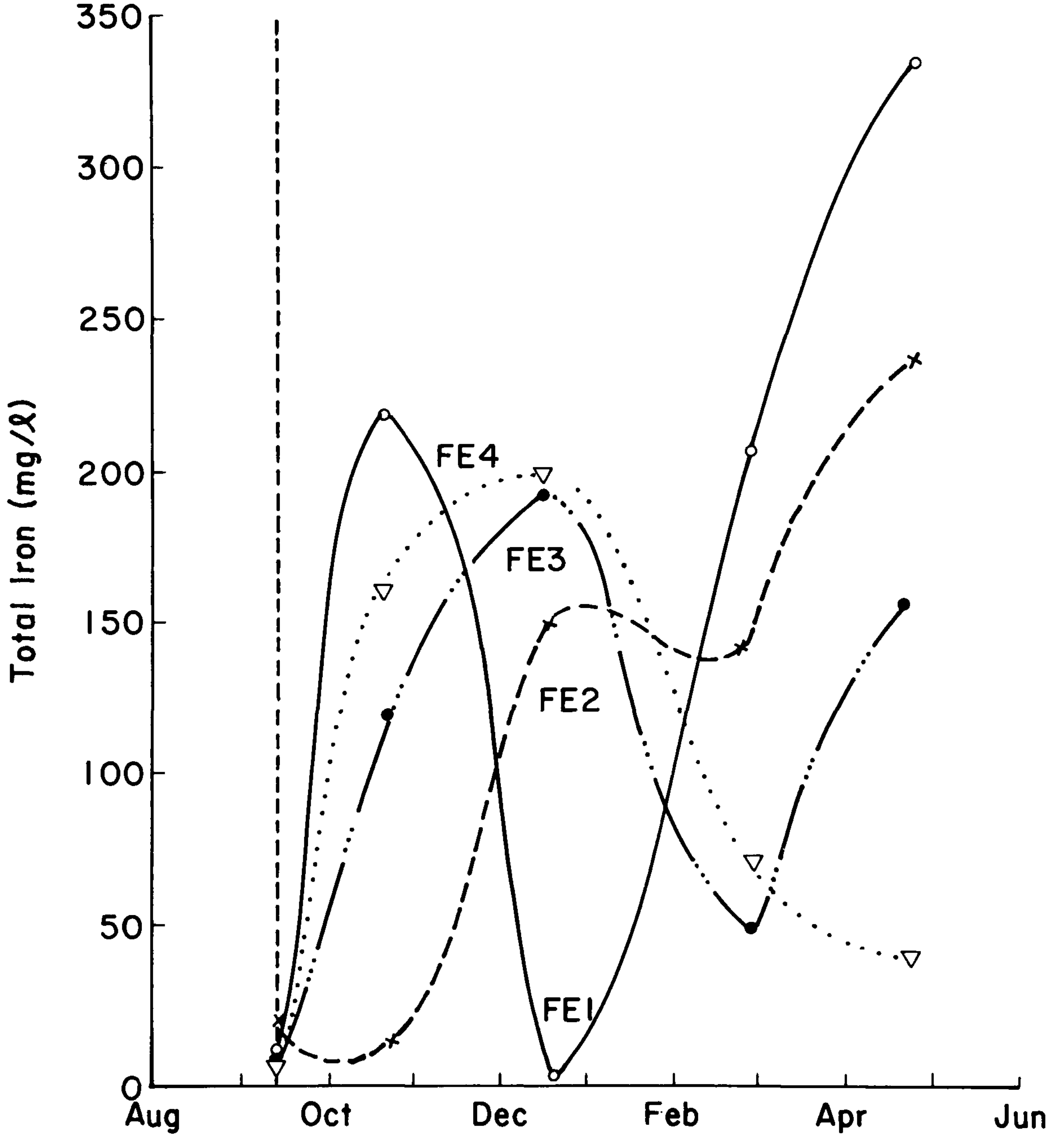


FIGURE 5.1. FLUCTUATION OF A TYPICAL LEACHATE CHARACTERISTIC (IRON) WITH TIME, AT FOUR SAMPLING POINTS, AT A LANDFILL IN SOLON, N.Y.

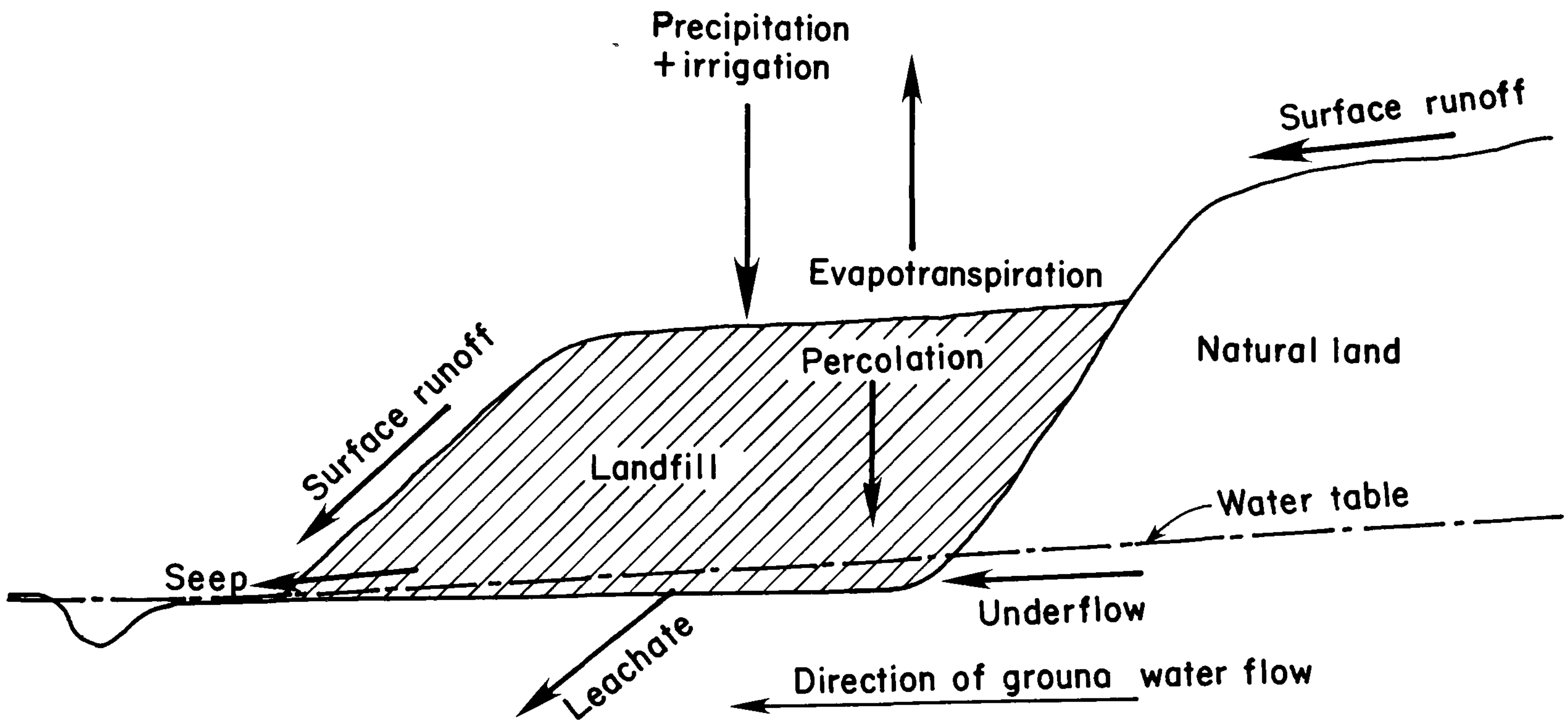


FIGURE 5.2. LANDFILL WATER BALANCE (AFTER WEHRAN ENGINEERING CORP. AND GERAGHTY & MILLER, INC., 1976)

the water table intersects a landfill or when leachates flow to the groundwater without sufficient attenuation. In this case the flow and ultimate destination of the contaminated groundwater is of concern.

A variety of methods is used to control the production of leachate in a landfill including surface or subsurface drains and low permeability blankets or barriers (American Society of Civil Engineers, 1976). These devices can significantly alter the flow of leachate as well as ground and surface water around a land disposal site and must be considered when using remote sensing systems. In many situations it is also appropriate to conduct a more quantitative analysis of the hydrogeologic regime associated with a land disposal site as part of a total monitoring program (Wehran Engineering and Geraghty & Miller, Inc., 1976). The methodology for doing such an analysis is well-developed and can be found in numerous references. In general a quantitative analysis of the water balance (Chow, 1964; EPA, 1975), surface and subsurface hydrology of site (Landon, 1969) requires specific on-site study by a professional geologist or groundwater engineer. A qualitative description of the general flow regime is usually helpful as part of a remote sensing program, however, and may not require the assistance of other professionals.

5.1.1 Classification of Land Disposal Sites

Leachate contamination may occur in many ways, depending on the climate, geological setting and control methods used. The effectiveness of remote sensing systems to monitor leachate contamination under these different conditions varies widely. If leachate is abundant and contamination of water at a specific location can be anticipated, detection through remotely sensed data is very straightforward. In other cases, however, the amount of leachate contamination at or near the ground surface is small, or the breakout may be quite remote from the actual land disposal site. The use or usefulness of remote sensors under these conditions will be very different. When evaluating the application of remote sensing systems to monitor leachate contamination, it is important to appreciate under what conditions these systems can be used effectively and under what conditions it is unreasonable to expect positive results.

The potential for leachate contamination from a land disposal site, and the related potential for applying remote monitoring technology, can be used as the basis for a classification system applied to the sites and their mode of operation. As outlined in Table 5.2, these classification units will be used in the development of the methodology in this report.

A detailed discussion of remote sensing applications in this classification system is presented in the body of this report. In general, however, the potential for applying remote sensing can be anticipated. Units A and B present no problem from leachate contamination, and if contamination develops in C, it will be undetectable using remote sensors. These three units are, therefore, one set with little or no potential for monitoring leachate contamination using remote sensing systems. For an inundated fill, D, there may or may not be a detectable expression of leachate pollution, while for conditions classified as E, F, or G there is a leachate contamination problem which can be identified using remote sensors. Conditions of subsurface flow away from a site, E, may be the most important application of remote sensing to define previously unknown problems, whereas F and G may be common conditions for monitoring to check conformance to regulations.

Table 5.2. Classification of Landfill Sites for Application of Remote Sensing to Monitor Leachate Contamination

Unit	Site Description
A.	No leachate production
B.	Effective positive leachate control and removal
C.	High permeability subsoil draining to a very deep groundwater
D.	Inundated land disposal with drainage into water
E.	Subsurface flow of leachate away from the site to break-out at ground surface
F.	Breakout through seep at the landfill toe
G.	Breakout through seep on the face or top of the landfill cover material

5.1.2 Characteristics of Leachate Detectable Using Remote Sensors

Leachate-contaminated water has several physical and chemical characteristics which are potentially detectable using a variety of remote sensors. Few of these chemical characteristics of leachate, Table 5.3, have any potential for direct measurement using remote sensors, however, many indirect consequences of the leachate chemistry are detectable. The chemical nature of leachate can cause stress in biota. Biological stress can be either positive, in which case it encourages growth, or it can be negative and toxic. Changes in the surface and subsurface hydrology near a land disposal area can also cause vegetative stress. This stress can be independent of leachate pollution, as in the case of surface drainage changes upstream of a landfill, or the vegetative stress can be a result of both contamination and hydrologic change. Regardless of the cause, vegetative stress can often be detected using remote sensors. The problem is to separate stress caused by leachate pollution from other stresses.

Leachates are sometimes distinctive because of color. The red-orange color of ferric iron compounds is one example while the unique color of some biological growths in leachate-contaminated water may be another. Although these colors can be detected using various sensors, the colors themselves are

TABLE 5.3. CHEMICAL CHARACTERISTICS OF LEACHATE

CONSTITUENT	RANGE* (mg/l)	RANGE† (mg/l)	RANGE‡ (mg/l)	LEACHATE§		WASTE WATER§	RATIO§
				FRESH	OLD		
Chloride (Cl)	34-2,800	100-2,400	600-800	742	197	50	15
Iron (Fe)	0.2-5,500	200-1,700	210-325	500	1.5	0.1	5,000
Manganese (Mn)	.06-1,400	--	75-125	49.	--	0.1	490
Zinc (Zn)	0-1,000	1-135	10-30	45	0.16	--	--
Magnesium (Mg)	16.5-15,600	--	160-250	277	81	30	9
Calcium (Ca)	5-4,080	--	900-1,700	2,136	254	50	43
Potassium (K)	2.8-3,770	--	295-310	--	--	--	--
Sodium (Na)	0- 7,700	100-3,800	450-500	--	--	--	--
Phosphate (P)	0-154	5-130	--	7.35	4.96	10	0.7
Copper (Cu)	0-9.9	--	0.5	0.5	0.1	--	--
Lead (Pb)	0-5.0	--	1.6	--	--	--	--
Cadmium (Cd)	----	--	0.4	--	--	--	--
Sulfate (SO_4)	1-1,826	25-500	400-650	--	--	--	--
Total N	0-1,416	20-500	--	989	7.51	40	25
Conductivity (μmhos)	----	--	6,000-9,000	9,200	1,400	700	13
TDS	0-42,276	--	10,000-14,000	12,620	1,144	--	--
TSS	6-2,685	--	100-700	327	266	200	1.6
pH	3.7-8.5	4.0-8.5	5.2-6.4	5.2	7.3	8.0	--
Alk as $CaCO_3$	0-20,850	---	800-4,000	--	--	--	--
Hardness tot.	0-22,800	200-5,250	3,500-5,000	--	--	--	--
BOD_5	9-54,610	--	7,500-10,000	14,950	--	200	75
COD	0-89,520	100-51,000	16,000-22,000	22,650	81	500	45

*Office of Solid Waste Management Programs, Hazardous Waste Management Division. An environmental assessment of potential gas and leachate problems at land disposal sites. Environmental Protection Publication SW-110 of. [Cincinnati], U.S. Environmental Protection Agency, 1973. 33 p. [Open-file report, restricted distribution].

†Steiner, R. C., A. A. Fungaroli, R. J. Schoenberger, and P. W. Purdom. Criteria for sanitary landfill development. Public Works, 102(2): 77-79, Mar. 1971.

‡Gas and Leachate from land disposal of municipal solid waste; summary report. Cincinnati, U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, 1975. (In preparation).

§Brunner, D. R., and R. A. Carnes. Characteristics of percolate of solid and hazardous waste deposits. Presented at AWWA American Water Works Association 94th Annual Conference, June 17, 1974. Boston, MA 23 p.

not unique in the natural environment and neither are there certain unique colors associated with all leachates. Many leachates and leachate-contaminated waters are clear. There is, nevertheless, potential for using certain spectral bands in leachate detection under some conditions.

Leachate-contaminated water can also have surface coatings of lipids or biological growths which can be detected using remote sensors. This may be a particularly important target for inundated land disposal areas (Classification D) where few other indicators can be used.

There is lively biological activity in both landfill and leachates which produces excess heat. Leachates can have a very high temperature and leachate-contaminated ground or surface water can have a distinctive temperature even when some distance from the land disposal site. From the standpoint of remote sensing potential, the significance of heat in leachate is the resulting difference between the temperature of leachate-contaminated and uncontaminated ground and surface waters. As illustrated in Figure 5.3, the temperature of leachate-contaminated water can be a potential target under certain conditions of time and climate.

The potential for using remote sensing systems to indicate certain characteristics of leachate-contaminated waters is summarized in Table 5.4. The remainder of this report will critically evaluate this potential. It is important to realize that remote sensing is only part of a total monitoring system. For a general survey to check compliance with certain regulations, there is considerable potential for using remote sensors. Similarly there are clearly applications to areas of complex geological setting. There is little potential, however, for collecting legally admissible conformance data using remote sensors. From the standpoint of cost effectiveness, the most important application of remote sensing is to provide an indication of where to look for leachate contamination. Ground sampling and analysis will usually be necessary to confirm the condition.

5.1.3 Examples of Applications

Illustrations of the successful application of remote sensing to the detection of leachate-contamination are presented in Section 6. The illustrations, and particularly the photographic plates, will be referenced in this section where the theoretical limits to application of the sensors and methods are described.

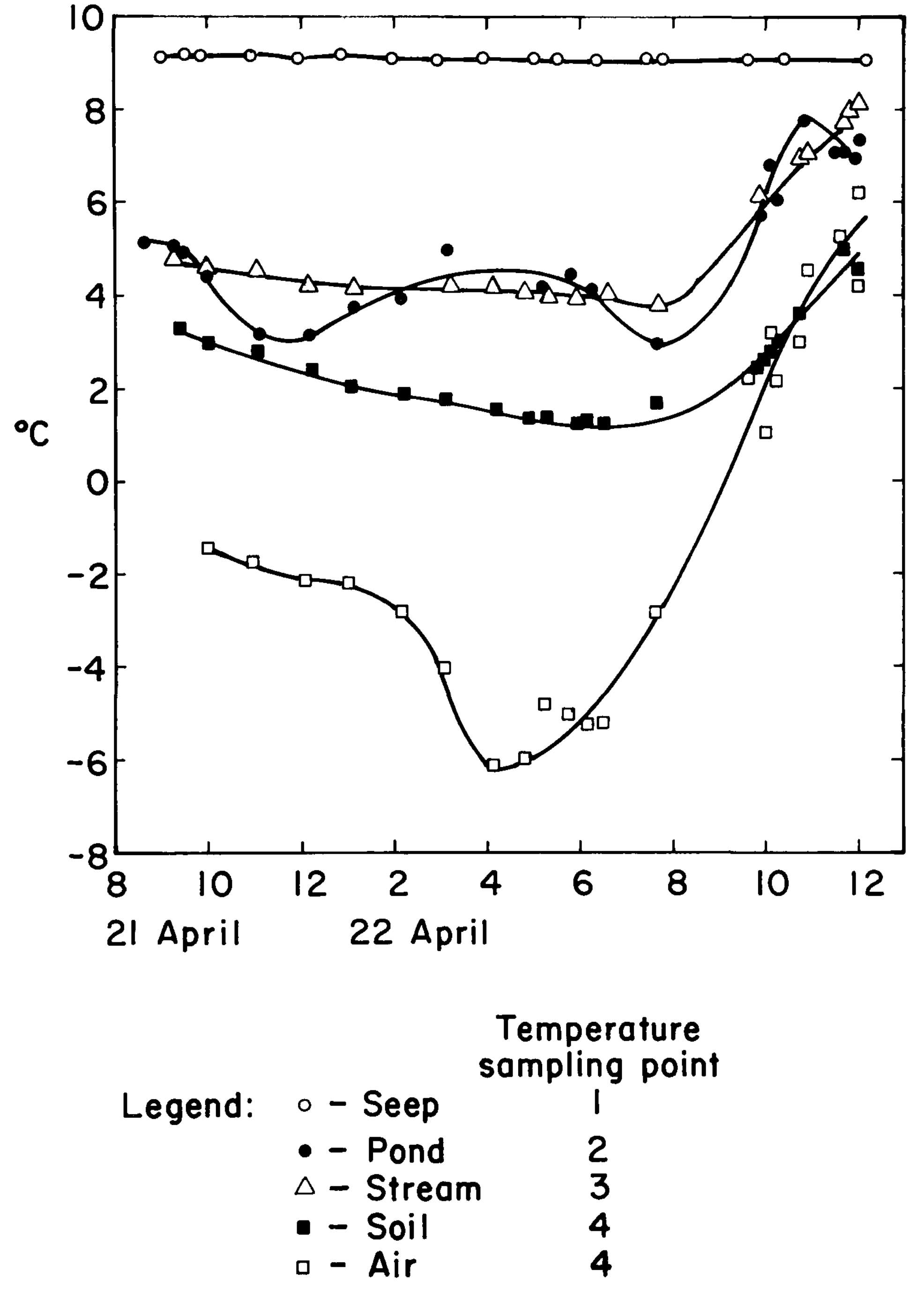


FIGURE 5.3. TYPICAL TEMPERATURE VARIATION AROUND A LANDFILL (AFTER SANGREY ET AL., 1976)

5.2 THEORETICAL POTENTIAL FOR REMOTE DETECTION OF LEACHATE

If leachate is to be identified directly or indirectly with remotely sensed data, then leachate or a leachate-related feature must, at the time of sensing, appear spectrally different from its surroundings or have some unique or identifiable spatial characteristic. The spectral and spatial indicators of leachate can be examined from the standpoint of detection with data acquired by airborne sensors of electromagnetic radiation.* A variety of sensors can be used depending on the characteristics of the target, Figure 5.4.

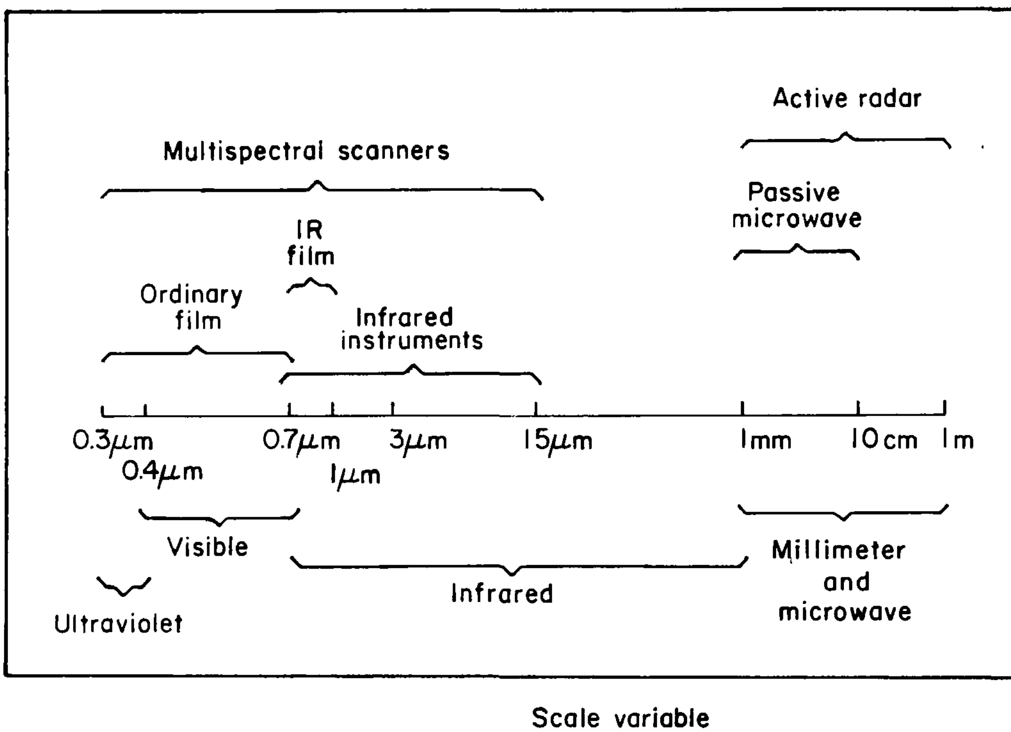


FIGURE 5.4. ELECTROMAGNETIC SPECTRUM WITH TYPES OF SENSORS (AFTER HOLTER, 1971)

5.2.1 Object Detection Through Sensing of Spectral Differences

In general, radiation from the ground that reaches an airborne sensor has been reflected or emitted into the sensor's field-of-view and transmitted through the atmosphere. The amount of radiation received by the sensor is directly proportional to the amount of radiation reflected or emitted by objects on the ground. Ground objects which reflect or emit different amounts

*A comprehensive treatment of all facets of remote sensing can be found in the American Society of Photogrammetry's Manual of Remote Sensing (Reeves, 1975).

of radiation of the wavelength being sensed are potentially separable with data acquired by the sensor--even if the objects are identical in spatial characteristics. For example, if a stressed tree reflects or emits different levels of radiation than an unstressed tree, then the trees can be differentiated. Similarly, a wet soil site will be distinguishable from a dry soil site if the two reflect or emit different amounts of radiation to a sensor.

The amount of radiation that will be reflected by an object, and thus potentially sensed, is determined by the incoming radiation and the surface characteristics of the object. The amount, incidence angle, wavelength and polarization of the incoming radiation are significant. An object's reflectance refers to the proportion of incoming radiation that will be reflected, the remaining radiation being absorbed or transmitted by the object.

The amount of radiation that will be emitted by an object is determined by the object's temperature and emissivity. All objects at a temperature above absolute zero (-273.15°C) emit radiation; the higher the temperature, the greater the amount of radiation emitted. Two objects at the same temperature will emit different levels of radiation if their emissivities differ. The emissivity of a material is, in effect, an efficiency factor, the ideal emitter (blackbody) having an emissivity of 1.0. In the infrared region, for example, most non-metals have emissivities greater than 0.8 and, commonly, over 0.9 (Wolfe, 1965).

The capacity for detection or separation is not limited to those objects that reflect or emit different total amounts of radiation. Objects may also be distinguishable when the total amounts of radiation they reflect or emit are identical. As long as the objects reflect or emit in at least one different wavelength or wavelength interval, which is capable of being sensed, the objects are potentially separable. For example, while a blue water body and green water body may reflect like amounts of radiation overall, the two are distinguishable if radiation in the blue and/or green can be sensed separately. Analogously, separating stressed from unstressed trees, or wet from dry sites, might be accomplished by sensing in certain wavelengths but not in others.

In this context, it is important to note that an object's reflectance and emissivity normally vary with wavelength. Objects can be characterized by their spectral reflectance or spectral emissivity, the former being applied in characterization more commonly than the latter, Figure 5.5.

When considering reflected radiation and an object's spectral reflectance, one must be conscious of the sources of radiation. The principal source for passive, airborne sensing of reflected radiation is the sun, the spectral distribution of which is shown in Figure 5.6. As can be seen, objects may reflect little radiation at wavelengths longer than, say, 1.5μm simply because relatively little solar radiation is available for reflection. In fact, at wavelengths longer than about 3 to 4μm, the amount of radiation that natural objects emit usually exceeds the amount of radiation that they reflect.

The maximum amount of radiation that any object can emit, at any temperature and wavelength, is described by Planck's Equation. As illustrated

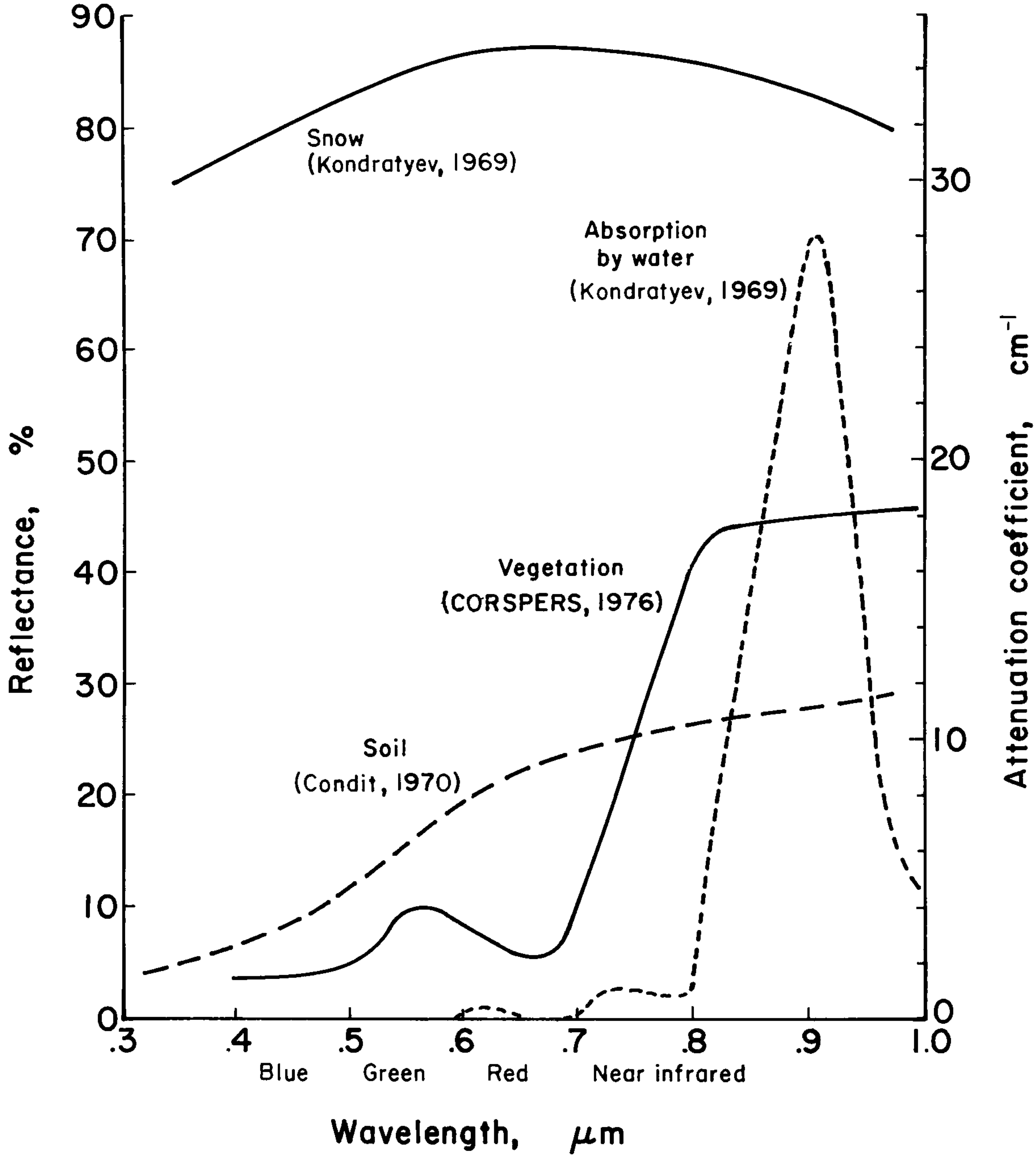


FIGURE 5.5. SPECTRAL REFLECTANCE OF TYPICAL VEGETATION, SOIL AND SNOW; AND ATTENUATION COEFFICIENTS OF WATER

in Figure 5.7, objects at temperatures normally encountered on the earth's surface emit maximum radiation near 10μm. The ideal maximum emission, given by Planck's Equation, is reduced for any real object because of the object's spectral emissivity.

One final point on airborne sensing of radiation concerns atmospheric transmission. If reflected or emitted radiation passes from ground to sensor, it will be affected (scattered, absorbed) by moisture, gases and various substances in the atmosphere (aerosols). In sensing of ground objects, one normally takes advantage of certain wavelength intervals of relatively high transparency, "windows," that characterize the atmosphere, Figure 5.6. Yet some effect is usually observed, especially from higher altitudes.

5.2.2 Leachate Indicators for Sensing

The spatial and spectral indicators of leachate are listed in Table 5.4. They include observable features of leachate itself--wetness or an anomalous spectral response from snow, water, soil or rock--and observable effects of leachate--gaps in a vegetative or snow cover, or an anomalous spectral response from grass or taller vegetation. The most useful wavelength intervals for identifying leachate indicators with reflected solar radiation are indicated in Table 5.5.

Gaps

If large or small gaps in snow or a vegetative cover can be related spatially to a landfill, they often signal the presence of leachate (see Plate 2). Caused by the leachate's wetness, toxicity or heat, the gaps can be isolated (Classification G)or they can radiate from the landfill (Classification E or F). Since heat would dissipate rather quickly with distance, heat-caused gaps should be found close to the landfill. In contrast, gaps caused by wetness or toxic substances can occur at longer distances from the landfill, 500 meters being quite reasonable.

Vegetative gaps which expose bare soil or rock would be easily detected in the visible or near-infrared regions. The spectral reflectance of vegetation is relatively high in the green and low in the red, while the spectral reflectance of soil is high in both, Figure 5.6. The near-infrared reflectance of vegetation and soil are both relatively high, but the reflectance of vegetation is normally much higher.

In the thermal infrared and microwave regions, the emissive properties of most taller vegetation are sufficiently different from those of bare soil that gaps would be distinguishable (Reeves, 1975); however, gaps in a grass cover are likely to go unnoticed. In contrast, active microwave sensing (by radar) should detect most vegetative-soil gaps that are not obscured from view (Matthews, 1975).

Compared to vegetation, snow presents an even greater contrast with soil or rock (Rango, 1975). The spectral reflectance of snow is high over the visible and near-infrared wavelengths, and the spectral emissivity of snow is different from that of soil in both the thermal infrared and microwave regions. Given the difference in electrical properties of snow and soil, gaps in a snow cover might also be detectable by virtue of microwave

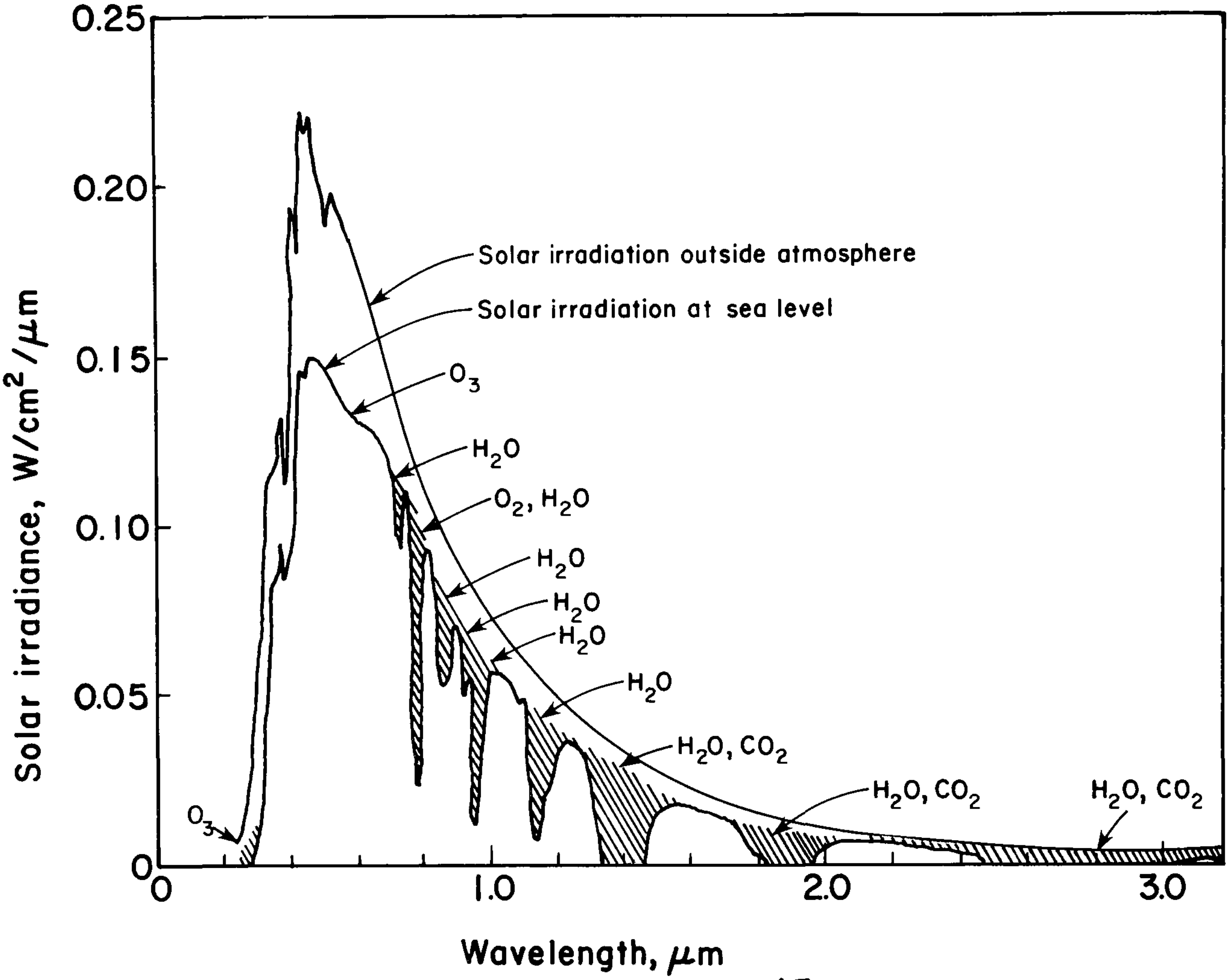


FIGURE 5.6. SPECTRAL IRRADIANCE OF SUN AND ABSORPTION BANDS OF ATMOSPHERIC CONSTITUENTS (AFTER VALLEY, 1965)

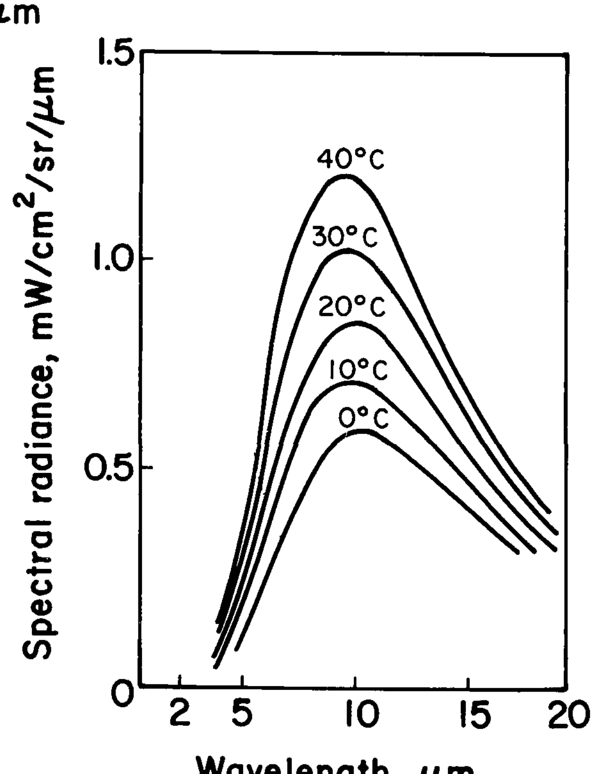


FIGURE 5.7. SPECTRAL RADIANCE OF A BLACKBODY (AFTER WOLFE, 1965)

TABLE 5.4. SPATIAL AND SPECTRAL INDICATORS OF LEACHATE

BACKGROUND/ SURROUNDINGS	GAP IN COVER*	WETNESS*	ANOMALOUS SPECTRAL RESPONSE	
			REFLECTIVE	EMISSIVE
soil/rock with grass cover	X	X	X	X
soil/rock with little or no grass cover		X	X	X
snow	X		X	
water			X	X
taller vegetation	X		X	X

*Although observable because of their spectral response, wetness and gaps in a vegetative or snow cover are listed separately for ease of discussion. Wetness ranges from damp areas to puddled water.

TABLE 5.5. SPECTRAL BANDS FOR DETECTING LEACHATE THROUGH REFLECTED RADIATION

LEACHATE INDICATOR	PRIMARY	SECONDARY
Gaps		
Vegetation/Soil, Rock	Infrared, Red	
Snow/Soil, Rock	Blue, Green	
Wetness		
Soil	Infrared	Red
Soil with Grass	Infrared	
Spectral Anomalies		
In Water	Red, Green	Blue
On Water (lipids)	Ultraviolet	Blue, Infrared
On Soil	Red, Green	Infrared
On Grass	Red	Infrared, Green
Stressed Vegetation	Infrared	Green, Red

reflectances.

Overall, recognition of a gap in a vegetative or snow cover should be easily accomplished through airborne sensing. Since these gaps are not limited to leachate-affected sites, the primary task would be to relate the gap to the landfill. Topographic and, to the extent possible, geologic analyses are normally required.

Wetness

Similar to gaps, any damp, saturated or puddled sites that can be related spatially to a landfill are potentially contaminated by leachate (see Plate 3). As with gaps, wetness can radiate from the landfill or occur in small or large isolated spots, or seeps, the distance and direction from the landfill being highly variable. Wetness can often be deduced from the vegetative types. If not, its spectral characteristics are sufficiently distinct that wetness is detectable over the entire electromagnetic spectrum.

In the red and near-infrared regions, for example, the reflectance of bare soil is relatively high while water usually exhibits increasing absorption from the green to the near-infrared (Fritz, 1967; Kondratyev, 1969). Under most circumstances, reflective differences between dry sites and saturated or puddled sites will be easily observed in the near-infrared and red regions. Although damp sites will not present as obvious a contrast as saturated or puddled sites, at least the wetter sites will be separable. With increasing soil moisture, soil reflectance decreases throughout the visible and near-infrared wavelengths (e.g., Bowers and Hanks, 1965).

The affect of a grass cover on the observed soil-water reflectances will be more pronounced as the density of the grass increases. Although soil reflectance decreases with increasing moisture, the green and especially the near-infrared reflectance of unstressed grass will tend to offset the effects of soil moisture. During drier periods, the wetter, grass-covered sites might be distinguished by their higher green and near-infrared reflectance if the surrounding grass cover is stressed by a moisture deficiency. The reverse effect might be observed if the grass at the wetter sites is stressed by excessive moisture.

In the thermal infrared region, water could be differentiated from soil or grass at the same temperature because of its higher emissivity. More significantly for sensing, however, the thermal properties (diffusivity and inertia) of water, soil and rock are such that land normally heats and cools more rapidly than water bodies. From midday to late afternoon and from late night to pre-dawn hours, the temperature of water will usually be at or approaching equilibrium with the surrounding land. At other times, the water will appear warmer (evening) or cooler (morning) than the land, Figure 5.3. Damp or saturated sites will not be as distinguishable as sites of standing water, but their apparent temperatures (emissions) should fall between those of water and land (Myers et al., 1970; Blanchard et al., 1974). Detection of wetness at microwave wavelengths can be accomplished with passive or active sensors. If observed directly, standing water is separable from its surroundings by virtue of its higher emission, at comparable temperatures, or by virtue of its specular reflective properties. Under certain conditions, fair correlation has also been demonstrated between levels of soil moisture and microwave emission or scattering coefficients (Schmugge et al., 1976; Ulaby et al., 1974).

Other Spectral Anomalies

Leachate will sometimes produce an anomalous spectral response besides that associated with wetness or gaps. Although these spectral anomalies usually provide a more positive indication of leachate than gaps or wetness, they must still be traceable to the landfill.

The spectrally reflective anomalies listed in Table 5.4 arise from the possible differences in reflectance between leachate and soil, grass, snow or water, and between leachate-stressed and unstressed vegetation (see Plate 4). As an example, leachate may exhibit an unusually high red reflectance because of its high ferric iron content (Section 5.1.2). Although this is not unique to leachate, the response contrasts markedly with that from grass, snow or otherwise clear water, and, to a lesser extent, with that from soil or rock (see Plate 5).

In a similar manner, lipid coatings on leachate-contaminated water should, like oil, be detectable through passive or active sensing in the ultraviolet, blue, thermal or microwave regions, or at various Fraunhofer lines in the visible region (Kennedy and Wermund, 1971; Vizy, 1974; Watson et al., 1975). Also, the spectral reflectance of positively or negatively stressed taller vegetation might show anomalies at any visible or near-infrared wavelength, though the near-infrared wavelengths are apparently more sensitive to a broader range of stresses (CORSPERS, 1976).

The spectrally emissive anomalies listed in Table 5.4 arise from the possible differences in temperatures and/or emissivities between leachate and soil, with or without grass cover; between leachate-affected and unaffected water; and between leachate-stressed and unstressed vegetation. Sensing for spectrally emissive anomalies can be conducted in the thermal infrared or microwave regions.

5.2.3 Temporal Aspects of Leachate Detection

Two categories of temporal factors must be considered in a leachate detection program. The first relates to the value of monitoring the development of the landfill from its initial stages to the present; the second relates to the effect of season and time of day on the capacity to detect leachate.

For many landfills, the prevailing drainage conditions were established prior to the development of the site, and they have been changed little by the landfill operation. In other cases, the development of the landfill causes significant change at the site proper, but does not affect subsurface drainage which surfaces at a distance from the site. Seldom will the development of a landfill alter the drainage so completely that it will be totally different from pre-landfill, or at least early-landfill, conditions. Consequently, as discussed in Section 5.4.1, examination of remotely sensed images (e.g., aerial photographs) of the undeveloped and developing site will normally provide valuable information regarding where to expect leachate (see Plate 1).

It should be obvious that since weather and climate are major determinants of the amount of leachate produced, as well as the amount of vegetation or snow present to hinder detection, seasonal factors become especially important. In general the potential for leachate production is high during wet periods and low during dry or frozen periods. The potential for leachate detection is normally lowest during times with deep snow or full canopies of taller vegetation (see Plate 7).

Among other effects of season (and latitude) is the amount of shadows which may obscure leachate indicators from overhead detection. As is obvious, sun shadows are also associated with the time of day. In most instances high sun angles at midday are best for detecting leachate indicators. Although the water surface glint that accompanies higher sun angles may obscure an anomalous spectral response, it will, at least, facilitate the identification of wetness. In contrast, sensing of emitted radiation might best be conducted during non-daylight hours (Section 5.2.2).

5.3 DEVELOPMENT OF A LEACHATE DETECTION PROGRAM

Landfill leachate has been described with emphasis placed on spatial and spectral features that might serve as direct or indirect indicators for detection. With this background, the elements of a leachate monitoring program can be reviewed.

5.3.1 Sensor Selection--Spatial Considerations

In developing a program for remote sensing of landfill leachate, one early consideration is the sensor. Of the many possible sensors that might be applied, which can provide data sufficient to detect leachate, and which is the best sensor or combination of sensors?

For leachate detection, a sensor must provide data which allow an assessment of the spatial relationships between indicators of leachate and the landfill under study. This requirement can only be filled effectively with an imaging sensor; spectrometers, radiometers and other non-imaging sensors cannot supply sufficient data unless numerous cross sections are flown.

In general, four types of imaging sensors would be judged applicable at this time: (1) photographic film cameras, frame (still or movie) or panoramic; (2) television or imaging tube cameras, (3) scanning radiometers ("scanners"); and (4) side-looking radars. From among these sensors, still or panoramic film cameras and scanners would be favored for a leachate detection program. Certain television, image tube and movie cameras are reasonable alternatives; however, their resolutions (spatial and/or spectral) or sensitivities, are usually inferior, and their outputs are not as conveniently processed or analyzed for detail (Baker et al., 1975). Similarly, side-looking radar data are costly to acquire, and the higher resolution, synthetic aperture radars require special facilities for data processing (Matthews, 1975). In addition, the spatial resolution of available radar imagery is insufficient to detect smaller features.

Photographic Cameras

The spatial aspects of camera selection call for a trade-off among camera focal length, photographic scale, film format and ground coverage, Figure 5.8. The photographic scale at any point in a vertical aerial photograph is:

$S = f/(H - h)$

where f = camera focal length

H = camera height above datum

h = height of point above datum

For example, in Figure 5.8,

photo scale at A = $S_a = f/(H - h_a)$

photo scale at B = $S_b = f/(H - h_b)$

Denoting the ground distance between points A and B by Dab,

$$D^2_{ab} = [(x_b/S_b) - (x_a/S_a)]^2 + [(y_b/S_b) - (y_a/S_a)]^2$$

where x_a, y_a and x_b, y_b are the photographic coordinates of points A and B (based on a Cartesian coordinate system defined by the fiducial marks).

As an approximation,

D_{ab} = (photo distance, a to b)/(average scale, A and B)

Commonly available aerial frame cameras have film formats of 23 by 23 cm (mapping or reconnaissance), 11.5-by-11.5 cm (13 cm reconnaissance), and 5.7 by 5.7 cm (70 mm reconnaissance); and the format of a 35 mm camera is 2.4 by 3.6 cm (Slater, 1975). While any of these cameras could be employed to acquire a desired scale of photography, the larger the format the greater the ground area imaged per photograph for the same scale, Table 5.6. Regardless of the scale, a photograph obtained with a 23-cm format camera will cover approximately 16 times the area covered by the same scale 70-mm photograph.

Available maps of a site can be a factor in camera selection. If a topographic map of the landfill site is already in existence (e.g., U.S. Geological Survey 7.5 minute map), a cartographic quality mapping camera would not be required for monitoring. Any of the reconnaissance cameras referred to above might be selected. Two other types of reconnaissance cameras that might also be considered are panoramic and multiband (multi-lens) cameras.

Panoramic cameras are typically high resolution, 13-cm or 70-mm film cameras. The angular coverage of most exceeds 100° and may reach from horizon to horizon. The disadvantage of panoramic cameras is that the photographs are systematically distorted in scale, there being substantially more ground area imaged along the horizon than along the line of flight. The characteristics of the image and distortion with various sensors are illustrated in Figure 5.9.

Most multiband cameras have four lenses, each of which forms a separate image (8.9 by 8.9 cm or 5.7 by 5.7 cm) on the same 24-cm film. By using

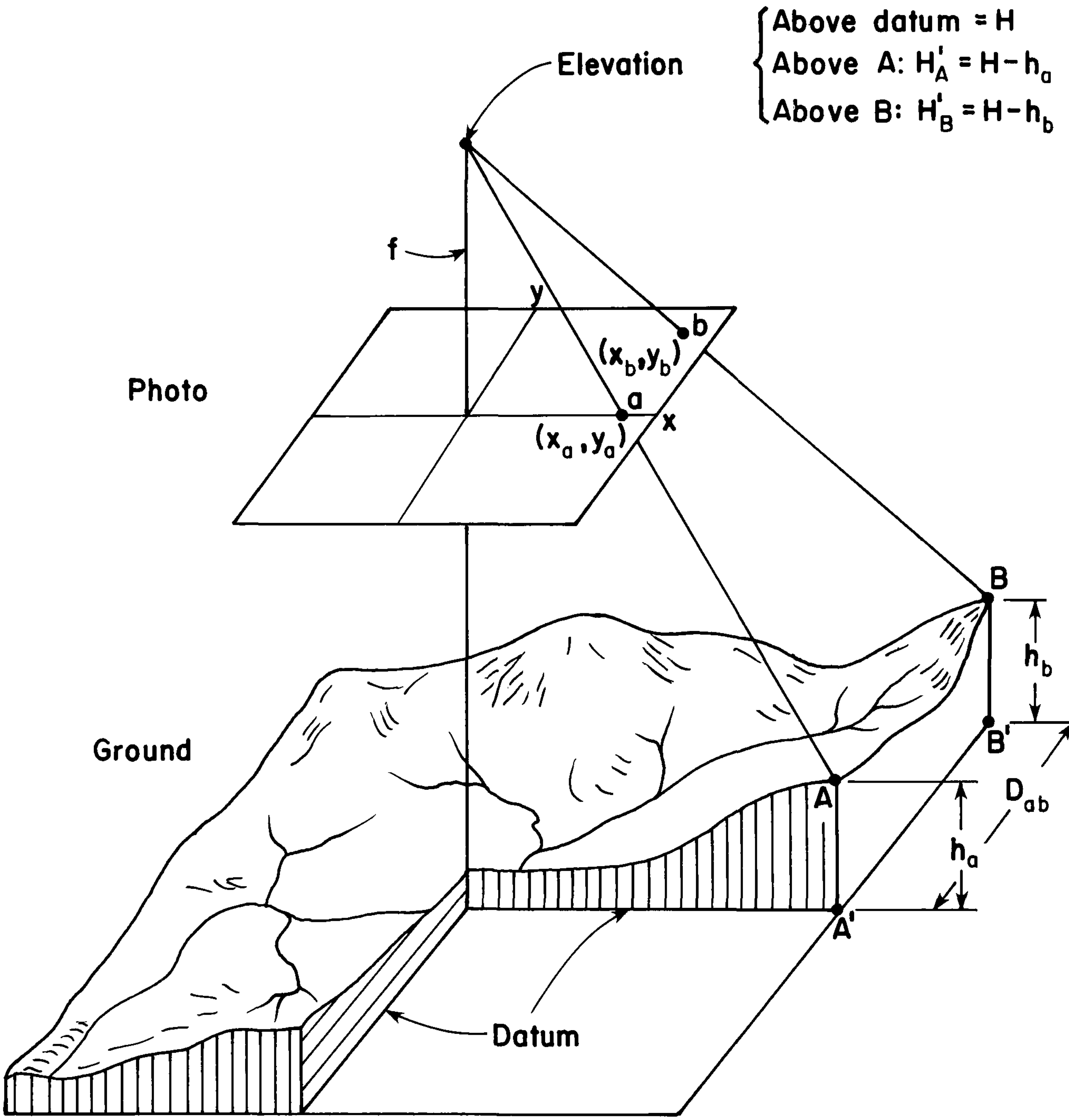


FIGURE 5.8. RELATION BETWEEN AERIAL PHOTOGRAPH AND GROUND SURFACE

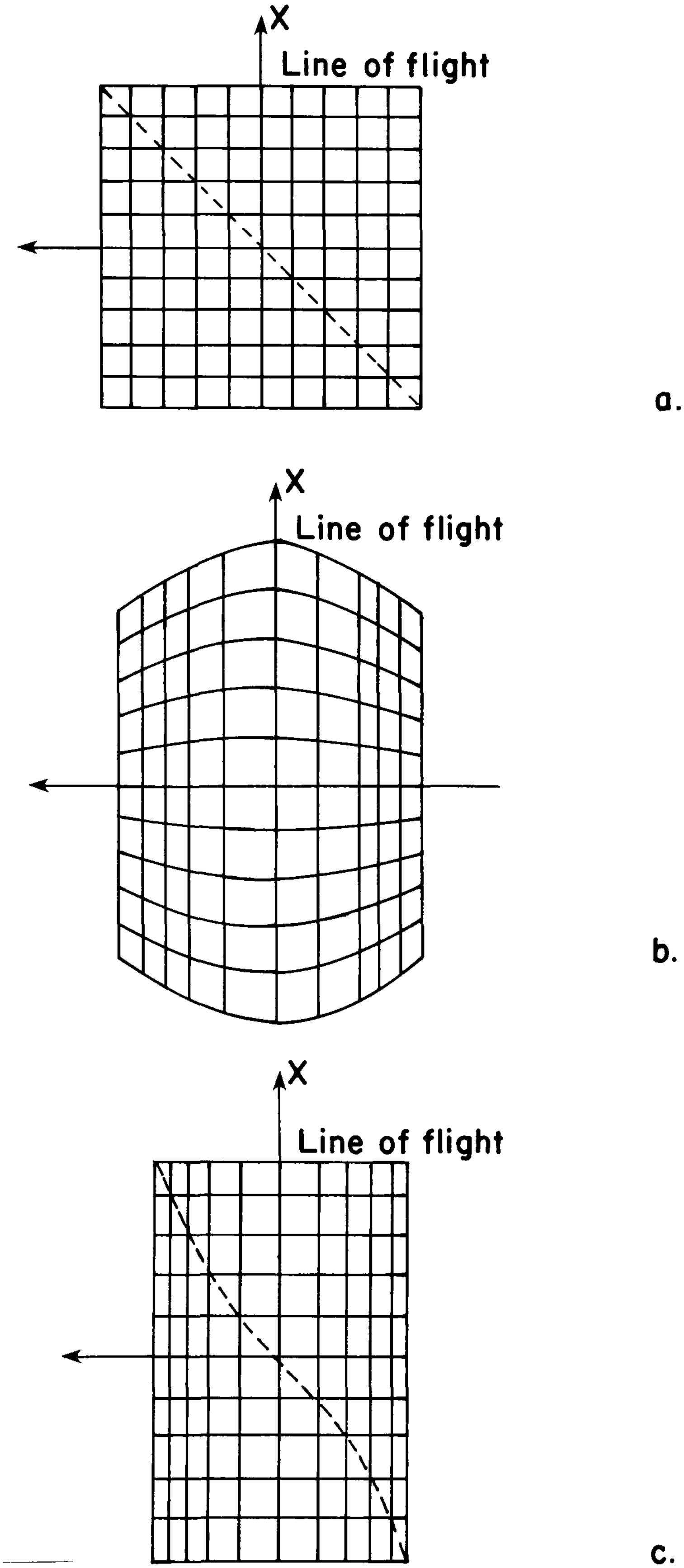


FIGURE 5.9. DISTORTION PATTERN OF A UNIT GRID BY FRAME CAMERA, a, PANORAMIC CAMERA, b, AND SCANNER, c (AFTER MASRY AND GIBBONS 1973)

TABLE 5.6. GROUND AREA IMAGED BY DIFFERENT FORMAT PHOTOGRAPHS OF DIFFERENT SCALES

CAMERA AND FORMAT (cm)	GROUND COVERAGE (meters) AT DIFFERENT SCALES 1:1,000	1:5,000	1:10,000
23-by-23 (mapping or reconn.)	230x230	1150x1150	2300x2300
11.5-by-11.5 (13 cm reconn.)	115x115	575x575	1150x1150
8.9-by-8.9 (multiband)	89x89	445x445	890x890
5.7-by-5.7 (70 mm reconn. or multiband)	57x57	285x285	570x570
2.4-by-3.6 (35 mm)	24x36	120x180	240x360

different spectral filters on each lens, and a black-and-white film sensitive to visible and near-infrared radiation, four different black-and-white spectral images (e.g., blue, green, red, near-infrared radiation) of the same scene may be acquired simultaneously. The spectral images can be viewed individually or together, as will be discussed in Section 5.3.2.

Scanners

Thermal infrared, multispectral and microwave scanners might all provide valuable data in a leachate monitoring program. Only thermal and multispectral scanners will be considered, however, since few microwave scanners are in existence, and their resolutions are inadequate for detecting most leachate indicators. In contrast, several potentially effective thermal and multispectral scanners are available commercially (Lowe et al., 1975) (see Plate 6).

The most common scanners are optical-mechanical sensors which use a mirror or prism to focus radiation from the ground to one or more detectors. The mirror revolves, scanning a line of incoming radiation perpendicular to the aircraft's direction, Figure 5.10. New, adjacent lines are scanned as the aircraft moves ahead.

The spatial aspects of a scanner which are of primary concern for sensing leachate are the scanner's instantaneous field-of-view (α-by-α in Figure 5.10), its total field-of-view (θ), and the ratio of its maximum allowable velocity to its height above ground [$(V/H)_{max}$, angular velocity with respect to a ground target].

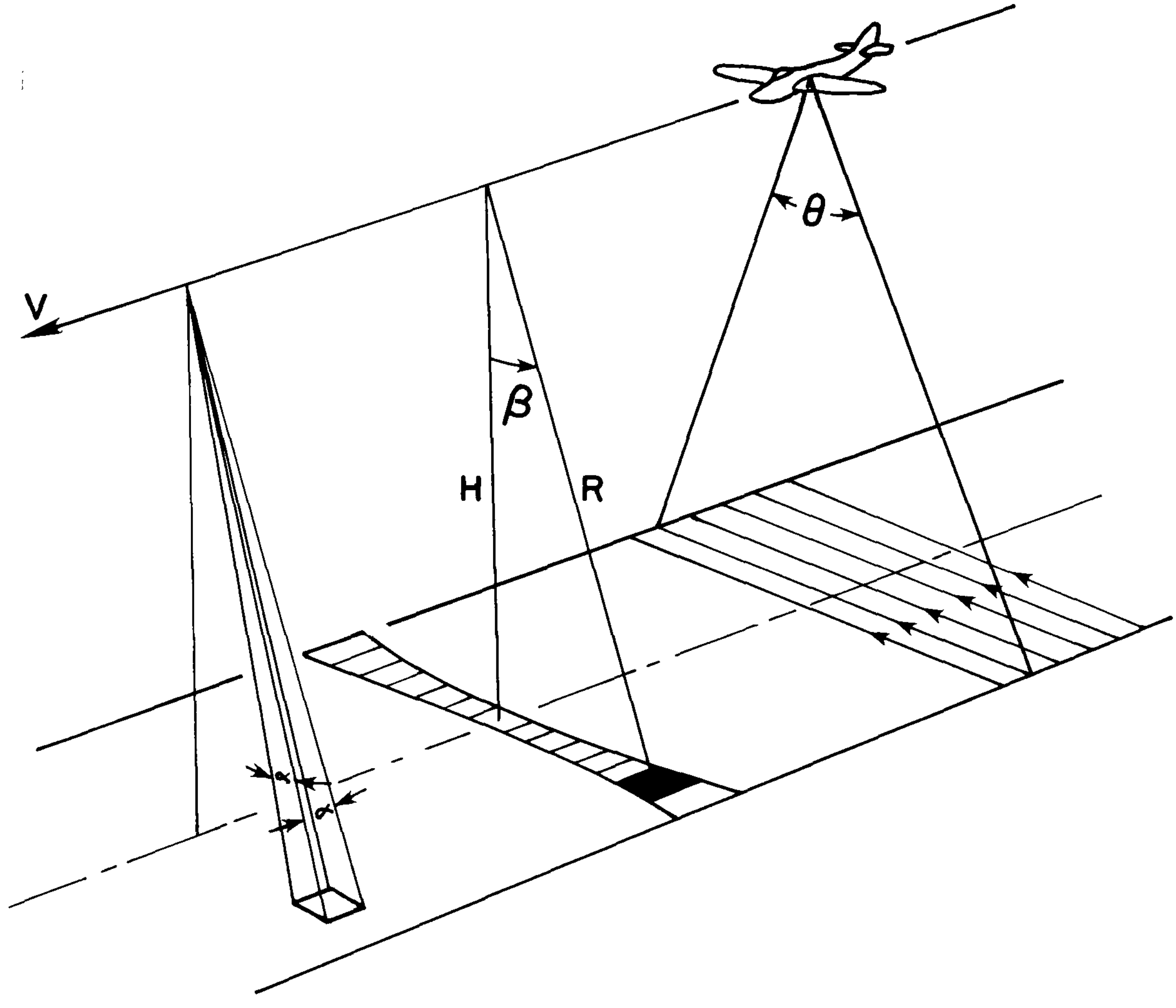


FIGURE 5.10. GEOMETRY OF AIRBORNE SCANNING RADIOMETER (SCANNER)

The total field-of-view of a scanner is the scanner's lateral coverage. It is analogous to the angular coverage of an aerial camera in the direction perpendicular to the aircraft's flight direction. Unlike a camera, however, a scanner does not collect radiation over its total field-of-view at one instant of time. As noted, the scanner mirror covers the total field-of-view by "looking" sequentially at numerous, adjacent ground spots (resolution elements) along one scan line. This ground spot is the smallest area that the scanner can "see"; all radiation emanating from the spot is integrated and seen as a single level of radiation for each wavelength interval sensed. The size of the ground spot is determined by the scanner's instantaneous field-of-view, its height above ground, and the scan angle β, the angle between the ground spot and the aircraft nadir.

To illustrate, a typical scanner might have a square instantaneous field-of-view of 2.5 milliradians on a side, and a total field-of-view, θ, of 120°, or 60° to either side of the aircraft. Approximating the length of the ground spot as the arc of a circle whose center is at the scanner, an angle of 2.5 milliradians would intercept an arc of 0.0025 times the radius. For every 1,000 meters of aircraft height above ground, the size of the ground spot viewed directly below the aircraft would increase by 2.5 meters ($R = H = 1{,}000$). The corresponding increase for ground spots away from the aircraft nadir would be larger because the distance between the scanner and spot (the radius of the circle) is longer. For every 1,000 meters, other ground spots would increase by $2.5/\cos\beta$, where β is the scan angle. If the instantaneous field-of-view were square (2.5 milliradians on each side), the area of the ground spots would increase by $(2.5/\cos\beta)^2$.

5.3.2 Sensor Selection--Spectral Considerations

Leachate indicators--gaps in a vegetative or snow cover, wetness, and other spectral anomalies that can be related spatially to a landfill--were discussed in Section 5.2.2. Sensors for identifying these indicators were reviewed in Section 5.3.1, where several types of photographic cameras and a multispectral or thermal scanner were judged most applicable on the basis of spatial factors. The spectral features of leachate indicators allow further refinement in sensor selection. Specifically, they provide the basis for selecting the most effective film-filter combinations and sensing bands for the cameras and scanners respectively.

The most useful wavelength intervals, or spectral bands, for detecting leachate indicators through reflected solar radiation are listed in Table 5.5. As shown in Table 5.7, these bands can be sensed by various photographic films, singly or in combination, and by a multispectral scanner. Although a multispectral scanner could be applied successfully in place of photographic camera systems, photographs are less expensive to acquire, process and analyze, and they are normally of higher spatial resolution. If photographic systems have the spectral capacity to monitor leachate in the ultraviolet, visible and near-infrared regions, the unique data acquirable by multispectral scanner are limited to the infrared region, particularly the thermal infrared. Thermal data can best be acquired during non-daylight hours at a time when the other possible multispectral scanner data would not be obtainable. Consequently, a thermal infrared scanner would seem preferable to a multispectral scanner with a thermal channel, Table 5.7.

TABLE 5.7. PHOTOGRAPHIC CAMERA AND SCANNER SYSTEMS FOR LEACHATE DETECTION

SENSING OPTION	METHOD OF SENSING	BANDS SENSED AND RECORDED SEPARATELY	COMMENTS
1. Photography			
a. color film	single camera; single image	B, G, and R* recorded as B, G, and R, respectively	UV can be sensed if recorded with B**; contrast of B layer will be lowered; proper exposure for UV and B will likely underexpose G & R
b. color infrared film	Idem	G, R, and IR recorded as B, G, and R respectively	UV and B cannot be sensed without affecting G, R, and IR
c. panchromatic film (black & white)	Multilens camera or several cameras, with spectral filters; multiple images	UV, B, G, and R, each recorded as black & white	Lower contrast of UV image will not affect other spectral images
d. black & white infrared film	Idem	UV, B, G, R, and IR, each recorded as black & white	Most multilens cameras have 4 lenses; lower contrast of UV image will not affect other spectral images
2. Multispectral scanner	Single scanner; magnetic tape, with or without image of one band off cathode ray tube or similar monitor	Any reflected or emitted bands from UV, visible & IR, including thermal; each band recorded as digital or analog signal on tape; if recorded in aircraft, one band as black & white film	Analog or digital data for any band or combination of bands can be printed on paper, displayed on video, or converted to photographic film
3. Thermal scanner	Single scanner; magnetic tape and/or image of one band off cathode ray tube or similar monitor	Commonly 8-14μm and/or 3 - 5μm; recorded as digital or analog signal on tape, or as black & white film	Idem, if recorded on tape

*B-Blue, G-green, R-red, IR-infrared, UV-ultraviolet

**Sensing of ultraviolet radiation will be limited by glass lens to wavelengths longer than about 0.36μm.

Selection of a photographic system is dependent upon the number and types of landfills to be monitored and the availability of equipment, facilities and/or funds. To illustrate, a local environmental group might wish to monitor a single landfill. This group would likely choose one photographic film for use with a hand-held 35-mm camera. A color infrared film would be more generally applicable than other films (Tables 5.5 and 5.7). But, if monitoring an inundated landfill (Classification D), where lipids might be expected, a black-and-white film filtered to receive ultraviolet and blue radiation might also be considered.

In contrast, a county environmental or health agency might employ one or more 70-mm or 13-cm cameras, loaded with spectrally filtered, black-and-white films or with some combination of color and black-and-white films. A state monitoring agency might prefer the flexibility of a four-lens multiband camera, as outlined in Table 5.7. The U.S. Environmental Protection Agency, which has limited familiarity with the specific landfills in a region to be overflown, might try to allow for all spectral and spatial indicators of leachate by carrying a 23-cm format camera, loaded with color infrared film, and smaller format cameras, loaded with other films (including one imaging blue and ultraviolet radiation). Overall, many combinations are possible and effective.

At this point, the value of thermal infrared data might be questioned. If leachate indicators can be identified with photographic systems, are thermal data really necessary? In general, thermal data may:

(1) confirm or refute the interpretation/existence of a photo-identified indicator (e.g., enhance wetness);

(2) provide some indication of the status of leachate contamination (e.g., if it is hot, a wet area is likely contaminated);

(3) detect other indicators which were overlooked or undetectable with photographic systems (e.g., very small hot spots or wet spots in a forested area); or

(4) provide no additional information.

Thermal data thus provide complementary and supplementary information which is of maximum value in limiting field checks to the most probable sites of leachate contamination.

5.3.3 Flight Parameters

The design of an aircraft mission for detecting leachate is governed largely by the sensor(s) utilized and the spatial, spectral and temporal characteristics of leachate. For a given sensor, the size and/or spectral response of leachate indicators and the size of the leachate-affected area set limits on the flight height. The seasonal and diurnal characteristics of the indicators as well as the local weather set limits on the optimum time for sensing.

Photographic Sensing

Leachate-related gaps in a vegetative or snow cover, and damp, saturated or puddled sites, are quite variable in size. Most, if not all, leachate problems would be discovered, at least potentially, if the photographic sensing could detect gaps and wetness of one meter across (see Plates 2 and 3).

If one-meter gaps or wet spots were spectrally distinct they should be detectable with photographic scales of about 1:5,000 or larger. On a 1:5,000 scale photograph, a one-meter ground spot would be 0.2 mm, which is easily seen with magnification. A scale of 1:5,000 could be obtained with a 150-mm focal length camera by flying at 750 meters above ground, while shorter focal lengths would require lower flying heights (H = 5,000f, where f = focal length in meters).

The ground areas photographed by different size films, at a scale of 1:5,000, are listed in Table 5.6. Although the size of landfills and their potentially affected areas vary (compare E, F, and G in Table 5.2), it is probable that several flight lines would be required to obtain the required coverage at 1:5,000 scale with 35-mm or 70-mm photography. The advantages of larger format photography are obvious, and these advantages may increase if stereoscopic coverage of the landfill is desired. Smaller film formats would require faster camera cycling or slower aircraft to obtain 1:5,000 scale photographs which overlap by at least 50% from any given flight height.

As described in Section 5.2.3, photographic sensing for leachate should be conducted with high sun angles. The likelihood of detecting potential sites of contamination with photographic sensors should increase as the amount of vegetative or snow cover decreases or as the amount of leachate increases. The optimum seasons and conditions for photographic and thermal sensing of leachate are summarized in Table 5.8. Ratings in the table are subjective and relative for photographic or thermal sensing; the two sets of ratings should not be considered as one.

Thermal Sensing

The temperature of leachate near a landfill may be several degrees Celsius higher than uncontaminated waters in the vicinity, Figure 5.3. Thermal infrared scanners can detect apparent temperature differences of less than a degree (Lowe et al., 1975). Nevertheless, two objects which emit different amounts of radiation because they are at different temperatures will be differentiated only if they are seen separately (i.e., if they are within the scanner's instantaneous field-of-view at different times).

As noted in Section 5.3.1, all radiation within the scanner's instantaneous field-of-view (IFOV) is integrated, such that a weighted average of radiation is sensed.

TABLE 5.8. THE POTENTIAL FOR DETECTING LEACHATE UNDER DIFFERENT VEGETATIVE AND SEASONAL CONDITIONS

		VEGETATIVE COVER			
SEASONAL CONDITIONS	MODE OF SENSING	NONE	GRASS	PARTIAL CANOPY	FULL CANOPY
Wet	photo	E*	E	G-F	F-P
	thermal	E-G	E-G	F	P
Dry or Frozen	photo	E-G	G	F	P
	thermal	E	E	G	P
Partial or Light Snow	photo	F	F	F	P
	thermal	E	E	G	P
Full or Heavy Snow	photo	F-P	F-P	P	P
	thermal	G	G	G-F	P

*Ratings of Excellent (E), Good (G), Fair (F), and Poor (P) are subjective for midday photographic or pre-dawn thermal sensing. The two ratings are not equivalent.

To illustrate, if an anomalously hot leachate seep fills the scanner's IFOV, its level of radiation (higher proportionately than the background radiation) would lead to detection. If the seep filled only a part of the scanner's IFOV, the radiation sensed would still exceed that from the background alone, but the difference may not be detectable, or discriminated, by the scanner's detector.

A general equation for estimating flight and scanner parameters required for detecting a leachate "target" with a thermal infrared scanner is (see derivation in Appendix A):

$$g_t \varepsilon_t T_t^4 - g_s \varepsilon_s T_s^4 > \frac{A_s (V/H)^{1/2} (\theta)^{1/2} (4F)}{A_t \alpha^2 (\cos\beta) DD^* (2p\gamma)^{1/2} \sigma \tau \tau_o}$$

t, s = subscripts denoting target and surroundings, respectively

g_t, g_s = fractions of total radiation emitted in spectral interval being sensed

ε_t, ε_s = spectral emissivities

T_t, T_s = temperatures (°K)

V/H = ratio of aircraft velocity to height (radians/sec)

α = instantaneous field-of-view of scanner (radians)

θ = total angular coverage of scanner; total field-of-view (radians)

σ = Stefan-Boltzmann constant = 5.67×10^{-8} Watts/m^2°K^4

A_s = area (m^2) within instantaneous field-of-view

A_t = area (m^2) of target, where A_t is less than A_s

β = angle (degrees) between aircraft nadir and target

F = aperture ratio of scanner optical system, where F = focal length/D
D = diameter (meter) of collecting aperture
τ = spectral transmissivity of atmosphere
τ_o = spectral transmissivity of scanner optical system
p = number of detecting elements; number of lines scanned per sweep
γ = scan duty cycle or efficiency
D^* = spectral detectivity of detector (m/Watt-sec$^{1/2}$)

A simple, single-mirror scan system might have the following design values (Lowe et al., 1975):

$F = 2$
$D = 8$ cm $= 0.08$ m
$V/H = 0.2$ radians/sec
$\theta = 120° = 2.1$ radians
$\alpha = 0.003$ radians
$\tau_o = 0.6$
$p = 1$
$\gamma = 120°/360° = 0.333$
$D^* = 10^8$ m/Watt-sec$^{1/2}$

Substituting these values into the equation, results in the following:

$$g_t \varepsilon_t T_t^4 - g_s \varepsilon_s T_s^4 > (2.59 \times 10^6)(A_s)/(A_t \tau \cos\beta)$$

The fractions g_t and g_s vary with the spectral interval being sensed and the temperature of the radiator (e.g., Siegel and Howell, 1972). If the target and surroundings are at temperatures of approximately 10°C (283°K), and if the emissions are being sensed over the 8 to 14-μm interval, g_t and g_s are both approximately 0.36. Further, while atmospheric transmissivity, τ, is highly variable and wavelength dependent, a reasonable estimate is 0.8. With these values, the equation becomes:

$$\varepsilon_t T_t^4 - \varepsilon_s T_s^4 > (9.00 \times 10^6)\ (A_s)/(A_t \cos\beta)$$

To use this equation for estimating the maximum height that an aircraft could fly and still detect a thermal target, one could replace A_s with H using the following relationship (Appendix A):

$$A_s = H^2 \alpha^2/\cos^2\beta$$

In estimating H, an average value for β would be 30°, and α was given as 0.003 radians. With these values, the equation could be written:

$$\varepsilon_t T_t^4 - \varepsilon_s T_s^4 > 124.72 H^2/A_t$$

This equation provides estimates for how much different the temperature of a target and it surroundings must be (T_t vs T_s) before a specific size target (A_t), located at a specific distance from the scanner ($H/\cos\beta$), can be detected by the scanner. To determine the maximum flight height, one needs estimates for the temperatures and emissivities of the target and its surroundings, and the size of the target.

As noted in Section 5.1.2, the highest temperature leachate and contaminated water will be near the landfill. At the point of breakout from the landfill or ground surface, the seep is usually at its smallest size, and designing for a 0.5-meter (0.25m^2) target seems reasonable.

A substantial temperature difference between a leachate seep and its surroundings would be observed in the evening (Sec. 5.2.2). But, at this time, all waters might appear equally warm. To optimize target detectability, the thermal mission should be flown just before sunrise (i.e., pre-dawn). At this time, warmer leachate seeps should be separable from other waters as well as from their vegetative and soil surroundings. While the temperature difference might be large or small, for design, a difference of 3°C would seem reasonable.

During the spring months, for example, the temperature of the seep might be at 10°C while the surroundings are at 7°C. The emissivity of the seep would be that of water, approximately 0.97, and the emissivity of the surroundings might be that of a soil-vegetation complex, say, 0.91.

With these values, the aircraft would have to fly less than 1,580 meters above ground to detect the 0.5 meter seep located at a scan angle, β, of 30°.

5.4 ANALYSIS OF REMOTELY SENSED DATA FOR LEACHATE

The specific technique(s) applied in analyzing remotely sensed data for leachate indicators are dependent upon the form of remotely sensed data and the available equipment, time and/or funds for analysis. More sophisticated or costly analysis techniques are not synonymous with more information. Whatever the approach to analysis, the results must be applicable in the field; suspected sites of leachate must be located in the field, via maps or photographs, as well as in or on the analyzed data.

If the recommendations of previous sections were followed, several forms of data might be available for analysis: (1) panchromatic contact prints, (2) black-and-white transparencies of different visible and near-infrared spectral bands, (3) color and/or color infrared transparencies, (4) black-and-white transparencies of one or two thermal bands, and (5) magnetic tape containing digital or analog thermal data.

5.4.1 Panchromatic Contact Prints

Most of the existing remotely sensed data depicting pre-landfill and developing conditions at a landfill site (Section 5.2.3) will be in the form of 23 by 23 cm, panchromatic contact prints, at scales of about 1:20,000. The panchromatic films, though sensitive to ultraviolet and all visible radiation, were likely exposed through a filter which absorbed the ultraviolet and most of the blue wavelength radiation. The black-and-white prints, therefore, depict the combined levels of green and red radiation. Analysis of these prints should be performed with pairs of overlapping photographs, using a lens or mirror stereoscope (Colwell, 1960). The stereoscopic analysis of topography and geology should aim at defining the drainage pattern and wet areas (dark tones associated with sites of lower reflectance, Section 5.2.2). The drainage information can be delineated directly on the photographs or on acetate overlays. This information will be compared to more recent images and/or maps. As desired, selected details may be transferred visually or with the aid of various types of equipment (e.g., Bausch & Lomb Zoom Transfer Scope).

5.4.2 Black-and-White Spectral Transparencies

The black-and-white spectral images, acquired simultaneously and at the same scale, can be examined individually or in combinations. Analysis of individual black-and-white spectral images can be conducted visually, as with panchromatic contact prints, though stereoscopic images may not be available. Since the images are film transparencies, a light table or projection device will be required for viewing. If the images were acquired stereoscopically, a variable magnification (zoom) stereoscope, attached to a light table, would be desirable.

One means for enhancing tones in the separate black-and-white images is to use a "density slicer." This is a device which electronically breaks the range of black to white film densities into as many as 32 increments, or levels, and subsequently assigns a different color to each level. Similar tones (densities) throughout the image will thereby be depicted with the same color, and slight tone differences will be enhanced.

In an effort to increase the information derived through analysis of single images, the different spectral images can be combined by: (1) overlaying various combinations of positive and negative images, (2) using a color-additive viewer, or (3) using diazo, a subtractive color process.

By "sandwiching" and registering different positive and negative spectral images of the same scene, and viewing the composite of transparencies over a source of white light, one can enhance or subdue various features in the scene (Simonett, 1974). For example, vegetative gaps would appear as light areas on a composite of a positive red image and a negative green image, and levels of wetness might be highlighted if a negative infrared image could be balanced with a positive red image (Sec. 5.3.2).

A color-additive viewer is a device which projects as many as four spectral images onto the same screen, where they can be registered to one another (Smith, 1968). The different images are placed behind or in front of one of four filters (blue, green, red or clear) such that registering the images on the screen will produce a multi-colored scene. Altering the intensity of any of the four projection lamps or changing the filter assignments will serve to enhance various spectral features.

In subtractive color enhancement with diazo, different color diazo foils are printed in contact with the different spectral images of a single scene. The resultant color densities of each diazo foil correspond to the gray-tone densities of the original spectral image. Registering the different color diazo, particularly yellow, magenta and cyan, over a white light will produce a multi-colored representation of the original scene. As with color-additive viewing, a wide range of color enhancements can be obtained by varying the color intensities of the diazo foils or the specific color-spectral image assignments. On the other hand, the preparation of appropriate diazo is too time-consuming and inefficient an approach to be considered for monitoring more than a few landfills.

Other analysis techniques, involving densitometric or digital methods, can be implemented with black-and-white spectral images. These techniques will be described in later sections.

5.4.3 Color and Color Infrared Transparencies

Color and color-infrared image transparencies can be projected or transferred onto a base map or another image, for comparison or recording of new information. If acquired stereoscopically, color and color-infrared transparencies can be examined on a light table with a stereoscope, preferably a zoom stereoscope. Moreover, much information can be derived through spectral analysis of single images with or without a stereoscope.

The emulsions of nearly all color and color infrared films consist of three layers (Smith, 1968). Each layer is sensitive to radiation of different spectral intervals, and each layer is separable, or "viewable," in the developed image through an appropriate filter. Consequently, the relative amounts of blue, green, red and/or near-infrared radiation that exposed the various layers of a color or color-infrared film can be examined by viewing the developed film through the proper spectral filter (Table 5.9). The film must be placed over, or projected by, a source of white light. If the aerial data were in the form of 35-mm or 70-mm transparencies, for example, they could be projected onto a white screen using a 35-mm or lantern-slide projector, and the spectral filters could be held in front of the projector lens.

Table 5.9. EXPOSING RADIATION (COLOR) VIEWED WHEN COLOR AND COLOR-INFRARED TRANSPARENCIES ARE EXAMINED OVER WHITE LIGHT THROUGH DIFFERENT SPECTRAL FILTERS

POSITIVE FILM	SPECTRAL FILTER					
TRANSPARENCY	BLUE	GREEN	RED	YELLOW	MAGENTA	CYAN
COLOR	blue	green	red	green & red	blue & red	blue & green
COLOR INFRARED	green	red	infra-red	red & infrared	green & infrared	green & red

5.4.4 Densitometric Analyses

The black-and-white, color or color-infrared films can be calibrated if they have been exposed with a sensitometer (Thomas, 1973). The sensitometer "images" a stepwedge of regularly varying densities on the film.

After controlled processing and development, the stepwedge can be read with a densitometer to obtain a characteristic curve, which relates density to relative exposure. This can apply to a black-and-white spectral film, or for each color (blue, green, or red) or color-infrared (green, red or infrared) film layer. The black-and-white or color layer density of any point on a black-and-white, color or color-infrared image can thereby be measured with a densitometer. Through the appropriate characteristic curve, the density can be converted to a precise value of the relative amount of exposing spectral radiation.

Relative exposures are informative in themselves (e.g., in determining dry versus wet soil), yet the ratios of exposures may provide even more information (Billingsley, 1973; Wagner et al., 1973). Working with color photography, for example, Piech and Walker (1974) found the ratio between the red and blue reflectances of soil to be useful for discriminating between soil moisture and texture variations. They also showed that densitometric readings, nominally point measurements, could form the basis for additional image processing in which whole images are ratioed photographically.

5.4.5 Thermal Infrared Image Transparencies

Black-and-white transparencies of one or two thermal infrared bands (8 to 14 μm, with or without 3 to 5 μm) can be examined like photographic black-and-white spectral images (Section 5.4.2 and Plate 6). Normally, however, the scanner-derived imagery will be distorted spatially (Figure 5.9), and it will not be available in stereoscopic form. A Bausch & Lomb Zoom Transfer Scope, which has an image "stretch" capability, is especially useful for transferring data from aircraft scanner imagery to maps or other images.

Because densities in quantitative thermal imagery correspond to apparent temperatures, density slicing of thermal imagery provides an expedient means for identifying objects and features of comparable apparent temperature (Section 5.4.2). Further density slicing provides a rapid means for separating slight density differences, as might be associated with leachate-contaminated versus uncontaminated waters.

5.4.6 Magnetic Tape

The thermal data may have been recorded on magnetic tape in analog or digital form. The primary advantage of collecting (and analyzing) data in this form is that the maximum spatial and spectral resolution afforded by the sensor has been recorded, much more data than can normally be shown on a single black-and-white film. A second advantage is that, in this form, the data are easily enhanced or otherwise manipulated.

The disadvantage of having the data on magnetic tape is cost. Special equipment is required to display the analog or digital data, or to convert them to photographic film. If the data are not first converted to film, a computer is required for their analysis, and special routines or facilities are required for printing or displaying the analyzed data.

In general, computer analysis of remotely sensed data is an extremely powerful and flexible approach to data analysis, whether the aim is to enhance or automatically recognize certain features in the data (Simonett, 1974). For this reason, one might consider digitizing any of the black-and-white, color or color-infrared photographs. Although the conversion of pictorial data to numerical form is an appropriate step for certain undertakings, for the requirements of a leachate detection program it is likely to be a poor alternative to collecting digital data with a multispectral scanner in the first place. As noted in Section 5.3.2, multispectral scanners are probably not required or desired for most leachate detection programs.

5.5 LEACHATE DETECTION METHODOLOGIES

Two general approaches to monitoring for landfill leachate are appropriate, depending on the objective. The first approach would be applicable by those groups that must monitor many landfills to check conformance to regulations and, consequently, have insufficient time to conduct a thorough examination of each.

The second would be applicable by those groups that are monitoring a limited number of landfills on a continual or control basis, and that have time to conduct a comprehensive study of each.

5.5.1 Typical Regulatory Monitoring Program

Step 1. Obtain topographic maps which locate landfills to be monitored.

Step 2. Fly 1:5,000 scale, aerial photographic coverage of each landfill, using film-filter combinations which record ultraviolet, blue, green, red, and near-infrared radiation (Sections 5.3.2 and 5.4.2). A panoramic camera might be used as a backup system to ensure complete coverage, though a 23 by 23-cm format camera, with color infrared film, is recommended as the primary sensor. The photographic flight should be conducted near midday during a wet, low vegetation period (e.g., spring in the northeastern United States).

(Alternative A)

Step 3A. Analyze the photographs to identify the most probable locations of leachate breakout or contamination (Sections 5.4.2 and 5.4.3).

Step 4A. Field check those landfills at which possible leachate breakout or contamination has been identified. The locations of any seeps encountered in the field should be marked on the field maps or photographs. The temperature of each seep should be measured, and a water sample taken for laboratory testing.

Step 5A. Upon verification of leachate contamination, take appropriate action.

(Alternative B)

Step 3B. Fly night-time/pre-dawn, thermal infrared coverage of all landfills overflown with photography. The thermal coverage should be acquired as quickly as possible after the photographic mission, and preferably, that same night. Flight parameters should allow for detection of a 0.25 m^2 seep, about 3°C warmer than its surroundings (Section 5.3.3).

Step 4B. Analyze the photographic and thermal data to identify the most probable locations of leachate breakout or contamination (Section 5.4).

Step 5B. (see Step 4A).

Step 6B. (see Step 5A).

(Alternative C)

Step 3C. (see Step 3A).

Step 4C. Based on the photographic analysis, select landfills to be overflown with pre-dawn, thermal infrared scanners. Conduct this sensing during a dry or frozen, low vegetation period to maximize effectiveness of this sensor. Field check other landfills as outlined in Steps 4A and 5A.

Step 5C. (see Step 4B).

Step 6C. (see Step 4A).

Step 7C. (see Step 5A).

5.5.2 Comprehensive Control Monitoring for Landfill Leachate

Step 1. Obtain all available background information on the landfill site, including topographic, soil and geologic maps and reports.

Step 2. Obtain aerial coverage of the undeveloped landfill site and, as available, coverage flown periodically during the development of the site (Appendix B for list of sources).

Step 3. Analyze available aerial coverage, together with background information, to identify the most probable locations of leachate breakout or contamination (Sections 5.2.3 and 5.4.1).

Step 4. Field check the landfill site(s), concentrating on those locations identified in Step 3. The locations of any seeps encountered in the field should be marked on the field maps or photographs. The temperature of each seep should be measured, and a water sample taken for laboratory testing.

Step 5. Fly new aerial photographic coverage of the landfills using: one or more film-filter combinations which are appropriate for the expected spectral leachate indicators (Sections 5.2.2 and 5.3.2); a photographic scale and film format which are in line with the size of the landfill-affected area and indicators (Sections 5.3.1 and 5.3.3); and a photographic system which is compatible with the aircraft, expected data analyses (Section 5.4) and available funds. The photographic flight should be conducted at midday during a wet, low vegetation period (e.g., spring in the northeastern United States)

Step 6. Analyze the new photographs, together with the other aerial and background data, to identify the most probable locations of leachate breakout or contamination (Section 5.4).

Step 7. Field check the landfill site(s), as in Step 4.

Step 8. Upon verification of leachate contamination, plan remedial measures.

(Steps 9 through 12 are optional extensions)

Step 9. Fly pre-dawn, thermal infrared coverage of the landfills. Flight parameters should allow for detection of a 0.25 m^2 seep, about 3°C warmer than its surroundings (Section 5.4.3).

Step 10. Analyze the thermal infrared data, together with all photographic and background data, to identify any additional locations of suspected leachate breakout or contamination (Sections 5.4.6 and 5.4.7).

Step 11. Field check any new locations of suspected leachate.

Step 12. If required, modify planned remedial measures.

Section 6

Illustrations of Remote Sensing Applications to Detect Leachate

Illustrations of the use of remote sensors to detect leachate contamination are presented in this section. The following examples are included, using photographic plates and a descriptive text for each:

1. Use of existing photographs
2. Gaps in vegetation and snow
3. Wetness
4. Stressed vegetation
5. Color anomalies
6. Thermal scanner data
7. Temporal effects

PLATE 1. USE OF EXISTING PHOTOGRAPHS

1a. May 1955, Black and White

1c. May 1967, Black and White

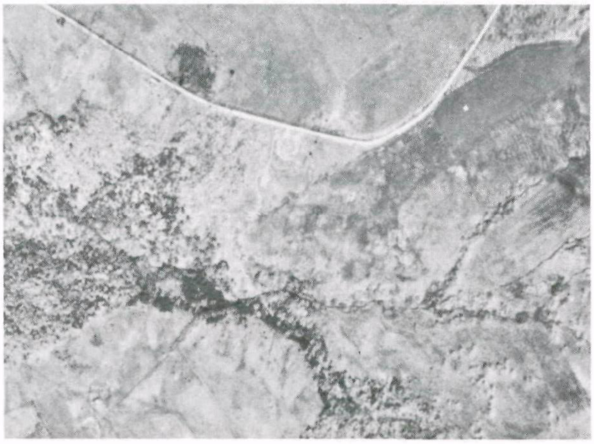
1e. March 1975, Color Infrared

Existing black-and-white (panchromatic) aerial photographs can be an important source of information, for both planning new landfill sites and detecting leachate contamination from existing landfills. Most areas have been covered by aerial photographs which are available to the public at low cost. Often there has been periodic coverage dating back thirty years or more. The historic nature of this photography enables the interpreter to define the conditions which existed at the site prior to its development as a landfill. This information is particularly valuable in assessing the sources and distribution of ground and surface water flow.

In the example on Plate 1, the 1955 photograph is pre-landfill (1a), solid waste is being placed on the site in 1967 (1c), and the final illustration is taken five years after the site was closed (1e). As illustrated by the wetness patterns (1b and 1d), the movement of ground and surface water around the site can be defined quite clearly in the older photographs. Based on this interpretation, it would be reasonable to expect leachate contamination of all those areas bracketed by the arrows on Plate 1e. There is a definite indication of this contamination from the color infrared photograph (1e), and this was confirmed by analysis of samples taken on the ground.

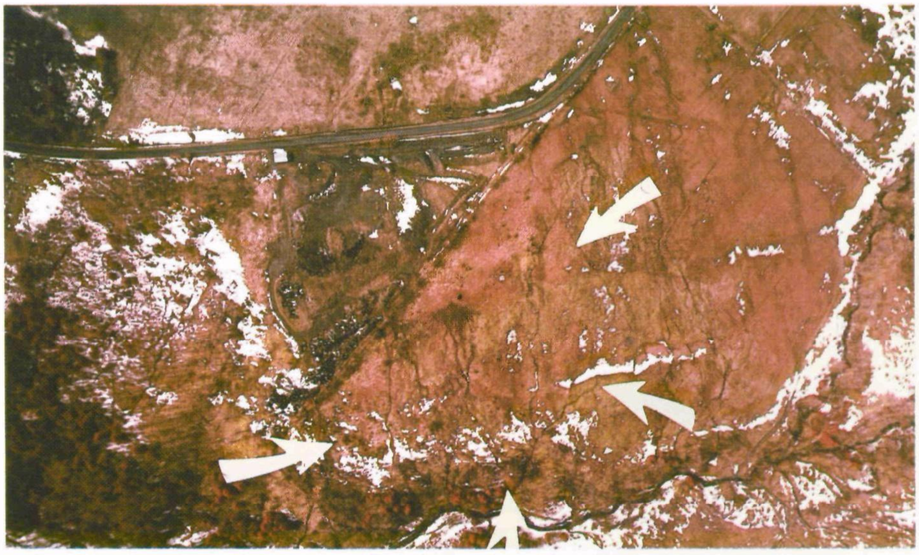
1a.

1b.



1c.

1d.



1e.

Plate 1

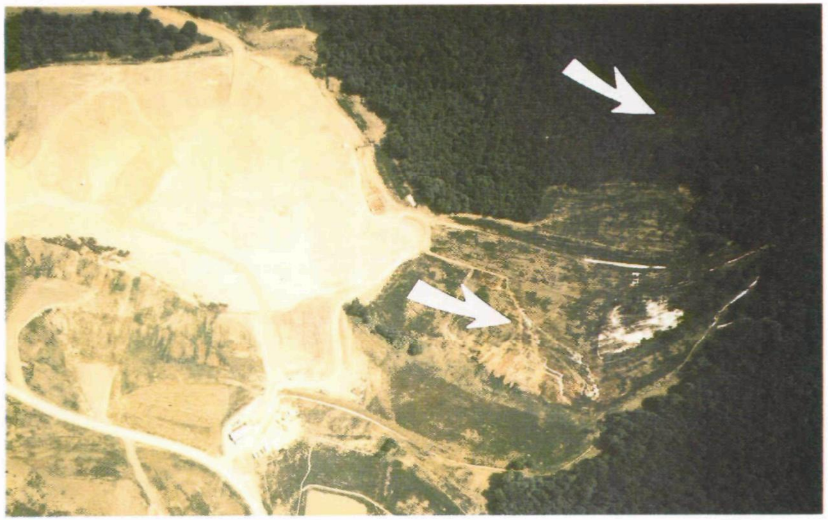
PLATE 2. GAPS IN VEGETATION AND SNOW

2a. June, Color	2b. Ground-level illustration of 2a
2c. December, Color	2d. Ground-level illustration of 2c

If large or small gaps in snow or vegetative cover can be related spatially to a landfill, they often indicate the presence of leachate. Gaps can be caused by increased wetness, toxicity or heat, and they can be isolated or radiate from a landfill. The significance of a remotely sensed gap is increased when it also demonstrates some other characteristic such as anomalous color, increased wetness or high thermal emission.

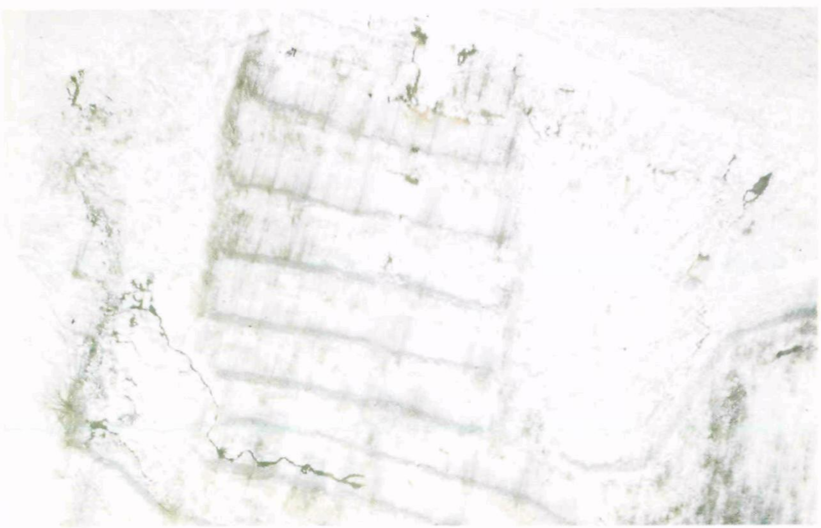
Gaps in vegetation are usually most apparent when the vegetation is low, as illustrated by the arrow in the center of Plate 2a. A ground-level illustration of this feature (2b) shows the grass and low brush which has been affected by the leachate. Only rarely will gaps show in heavy vegetation, as illustrated in the upper right hand corner of Plate 2a. In this case the gap was produced by severe leachate flooding which killed the large trees.

Gaps in a light snow cover are often a dramatic indication of leachate (2c). The combination of heat and salinity in the leachate can melt a light snow cover. If this can be associated spatially with a landfill, it is a logical location for sampling to confirm the contamination (2d).



2a.

2b.



2c.

2d.

Plate 2

PLATE 3. WETNESS

3a. March, Color

3b. March, Color Infrared

Any wet area that can be related spatially to a landfill is potentially contaminated by leachate. Consequently, wetness is a primary leachate indicator. Wetness can normally be deduced from the type of vegetation or the spectral characteristics of the wet area. Although sensors operating in many parts of the electromagnetic spectrum might be applied to detect wetness, cameras with color or color infrared film are the sensors that would most likely be used in a leachate detection program. The reflective differences between water and soil or vegetation are particularly high in the infrared spectral region (reference Figure 5.5), where absorption of radiation by water results in a blue to black color on a color infrared photograph.

The illustrations on Plate 3 are typical in that the majority of wet areas can be detected on both the color (3a) and color infrared (3b) photographs. The wet areas related spatially to the landfill (arrows) are areas of probable leachate contamination. These two images also illustrate that infrared photography gives a better indication of wetness, particularly for small features, shallow water and damp areas.

3b.

Plate 3

3a.

PLATE 4. STRESSED VEGETATION

4a. June, Color Infrared	4b. June, Color
4c. June, Color Infrared	4d. June, Color
4e. June, Color Infrared	4f. June, Color

Vegetative stress, when produced by leachate, can usually be detected more easily with color infrared than with color photography. However, leachate may or may not produce a vegetative stress, and the stress may be positive or negative. Leachate toxicity and drowning of root systems are common causes of negative stress, but increased nutrients and moisture levels may enhance vegetative growth.

The examples on Plate 4 illustrate the advantages of color infrared over color photography. The large, negatively stressed areas on Plate 4a are the result of excessive rates of application in a spray irrigation project. Vegetation near the center of the photograph has been drowned, while vegetation toward the lower left corner (downhill) has been affected by excess moisture and toxicity.

Much more subtle, negative stress effects are illustrated on Plates 4c and 4e (arrows). These often involve only one to several trees, and they are very difficult to use as leachate indicators unless they are in close spatial association with the landfill.

An illustration of a positive vegetative stress is the vigorous vegetation (bright red) going upward from the left center of Plate 4e.

4a.

4b.

4c.

4d.

4e.

4f.

Plate 4

PLATE 5. COLOR ANOMALIES

5a. March, Color — 5b. Ground-level illustration of 5b

5c. April, Color — 5d. Ground-level illustration of 5c

Color anomalies are among the most distinctive leachate features that can be detected using remote sensors. Almost all of these anomalies are a consequence of the high iron content of most leachates and the resulting red or red-orange reflectance of ferric iron. The iron can be dissolved in the leachate or precipitated on the bottom of ponds or streams. Even for seasonally dry, leachate breakout areas, the red-stained soils can be distinctive.

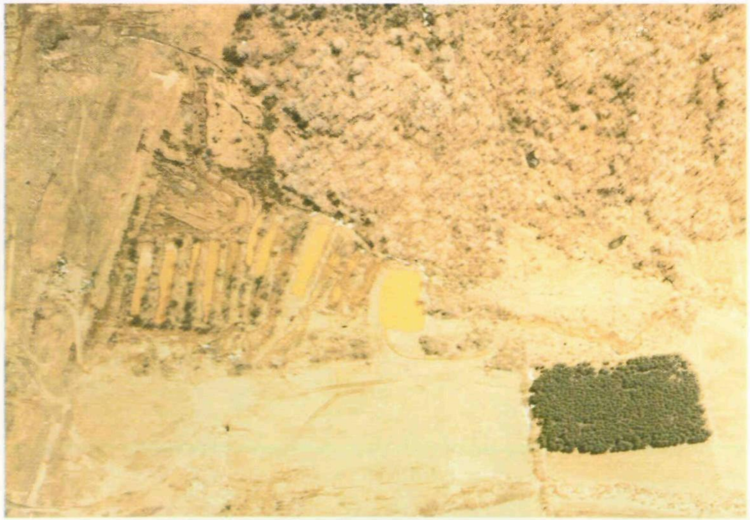
The red leachate seeps shown in Plate 5a (arrows) are typical and in contrast to the uncontaminated springs in the same area. In this illustration, the leachate-contaminated water has travelled several hundred meters underground before surfacing. A ground-level photograph (5b) indicates the size of these features.

The color of leachate-contaminated water (5c) is distinctive only when the contamination is at relatively high levels and when the iron is in the form of ferric oxide or similar compounds. Seasonal variation in the proportion of leachate being contributed to a water body may limit the distinctive color to certain times of the year, as illustrated in Plate 7.

Sometimes the anomalous color may be indirectly related to water in the form of a scum or biological growth on the water surface (5d). Snow may also be stained with a distinctive color anomaly (7a).

5a.

5b.



5c.

5d.

Plate 5

PLATE 6. THERMAL SCANNER DATA

6a. December, Thermal (pre-dawn)

6b. April, Thermal (pre-dawn)

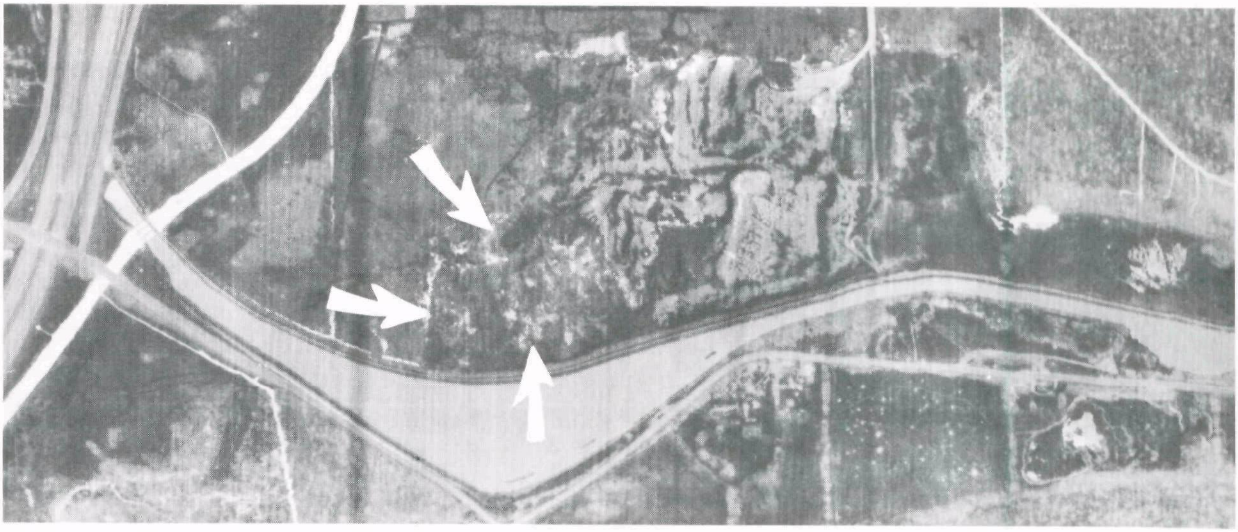
6c. April, Color

Although thermal data are useful for detecting wet areas, their principal value is for differentiating higher temperature leachate from uncontaminated ground and surface water. The difference in emissions between leachate and its surroundings is likely to be maximum at certain seasons of the year (late winter and early spring) and at night. To optimize target detectability, the thermal scanner should be flown just before sunrise (reference Figure 5.3).

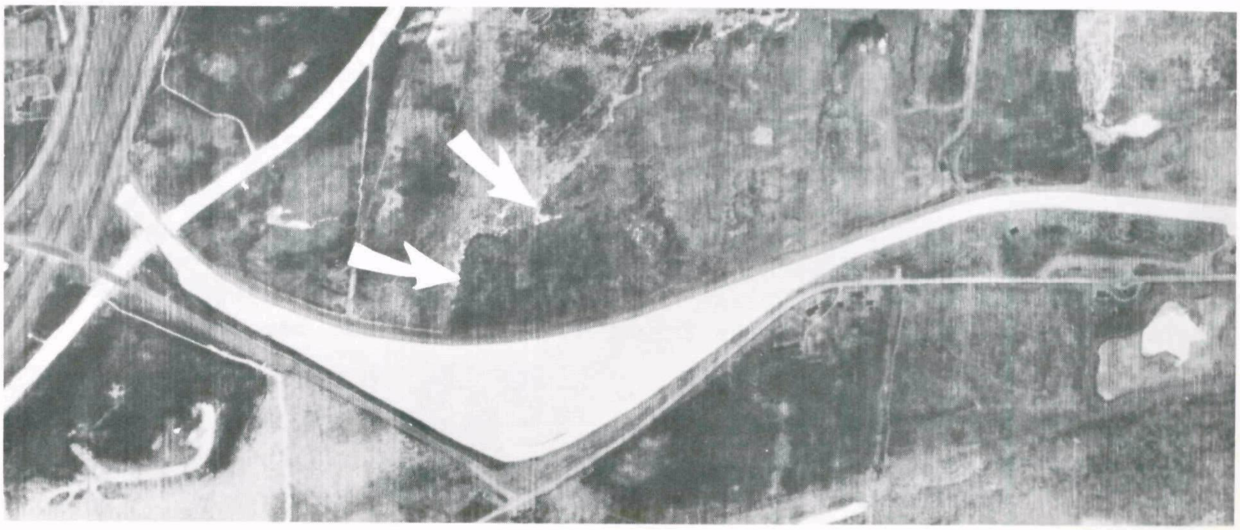
In the illustration, leachate breakout is occurring along the landfill perimeter (arrows). It is necessary to have this spatial association to define the leachate because there are other, similarly emitting targets on the image.

Snow cover during December (6a) masks some of the temperature and/or emissivity differences which show on the April data (6b). Leachate is ponding on parts of the landfill in April.

Plate 6c is a reference color photograph of this area. The landfill is being actively filled at the time these data were collected.



6a.



6b.

6c.

Plate 6

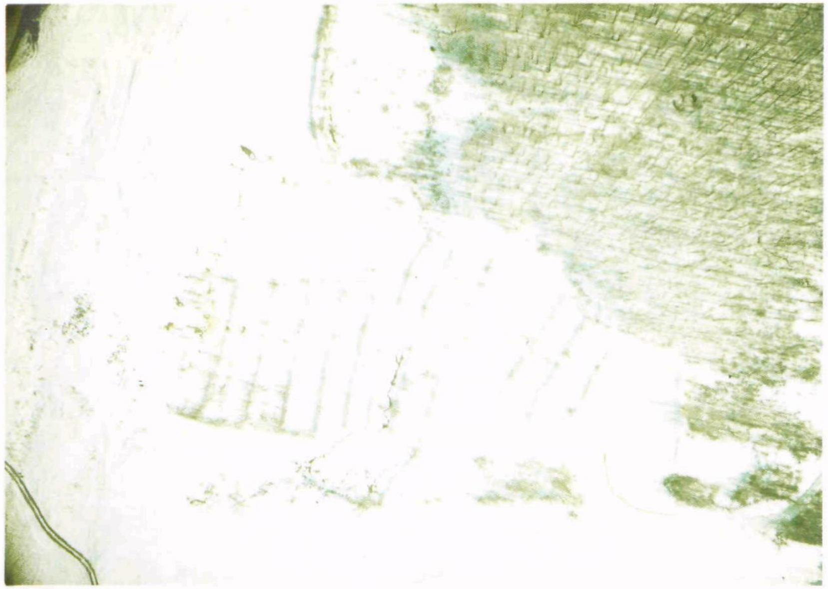
PLATE 7. TEMPORAL EFFECTS

7a. December, Color	7b. March, Color
7c. April, Color	7d. June, Color

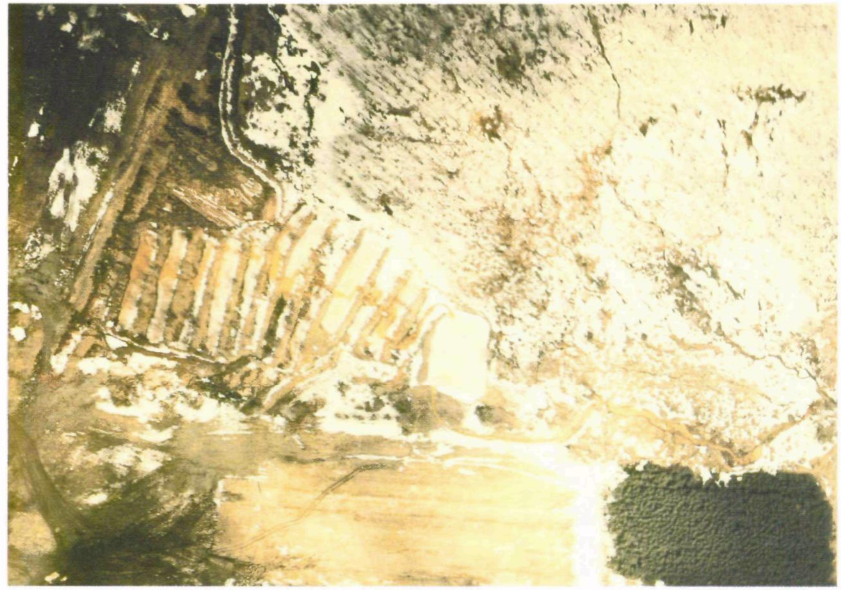
Temporal factors are extremely important in planning a leachate detection program since the production of leachate, as well as the interference by vegetation and heavy snow cover, are highly dependent on season and climate. Remote sensing missions to detect leachate should be planned for a time which optimizes the production of leachate and minimizes the interference from snow and heavy vegetation. In general, the potential for leachate production is high during wet periods and low during dry or frozen periods. Depending on the climate of a particular region, the wet periods may occur at different seasons or may not occur at all.

The illustration in Plate 7 is typical of a northern temperate region. Heavy snow cover during winter (7a) covers the leachate except where the higher temperature melts the snow and produces a gap. During late winter and early spring, the production of leachate will usually be near its annual maximum because of heavy rain and snow melt. Ideal conditions for detecting leachate will occur between the melting of snow, with its interference (7b), and the growth of new spring vegetation (7c). By late spring (7d), the full canopy of taller vegetation will obscure many of the features which could be detected earlier in the season.

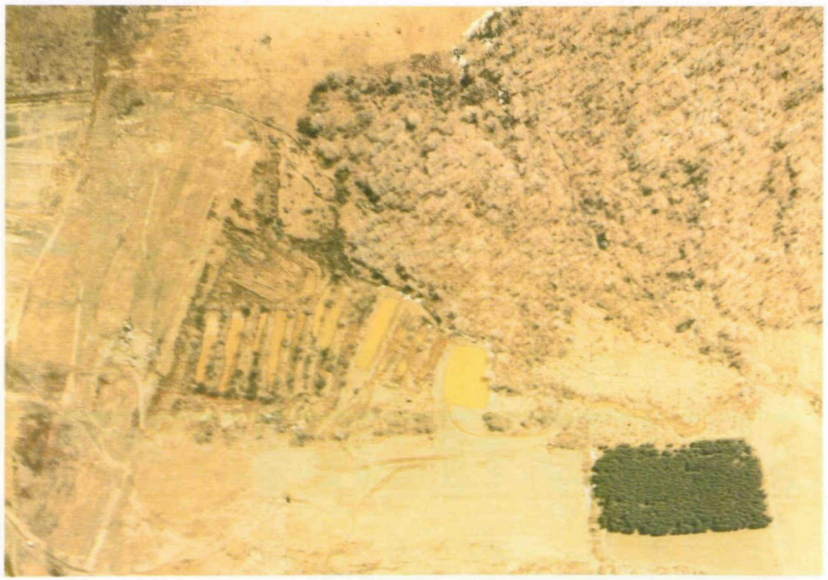
In some regions there will be a period during the late autumn or winter when the vegetation canopy will be gone and there will be no snow cover. When there is sufficient moisture to produce leachate, this can be an ideal season, comparable to the conditions illustrated in Plate 7b.



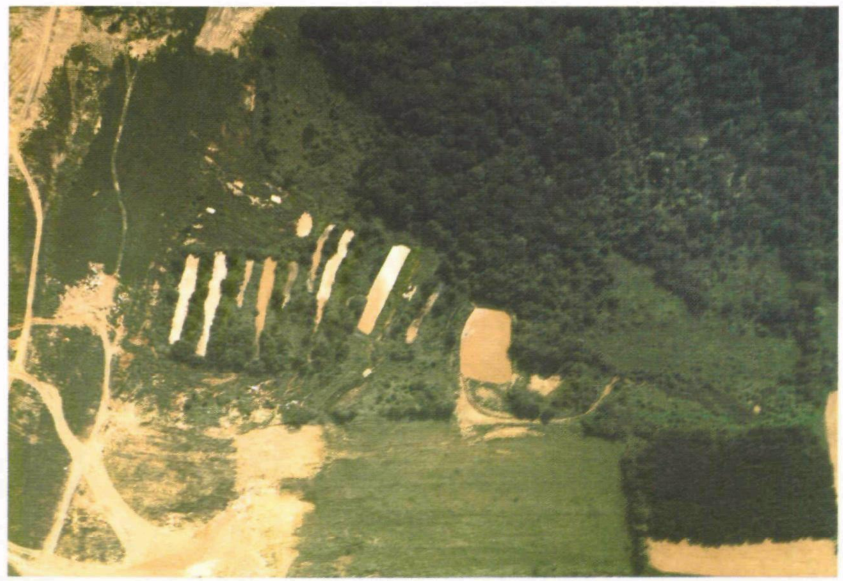
7a.



7b.



7c.



7d.

Plate 7

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APPENDIX A

In Section 5.3.3, the general equation for estimating flight and scanner parameters required for detecting a thermal target was derived as follows (refer to Reeves, 1975, p. 340 and 377):

$$NEP = (AdB)^{1/2}/D^* \tag{1}$$

and, $$B = [(V/H)\theta]/[2\alpha^2 p\gamma] \tag{2}$$

where, NEP = noise equivalent power of detector

B = electrical bandwidth

Ad = area of detector

D^* = detectivity

V/H = ratio of sensor platform velocity to height

θ = total field-of-view; angular coverage

α = angular resolution; instantaneous field-of-view in one direction (assume square field)

p = number of detecting elements

γ = scan duty cycle or efficiency

Since $\alpha^2 = Ad/f^2$, where f = focal length of optical system

then, $$NEP = [f(V/H)^{1/2}(\theta)^{1/2}]/[(2p\gamma)^{1/2}D^*] \tag{3}$$

The radiant power, P, which enters the optical system and ultimately strikes the detector is:

$$P = \tau\tau_o\alpha^2 A_c L_s \cos\beta \tag{4}$$

where, τ = transmissivity of atmosphere

τ_o = transmissivity of optical system

L_s = radiance from source, A_s

β = angle between nadir (vertical) and source

A_c = area of collector optics

In order that two adjacent resolution elements can be distinguished, the difference between the power received at the detector from the two elements must exceed the NEP of the detector, or

$$P_1 - P_2 > NEP \quad (5)$$

Then, $(\tau\tau_o\alpha^2 A_c L_s \cos\beta)_1 - (\tau\tau_o\alpha^2 A_c L_s \cos\beta)_2 > NEP \quad (6)$

or, $L_{s_1}\cos\beta_1 - L_{s_2}\cos\beta_2 > NEP/(\tau\tau_o\alpha^2 A_c) \quad (7)$

For adjacent resolution elements, β_1 is approximately equal to β_2. Letting, $\beta_1=\beta_2=\beta$, then,

$$L_{s_1} - L_{s_2} > NEP/(\tau\tau_o\alpha^2 A_c \cos\beta) \quad (8)$$

Assuming the target and surroundings are Lambertian radiators, radiating into a hemisphere of space,

$$L_{s_1} = M_1/\pi \; ; \; L_{s_2} = M_2/\pi$$

where, M = radiant exitance (or emittance).

Substituting in equation 8, $M_1 - M_2 > \pi(NEP)/(\tau\tau_o\alpha^2 A_c \cos\beta)$ (9)

The radiant exitance from the resolution element that contains a hot target will be

$$M_1 = (M_t A_t + M_s A_b)/A_s$$

where, M_t, M_s = exitance from the target and background area within the instantaneous field-of-view (IFOV)

A_t, A_b = area of target and background within IFOV

A_s = area within IFOV; $A_s = A_t + A_b$

The radiant exitance from an adjacent resolution element will be M_s, and the area will be approximately A_s.

Substituting in equation 9,

$$[(M_t A_t + M_s A_b)/A_s] - M_s > \pi(NEP)/(\tau\tau_o\alpha^2 A_c \cos\beta) \quad (10)$$

Solving,

$$M_t - M_s > A_s\pi(NEP)/(A_t\tau\tau_o\alpha^2 A_c \cos\beta) \quad (11)$$

Substituting equation 3 into equation 11,

$$M_t - M_s > \frac{A_s \pi [f(V/H)^{1/2} (\theta)^{1/2}]}{A_t \tau \tau_o \alpha^2 A_c \cos\beta [(2p\gamma)^{1/2} D^*]}$$

Since,

$A_c = \pi D^2/4$ and $F = f/D$

where,

D = collector diameter

F = aperture ratio of optical system

then,

$$M_t - M_s > \frac{A_s (V/H)^{1/2} (\theta)^{1/2} (4F)}{A_t \alpha^2 (\cos\beta) DD^* (2p\gamma)^{1/2} \tau\tau_o} \quad (13)$$

In general, from the Stefan-Boltzmann law,

$M = g\sigma\varepsilon T^4$

where,

T = absolute temperature of body

ε = emissivity of body

σ = Stefan-Boltzmann constant

g = fraction dependent upon T and wavelength interval being sensed (e.g., determined from tables; see Siegel and Howell, 1972).

Further, an alternative form of equation 13 would be presented by replacing A_s, the ground area of the resolution element seen at a scan angle of β. In general, from the solid angle relationship,

$\alpha^2 = A_s/R^2$

where,

R = radial distance between resolution element and scanner.

Since,

$R = H/\cos\beta$

then,

$A_s = H^2\alpha^2/\cos^2\beta$

APPENDIX B

SOURCES OF AERIAL PHOTOGRAPHS AND OTHER REMOTELY SENSED DATA

TYPE OF COVERAGE	PRIMARY SOURCE
1. Aerial photographs acquired by federal agencies, other than military, prior to about 1942	National Archives and Records Service Cartographic Branch 8 Pennsylvania Avenue, N.W. Washington, D.C. 20408
2. Aircraft data acquired by federal agencies, other than military and USDA; also, Landsat and Skylab satellite data	EROS Data Center U.S. Geological Survey Sioux Falls, South Dakota 57198
3. Aerial photography acquired under U.S. Dept of Agriculture; usually by county	
a. Acquired by Agricultural Stabilization and Conservation Service	Agricultural Stabilization and Conservation Service U.S. Dept. of Agriculture 205 Parley's Way Salt Lake City, Utah 84109
b. Acquired by Soil Conservation Service	Soil Conservation Service U.S. Dept. of Agriculture Cartographic Section 6505 Delcrest Road Hyattsville, Maryland 20782
4. Aircraft data acquired by the U.S. Environmental Protection Agency	EPA/EPIC P.O. Box 1587 Vint Hill Station Warrenton, Virginia 22186 EPA/EMSL-Las Vegas P.O. Box 15027 Las Vegas, Nevada 89114
5. Aircraft data acquired by state agencies	Varies with state; information is commonly available through the state department of transportation

TYPE OF COVERAGE	PRIMARY SOURCE
6. Aircraft photography acquired for tax mapping	Usually by county; information normally available through county assessment office
7. Other (e.g., commercial or non-government research data)	Variable; list of most commercial firms available from American Society of Photogrammetry, 105 Virginia Ave., Falls Church, Virginia; also, information often available through major universities in region

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16. ABSTRACT

A methodology for using remote sensing to detect landfill leachate contamination of ground and surface water is described. Among the topics covered are leachate indicators, spatial and temporal aspects of leachate detection, sensor selection, flight design and data interpretation. Specific methodologies for using remote sensing to detect leachate under various situations are described. These range from survey monitoring of individual landfills to comprehensive programs for regualtory monitoring and landfills.

Data and imagery from a field research and demonstration project are used to illustrate the use of remote sensors to detect leachate.

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