PRACTICAL PAPER

A Temporal and Spatial Resolution Remote Sensing Study of a Michigan Superfund Site

John D. Herman, Jane E. Waites, Randal M. Ponitz, and Paul Etzler

Abstract

Color infrared aerial photography collected for the years 1969, 1974, 1978, 1981, and 1986 showed a decrease over time in the intensity and extent of vegetation stress within the lowland hardwoods along the valley of Big Black Creek which flows east to west adjacent to the south edge of the Superfund site. The change in vegetation vigor corresponds to the initiation of groundwater remediation at the site in the late 70's, and containment of the chemical plume by groundwater pumping by 1986. The CIR aerial photography shows a definite improvement in the health and vigor of vegetation within Big Black Creek since the beginning of clean-up and remediation activities at the site.

A portion of the 1978 CIR photography was digitized and computer processed to simulate the pixel sizes of SPOT multispectral 20-metre, Landsat TM, and Landsat MSS satellite imagery to determine at what resolution the most extensive vegetation stress anomaly is no longer detectable. The vegetation damage associated with the site in 1978 was easily mappable on the SPOT and Landsat TM simulation imagery with 20- and 30-metre pixel sizes, respectively. However, it was difficult to detect on the simulated Landsat MSS imagery, with 80-metre pixels.

Introduction

Remote sensing techniques can aid in evaluation of historical changes in land use within and near hazardous waste and sanitary landfills (Erb *et al.*, 1981; Lyon, 1987; Stohr *et al.*, 1987). The effects of landfill leachate contamination are also detectable with remote sensing techniques (Sangrey and Phillipson, 1979). This previous work indicates that remote sensing techniques would be useful tools to assess the historical environmental impact of industrial sites which have had known or suspected releases of harmful contaminants.

The purpose of this study was to map possibly stressed or damaged vegetation near an U. S. Environmental Protection Agency (USEPA) Superfund Site in Muskegon County, Michigan (Figure 1). The work presented in this report is a first step toward the ultimate goal which would be the evaluation of remotely sensed vegetation health as an indicator of surface water and groundwater quality, and degree of soil contamination.

Project objectives were as follows: (1) determine as closely as possible the beginning of vegetation damage or stress near the Superfund Site using historical aerial photography (black-and-white, natural color, and color infrared); (2) track the extent of vegetation damage through time using the historical photography; (3) use digitized aerial photography to generate computer derived simulations of SPOT, Landsat TM, and Landsat MSS images of the Superfund Site vicinity at peak vegetation damage to determine the lowest resolution at which the damage is detectable; and (4) compare vegetation stress magnitude with groundwater, surface water, and soil chemical analytical data to assess the usefulness of remote sensing data for early warning of the extent of contamination and effectiveness of remediation efforts to remove contamination emanating from the Superfund site.

General Physical Setting

Study Area and Geology

The site is located approximately 6 miles east of the city of Muskegon, in Muskegon County, Michigan, adjacent to Big Black Creek which flows westward into Mona Lake (Figure 1). Surface material at the site consist of Pleistocene glacial lacustrine sands and silts, approximately 30 metres in thickness. These deposits overlie approximately 50 metres of Pleistocene glacial moraine consisting mostly of clay which rests upon the Mississippian age Marshall Sandstone bedrock (GZA-Donahue, 1990).

Depth to water table within the study area varies from 0 metres at the Creek to 7 metres at the northern edge of the site. Groundwater generally flows southward across the site toward Big Black Creek where it is discharged (GZA-Donahue, 1990) (Figure 2). Most of the detected groundwater contamination was found in the upper sandy and silty glacial lacustrine deposits (GZA-Donahue, 1990).

Vegetation

There are two general types of natural vegetation within the study area. Within predominantly moist zones in the valley of Big Black Creek, there are lowland hardwoods including Black Ash, Red Maple, Cottonwood, Willows, and Elm. Upland hardwoods consisting of Red and White Oak, Hickory, and Maple occupy the relatively well-drained higher elevations (Hudson, 1988)(Figure 2).

J.D. Herman, J.E. Waites, and R.M. Ponitz are with ENCOTEC, Inc, 3985 Research Park Drive, Ann Arbor, MI 48108.
P. Etzler is with Lockheed Environmental Systems and Technologies Company, 980 Kelly Johnson Drive, Las Vegas, NV 89119.

Photogrammetric Engineering & Remote Sensing,
Vol. 60, No. 8, August 1994, pp. 1007–1017.

0099-1112/94/$3.00/0
© 1994 American Society for Photogrammetry and Remote Sensing

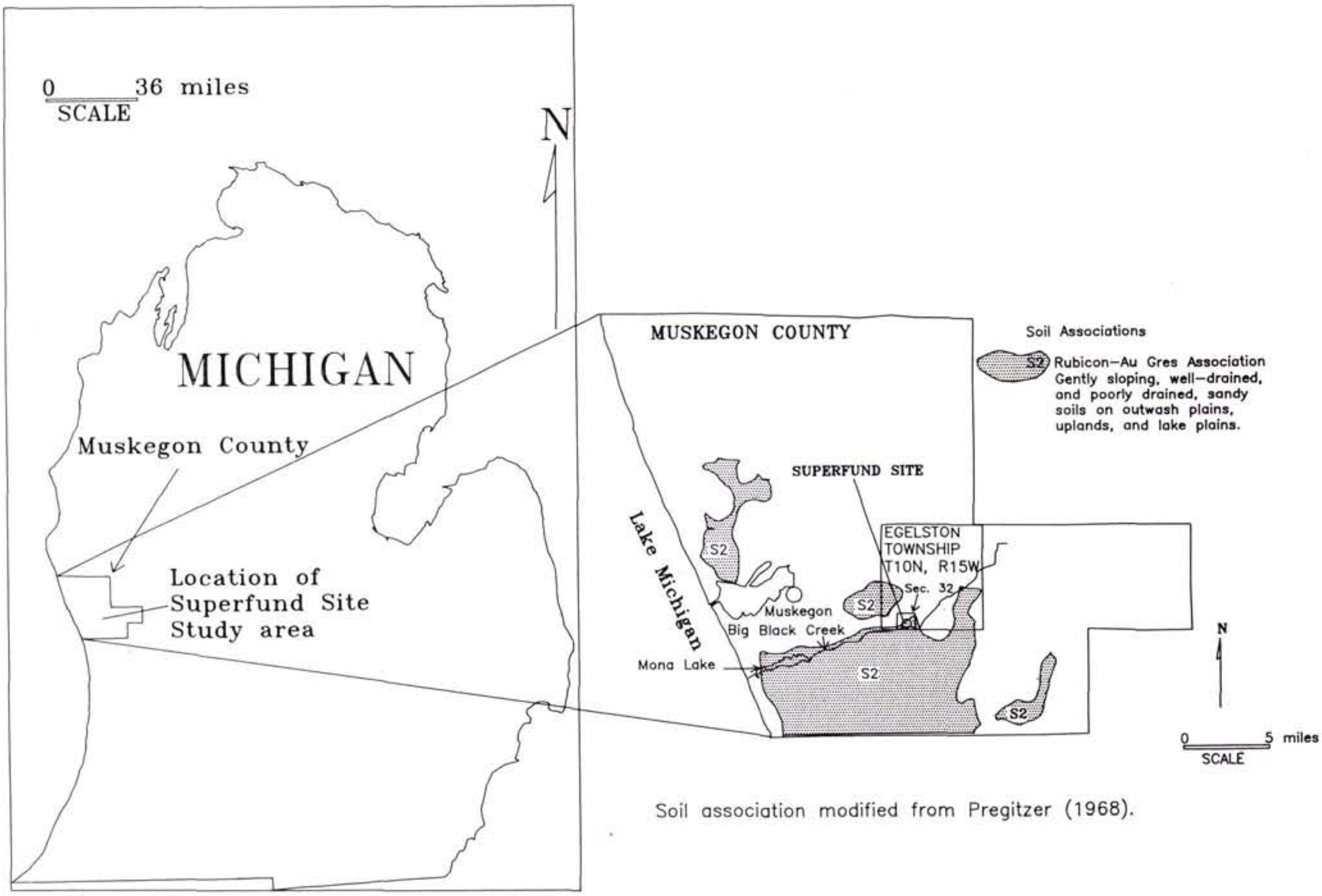


Figure 1. Location of study area.

Site Use History Summary
The Superfund site has been used by several companies from 1960 to the present time for the manufacture of industrial chemicals. In the 1960s and early 1970s, wastewater was discharged through open trenches into unlined lagoons adjacent to Big Black Creek (Figure 2). Compounds of concern found in soil, surface water, and groundwater within and near the site include benzene, toluene, tetrachloroethylene, methylene chloride, 3,3 dichlorobenzidine, azobenzene, and benzidine (GZA-Donahue, 1991). In 1993, the site was divided into two parts: (1) northern Plant Operable Unit (POU) where chemical manufacturing activities are ongoing, and (2) southern Lagoon Operable Unit (LOU) where remediation activities are continuing.

Methods
The first step in a remote sensing study evaluating vegetation health is the establishment of normal vegetation patterns within the study area. Surface elevation, soil types, and climate affect vegetation distributions.

Elevation and Soil Data
Portions of the Muskegon East and Sullivan USGS 7.5-minute topographic maps covering the study area were examined to compare elevation differences with vegetation types. A USDA soil survey of Muskegon County was used for comparison with vegetation types and areas of suspected stress (Pregitzer, 1968).

Climate and Vegetation Type
The climate of Muskegon County, Michigan is such that all the trees acquire their full complement of leaves by mid to late May, while most deciduous trees begin to acquire autumn colors and drop their leaves by early to mid October. The ideal time period for acquisition of aerial photography or other multispectral imagery for vegetation health studies is within this time frame. Aerial photography acquired in autumn (October or November) over the study area would be useful for vegetation species mapping because of the color contrast between trees which dropped their leaves and those which did not (Wetland Mapping Workshop, 1992). A stereo pair of 1:20,000-scale black-and-white panchromatic aerial photos acquired on 24 October 1961 was used to compare vegetation species with a vegetation-classification map covering the study area (Michigan Resource Inventory Program, 1978) to insure that vegetation stress anomalies were not confused with vegetation species variations.

Surface Water and Groundwater Quality data
Information on the chemical composition of the surface water of Big Black Creek and its capability to support aquatic life such as insects and fish was obtained from the Michigan

Department of Natural Resources regional office in Grand Rapids. Biological and chemical assessments of Big Black Creek upstream and downstream of the Superfund Site are found in Willson (1967), Willson (1970), Riley (1976), DeKraker and Riley (1977), Evans (1979), Ballantyne *et al.* (1982), West Michigan Shoreline Regional Development Commission (1982), Wuycheck (1986), and Donahue and Associates (1990).

Groundwater chemical composition data was reported by Donahue and Associates (1990) and West Michigan Shoreline Regional Development Commission (1978).

Soil Contamination Data

Chemical contaminants in soil were reported in Ballantyne *et al.* (1982) and GZA-Donahue (1990).

The soil, surface water, and groundwater data trends were compared with vegetation anomalies mapped from the aerial photography. This was done to determine how closely vegetation health trends corresponded to trends in water and soil quality.

Aerial Photography

Color infrared aerial photography was the chief tool used to track changes in vegetation health through time. Color photography would also be useful for vegetation health evaluations (Murtha, 1978). Unfortunately, high quality color photography was not available from 1969 to 1980 for this site. A list of color infrared aerial photography used for this work is shown on Table 1 below. For illustration in this paper, gray- level ratio images of digitized portions of the photography used for this work are shown on Figures 3A, 3B, 3C, 3D, and 3E. The ratio used in these images is reflected infrared divided by reflected visible red light. Healthy vegetation should appear bright white or light gray, while stressed vegetation should appear dark gray to black.

TABLE 1. AERIAL PHOTOGRAPHY USED TO EVALUATE VEGETATION HEALTH

Acquisition Date	Scale	Film Type	Source
21 Oct 61	1:20,000	B&W PAN	USDA
10 Sep 69	1:64,469	CIR	EROS, NASA
20 Jul 74	1:129,000	CIR	EROS, NASA
15 Aug 78	1:24,000	CIR	MI DNR
01 May 81	1:58,000	CIR	EROS, NASA
01 Jun 86	1:58,000	CIR	EROS, NASA

EROS, NASA = EROS data center in Sioux Falls, South Dakota
MI DNR = Michigan Department of Natural Resources
USDA = United States Department of Agriculture, Salt Lake City, Utah

Color infrared or natural color aerial photography collected during summer months provides an overall view of vegetation health. Table 2 below summarizes the appearance of progressively stressed or damaged vegetation on color infrared and natural color photography.

Healthy deciduous trees with green leaves should appear bright red or magenta on color infrared film. During the summer season, stressed leaves or trees with bare branches will

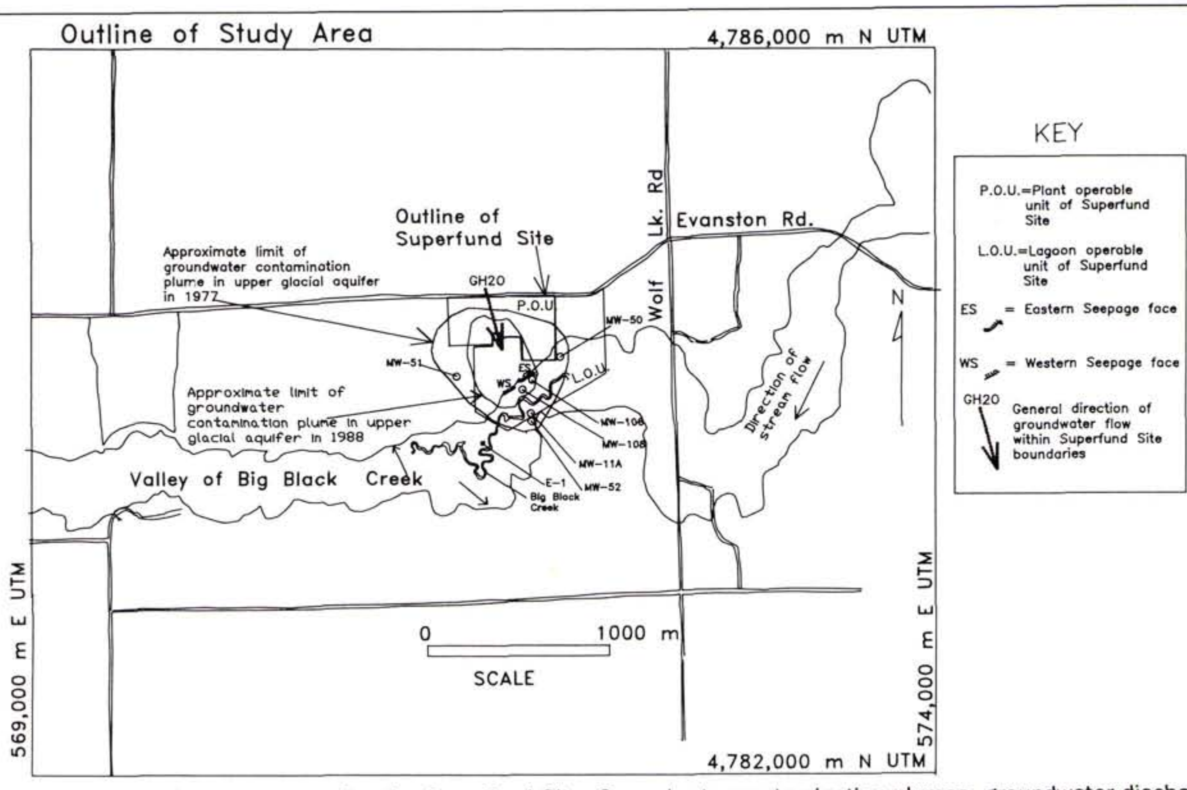
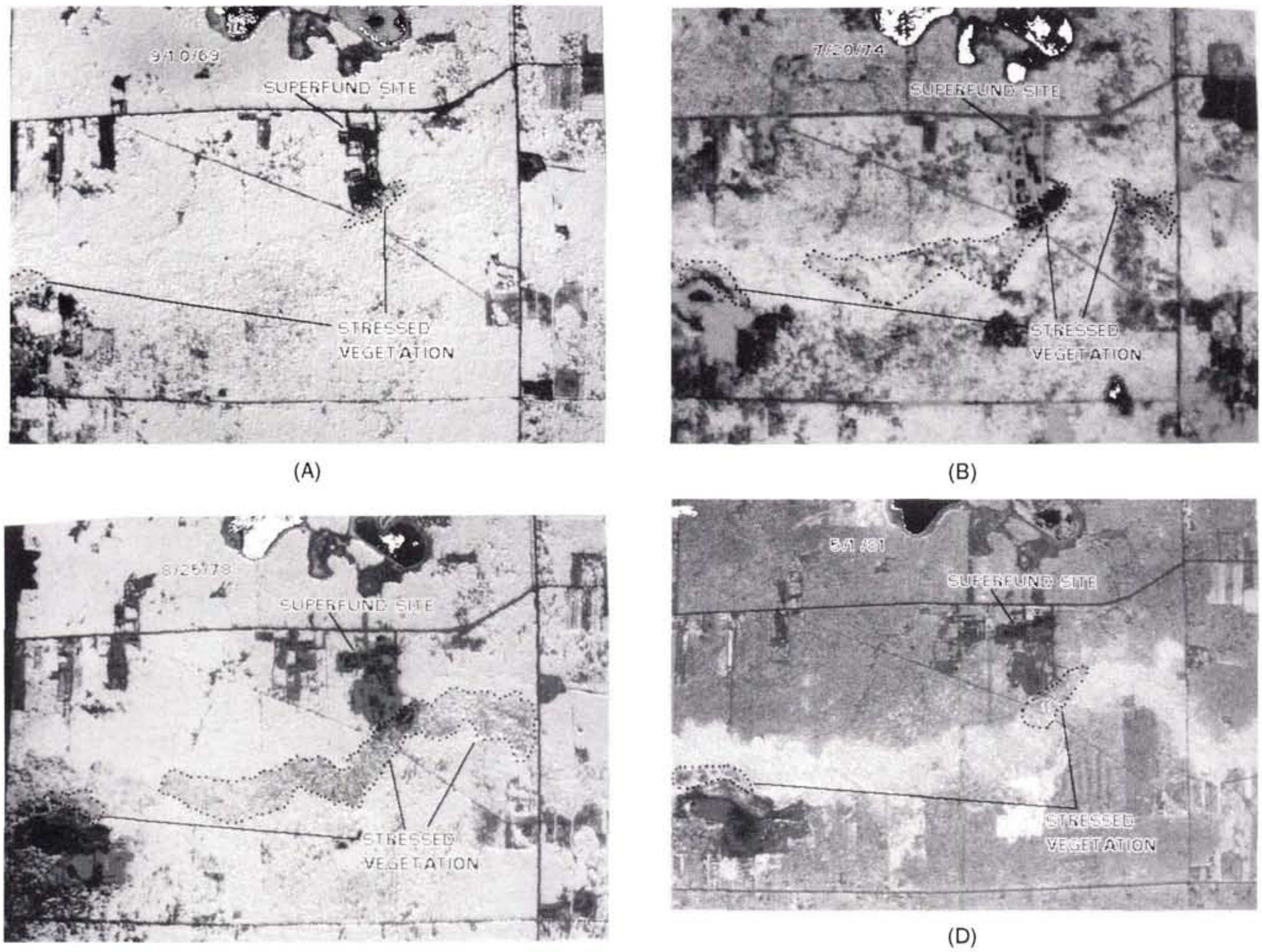
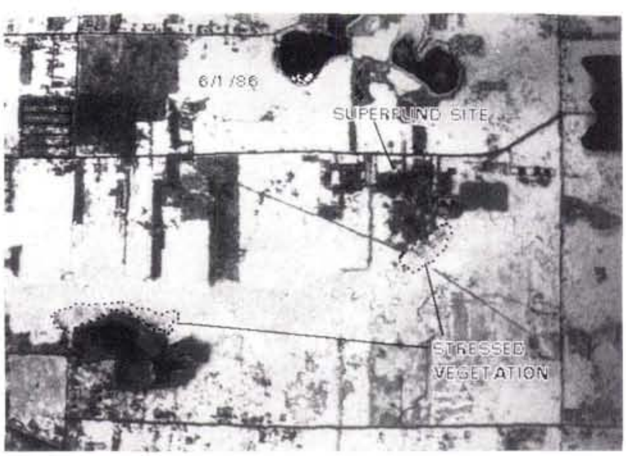


Figure 2. Extent of study area surrounding the Superfund Site. Groundwater contamination plumes, groundwater discharge areas (seepage faces) and the valley of Big Black Creek are also shown. Monitoring wells (MW) and soil sampling locations (E-1) discussed in the text are shown.



(A) (B) (C) (D)



(E)

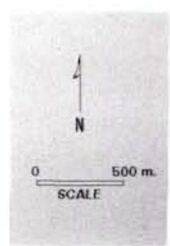


Figure 3. Ratio of reflected infrared divided by reflected red light derived from digitized color infrared aerial photos collected in 1969 (A), 1974 (B), 1978 (C), 1981 (D), and 1986 (E). Healthy vegetation appears white to light gray, while stressed vegetation appears dark gray to black.

appear as shades of pink, purple, green, blue, yellow, and white on color infrared film (Murtha, 1978).

The aerial photography was interpreted stereoscopically or monoscopically. Areas interpreted to be stressed or dam-

TABLE 2. FILM COLOR FOR VEGETATION IN VARIOUS STAGES OF STRESS

Film Type	Healthy	Initial Stress	Very Stressed	Dead or Defoliated
Natural Color	Green	Light Green	Yellow	Brown
Color Infrared	Magenta	Dark Magenta Pink	White Mauve	Yellow Green Blue

(from Murtha (1978)).

aged vegetation immediately surrounding the Superfund Site were delineated and digitized from unrectified photos (Figures 4A, 4B, 4C, 4D, and 4E). The total area of stressed vegetation for each year was recorded for comparison with available surface water, groundwater, and soil chemical and biological data (Figure 7).

Satellite Imagery

Simulated SPOT, Landsat TM, and Landsat MSS imagery were produced from digitized 15 August 1978 color infrared aerial photography. A 35-mm slide of the 1978 color infrared aerial photo was scanned by a Nikon CCD color slide scanner for desktop image processing on a personel computer. The pixel size of the digitized aerial photography represented 4.5 metres on the ground. The digitization process resulted in three separate files of blue intensity proportional to reflected visible green light, green intensity proportional to reflected visible red light, and red intensity proportional to reflected infrared light. Pixels were averaged to produce 20-metre, 30-metre, and 80-metre pixels to simulate SPOT, Landsat TM, and Landsat MSS imagery, respectively. The satellite bands represented by the blue, green, and red files of the digitized aerial photography are shown on Figure 5.

The spectral information displayed by minus blue filtered color infrared aerial photography is approximately equivalent to false-color images of the following satellite band combinations: (1) SPOT multispectral image with band 1 (visible green), band 2 (visible red), and band 3 (near infrared) displayed as blue, green, and red; (2) Landsat TM image with band 2 (visible green), band 3 (visible red), and band 4 (near infrared) displayed as blue, green, and red; and (3) Landsat MSS image with band 4 (visible green), band 5 (visible red), and the average of bands 6 and 7 (near infrared) displayed as blue, green, and red (Figure 5). The reflected red light band of the digitized aerial photography and satellite simulations derived from it are shown as gray level images on Figures 6A, 6B, 6C, and 6D.

Actual Landsat MSS satellite data collected on 26 September 1978, scene ID # LM82134315293X0, were available for comparison with the simulated Landsat MSS data (Figures 7A and 7B). TM and SPOT data were not available because these satellites were not yet operational at this time. Black-and-white positive transparencies of single bands (4, 5, 6, and 7) for Landsat MSS path 23, row 30 were digitized with a Hewlett-Packard flat-bed scanner. They were then combined to produce a false-color composite image for comparison with the simulated Landsat MSS imagery.

For illustration in this paper, the average of actual MSS bands 6 and 7 is displayed as a gray level image for comparison with a gray level image of the simulated MSS infrared band on Figures 7A and 7B. Digital 0 to 10 percent cloud-cover September 1978 Landsat MSS imagery on 9-track tapes was not available.

Results of Aerial Photointerpretation

10 September 1969

Figure 4A shows 24 hectares of stressed or damaged vegetation. Most of the stressed vegetation was within the valley of Big Black Creek. The level of stress was low or slight, being characterized by light pink coloration indicative of yellowish- green or light green leaves. However, there were some isolated areas of nearly dark blue to gray tones, indicating defoliation of the trees at the south end of the Superfund Site (Figure 3A).

Surface Water Quality before 1960

From 1921 to 1944 Big Black Creek was stocked with trout, and self-sustaining brook trout were present to the mid-1950s (Evans, 1979). The creek was considered among the premier trout fisheries in southern Michigan.

Site Activities 1960 to 1969

Chemical manufacturing at the Superfund Site had been proceeding for 9 years up to 1969. During that time, the plant in operation on the site produced alcohol-based detergents and dye intermediates such as dichlorobenzidine (DCB), benzidine, and azobenzene. DCB waste, zinc oxide waste, and other liquid waste was discharged along trenches or flumes into unlined holding ponds or lagoons in sandy soil at the south end of the site on the north side of Big Black Creek (GZA- Donahue, 1990).

Surface Water and Groundwater Quality, 1960 to 1969

Degradation of aquatic life in the Big Black Creek was first noticed in the 1960s. In the summer of 1967, the Michigan Water Resources Commission conducted a biological survey of Big Black Creek. The results of the study indicated that slime growths in the stream extended 2.3 km downstream of the Superfund Site's discharge zone into the Creek. The water quality of the Creek was adversely affected by seepage from the settling ponds or lagoons on the south side of the Superfund Site (Willson, 1967).

Complaints concerning the groundwater quality in the site area began in 1967.

24 July 1974

Figure 4B shows 46 hectares of stressed vegetation mostly within the valley of Big Black Creek mapped from photography, and a large increase in damaged vegetation acreage from 1969 photography. The level of stress within the vegetation was interpreted to be more severe than that displayed by the 1969 photography (Figures 3A and 3B). In particular, a distinctive dark bluish, purple, to dark gray zone almost 1 km long and 0.25 km wide extended downstream from the southwest end of the Site. These tones are indicative of severe vegetation damage characterized by yellow and brown leaves, or complete defoliation.

Site Activities, 1970 to 1974

An attempt was made to construct a lined lagoon for wastewater disposal in 1971 and 1972, but the liner deteriorated and it was subsequently abandoned (GZA-Donahue, 1990).

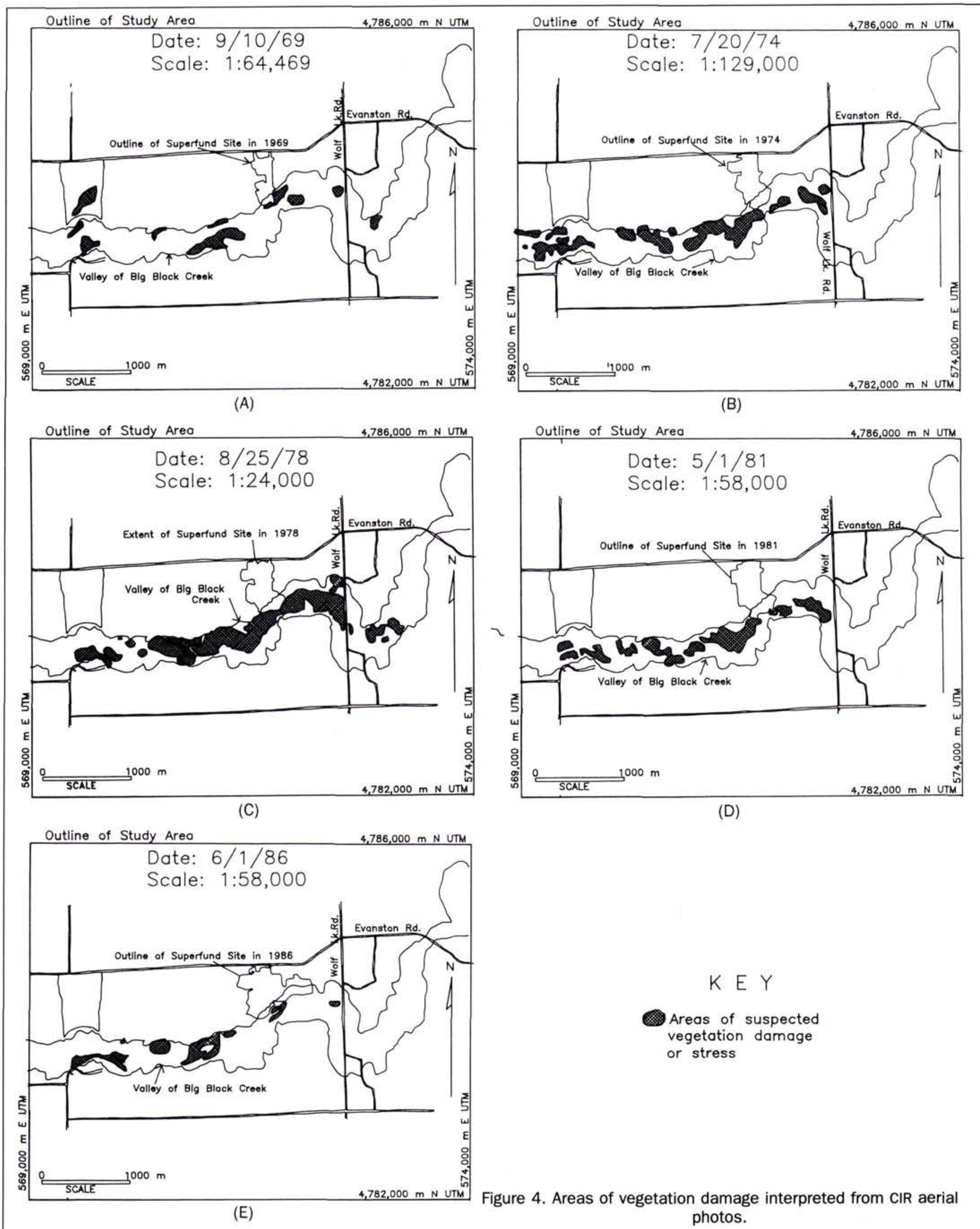


Figure 4. Areas of vegetation damage interpreted from CIR aerial photos.

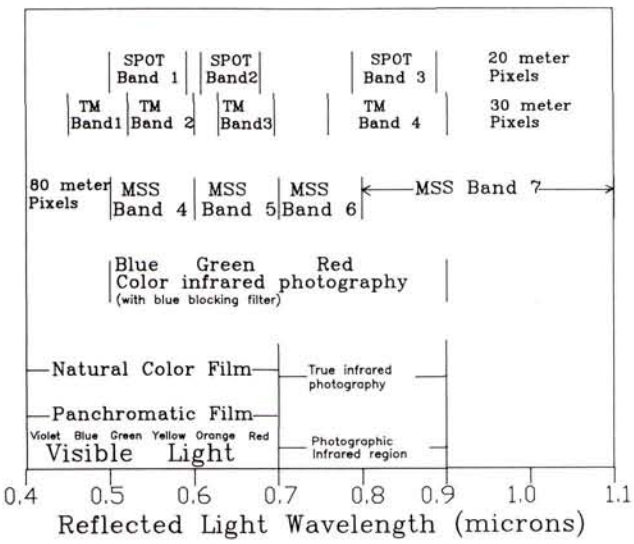


Figure 5. Comparison of reflected electromagnetic energy recorded by aerial photography and satellite imagery.

Surface Water and Groundwater Quality, 1970 to 1974
A 1970 biological survey of Big Black Creek found degradation of stream ecosystem 4.8 km downstream from the Superfund Site. Black sludge deposits were found in the site discharge area and for a distance of 4 km downstream of the site (Willson, 1970).

15 August 1978
Figure 4C shows 75.6 hectares of damaged or stressed vegetation within the lowland hardwoods of Big Black Creek downstream and upstream of the Site interpreted from the aerial photography. This is a significant increase in the area of stressed vegetation from 1974 to 1978. The level of vegetation stress was quite high or severe as exemplified by the abundance of white, yellow, blue, and green colors indicative of yellow or brown leaves or defoliated trees (Figure 3C).

Site Activities, 1975 to 1978
Three additional unlined lagoons were constructed in 1974 and 1975. Berm failures at the southernmost two lagoons constructed before 1970 occurred in 1974 and 1975, resulting in discharge of sludges into the valley of Big Black Creek (GZA-Donahue, 1990).

Surface Water and Groundwater Quality, 1975 to 1978
A 1976 Michigan Department of Natural Resources biological and chemical survey of Big Black Creek in the vicinity of Superfund Site found that the seepage effluent from the lagoons was extremely toxic to fish. This seepage effluent was leaking from the lagoons into Big Black Creek. A 72-hour LC50 bioassay test of the lagoon seepage water was found to be 4.4 percent seepage effluent (Dekraker, 1976)(72 hour LC50 is the percentage of effluent in water required to kill 50 percent of the fish in 72 hours). Grab samples of eastern seepage water (Figure 2), taken in July of 1976, contained 5 to 21 mg/litre benzene, 7 to 19 mg/litre toluene, 55 to 60 mg/litre hydrogen sulfide, and 4,530 to 4,880 mg/litre total dissolved solids (DeKraker, 1976).

Groundwater monitoring wells were installed in 1976, 1977, 1978, and 1979 to determine the vertical and horizontal extent of groundwater contamination. The water from these wells was analyzed for COD, pH, nitrate, phenols, chloride, sulfate, phosphorus, sodium, MBAS, and aromatic amines. The groundwater contaminant plume was found to extend at least 61 metres south of Big Black Creek based on the presence of aromatic amines in monitoring well no. 11A (Figure 2) (GZA-Donahue, 1990).

Site Remediation Activities, 1975 to 1978
Use of the lagoons for waste disposal was discontinued in 1976 when wastewater from the Superfund Site was sent to the Muskegon County Wastewater Treatment system. A total of 12 purge wells were installed along the southern half of the site in 1977 and 1978 for pumping and containment of contaminated groundwater (GZA-Donahue, 1990).

1 May 1981
This was the most difficult photography to interpret because not all the trees had acquired their full complements of leaves at the time it was collected (Figure 3D). In general, the lowland hardwoods acquire their leaves before those in uplands. Those trees within the valley of Big Black Creek with the least amount of leaves, exemplified by dark gray and blue colors, were suspected of being stressed. Interpretation based on this assumption found 36.8 hectares of stressed vegetation within the valley of Big Black Creek in the study area (Figure 4D). This was a substantial decrease in the acreage of damaged trees from 1978 to 1981, but the actual percentage decrease may be more or less because of the previously mentioned difficulties with interpretation of spring time color infrared imagery.

Groundwater and Surface Water Quality, 1979 to 1981
Water well clusters MW-50, 51, and 52 were installed in the summer of 1981 to determine the vertical extent of groundwater contamination. Sampling and analysis of water from these wells prior to 1986 indicated some contamination in all three clusters (GZA-Donahue, 1990). The approximate limits of the pre-1986 contamination plume is shown on Figure 2.

Site Remediation Activities, 1979 to 1981
In the summer of 1979, two additional purge wells were installed for pumping and containment of contaminated groundwater.

1 June 1986
Figure 4E shows 16.8 hectares of stressed vegetation were delineated within the valley, a substantial decrease in damaged tree acreage from 1978 to 1986. The level of stress within the lowland hardwoods was slight, as exemplified by areas of pink coloration indicative of light greenish to yellowish-green leaves (Figure 3E). An isolated area of severe vegetation stress characterized by dark gray and blue colors was mapped on the south side of the Superfund Site, adjacent to the east seepage face where contaminated groundwater was discharged in the past.

Surface Water, Groundwater Quality, and Soil Contamination, 1982 to 1986
A 1982 biological and chemical study of Big Black Creek by Ballantyne *et al.* (1982) showed similar pollution-tolerant macroinvertebrate communities upstream and downstream of the Superfund Site. Fish species and numbers actually in-

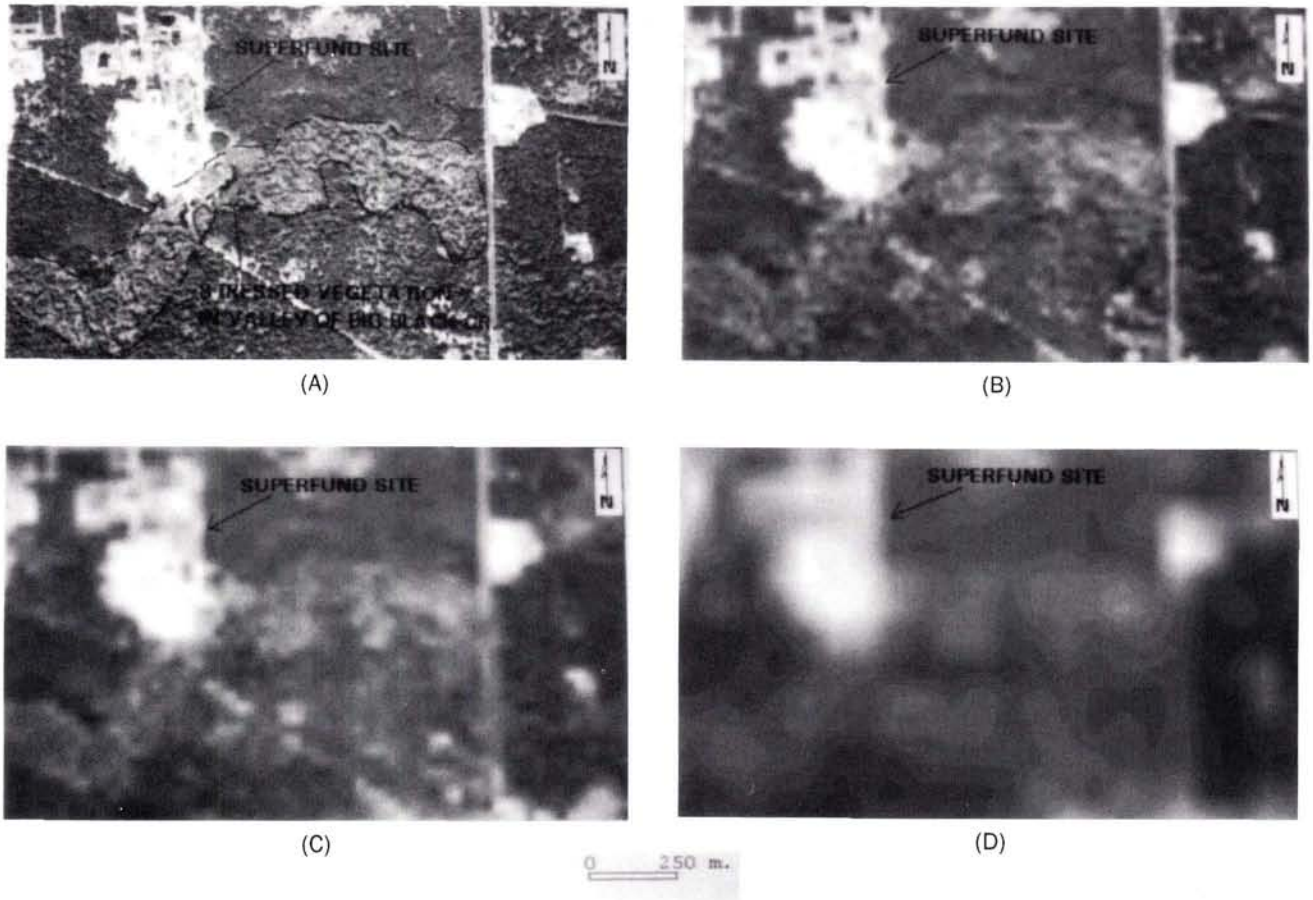


Figure 6. SPOT (B) with pixel size of 20 metres, Landsat TM (C) with pixel size of 30 metres, and Landsat MSS (D) with pixel size of 80 metres, gray level simulation images derived from digitized reflected red light portion of 1978 CIR aerial photo with pixel size of 4.5 metres (A).

creased downstream of the site. However, some contaminants were detected in sediment 360 metres downstream of the site at station E-1 (Figure 2). At this sampling location, sediment contained up to 16,200 ng/g benzidine, 51,900 ng/g DCB (3,3 Dichlorobenzidine), and 24.0 ng/g of aniline. Detection limits for benzidine, DCB, and aniline were estimated at 20.0 ng/g for all three compounds in sediment.

The MDNR (Michigan Department of Natural Resources) conducted a fish shocking and macroinvertebrate community assessment of Big Black Creek in 1986 (Wuycheck, 1986). The study concluded that water quality was sufficiently restored in the vicinity of the Superfund Site to warrant stocking the creek with trout.

Groundwater samples from monitoring well cluster MW-50 on the east side of the Superfund Site contained 2 to 4 ppb (0.002 to 0.004 mg/litre) during November 1986 sampling events (Figure 2)(GZA-Donahue, 1990).

Site Remediation Activities, 1982 to 1986

Three additional purge wells were installed for pumping and containment of groundwater in July of 1983, south of the existing purge system. Groundwater elevations indicated that groundwater flow had reversed direction in the vicinity of the purge wells (south to north), indicating groundwater capture caused by the purge well system by 1986 (GZA-Donahue, 1990; O'Donnell, personal communication, 1993).

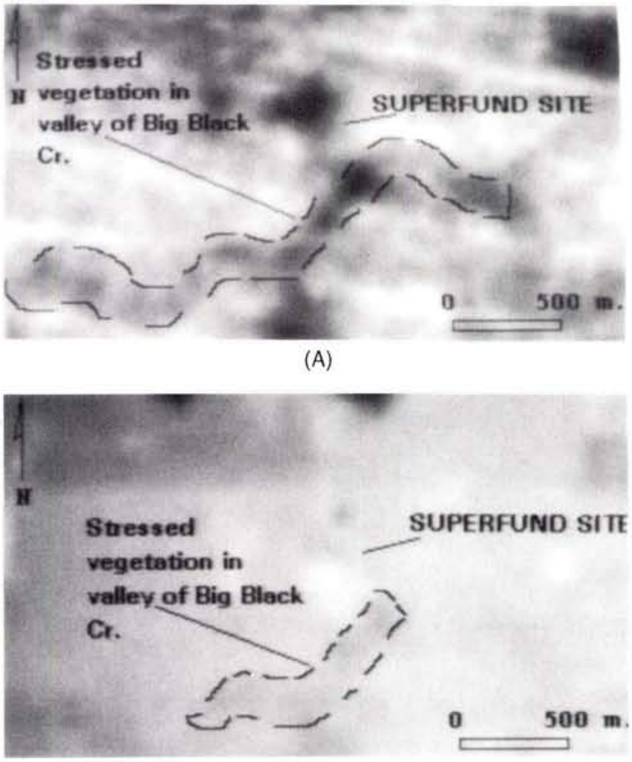
Sediments contaminated with DCB 360 metres downstream of the Superfund Site were removed by the site operator in 1985 (GZA- Donahue, 1990).

Site Activities, 1987 to 1993

The site was placed on the National Priorities List (Superfund) in March 1989.

Surface Water and Groundwater Quality, 1987 to 1993

MDNR personnel released 9,000 brook trout into the creek in 1987. The trout were reported to be doing well in 1988. However, MDNR personnel studying other Superfund sites downstream of the site indicated that, in 1992 and 1993, trout were rare or not found in Big Black Creek upstream and downstream of the site studied in this report (Adelman, personal communication, 1993).



(B)

Figure 7. Actual September 1978 Landsat MSS gray-level image of the average of bands 6 and 7 (A). Simulated Landsat image derived from digitized 1978 CIR aerial photo, showing gray level image of the reflected infrared (red of CIR photo) (B).

Groundwater samples from monitoring wells MW-106 and MW-108 in the eastern seepage area contained up to 4.0 and 0.31 mg/litre benzene, respectively, during sampling and analysis in June and July of 1988 (Figure 2). This was a significant decrease in benzene content of groundwater in this area from 1976, when grab samples of eastern seepage water contained 5.0 to 21.0 mg/litre of benzene. Sampling events in 1987 and 1988 did not detect any volatile organics in the MW-50 well cluster (GZA-Donahue, 1990). This indicated a decrease in volatile organics at this cluster since 1986 when 0.002 to 0.004 mg/litre of benzene was detected. The approximate area of the groundwater contamination plume outlined by 1988 well sampling activities is shown on Figure 2. The 1988 plume area is considerably smaller than the plume defined by sampling activities performed from 1976 to 1979 (GZA-Donahue, 1990).

Satellite Imagery Simulations

Digitized 1978 color infrared photography and the SPOT, Landsat TM, and Landsat MSS simulations derived from this photography are shown on Figures 6A, 6B, 6C, and 6D. The roads, facility building boundaries of the Superfund Site, and vegetation stress within Big Black Creek are still quite easily mapped on the SPOT (Figure 6B) and Landsat TM (Figure 6C) simulated images. These cultural features are difficult to discern on the MSS imagery (Figure 6D) without prior knowledge of the Superfund Site location and associated vegetation damage.

The actual false-color Landsat MSS image shows that the vegetation of Big Black Creek changes from bright red upstream of the Superfund Site to dark blue adjacent to and downstream of the site. This spectral variation corresponds to a change from bright white or light gray to dark gray or black on a gray-level image of the average of bands 6 and 7 (Figure 7A). The vegetation 1.5 km downstream of the site changes to bright red (false-color composite) or light gray (gray-level image of the average of bands 6 and 7) appearance on the real Landsat image (Figure 7A). This spectral change 1.5 km downstream of the site indicates presence of healthier trees with green leaves.

Summary and Conclusions

A comparison of the damaged vegetation acreage derived from aerial photo interpretation, surface water and groundwater quality, site activities, and remediation efforts is summarized on Figure 8. Vegetation damage increased in area and intensity from 1969 until 1978. In 1976, surface water and groundwater remediation efforts at the site began in earnest. Coincidentally, the area of stressed vegetation decreased in Big Black Creek from 1978 until 1986, at which time the groundwater contamination plume within the Superfund site area was thought to be contained (GZA-Donahue, 1990; O'Donnell, personal communication, 1993). This was confirmed by 1981 and 1986 CIR aerial photography.

The most severe vegetation stress anomalies delineated in 1978 should be mappable on SPOT multispectral and Landsat TM imagery based on examination of SPOT and Landsat TM simulations derived from digitized aerial photography (Figures 6A, 6B, and 6C). The most severe vegetation stress would be difficult to interpret from Landsat MSS data based on the simulated and real Landsat MSS imagery (Figures 7A and 7B), without prior knowledge of the site, and the vegetation anomalies.

Color infrared aerial photography, SPOT multispectral, and Landsat TM imagery can provide valuable information on vegetation vigor, which can serve as an indicator of surface water and near surface groundwater quality between wells and surface sample locations. Detailed information on vegetation vigor is difficult to discern on Landsat MSS data alone. These data can be used to evaluate the effectiveness of remediation or corrective measures efforts at severely contaminated sites. Detectable or mappable vegetation damage was associated with benzene and toluene levels of 100's to 1000's of ppb in groundwater at this site. Vegetation stress due to contaminants such as volatile organics at levels lower than these in the groundwater may not be easily mappable or detectable by manual or visual inspection of color infrared aerial photography or satellite imagery.

Acknowledgments

The authors gratefully acknowledge the support of Peter J. Atkins, co-founder and former President of ENCOTEC, Inc., who encouraged remote sensing research and projects for monitoring environmental contamination at RCRA facilities in conjunction with corrective measures studies. We also thank Robert Vincent, President of GeoSpectra Inc., and William (Terry) Lehman, of EOSAT Inc. for their encouragement and helpful comments related to the initial portion of this study which began in 1989 while three of the authors were at GeoSpectra.

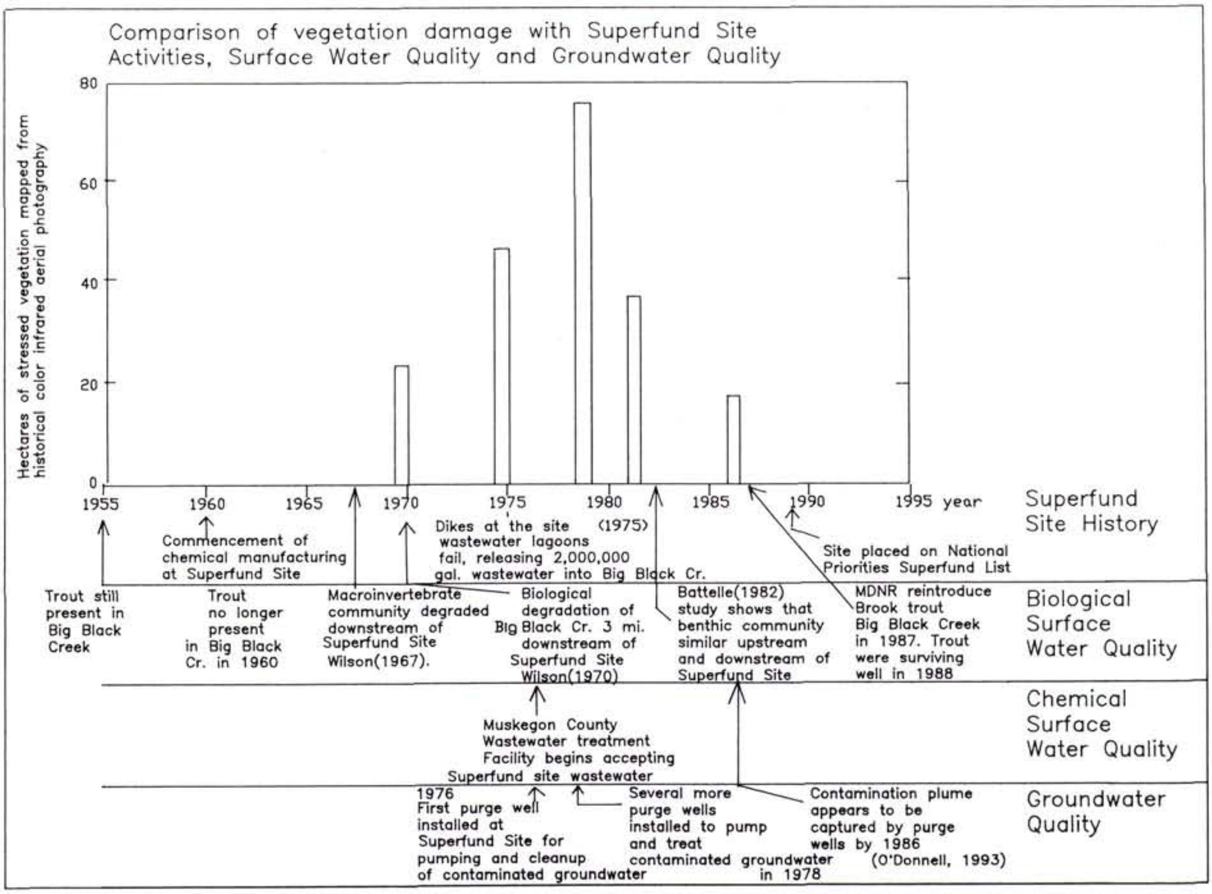


Figure 8. Comparison of vegetation damage interpreted from aerial photography with Superfund Site activities, surface water quality, and groundwater quality.

References

Ballantyne, M., D. Bean, C. Howard, and R. Riggin, 1982. Biological and Chemical Assessment of Big Black Creek, Muskegon County, Michigan."Superfund Site," October 29, 1982.

DeKraker, D., and C. Riley, 1977. Report on a Caged Fish Study Conducted on Big Black Creek Continuous Flow Bioassay in the Vicinity of and Downstream from "Superfund Site," Muskegon County, Michigan, October 5–17, 1977, Michigan Department of Natural Resources.

Erb, T., W. Phillipson, W. Teng, and T. Liang, 1981. Analysis of Landfills with Historical Airphotos, *Photogrammetric Engineering & Remote Sensing*, 47:1363–1369.

Evans, E., 1979. A Biological Evaluation of Big Black Creek Basin, Muskegon County, Michigan, July 10 to September 7, 1978. Michigan Department of Natural Resources.

GZA-Donahue, 1990. Remedial Investigation Report for the "Superfund" Site, Muskegon, Michigan, Volume 1 of 2, Chapters 1–7, prepared for State of Michigan Department of Natural Resources, Grand Rapids, Michigan.

———, 1991. Draft Public Comment Feasibility Study Report for Superfund Site Groundwater/Plant Area Operable Unit, Muskegon, Michigan, November 1991, Report Prepared for State of Michigan Department of Natural Resources, Grand Rapids, Michigan, by GZA-Donahue.

Hudson, W. D., 1988. *Interpreting Michigan Forest Cover Types from Color Infrared Aerial Photographs*, Natural Resources Research Report 452, Michigan State University Agricultural Experiment Station, East Lansing, Michigan, pp. 2–3, 18–23.

Lyon, John Grimson, 1987. Use of Maps, Aerial Photographs, and other Remote Sensor Data for Practical Evaluations of Hazardous Waste Sites, *Photogrammetric Engineering & Remote Sensing*, 53(5):515–519.

Michigan Resources Inventory Program, 1978. *Land Use Inventory Classification Maps and Key*, Michigan Resource Inventory Program, Lansing, Michigan.

Murtha, P. A., 1978. Remote Sensing and Vegetation Damage: A Theory for Detection and Assessment, *Proceedings, Symposium on Remote Sensing for Vegetation Damage Assessment*, 14–16 February 1978, Seattle, Washington, American Society of Photogrammetry, pp. 19–52.

Pregitzer, K. E., 1968. *Soil Survey of Muskegon County, Michigan*, United States Department of Agriculture in cooperation with Michigan Agricultural Experiment Station, pp. 12–89.

Riley, C., 1976. Report of Caged Fish Study Conducted on Big Black Creek in the Vicinity of and Downstream from the "Superfund Site," Muskegon County, Michigan, November 4–15, 1976, Michigan Department of Natural Resources.

Sangrey, D. A., and W. R. Phillipson, 1979. *Detecting Landfill Leachate Contamination Using Remote Sensors*, Research Report EPA-600/4-7-060, E.P.A., Las Vegas, Nevada, 67 p.

Stohr, Christopher, W. J. Su, P. B. DuMontelle, and R. A. Griffin,

1987. Remote Sensing Investigations at a Hazardous Waste Landfill, *Photogrammetric Engineering & Remote Sensing*, 53(11):1555–1563.

Waites, J., Paul Etzler, and John Herman, 1989. Aerial Photography Study of Hazardous Waste Effects of the South Half, Section 32, T10N, R15W, Egelston Township, Muskegon County, Michigan, report prepared by GeoSpectra Corporation for GZA-Donahue, incorporated into Remedial Investigation Report on Superfund Site by GZA-Donahue, 1990.

West Michigan Shoreline Regional Development Commission, 1982. *The Muskegon County Surface Water Toxics Study*, Toxic Survey General Summary, September 1982.

Wetland Mapping Workshop, 1992. *Wetland Vegetation Remote Sensing and Mapping Workshop*, United States Geological Survey, Stennis Space Center, Mississippi, 26–30 October 1992.

Willson, R. B., 1967. Biological Surveys of Big Black Creek, Vicinity of "Superfund Site," Muskegon County, Michigan, During High and Low Flow Periods, June 7 and August 17, Michigan Department of Natural Resources.

———, 1970. Biological Investigation of Big Black Creek, Vicinity of "Superfund Site," Muskegon County, Michigan, August 4, Michigan Department of Natural Resources.

Wuycheck, J., 1986. Big Black Creek/Muskegon County/Pre-Fish Stocking Evaluation Survey, March 27, 1986, Michigan Department of Natural Resources.

John D. Herman

John D. Herman received a B.S. degree in Geophysics from the University of Missouri-Rolla in 1976 and an M.S. degree in geology from the University of Michigan in 1985. He worked as an exploration geophysicist and geologist for Phillips Petroleum Co., the Missouri State Geological Survey, St. Joe American Mining Co., and GeoSpectra Corporation from 1975 to 1991 mapping and developing oil, gas, coal, and mineral prospects using remote sensing, subsurface, and geophysical data, and mapping environmental pollution with aerial photography and Landsat TM data. He joined Environmental Control Technology Corporation (ENCOTEC, Inc.) in Ann Arbor, Michigan in 1991 where his primary responsibilities include project management of remote sensing and mapping studies for environmental site assessment and ongoing monitoring, as well as groundwater and soil contaminant transport modeling.

Jane E. Waites

Jane E. Waites received a B.S. in Natural Resources and Environmental Science/Education from Michigan State University in 1980. She was employed by ERCO Petroleum Services Laboratory in Houston, Texas from 1981 to 1982. She managed the scanning electron microscopy laboratory for the Houston Region for Amoco Oil Production Company in Houston from 1982 to 1984. She worked for GeoSpectra Corporation, Ann Arbor, Michigan from 1984 to 1990, doing geobotanical research and remote sensing studies for environmental, oil and gas exploration, and defense applications. She joined the Environmental Assessment Group of Environmental Control Technology Corporation (ENCOTEC, Inc.) in 1990. Her work at ENCOTEC has involved RCRA facility investigations, corrective measures studies, and aerial photographic interpretation for Phase I site assessments and vegetation health analyses.

Randal M. Ponitz

Randal M. Ponitz received a B.S. degree in Earth Sciences and Geology from Eastern Michigan University in 1982 and an M.S. degree in marine geology from the University of Michigan in 1985. He joined the Engineering and Assessment Group of Environmental Control Technology Corporation of Ann Arbor, Michigan in 1988 and has been actively involved in a wide range of projects in both technical support and project coordination/management roles. He is a member of the American Association of Petroleum Geologists, the Association of Engineering Geologists, and the American Society for Photogrammetry and Remote Sensing. He is also an instrument rated commercial pilot and holds registration as a professional geologist in several states.

Paul J. Etzler

Paul J. Etzler's experience includes all aspects of the practical application of remote sensing and other types of regional data. This experience has included data selection, acquisition, processing, and analysis. The data used have included numerous satellite- and aircraft-based instruments as well as geophysical and field measurements. Mr. Etzler specializes in combining data sets into integrated studies. His study goals have included petroleum and mineral resource searches, ecological applications, military applications, and scientific research.

Mr. Etzler's educational background includes an M.S. in Geology and Planetary Sciences from the University of Pittsburgh, and a B.S. in Astronomy from the University of Michigan. He has worked at GeoSpectra Corporation and The Environmental Research Institute of Michigan (ERIM). He is currently living on the back of the Spring Mountain Overthrust and working on the North American Land Characterization (NALC) program as Senior Scientist at Lockheed Environmental Systems and Technologies Company in Las Vegas, Nevada.

To receive your free copy of the ASPRS Publications Catalog, write to:

ASPRS
Attn: Julie Hill
5410 Grosvenor Lane, Suite 210
Bethesda, MD 20814-2160

Please indicate your area of interest: Photogrammetry, Remote Sensing, GIS, Cartography, all of the above.