Classification of Depressions in Landfill Covers Using Uncalibrated Thermal-Infrared Imagery

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Abstract
A two-step analysis was used to classify depressions developed in covers of two landfills: (1) manual delineation of depressions by stereoscopic, aerial photographic interpretation, followed by (2) classification of depressions according to infiltration characteristics using uncalibrated, nighttime, airborne, thermal IR imagery. Depressions were delineated as landforms according to their topographic expression using color infrared aerial photography.

Classification of depressions into Type I or Type II was made by comparison of mean values of the digital numbers (exitance) inside and outside of a depression (interdepressional area). Samples are taken along a single scan line in order to eliminate variations caused by the gain adjustment of the scanner. Comparison of sample means of digital numbers was made using the t-test. The use of the two-step method will permit early detection of apparent infiltration characteristics of depressions formed in landfill covers.

Background
The purpose of sanitary landfilling is to isolate wastes from human society and the ecosystem. Settlement of a landfill cover caused by decomposition and consolidation of wastes can initiate cracking, irregularities, and depressions in the cover which can allow water to infiltrate into the wastes (Stohr *et al.*, 1990; Booth and Price, 1989), and can lead to groundwater contamination. If water mixes with the wastes, the wastes decompose to produce methane, leachate, and a reduced volume of refuse (EMCON Associates, 1980; Lu *et al.*, 1985; Christensen and Kjeldsen, 1989; Bogner *et al.*, 1990). An increase in the amount of water mixing with the wastes will cause an increase in the amount of leachate and methane generated by decomposition. The production and release of methane into the atmosphere and of leachate into groundwater can be detrimental to the surrounding ecosystem (Campbell, 1989).

Prevailing practices for evaluating the effectiveness of a landfill in isolating wastes from the surrounding ecosystem include monitoring wells and leachate collection systems, and field reconnaissance (Bagchi, 1989; Stohr *et al.*, 1990). If waste products are detected in a well, then leachate is known to have formed and discharged in the direction of that well. This passive monitoring by sampling and testing of wells detects contaminant movement after it has occurred. Monitoring by wells does not indicate where water is entering the landfill nor does it provide early warning of the need for remedial efforts to contain pollution.

Stohr *et al.* (1987) separated two types of depressions at a hazardous-waste landfill using thermal characteristics of post-sun- set, ground-based, thermal infrared (IR) imagery. These types were considered to be moisture-retaining and freely infiltrating. Moisture-retaining depressions are thought to lose water by evapotranspiration and so appeared relatively cooler than surrounding ground. Freely draining depressions appeared to lose water by flow through the cover and so appeared about the same as the surrounding ground. In this study, probable moisture-retaining depressions were classified as Type I depressions, and probable freely infiltrating depressions were classified as Type II depressions.

Objectives
This study examines the use of a decisive statistical procedure with uncalibrated, airborne thermal IR imagery to identify and classify depressions on landfills. The goal of the research is to develop a procedure to identify depressions as sources of infiltration on landfill covers and to classify the depressions according to their infiltration characteristics using two types of remote sensing: stereoscopic aerial photography and thermal IR imagery. The use of uncalibrated thermal IR imagery was intended to develop a relatively low-cost and effective procedure for classifying infiltration characteristics of depressions in landfill covers. The statistical t-test allows objective classification of the depressions.

Site Descriptions
Two landfills 11.5 km (6.5 mi) apart in east-central Illinois were selected for study. Both of the landfills were constructed in an area of thick loess and silty diamicton (glacial till). Both have earthen covers approximately 1 m (3 feet) thick covered by mixed vegetation.

Landfill A, closed in 1988, encompasses approximately 36.4 ha. Figure 1 shows Landfill A bounded by an interstate

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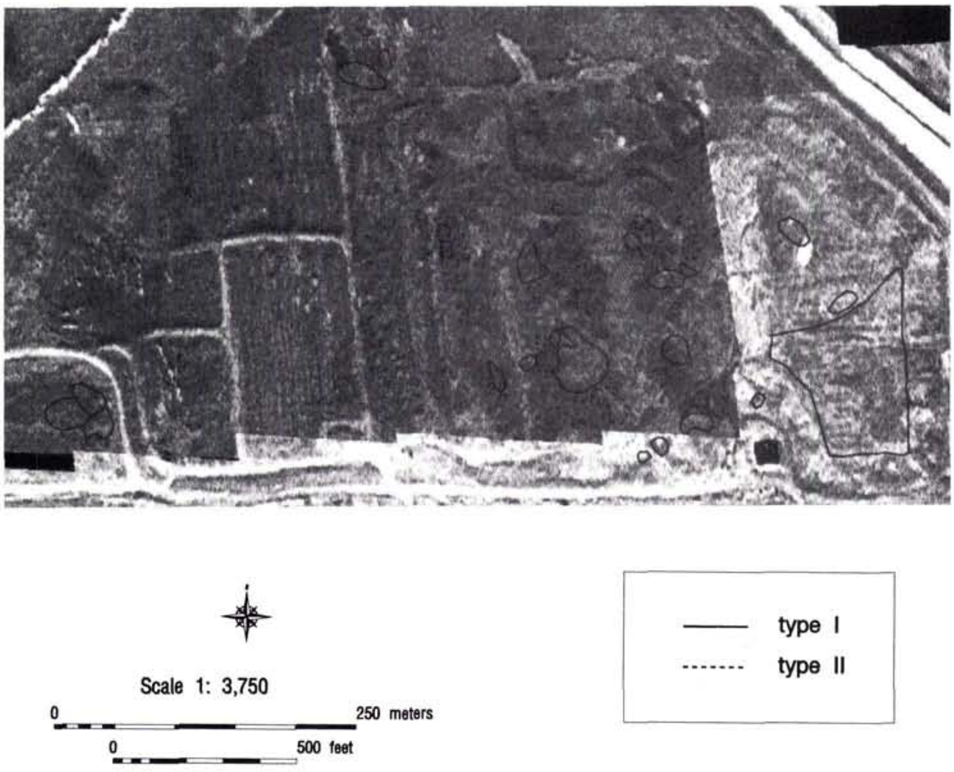

Figure 1. Image map of mosaicked, nighttime thermal infrared imagery of Landfill A recorded on 8 June 1992. Depressions are classified using uncalibrated imagery by statistical comparison of exitance inside and outside of a depression. Solid lines indicate moisture-retaining depressions, dashed lines indicate freely infiltrating depressions. Moisture-retaining depressions have a darker interior than surrounding ground because of the evaporation of excess moisture. The landfill is bounded to the northeast by a divided highway and to the south by a gravel road. A tool shed appears as a dark square at the lower right.

highway on the north, vacant land and residences to the east and southeast, agricultural fields to the south, and a wastewater treatment plant, a drainage ditch, and sludge treatment ponds to the west. Excavation depths at the site during construction ranged from 0 to 9 metres. Total thickness of waste ranges between 3 and about 18 metres. The landfill was operated as a trench fill in the eastern and western ends and an area fill in the central part.

Landfill B, closed in 1976, occupies a 66.8-ha tract. Figure 2 shows Landfill B bounded by an interstate highway to the north, and agricultural fields and a few private residences on the remaining sides. The landfill was operated by the trench and fill method. A drag-line crane was used for excavation and a bulldozer was used for leveling. Total thickness of the wastes is about 7.6 m; however, two former landfill workers estimated the depth of the trenches to be 12 m.

At the time of aerial data collection, field reconnaissance at both landfills found some moisture-retaining depressions, a few of which contained cattails. Gravimetric soil moisture measurements of samples from soil borings were made in the expectation that the standing water and cattails indicated moisture-retaining characteristics. One soil boring and gravimetric soil moisture measurement was made at Landfill B at a depression thought to have freely infiltrating characteristics. Additional borings and soil moisture measurements were made in areas between depressions.

Aerial Data

Nine-inch, 1:3000-scale, color-infrared (CIR) aerial photography was collected on 18 June 1991 for both landfills. Post-sunset thermal IR imagery was collected about one year later at midnight on 8 June 1992 using a FLIR, Inc. 2000A thermal IR scanner provided by the Illinois Department of Corrections flown on an Illinois Department of Transportation helicopter. The scanner was mounted on gimbals for vertical data collection. It has no internal standards for absolute calibration; hence, its imagery was uncalibrated. Thermal IR imagery was recorded on a portable VHS video cassette recorder.

Thermal IR imagery was flown at midnight in order to avoid problems with ground fog that may develop near sun-

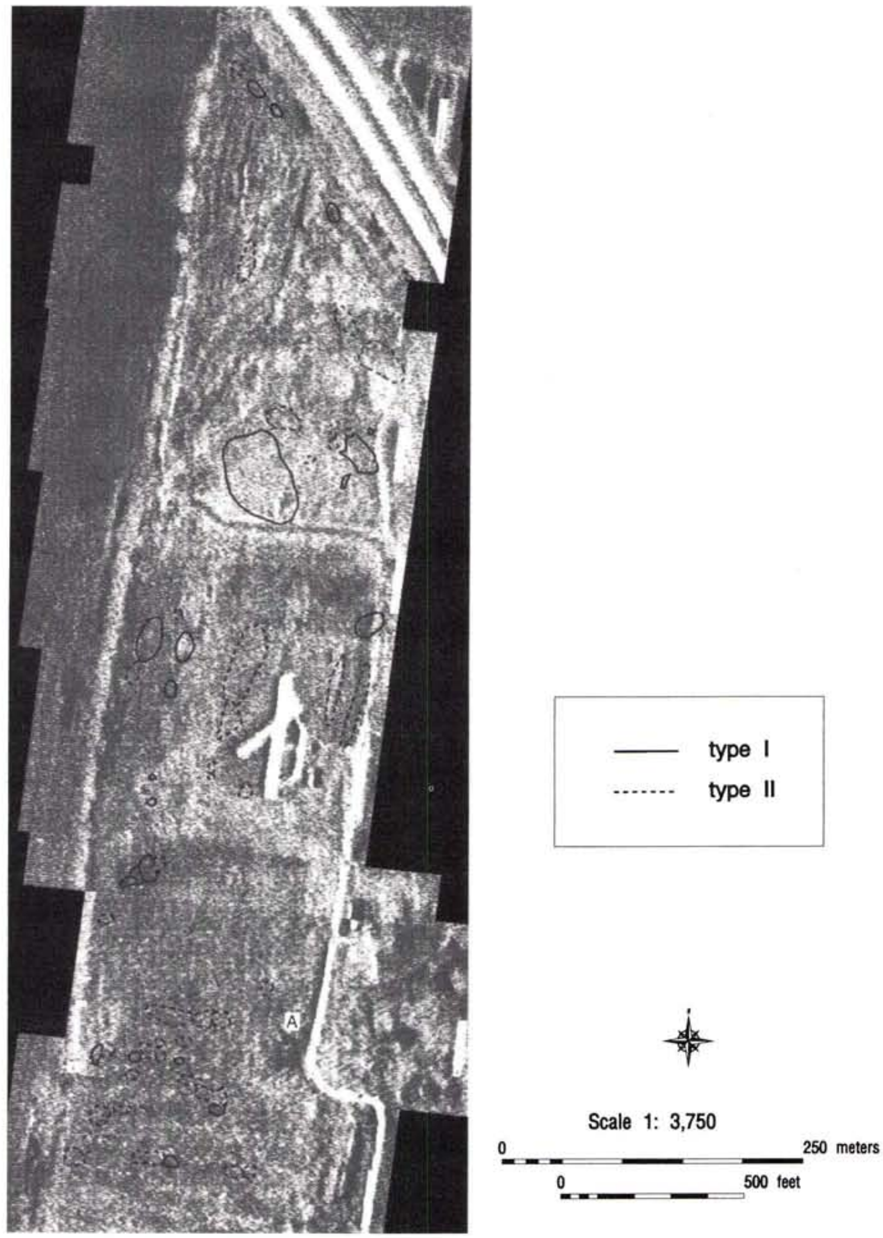

Figure 2. Image map of mosaicked, nighttime thermal infrared imagery of Landfill B recorded on 8 June 1992. Depressions are classified using uncalibrated imagery by statistical comparison of exitance on the inside and outside of a depression. Solid lines indicate a moisture-retaining depression, dashed lines indicate a freely infiltrating depression. Moisture-retaining depressions have a darker interior than surrounding ground because of the evaporation of the excess moisture. The landfill is bounded to the north by a divided highway and to the east by a gravel road. Small trees and shrubs lining the west property line appear bright. A radio-controlled model airplane runway (bright) and equipment shed (dark) are in the center of the image. A dark-toned spring on the edge of the landfill cover and immediately west of the gravel road, is marked at A.

rise, and problems with dew that may develop a few hours after sunset. Because vegetation type and density were nearly uniform around individual depressions, we assumed that variations in thermal exitance of the landfill cover around

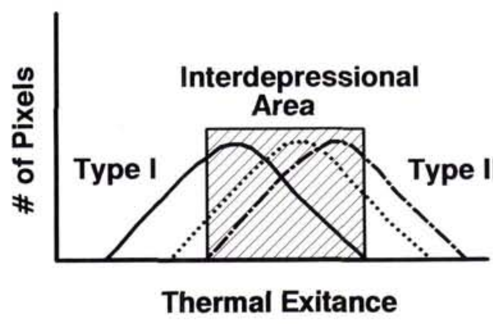

Figure 3. Comparison of hypothetical histograms of thermal exitance for Type I and Type II depressions and interdepressional areas (outside). The overlapping exitance of the two types of depressions preempts the use of maxima and minima for classification of depressions.

the depressions are related to soil moisture as a consequence of both surface drainage of the cover and internal drainage of the depressions.

A 3.8-cm (1.5-in.) rainstorm (as recorded at a nearby climatological station) occurred on the evening of 6 June 1992, two days before the thermal IR data collection. The rainfall was observed to fill some depressions at Landfill A to a depth of a few inches. Actual rainfall amounts at each landfill are unknown.

Registration of photography was accomplished using a combination of previously surveyed ground-control points and new points derived from phototriangulation of 1:7600-scale, black-and-white aerial photography recorded on 30 March 1988. Registration of individual photos to the ARC/INFO geographic information system (ESRI, 1991) was performed in lieu of rectification of the photos because the amount of tip of the 1992 photos could not be compensated by the stereoplotter. Registration of photography with the ground control was found to be within 3 m at Landfill A and 0.5 m at Landfill B. The higher RMSE at Landfill A was probably caused by the registration of three flightlines of mosaicked imagery.

Procedure

The procedure used to identify and classify depressions on landfill covers was

- set panel ground control points at landfills;
- collect stereoscopic color infrared aerial photography of landfills;
- delineate depressions on stereoscopic, color-infrared aerial photographs using a mirror stereoscope;
- make soil borings, collect samples, and determine gravimetric moisture content for profiles at selected depressions;
- collect vertical, nighttime thermal infrared imagery on a VHS video cassette recorder;
- create geographic information system (GIS) coverage for each landfill;
- add additional control points into GIS;
- digitize depressions into GIS;
- capture/convert frames of thermal IR imagery from analog VHS video cassette tape to digital format;
- mosaic digital thermal IR imagery;
- identify control points and geometrically register thermal IR mosaic to GIS coverage;
- overlay photointerpreted depressions on mosaicked thermal IR imagery;
- select pixels on interior and exterior of individual depressions along same scan line;
- classify depressions by comparing means of raw digital numbers using t-test; and
- compare remote sensing classification with soil moisture profiles.

A MATROX Illuminator (TM) frame-grabber was used to capture and digitize the thermal IR imagery for image processing. Mosaicking of the uncalibrated thermal IR imagery was performed by manually matching common points on individual frames. Thirty-three frames (11 frames in three flightlines) were mosaicked for Landfill A; ten frames were mosaicked for Landfill B using ERDAS (1991) (TM) image processing software. First-order transformation of the mosaicked imagery registered to a GIS of each landfill using ERDAS (TM) GCP and COORDN software had 10-foot root-mean-square error (RMSE) and 2-foot RMSE for Landfills A and B, respectively. Resolution of pixels was estimated to be about 0.5 metre (1.7 feet).

Identification and Classification of Depressions

Identification of Depressions

Depressions are commonly recognized by topographic relief and associated visual cues: change in tone, color, land cover, and shadowing. Topographic maps having a two-foot contour interval can be insufficiently detailed to show depressions found by aerial-photointerpretation and field reconnaissance (Stohr *et al.*, 1992).

The combination of unevenly distributed vegetation on light and dark soils can pose problems for interpreting depressions on a graded landfill cover. Color infrared photography is more useful than black-and-white in distinguishing soils from vegetation (Stohr *et al.*, 1992). However, vegetation density (biomass) as perceived on the ground may have a different appearance on color IR photography. Grassy vegetation up to one metre high may appear to be lush in the field, but may have only a pink or pale red color on the color IR photography. The pink color ambiguously indicates either vegetation stress, small leaf area, or lack of sufficient biomass to generate the familiar magenta color associated with healthy foliage in humid regions during late spring.

Classification of Depressions

Traditional image processing relies upon two strategies, density slicing and pattern recognition, that allow the use of computers to classify an image (i.e., categorize the digital numbers (DNs) of an image into suitable classes). Density slicing separates spectral classes on the basis of strictly defined maxima and minima (Figure 3). Pattern recognition, usually used for multiband analysis, employs statistical decision-making methods to classify the imagery into categories based solely upon DNs.

Both of these techniques require that all features in a class be statistically similar and spectrally separable from other classes in order to (a) identify physical features such as depressions on the imagery and (b) distinguish (classify) the features according to some criteria such as soil moisture or infiltration characteristics. Such an assumption can not be made for this analysis because:

- each image in the mosaic has a slightly different range in measured exitance as shown in Figure 1,

- landforms such as depressions are rarely distinguishable on the basis of spectral response (Stohr and West, 1974), and
- exitance for the depressions and surrounding ground is spectrally similar (Figure 3).

Circuits in the thermal IR scanner adjust the signal gain by as much as 33 percent of the previous image for successive scans. Sampling and statistically comparing DNs from a depression along a single scan line effectively eliminates variations caused by the gain adjustment. Comparing means of DNs inside and outside of a depression along a single scan line permits the use of uncalibrated imagery for analysis and classification. This is based on the assumption that thermal exitance of the landfill cover around the depressions is primarily related to soil moisture as a consequence of both surface drainage of the cover and internal drainage of the depressions, as shown in Figure 4a (Stohr *et al.*, 1987). However, Figure 3 illustrates the diversity in thermal exitance inside and outside of a depression, which complicates classification.

Figure 4b shows the method for sampling exitance inside and outside of a depression. Note that there is a bias in collecting a sample from a depression. Generally, sampling should be done from the lowest part of a depression. However, standing water must be avoided. Standing water should not be sampled because this violates the assumption of sampling a common cover type, and because water temperature can be influenced by many environmental factors. Sampling in areas other than in the bottom could cause a depression to be erroneously classified as freely infiltrating because the upper part of a depression is sloping and generally better drained.

The Student's t distribution was used to analyze the data. The t-test determines whether the mean for a sample of pixels from inside a depression is like or unlike a sample from outside of a depression. A 95 percent confidence limit was selected for this test. The classifications of the depressions are summarized in Table 1.

According to the previous study (Stohr *et al.*, 1987), freely infiltrating depressions will have the same or a higher exitance than surrounding ground. Consequently, the t-test should be a one-tailed test. Mean DN values of depressions having t-critical values less than the t-value at the 95 percent confidence level are classified as Type I, probably moisture-retaining depressions. All others were classified as Type II, probably freely infiltrating depressions.

In statistical terms:

H_0: $\mu_1 \leq \mu_2$, Type II depression

H_1: $\mu_1 < \mu_2$, Type I depression

where

H_0, H_1 - Null hypothesis, alternative hypothesis;

X_1 - mean of depression under examination;

X_2 - mean of surrounding ground;

s - standard deviation of sample; and

N - number of observations (pixels).

The formula for the t-test is

$$t_{calc} = \frac{X_1 - X_2}{\sigma\sqrt{1/N_1 + 1/N_2}} \quad \text{where } \sigma = \sqrt{\frac{N_1 s_1^2 + N_2 s_2^2}{N_1 + N_2 - 2}}$$

In terms of "rules":

1. If t_{calc} is positive, then the depression is a freely-draining depression.
2. If t_{calc} is negative, then compare t_{calc} with $t_{0.95}$
   2a. If $t_{calc} > t_{0.95}$, then the depression is a freely draining depression.
   2b. If $t_{calc} < t_{0.95}$, then the depression is a moisture-retaining depression.

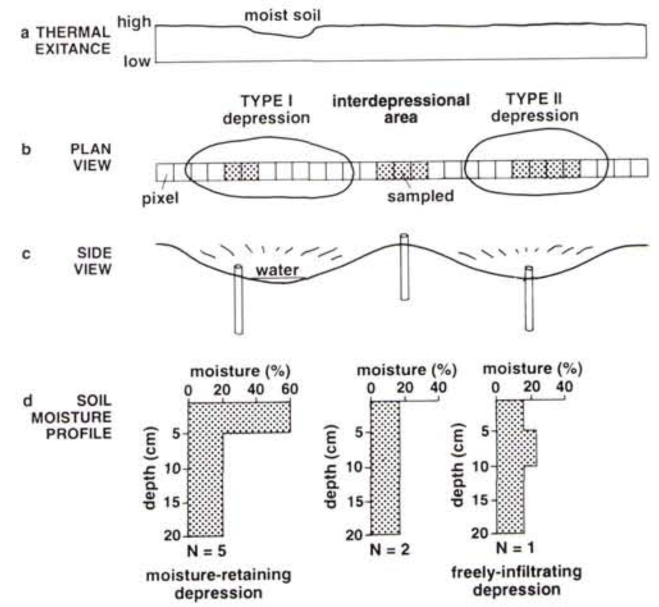

Figure 4. Warm season, nighttime thermal-exitance sampling scheme, topographic profile, and soil moisture profile to Type I and II depressions and interdepressional areas. Type I depressions have lower thermal exitance (a) than surrounding ground and should be sampled (b) in the lowest, moist areas of the interior of the depression, but standing water should not be sampled (c). The Type I depressions exhibit a high soil moisture content at the surface which decreases to field moisture capacity below the surface indicating slow infiltration (d).
Interdepressional areas (outside) exhibit same or slightly increased moisture at the surface and field moisture conditions at depth (d). Pipes in the side view (b and c) show locations of borings for soil moisture profiles. Thermal exitance is about the same as Type II depressions (a).
The Type II depressions have about the same thermal exitance than the *surrounding* ground (a). Samples should be taken at the lowest part of the interior of the depression (b and c). The Type II depressions are at field moisture capacity at the surface, but exhibit an increase in soil moisture at depth, suggesting a wetting front moving through the cover (d). Water is apparently infiltrating through the cover in Type II depressions.

Results and Discussion

Depressions as landforms on the covers of the two landfills were delineated by their topographic expression using stereoscopic interpretation of color infrared aerial photography, then the depressions were classified on the basis of thermal exitance. Infiltration characteristics of the depressions can be inferred from the thermal IR classification based upon the previous, ground-based study which concluded that the

- relatively "cool" exitance of the interior of depressions on nighttime thermal IR imagery in warm months was caused by

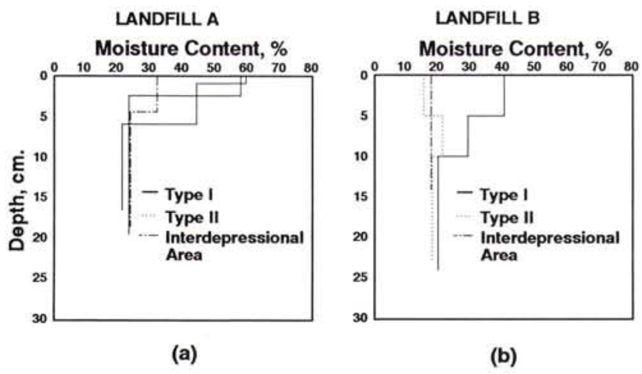

Figure 5. Gravimetric soil moisture profile of 8 June 1992 borings of four Type I depressions and one interdepressional area at Landfill A (a), and borings of two depressions and one interdepressional area at Landfill B. The interdepressional areas (outside of depressions) represent the freely draining surface of the landfill about one day after a rainstorm event, and shows about 10 percent more moisture in the upper 5 cm than in the lower 15 cm which is considered to approximate field moisture capacity of the cover. The soil moisture profile of Type I depressions show that moisture remains at the surface, but remains at about field capacity at about 5 cm below the surface. Depressions 35 and 37 in Landfill A contained water and thick partially decomposed vegetation obscuring the top of the earthen cover; consequently, the higher than field capacity moisture appears at greater depths. The soil moisture profile of the Type I depression in Landfill B (b) shows that elevated moisture remains at the surface probably artificially thickened by soil accumulation, but decreases to about field capacity at about 10 cm below the surface. The Type II depression in Landfill B, Depression 55, shows a lower than field capacity moisture at the surface, elevating to about 3.5 percent above field capacity between 5 to 10 cm, returning to about field capacity below the 10-cm depth.
Although moisture has partially infiltrated into the cover, most remains near the surface for the Type I depressions; moisture appears to be infiltrating through the cover of the Type II depression at Landfill B.

the evaporation of moisture retained at the surface (moisture-retaining depressions), although other causes may also contribute to the exitance contrast; and

- the same or slightly warmer exitance of the interior of depressions and surrounding well-drained ground because moisture was no longer at the surface but had infiltrated into or through the cover (freely infiltrating depressions).

The differences in moisture content of the surface soils are represented by the difference in thermal exitance (as recorded on the imagery) inside and outside of the depressions, and between the two types of depressions (Figure 3 and 4).

In this study, we infer that depressions having relatively lower exitance (Type I depressions) also have moisture at the surface like the moisture-retaining depressions in the previous study. All other depressions (Type II depressions) have no difference between the interior and exterior thermal exitance, and are inferred to lack moisture at the surface like the freely infiltrating depressions in the previous study. The inference of infiltration characteristics from surface moisture is supported by soil moisture profiles which indicate moisture movement through the cover.

Soil moisture profiles of the landfill covers were compiled from field sampling at seven sites. Cores were taken from inside six depressions and two interdepressional areas (Figure 4c) on the day prior to the thermal IR image gathering using a soil probe to sample to a depth of about 20 cm. Figures 5 and 6 show soil moisture profiles for the two landfills. A composite of the moisture profiles is shown in Figure 4d. The moisture profile data are consistent with the infiltration interpretations of the thermal characteristics of four depressions in Landfill A and two depressions in Landfill B.

Landfill A

When Landfill A was closed in 1988 with a one-metre thick compacted earth cap, the cover was a convex topographic surface shedding water in all directions. Depressions had formed in the cover prior to aerial data collection four years after closure. The landfill had 30 depressions formed in the cover of which 22 were Type I depressions and 8 were Type II depressions based upon t-tests of the thermal IR imagery (Table 1 and Figure 1). The smallest depression was 5.6 m^2 and the largest about 13,000 m^2 (Table 2). Two Type II depressions were very small, 8.4 m^2 and 9.3 m^2, and may have insufficient drainage area to develop characteristics for analysis by this method.

The large 13,000 m^2 depression had about 100 m^2 of surface water at the time of overflight. Several small depressions within the large 13,000 m^2 depression were not analyzed separately. The occurrence of small depressions within the large one is unusual, and suggests that further investigation is warranted to determine the active processes. At the time of thermal IR data collection, many of the small depressions were observed to be ponding water, except for one surrounding a methane ventilation pipe.

Moisture content profiles were made from soil borings of four Type I depressions and from an area between two depressions. The profiles shown in Figure 5a show high moisture levels (60 percent) at the surface of the depressions, decreasing abruptly to about 20 percent from the 5- to 20-cm depth. This contrasts with moisture of soils composing the area between depressions which showed a relatively constant moisture level throughout the profile.

Landfill B

The topography of this landfill immediately following the 1976 closure is unknown, but is thought to have been a positive topographic surface having linear, parallel swales constructed to improve surface drainage. Currently, the swales

TABLE 1. SUMMARY OF THE CLASSIFICATION OF THE DEPRESSIONS IN THE EARTHEN COVERS OF TWO LANDFILLS IN ILLINOIS. CLASSIFICATION OF DEPRESSIONS WAS MADE ACCORDING TO APPARENT INFILTRATION CHARACTERISTICS DETERMINED FROM THERMAL IR IMAGERY. TYPE I DEPRESSIONS ARE TENTATIVELY CONSIDERED TO BE MOISTURE-RETAINING DEPRESSIONS; TYPE II DEPRESSIONS ARE TENTATIVELY CONSIDERED TO BE FREELY INFILTRATING DEPRESSIONS.

Landfill	No. of Depressions	Type I	Type II
A	29	22	7
B	60	20	40

TABLE 2. SUMMARY STATISTICS OF DEPRESSIONS OF LANDFILL A. CLASSIFICATION OF DEPRESSIONS IS BASED UPON THERMAL EXITANCE. TYPE I DEPRESSIONS HAVE RELATIVELY LOW EXITANCE, TYPE II DEPRESSIONS HAVE ABOUT THE SAME EXITANCE AS SURROUNDING GROUND.

Landfill A

Depression	Area m^2	N in	Mean in	S.D. in	Var. in	N out	Mean out	S.D. out	Var. out	t_{calc}	$t_{0.95}$	$t_{calc} < t_{crit}$	Type
1	126	21	115	14	194	15	132	6	40	−4.3	1.72	Y	I
2	605	21	103	14	210	33	117	12	138	−3.7	1.72	Y	I
3	207	16	105	9	78	16	101	16	267	0.8	1.75	N	II
4	154	15	97	9	77	20	100	12	146	−0.7	1.76	N	II
5	105	8	131	10	105	16	110	4	20	6.7	1.9	N	II
6	362	17	136	7	53	36	155	14	183	−5.4	1.75	Y	I
7	122	13	90	7	53	14	121	12	152	−7.5	1.78	Y	I
8	146	12	88	7	52	15	111	8	71	−7.3	1.8	Y	I
9	185	13	106	11	124	13	110	12	138	−0.8	1.78	N	II
10	106	9	88	19	356	16	119	13	175	−4.7	1.86	Y	I
11	524	6	85	8	67	11	119	7	54	−8.1	2.02	Y	I
13	361	7	100	6	42	20	115	16	242	−2.5	1.94	Y	I
14	254	4	118	14	199	7	151	3	6	−5.5	2.35	Y	I
15	10,495	10	126	12	147	19	164	10	102	−8.8	1.83	Y	I
16	57	9	116	11	123	8	115	6	41	0.2	1.86	N	II
17	1,521	6	102	2	6	15	125	9	77	−6.0	2.02	Y	I
18	90	7	115	2	5	14	129	13	179	−2.7	1.94	Y	I
19	434	11	93	11	118	14	134	10	102	−9.3	1.81	Y	I
20	65	8	113	6	34	13	108	12	147	1.1	1.9	N	II
24	125	9	106	12	151	16	126	17	295	−2.9	1.86	Y	I
27	185	11	86	9	75	15	119	10	92	−8.9	1.81	Y	I
30	470	7	104	10	94	8	116	8	60	−2.5	1.94	Y	I
32	490	7	132	12	144	18	117	6	34	4.1	1.94	N	II
34	92	4	92	11	111	8	147	14	199	−6.3	2.35	Y	I
35	698	9	103	8	62	10	130	9	82	−6.5	1.86	Y	I
37	423	5	92	10	91	9	143	18	320	−5.5	2.13	Y	I
39	334	12	120	8	61	15	139	12	135	−4.6	1.8	Y	I
44	519	7	131	14	185	15	108	6	34	5.3	1.94	N	II
45	144	3	96	22	485	8	190	12	135	−8.2	2.92	Y	I
49	71	8	192	10	94	13	209	6	40	−4.5	1.9	Y	I

vary in length from about 92 to 122 metres, the gradients are low, and Type II depressions have formed along the courses. Based upon interpretations of the thermal IR imagery, Landfill B had 20 Type I depressions and 40 Type II depressions (Tables 1 and 2, and Figure 2). The smallest depression was 4 m^2 and the largest about 3377 m^2 (Table 3). The largest depression was classified as a moisture-retaining depression; there were hydrophilic plants growing in the depression at the time of data collection. Of the 40 Type II depressions, nine were small, less than 50 m^2.

The depressions appear to cluster in groups having like infiltration characteristics. This occurs particularly in the southern part of the landfill where Type II depressions develop in the long, low-gradient swales. The Type I depressions tend to occur in the west and north portions of the landfill. Occasional occurrence of Type II depressions in these areas may be an artifact of the small drainage area of the depressions. Figure 5b shows the moisture content profiles from soil borings of one Type I depression, a Type II depression, and an interdepressional area. The profiles show high gravimetric moisture, 40 percent at the surface of the Type I depression decreasing gradually to less than 20 percent, approaching the same moisture content of the interdepressional area, 15 percent. The Type I depression had been ditched to improve surface drainage prior to data collection, and was sampled in the center of the nearly dry depression. The high moisture at the top of the profile indicates the ponding of the rainfall which has not yet infiltrated into the landfill cover.

The soil moisture profile of an interdepressional area is a near constant 17 percent, apparently the "field" moisture capacity of the cover. Field observations at Landfill B found drier soils, less moist soil in all areas, less ponded water, etc., the 17 percent soil field moisture capacity at Landfill B is less than the approximately 20 percent field capacity of Landfill A, which suggests that although both landfills were sampled in the same day; and there may have been less rainfall at Landfill B than 11.5 km (6.5 mi.) to the east at Landfill A (Figures 5 and 6).

Figure 5b shows a low moisture (15 percent) in the upper (0 to 5 cm) part of the profile of the Type II depression, increasing to 21 percent between 5 to 10 cm depth, surpassing that of the interdepressional area, and then diminishing to about 18 percent, the apparent "field" moisture of the cover at lower depths. The bulge in the profile probably represents the movement of moisture (from rainfall) down through the landfill cover.

Conclusions

A two-step analysis used to classify depressions developed in landfill covers consisting of (1) manual delineation of depressions by stereoscopic, aerial photographic interpretation,

Table 3. Summary Statistics of Depressions of Landfill B. Classification of Depressions is Based upon Thermal Exitance. Type I Depressions Have Relatively Low Exitance, Type II Depressions Have about the Same Exitance as Surrounding Ground.

Landfill B

Depression	Area m²	N in	Mean in	S.D. in	Var. in	N out	Mean out	S.D. out	Var. out	t_{calc}	$t_{0.95}$	$t_{calc} < t_{crit}$	Type
3	82	10	108	8	62	29	114	14	199	−1.2	1.83	N	II
4	115	16	84	12	155	31	123	6	41	−14.0	1.75	Y	I
5	72	17	83	10	98	23	123	11	118	−11.6	1.75	Y	I
6	133	18	105	8	61	112	126	10	99	−8.5	−1.74	Y	I
7	303	16	119	7	54	30	122	11	119	−1.0	1.75	N	II
9	269	19	129	11	114	24	132	7	42	−1.0	1.73	N	II
11	803	39	121	12	143	41	125	12	150	−1.6	2.42	N	II
13	410	32	128	15	236	25	129	7	48	−0.3	1.7	N	II
14	18	6	136	5	29	13	125	11	124	2.2	2.02	Y	I
15	37	7	122	3	9	12	122	8	72	−0.2	1.94	N	II
16	3,377	10	114	7	47	22	139	7	49	−9.0	1.83	Y	I
17	28	6	111	7	46	9	116	18	327	−0.7	2.02	N	II
18	567	19	124	18	316	38	141	8	71	−4.8	1.73	Y	I
19	43	7	126	14	190	10	124	2	3	0.3	1.94	N	II
20	36	9	142	3	9	18	138	7	45	1.7	1.86	N	II
21	40	18	140	10	106	6	127	2	5	2.9	1.74	Y	I
22	50	9	128	8	57	8	127	6	32	0.5	−1.86	N	II
24	365	19	113	6	41	36	120	14	208	−1.9	1.73	Y	I
27	1,349	30	122	7	54	24	120	10	102	0.7	1.7	N	II
28	262	13	121	8	64	13	128	6	39	−7.3	−1.77	Y	I
29	464	22	101	9	77	42	118	8	66	−7.3	−1.66	Y	I
31	415	13	147	7	45	18	126	6	34	8.9	1.78	N	II
33	143	14	113	9	90	24	116	12	155	−0.8	1.77	N	II
34	563	12	125	9	84	16	119	11	113	1.4	1.8	N	II
35	112	19	110	12	147	19	120	16	246	−2.1	−1.69	Y	I
37	362	19	128	14	192	21	132	8	59	−1.1	1.73	N	II
39	45	6	134	10	90	12	127	12	143	1.1	2.02	N	II
40	25	5	132	3	7	17	120	6	35	4.3	2.13	N	II
41	16	9	108	20	388	8	133	7	47	−3.1	−1.86	Y	I
42	100	13	134	7	55	16	125	12	148	2.3	1.78	N	II
43	31	5	91	3	10	9	119	11	124	−5.1	−2.13	Y	I
44	237	27	108	10	109	22	116	10	110	−2.7	1.71	Y	I
45	98	10	110	10	99	16	107	19	361	0.5	−1.83	N	II
46	46	16	107	14	187	44	114	10	96	−2.2	−1.75	Y	I
47	24	28	106	8	57	76	110	10	108	−0.8	−1.7	N	II
48	102	45	114	12	135	45	121	12	151	−2.7	−1.68	Y	I
50	77	12	125	3	8	21	122	6	36	1.7	1.8	N	II
52	85	11	128	6	36	28	122	8	57	2.4	1.81	N	II
54	424	36	116	9	83	104	115	13	178	0.5	−1.69	N	II
55	178	33	124	16	255	80	119	12	140	1.5	−1.7	N	II
56	170	22	120	11	123	80	119	12	140	0.1	−1.72	N	II
59	71	16	117	6	32	31	117	8	63	0.2	1.75	N	II
60	4	8	136	4	15	13	112	12	151	5.0	1.9	N	II
62	153	11	114	11	117	20	115	8	66	−0.2	1.81	N	II
63	96	13	130	13	175	13	120	8	69	2.2	1.78	N	II
64	93	13	133	22	472	16	134	8	69	0.0	1.78	N	II
64	93	13	111	8	72	16	118	7	49	−2.5	1.78	Y	I
65	69	10	110	7	48	16	118	7	49	−2.9	1.83	Y	I
66	46	9	127	6	32	10	131	7	49	−1.4	1.81	N	II
67	32	10	115	4	20	13	126	9	75	−3.5	1.83	Y	I
68	69	12	122	5	22	19	122	4	17	0.1	1.8	N	II
69	121	25	118	8	70	17	115	10	103	1.2	1.71	N	II
70A	280	8	136	12	133	21	125	11	118	2.2	1.9	N	II
70B	280	35	123	8	66	40	119	14	195	1.6	1.7	N	II
72	85	18	111	5	26	16	121	5	21	−6.0	1.74	Y	I
73	216	27	120	14	184	62	122	10	94	−0.4	−1.71	N	II
74	73	13	124	4	17	24	107	13	178	4.2	−1.78	N	II
77	243	62	123	10	105	124	119	10	92	2.4	−1.67	N	II
78	89	30	113	9	76	250	117	14	196	−1.3	−1.7	N	II
79	137	44	123	13	159	112	115	9	75	4.6	−1.68	N	II
80	90	11	127	9	88	25	125	6	37	0.7	1.81	N	II

followed by (2) classification of depressions according to apparent infiltration characteristics using uncalibrated, nighttime, airborne, thermal IR imagery.

The thermal IR exitance expressed in the raw DNs of the inside and outside of a depression was sampled along a single scan line to eliminate variations caused by the gain adjustment of the thermal IR scanner. Sampling was restricted to the lowest parts of depressions excluding standing water. A one-tailed t-test determined whether the depression was Type I or Type II. Type I depressions are considered to be moisture-retaining depressions, those retaining rainfall near the surface where evapotranspiration can reduce infiltration, have relatively lower ("cooler") exitance than surrounding ground. Type II depressions, considered to be freely infiltrating depressions that permit water to infiltrate relatively quickly through the cover into the underlying wastes, had nearly the same or slightly higher thermal exitance than surrounding ground. Type II depressions may pose a greater problem in the prevention of landfill leachate and methane production by allowing water to infiltrate freely through the landfill cover.

The apparent infiltration characteristics of depressions in landfill covers tend to be the same for regions of the cover at the two landfills studied. Soil moisture profiles of five depressions (four Type I and one Type II) at the two landfills confirm their classification from the thermal IR imagery. The use of this two- step method will permit early detection of depressions in landfill covers and classification of their apparent infiltration characteristics.

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