Determining Remaining Permitted Capacity of California's Sanitary Landfills

April 1995

Integrated Waste Management Board

For additional copies of this publication contact the

Integrated Waste Management Board
Public Affairs Office/Recycling Hotline
8800 Cal Center Drive, MS 12
Sacramento, CA 95826

http://www.ciwmb.ca.gov

(800) 553-2962 (CA only) or (916) 341-6308

Publication #210-97-009
Printed on Recycled Paper

Prepared for the Integrated Waste Management Board by Environmental Science Associates, Inc.
as part of contract number IWM-C1089 ($75,000).

TABLE OF CONTENTS

Page

APPENDICES

LIST OF FIGURES

TABLE OF CONTENTS (Continued)

Page

LIST OF TABLES

DETERMINING REMAINING PERMITTED CAPACITY OF CALIFORNIA'S SANITARY LANDFILLS

In 1993 and 1994 the California Integrated Waste Management Board (the Board) conducted a survey of all of California's permitted sanitary landfills. The primary aim of the survey was to glean from landfill owners and operators their best estimate of their remaining permitted capacity. The Board then compiled this information to try to determine the State's overall remaining permitted capacity, and to discern which areas of the State lack long-term permitted disposal capacity. An ancillary inquiry solicited information from landfill owners on what methods they use to determine their remaining capacity, in order to assess whether the methods currently in use are consistent, comparable, and standard. The results of this inquiry indicate that while nearly all of the State's large publicly and privately owned landfills use accepted engineering practices to determine their remaining permitted capacity, many of the State's smaller facilities use non-standard methods or do not regularly gauge their remaining permitted capacity. It is believed that it is in the interest of the people of the State, as well as in the interest of individual landfill owners, to have a firm idea of remaining permitted landfill capacity, both to serve as a basis for strategic local integrated waste management planning, and to allow more accurate gauging of regional and state-wide permitted capacity.

This report recommends three methods for determining a landfill's remaining permitted capacity. These methods -- topographical surveys, weight-to-volume conversion, and trench volume calculations -- all are capable of producing estimates of remaining permitted capacity that are reasonably accurate and comparable. The latter two, furthermore, are intended especially for smaller landfills whose owners lack the funds or the resources to conduct topographical surveys. The intent of this report is to assist landfill owners in accurately determining their remaining permitted capacity and the life span of their facility, and to work toward the establishment of a set of informal standards and methods for assessing remaining permitted capacity.

The main body of this report is organized into three sections. Section I presents the results of the Board's landfill survey on methods now in use to determine remaining capacity, and analyzes the adequacy of each method. Section II assesses the need to establish informal standards or guidelines for remaining landfill capacity, and presents recommendations on the appropriate role for the Board to play in assisting landfill owners in determining their remaining permitted capacity. Section III discusses the three methods that appear to be the most acceptable in terms of accuracy, comparability, and applicability to the range of types and sizes of landfills throughout the State. This section discusses the strengths and weaknesses of each method, and compares the accuracy, cost, and applicability of the three. In addition to the main text, the report contains technical appendices on performing each of the preferred methodologies, and methodologies for determining landfill density and refuse:soil ratios.

I. BACKGROUND

In 1993 and 1994 the Board surveyed all of the State's landfill owners and requested information on basic operating characteristics, including how much permitted capacity was remaining in the landfill, and how remaining permitted capacity is determined. After surveys had been sent to every landfill in the State and a second survey sent to those not initially responding, Board staff and the contractor conducting the survey determined that the sample size of those responding was sufficient to gain an understanding of how California landfills determine their remaining permitted capacity. At that time, 157 of approximately 250 active landfills (63%) had responded, representing 38 counties.

Since the survey question regarding the method used to determine remaining permitted capacity was open-ended, the first step in the analysis was to classify the methods used. The responses can be grouped into six classifications:

- Topographic Survey Estimates
- Projections of Remaining Landfill Life (in years)
- Cell/Trench Volume-Based Estimates
- Weight-Based Estimates
- Unclear - Not Enough Information to Determine Method
- No Response

The responding landfills are listed according to method used in Table 1. One hundred twenty-one active landfills estimated capacity using one of the first four methods, while the remaining 36 active landfills either did not respond, or gave insufficient information to classify their answers. Figures 1-4 display the number of landfills utilizing each methodology, how much of the State's permitted daily capacity and total remaining permitted capacity is represented by landfills using each method, and percentages of landfills grouped by ownership, permitted remaining capacity, and permitted daily capacity utilizing each method. The methodologies are described in more detail below.

Figure 1 shows the landfills that represent the great majority of California's daily and remaining capacity use topographic surveys to estimate their remaining permitted capacity. Since the topographic surveys can be considered the most accurate and reliable method used, it is likely that the landfill survey produced a reasonably accurate assessment of California's remaining landfill capacity. Figure 1 also shows, however, that a slim majority of landfills responding to the survey do not use topographic surveys to determine their remaining capacity. Figures 2, 3 and 4 indicate that methods other than topographic surveys are commonly used by county landfills, by landfills with permitted daily capacity of less than 100 tons per day, and by landfills with initial permit dates before 1980.

Topographic Survey Estimates

The category *topographic survey estimates* encompasses landfills that use topographic data from periodic aerial or ground surveys to develop an estimate of total available airspace. Nearly half the 157 active landfills (75, or 48%) use this method to determine remaining capacity. Landfills using survey methods included the 10 largest active landfills in the survey as well as

TABLE 1: LISTING OF ACTIVE LANDFILLS RESPONDING TO SURVEY BY TYPE OF METHODOLOGY EMPLOYED TO ESTIMATE REMAINING CAPACITY

NAME	SWIS	COUNTY	TPD
TOPOGRAPHIC/SURVEY ESTIMATES			
Altamont Sanitary Landfill	01-AA-0009	Alameda	11150
Neal Road Landfill	04-AA-0002	Butte	750
Keller Canyon Landfill	07-AA-0032	Contra Costa	2750
Union Mine Disposal Site	09-AA-0003	El Dorado	400
Chateau Fresno Landfill	10-AA-0002	Fresno	1800
City of Clovis Landfill	10-AA-0004	Fresno	51
Chestnut Avenue Sanitary Landfill	10-AA-0025	Fresno	850
Boron Sanitary Landfill	15-AA-0045	Kern	20
Buttonwillow Sanitary Landfill	15-AA-0047	Kern	20
Shafter-Wasco Sanitary Landfill	15-AA-0057	Kern	96
Mojave-Rosamond Sanitary Landfill	15-AA-0058	Kern	32
Ridgecrest-Inyokern Sanitary Landfill	15-AA-0059	Kern	130
Taft Sanitary Landfill	15-AA-0061	Kern	53
Tehachapi Sanitary Landfill	15-AA-0062	Kern	32
Bakersfield S.L.F.	15-AA-0273	Kern	1764
Antelope Valley Public Dump	19-AA-0009	Los Angeles	750
Scholl Canyon Sanitary Landfill	19-AA-0012	Los Angeles	3400
Azusa Land Reclamation Co., I	19-AA-0013	Los Angeles	6500
Spadra Sanitary Landfill #2	19-AA-0015	Los Angeles	3700
Puente Hills Landfill #6	19-AA-0053	Los Angeles	13200
Calabasas Landfill #5	19-AA-0056	Los Angeles	3500
Lopez Canyon Sanitary Landfill	19-AA-0820	Los Angeles	4000
BKK West Covina Disposal Site	19-AF-0001	Los Angeles	12000
Bradley Avenue West Sanitary Landfill	19-AR-0008	Los Angeles	7000
Redwood Sanitary Landfill	21-AA-0001	Marin	800
City of Ukiah Solid Waste Disposal Site	23-AA-0019	Mendocino	50
City of Willits Disposal Site	23-AA-0021	Mendocino	50
Crazy Horse Sanitary Landfill	27-AA-0007	Monterey	375
Olinda Sanitary Landfill	30-AB-0016	Orange	2400
Santiago Canyon Sanitary Landfill	30-AB-0018	Orange	4900
Prima Desheca Sanitary Landfill	30-AB-0019	Orange	753
Olinda Alpha Sanitary Landfill	30-AB-0035	Orange	8000
Frank R. Bowerman Sanitary Landfill	30-AB-0360	Orange	6432
Western Regional Landfill	31-AA-0210	Placer	900
Eastern Regional Landfill	31-AA-0560	Placer	250
Highgrove Sanitary Landfill	33-AA-0003	Riverside	2700
Badlands Disposal Site	33-AA-0006	Riverside	1400
Lamb Canyon Disposal Site	33-AA-0007	Riverside	1900
Double Butte Disposal Site	33-AA-0008	Riverside	600
Mead Valley Disposal Site	33-AA-0009	Riverside	1109
Edom Hill Disposal Site	33-AA-0011	Riverside	1200
Coachella Valley Disposal Site	33-AA-0012	Riverside	2000
Anza Sanitary Landfill	33-AA-0013	Riverside	40

TABLE 1: LISTING OF ACTIVE LANDFILLS RESPONDING TO SURVEY BY TYPE OF METHODOLOGY EMPLOYED TO ESTIMATE REMAINING CAPACITY (Continued)

NAME	**SWIS**	**COUNTY**	**TPD**
TOPOGRAPHIC/SURVEY ESTIMATES (Continued)			
Oasis Disposal Site	33-AA-0015	Riverside	41
Desert Center L.F. (Eagle Mountain)	33-AA-0016	Riverside	9
Blythe Sanitary Landfill	33-AA-0017	Riverside	62
Mecca Landfill II	33-AA-0071	Riverside	50
Sacramento County Landfill	34-AA-0001	Sacramento	2200
California Street Landfill	36-AA-0017	San Bernardino	90
Ramona Landfill	37-AA-0005	San Diego	35
Borrego Springs Landfill	37-AA-0006	San Diego	30
San Marcos Landfill	37-AA-0008	San Diego	6200
Otay Annex Landfill	37-AA-0010	San Diego	2400
Miramar Sanitary Landfill	37-AA-0020	San Diego	4200
Sycamore Sanitary Landfill	37-AA-0023	San Diego	2500
Las Pulgas Landfill	37-AA-0903	San Diego	364
Foothill Sanitary Landfill	39-AA-0004	San Joaquin	720
North County Landfill	39-AA-0022	San Joaquin	825
Ox Mountain Sanitary Landfill	41-AA-0002	San Mateo	3598
Hillside Solid Waste Disposal	41-AA-0008	San Mateo	400
Foxen Canyon Sanitary Landfill	42-AA-0011	Santa Barbara	86
Tajiguas Sanitary Landfill	42-AA-0015	Santa Barbara	1200
City of Santa Maria Refuse Disposal Site	42-AA-0016	Santa Barbara	550
City of Lompoc Sanitary Landfill	42-AA-0017	Santa Barbara	500
City of Sunnyvale Landfill	43-AA-0007	Santa Clara	500
City of Palo Alto Refuse Disposal Site	43-AM-0001	Santa Clara	450
Newby Island Sanitary Landfill	43-AN-0003	Santa Clara	3260
Buena Vista Disposal Site	44-AA-0004	Santa Cruz	450
Potrero Hills Sanitary Landfill	48-AA-0075	Solano	850
Central Landfill	49-AA-0001	Sonoma	2500
Annapolis Landfill	49-AA-0002	Sonoma	65
Fink Road Landfill	50-AA-0001	Stanislaus	1500
Toland Road Sanitary Landfill	56-AA-0005	Ventura	135
Bailard Landfill	56-AA-0011	Ventura	2000
Yolo County Central Landfill	57-AA-0001	Yolo	1400
WEIGHT BASED ESTIMATES			
Vasco Road Sanitary Landfill	01-AA-0010	Alameda	2329
Coalinga Disposal Site	10-AA-0006	Fresno	30
American Avenue Disposal Site	10-AA-0009	Fresno	1200
North Belridge Solid Waste Disposal Site	15-AA-0067	Kern	10
Brand Park Landfill	19-AA-0006	Los Angeles	35
Burbank Landfill Site #3	19-AA-0040	Los Angeles	240
Mariposa County Sanitary Landfill	22-AA-0001	Mariposa	60
Highway 59 Disposal Site	24-AA-0001	Merced	600

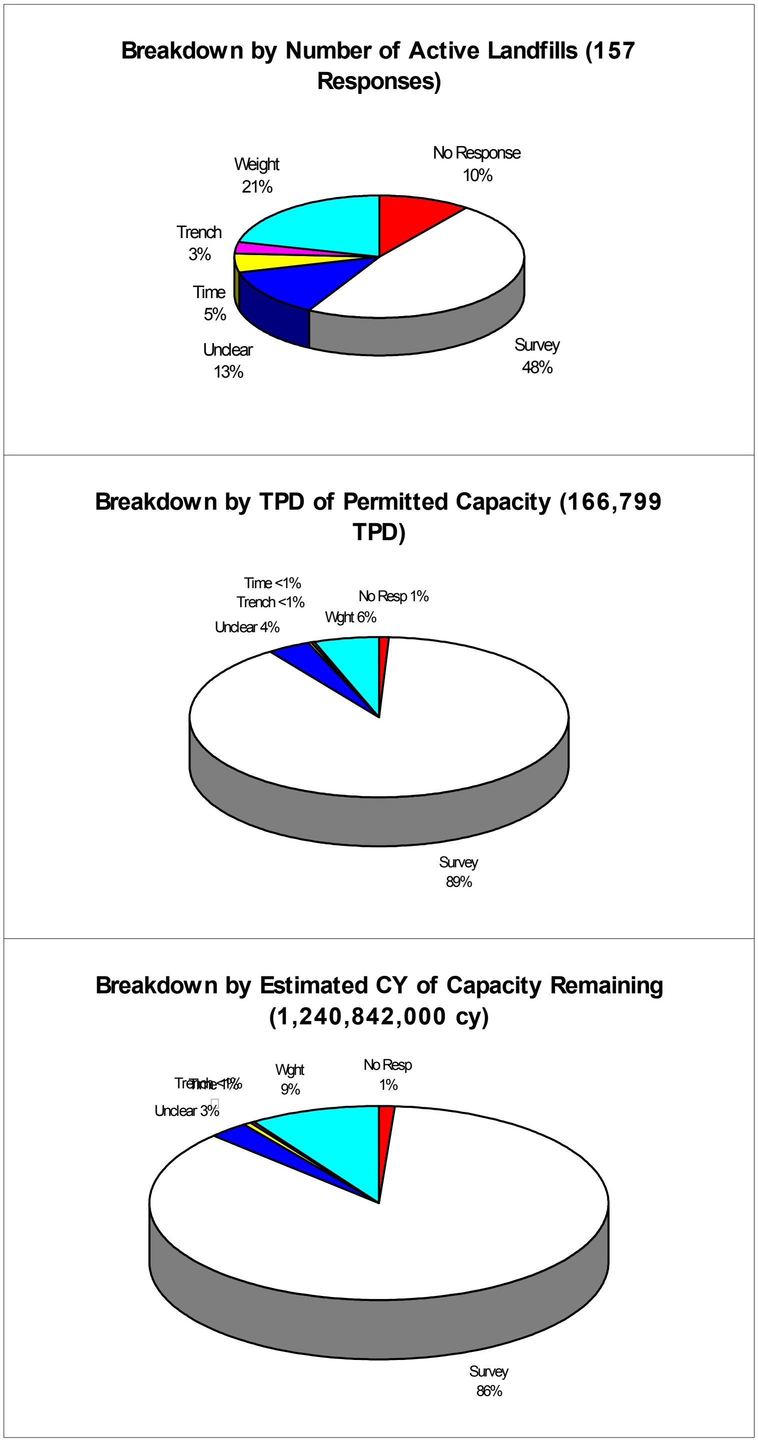
TABLE 1: LISTING OF ACTIVE LANDFILLS RESPONDING TO SURVEY BY TYPE OF METHODOLOGY EMPLOYED TO ESTIMATE REMAINING CAPACITY (Continued)

NAME	SWIS	COUNTY	TPD
WEIGHT BASED ESTIMATES (Continued)			
Billy Wright Dump Site	24-AA-0002	Merced	125
Lewis Road Sanitary Landfill	27-AA-0003	Monterey	60
Trona-Argus Refuse Disposal Site	36-AA-0041	San Bernardino	19
Phelan Refuse Disposal Site	36-AA-0044	San Bernardino	12
Victorville Refuse Disposal Site	36-AA-0045	San Bernardino	22
Barstow Refuse Disposal Site	36-AA-0046	San Bernardino	32
Yermo Disposal Site	36-AA-0047	San Bernardino	7
Apple Valley Disposal Site	36-AA-0048	San Bernardino	40
Baker Refuse Disposal Site	36-AA-0049	San Bernardino	1
Hesperia Refuse Disposal Site	36-AA-0050	San Bernardino	17
Colton Refuse Disposal Site	36-AA-0051	San Bernardino	180
Milliken Sanitary Landfill	36-AA-0054	San Bernardino	1200
Fontana Refuse Disposal Site	36-AA-0055	San Bernardino	280
Big Bear Refuse Disposal Site	36-AA-0056	San Bernardino	28
Landers Disposal Site	36-AA-0057	San Bernardino	14
Morongo Disposal Site	36-AA-0058	San Bernardino	11
29 Palms Disposal Site	36-AA-0060	San Bernardino	18
Lenwood-Hinkley Refuse Disposal Site	36-AA-0061	San Bernardino	12
San Timoteo Solid Waste Disposal Site	36-AA-0087	San Bernardino	1000
City of Paso Robles Landfill	40-AA-0001	San Luis Obispo	112
Sante Fe Energy Resources, Inc.	40-AA-0003	San Luis Obispo	3
Intermountain Landfill	45-AA-0002	Shasta	120
West Central Landfill	45-AA-0043	Shasta	700
Twin Bridges Landfill	45-AA-0058	Shasta	50
Visalia Disposal Site	54-AA-0009	Tulare	872
PROJECTIONS OF LANDFILL LIFE (Time)			
Simpson Wood Waste Disposal Site	12-AA-0029	Humboldt	370
Lone Pine Disposal Site	14-AA-0003	Inyo	16
Independece Disposal Site	14-AA-0004	Inyo	15
Bishop Sunland	14-AA-0005	Inyo	30
Shoshone Disposal Site	14-AA-0006	Inyo	10
Tecopa Disposal Site	14-AA-0007	Inyo	12
Vandenberg AFB Landfill	42-AA-0012	Santa Barbara	75
Weaverville Landfill Disposal Site	53-AA-0013	Trinity	70
CELL/TRENCH VOLUME ESTIMATES			
Two Harbors Landfill Site	19-AA-0062	Los Angeles	1
Johnson Canyon Sanitary Landfill	27-AA-0005	Monterey	97
Metro Water District - Iron Mt.	36-AA-0003	San Bernardino	2
Holliday Sanitary Landfill	36-AA-0064	San Bernardino	5
California Valley Landfill	40-AA-0014	San Luis Obispo	1

TABLE 1: LISTING OF ACTIVE LANDFILLS RESPONDING TO SURVEY BY TYPE OF METHODOLOGY EMPLOYED TO ESTIMATE REMAINING CAPACITY (Continued)

NAME	SWIS	COUNTY	TPD
NO DATA OR INCOMPLETE RESPONSE			
Worthington Cut and Fill Site	13-AA-0001	Imperial	28
Calexico Solid Waste Disposal Site	13-AA-0004	Imperial	70
Ocotillo Cut and Fill	13-AA-0005	Imperial	1
Holtville Disposal Site	13-AA-0006	Imperial	19
Palo Verde Cut and Fill Site	13-AA-0007	Imperial	1
Brawley Disposal Site	13-AA-0008	Imperial	68
Niland Cut and Fill Site	13-AA-0009	Imperial	5
Hot Spa Cut and Fill Site	13-AA-0010	Imperial	4
Salton City Cut and Fill Site	13-AA-0011	Imperial	5
Picacho Cut and Fill Site	13-AA-0012	Imperial	20
US Navy Landfill	19-AA-0063	Los Angeles	4
Georgia-Pacific Wood Waste Disposal Site	23-AA-0005	Mendocino	18
City of Rialto Disposal Site	36-AA-0250	San Bernardino	23
Austin Road Landfill	39-AA-0001	San Joaquin	1200
McCloud Community Services	47-AA-0001	Siskiyou	5
Mare Island Naval Shipyard Sanitary Landfill	48-AA-0008	Solano	44
Amador County Sanitary Landfill	03-AA-0001	Amador	275
Desert Valley Company	13-AA-0022	Imperial	150
Lost Hills Sanitary Landfill	15-AA-0052	Kern	10
EL Sobrante Sanitary Landfill	33-AA-0217	Riverside	1152
Guadalupe Sanitary Landfill	43-AN-0015	Santa Clara	3245
Santa Cruz City Sanitary Landfill	44-AA-0001	Santa Cruz	99
Yreka Solid Waste Landfill	47-AA-0002	Siskiyou	50
Tulelake Solid Waste Landfill	47-AA-0027	Siskiyou	7
Kelly Gulch Solid Waste Disposal Site	47-AA-0029	Siskiyou	1
Lava Beds Disposal Site	47-AA-0031	Siskiyou	1
New Tennant Solid Waste Disposal Site	47-AA-0033	Siskiyou	1
Rogers Creek	47-AA-0044	Siskiyou	1
Hotelling Gulch Disposal Landfill	47-AA-0045	Siskiyou	1
Earlimart Disposal Site	54-AA-0001	Tulare	50
Teapot Dome Site	54-AA-0004	Tulare	364
Woodville Disposal Site	54-AA-0008	Tulare	205
Balance Rock Disposal Site	54-AA-0010	Tulare	7
Kennedy Meadows Disposal Site	54-AA-0011	Tulare	1
University of California, Davis	57-AA-0004	Yolo	500
Beale AFB Sanitary Landfill	58-AA-0001	Yuba	44

Figure 1: Characterization of Landfills by Method Used to Estimate Remaining Capacity

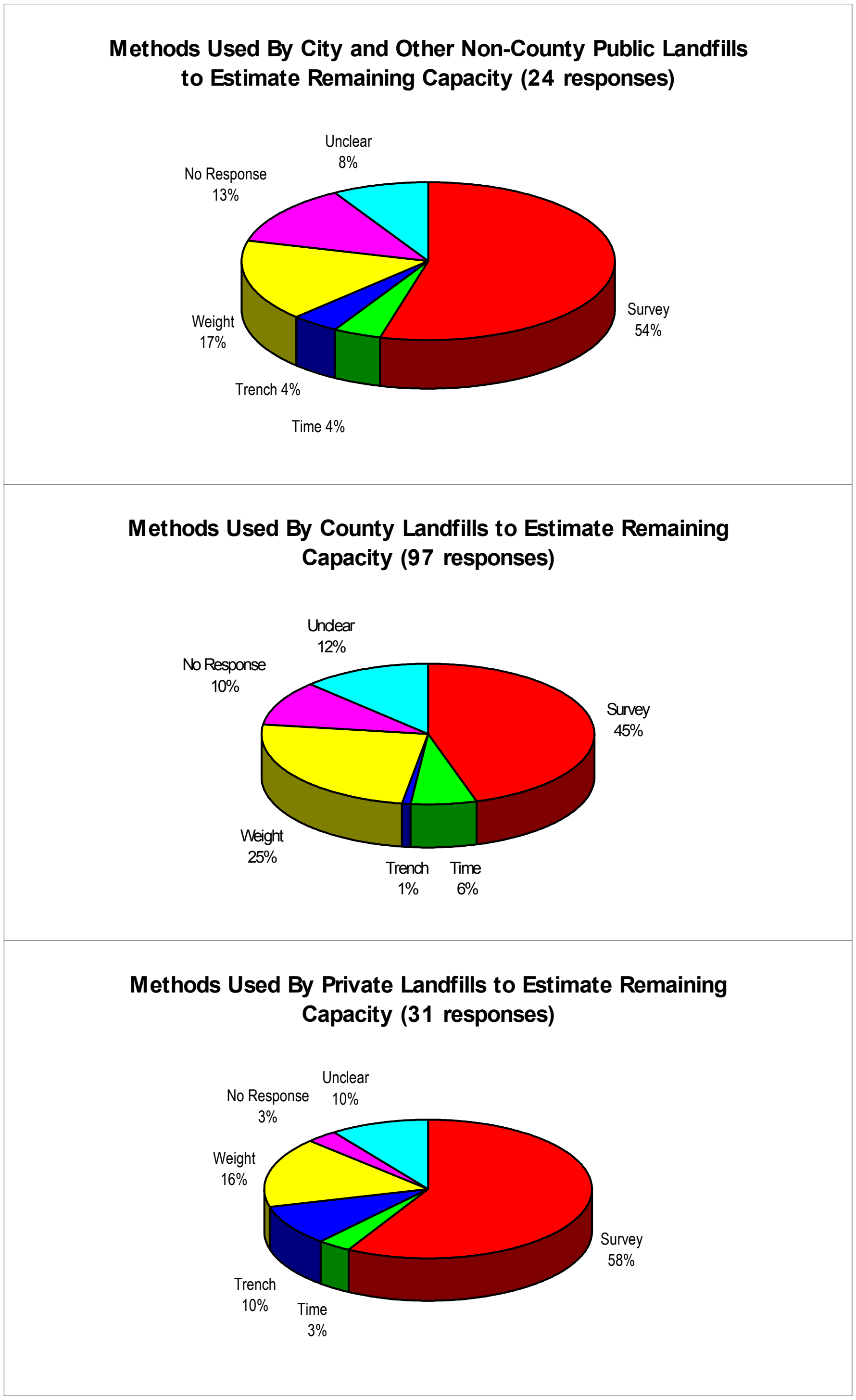


Breakdown by Number of Active Landfills (157 Responses)

Breakdown by TPD of Permitted Capacity (166,799 TPD)

Breakdown by Estimated CY of Capacity Remaining (1,240,842,000 cy)

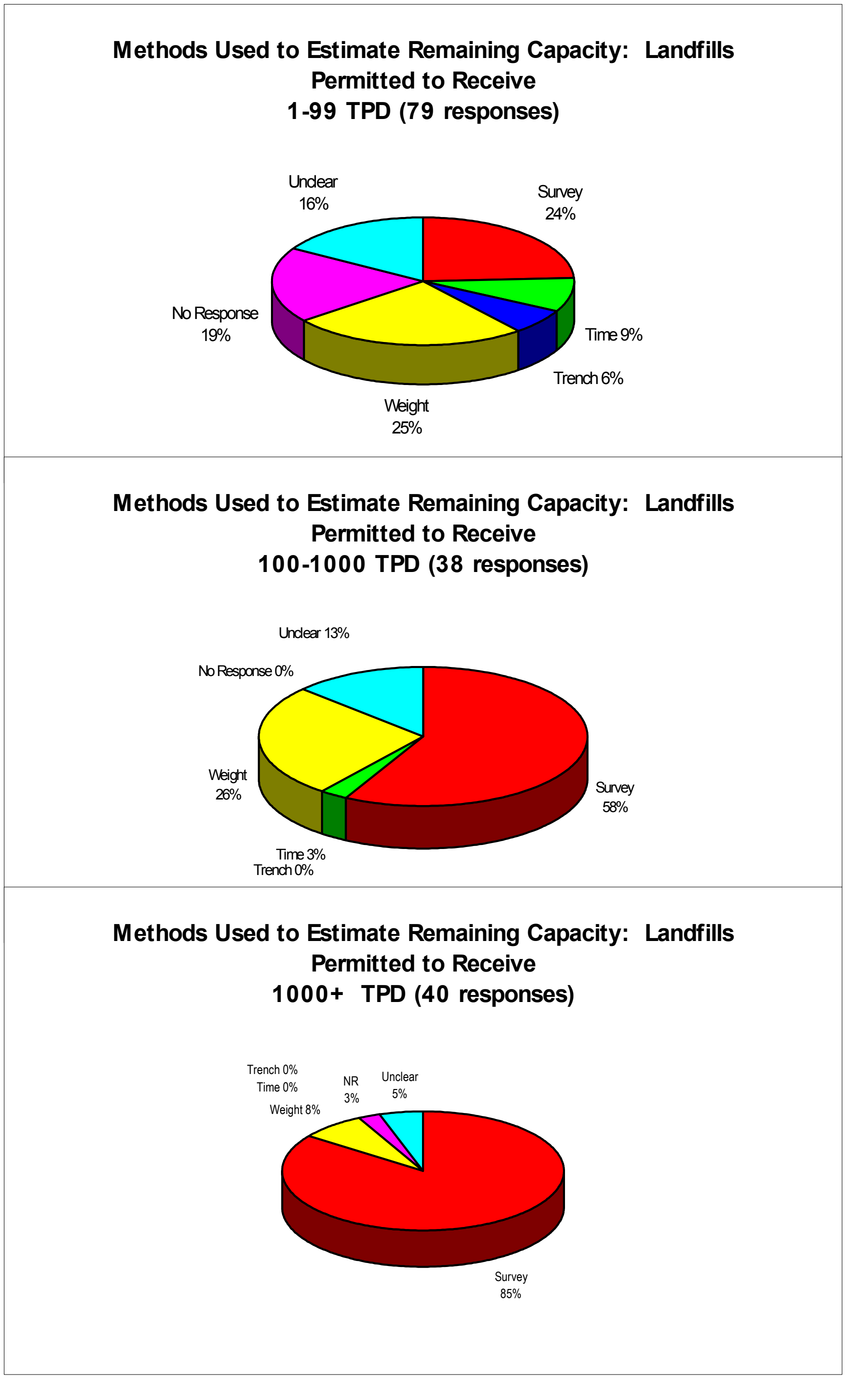
Figure 2: Method of Estimating Remaining Capacity Analyzed by Operator Type, Grouped by Percentage of Active Landfills Responding


Methods Used By City and Other Non-County Public Landfills to Estimate Remaining Capacity (24 responses)

Methods Used By County Landfills to Estimate Remaining Capacity (97 responses)

Methods Used By Private Landfills to Estimate Remaining Capacity (31 responses)

Figure 3: Method of Estimating Remaining Capacity Analyzed by Landfill Capacity in TPD, Grouped by Percentage of Active Landfills Responding

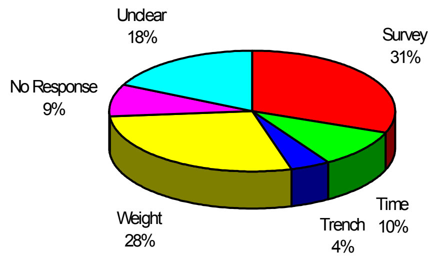


Methods Used to Estimate Remaining Capacity: Landfills Permitted to Receive 1-99 TPD (79 responses)

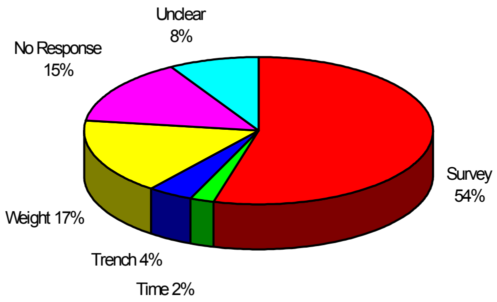
Methods Used to Estimate Remaining Capacity: Landfills Permitted to Receive 100-1000 TPD (38 responses)

Methods Used to Estimate Remaining Capacity: Landfills Permitted to Receive 1000+ TPD (40 responses)

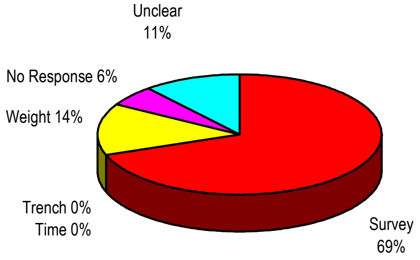
Figure 4: Method of Estimating Remaining Capacity Analyzed By Initial Permit Year, Grouped by Percentage of Active Landfills Responding



Methods Used to Estimate Remaining Capacity: Landfills With Initial Permit Year Before 1980 (68 responses)



Methods Used to Estimate Remaining Capacity: Landfills With Initial Permit Year Between 1980 and 1989 (48 responses)



Methods Used to Estimate Remaining Capacity: Landfills With Initial Permit Year After 1990 (36 responses)

several very small landfills. Landfill operators use topographic surveys to determine total remaining capacity by comparing current topography to the landfill's final permitted contours, and calculating the volume difference between the two. Landfill operators must also develop assumptions regarding density of in-place waste, refuse:soil ratio, and thickness of the final cover in order to determine the tonnage of waste that can be placed in the remaining airspace. This process requires surveying and engineering expertise.

"Topographic surveys" is not an homogenous category. Survey respondents used either ground survey methods or aerial surveys to develop topographical maps of their landfills. Some of the respondents indicated that they used computer aided design (CAD) systems or digital mapping terrain models in order to facilitate calculations of gross airspace capacity and net remaining refuse capacity, while others stated that they performed manual measurements and calculations to determine remaining airspace. Several stated that they conduct an interim estimate of the amount of capacity consumed in between surveys by subtracting an estimate of the volume of waste received since the last survey from their last calculation of remaining capacity. Some operators use a calculation of the airspace used since the last survey, combined with records of weight of materials received, to determine in-place density. It is reasonable to assume that computer assistance facilitates an accurate assessment, and that periodic estimates between surveys further refine the capacity estimates, as long as whomever is performing the analysis has sufficient expertise and accurate data. It is also reasonable to assume that survey methods are more reliable than the other methodologies used, but once again, accuracy depends upon the expertise and care of those conducting the surveys and performing the volume calculations.

Weight-Based Estimates

The category *weight-based estimates* encompasses landfills that convert weight data to volume using an assumption about the in-fill density of waste materials. The converted volume of material is subtracted from the total available airspace (capacity). This method is relatively simple to apply: the only equipment required is a scale for weighing the amount of waste received and landfilled. This method is generally not as accurate as using topographic information since it relies entirely on assumptions about density and refuse:soil ratios, with no or only infrequent cross checks using topographic surveys. While it is not clear from the survey responses how airspace is initially determined, this is commonly based on information developed for the initial design of the landfill. Approximately 21% of the respondents (33 landfills) appear to use this method to determine remaining capacity.

Projections of Remaining Landfill Life (in years)

Eight small landfills responded with calculations for projecting remaining landfill lifetime (instead of remaining capacity). Respondents in this category generally did not address the issue of how they determine the remaining capacity expressed as volume or tonnage, though the calculation for estimating remaining landfill life requires such an assumption. Some respondents who use this method indicated that they used the calculation developed by the Board for use in preparing the facility capacity component of the Source Reduction and Recycling Element (SRRE). While this calculation is useful for county planning purposes in order to project when existing facilities are approaching capacity, it is not adequate for determining the total amount of remaining capacity at a specific landfill. This method is simple to apply, but it relies heavily upon assumptions as opposed to actual survey data or measurements of waste buried in landfills.

Some respondents used slightly different calculations or responded by providing assumptions about the future life of the landfill. The latter appear to have information pertaining to weight or volume but did not indicate how these data were obtained or derived.

Cell/Trench Volume-Based Estimates

Landfills that use cells or trenches of consistent dimensions can estimate remaining capacity by calculating the total percentage of cell or trench space used. Where cells or trenches are of consistent dimensions, calculating remaining capacity (in volume) is a simple matter of multiplying remaining trench length by the cross-sectional area of the trench. These operators are able, furthermore, to calculate density, as long as they know how many feet of trench are used and how much weight of solid waste they have received over a period of time. There were only five landfills in this category among respondents to the survey, representing three percent of the total sample size. Combined, these landfills represent less than 100 TPD of the State's landfill capacity.

Unclear/No Response

Thirty-six landfills did not provide enough information to evaluate their approach for determining capacity. Eighteen of the landfills in this group are permitted to receive under 20 TPD of waste. Sixteen of the 36 did not respond at all; we assume that these landfills do not estimate remaining disposal capacity, or had no currently available information, or did not choose to respond for other reasons. In the remaining 20 cases, respondents attempted to answer the question, though that information was not sufficient for classification.

To summarize, most of the landfills which responded to the Board survey use one of four methodologies for estimating remaining landfill capacity. Of these, most landfills use topographical survey information, although a significant number of landfills use weight-based analysis methods. Only a small number of the State's landfills use cell/trench volume-based methods or time-based analyses, and these landfills receive very little waste for disposal. In terms of the amount of capacity - both the permitted daily disposal capacity and the amount of capacity remaining - survey-based methods predominate; Figure 1 indicates that while 48% percent of the landfills which responded used survey methodologies, these landfills accounted for nearly 90% of the permitted capacity in tons per day, and 86% of the estimated remaining disposal capacity. Approximately 10% of the remaining disposal capacity is estimated using weight-based methods, while only a small fraction is estimated using time-based or cell/trench-based methodologies.

II. NEEDS ASSESSMENT

Figures 2, 3 and 4 indicate that larger, newer, and privately-owned landfills are more likely to use topographic survey methods to determine their remaining permitted capacity. Conversely, smaller, older, and publicly-owned facilities are more likely to use weight-based or other methods, or not to assess their remaining capacity on a regular basis. While specifications and standards for topographic survey methods may not be entirely consistent, surveys can be expected to produce more uniform, comparable, and accurate data than the other methods employed. The survey results, therefore, seem to indicate that owners and operators of small, rural, publicly-owned landfills may require assistance to improve their ability to assess their remaining permitted capacity. Given the likelihood that the cities and counties that own and operate these facilities lack the staff, the equipment, and the funds to perform state-of-the-art topographic surveys, there appears to be a further need to present them with alternative means of determining their remaining capacity that will produce acceptable results at low cost and with existing resources. Many within this group of landfill owners are already conducting periodic studies of their remaining capacity and producing excellent results. Others, however, may benefit from some guidance in selecting and implementing an appropriate methodology for determining their remaining capacity.

There are several ways that the Board can assist landfill owners and operators around the State in regularly and accurately determining their remaining capacity. These may include:

1. development and distribution of clear recommendations on which methods are most useful and accurate for landfill owners and operators to use in assessing their own remaining capacity;

2. development of guidelines for landfill operators to use in selecting a methodology;

3. publication of clear, step-by-step procedures for using the recommended methodologies;

4. establishing guidelines for developing ancillary assumptions, e.g., density of in-place material, refuse:soil ratios, and maximizing use of permitted capacity;

5. providing guidelines for contracting out for survey services; and

6. providing technical assistance from Board engineering staff as needed.

III. RECOMMENDED METHODS

This section presents an overview of three methodologies that are recommended for use by landfill operators in assessing their remaining capacity. The use of the recommended methodologies is not a regulatory requirement; however, in the interest of all concerned parties, it is recommended that landfill owners and operators follow these guidelines and perform remaining capacity assessments on a regular basis. The information developed through use of the techniques described in this section will assist site managers in meeting reporting requirements, managing remaining fill space, and tracking the use of cover soil. The information will, furthermore, assist in local government, regional, and state-wide planning of integrated waste management facilities and programs.

A variety of factors will influence the frequency with which a landfill operator should determine remaining site capacity. Probably the most common is a timeframe requirement specified in the solid waste facility permit. The 5-year Periodic Site Review also includes a requirement to estimate remaining site life. New computations may be indicated when the reliability or accuracy of previous computations or supporting assumptions is questionable or when it is decided that more accurate projections are needed. The latter could be true when a permit revision is sought or when there is a change of owner or operator. Survey and map data are often updated when a facility reaches a significant milestone in its service life, for example, to confirm the accuracy of a completed unit, or to check specific altitudes and slopes.

All the methods recommended may be used for two types of computations: the use of <u>current</u> and <u>final</u> fill plan data may be used to estimate remaining capacity and site life; and the use of <u>previous</u> and <u>current</u> fill data may be used to determine the extent and rate of fill since the last computation. Both computations are in turn influenced by several factors that must be determined and periodically reconfirmed. These factors are:

- In-place densities (at the time of placement and initial compaction);
- Settlement / decomposition rates; and
- Refuse:soil ratios.

The computations are inter-related and build on each other. For example, volume data derived from surveys and mapping can be used for several purposes, such as to:

- Determine remaining capacity;
- Prepare or revise site life estimates;
- Determine refuse:soil ratios;
- Compute in-place density; and
- Estimate settlement rates.

For each methodology recommended here, however, at least some factors must be assumed or derived from other data. Therefore, all factors should be updated periodically to ensure their accuracy and reliability: the least accurate factor will directly influence the accuracy of all the others.

Each of the three recommended methodologies is discussed here in terms of the basic concept of the method; who might be qualified to carry out the method successfully; equipment and personnel requirements; and the type and size of landfill for which the method is appropriate.

TABLE 2: COMPARISON OF RECOMMENDED METHODS FOR DETERMINING REMAINING CAPACITY

Method	Cost	Accuracy	Type of Landfill	Size of Landfill	Equipment/ Expertise Required
Aerial Surveys with Computer-assisted Calculations	Generally highest cost, though may be less expensive than ground surveys for larger (over 10 acres) landfills.	Highest level of accuracy, with built-in cross checks. Should be accurate to within 10%.	All types of area landfills.	Appropriate for landfills over 10 acres.	Airplane, photogrammetry equipment, stereo plotter, autocad with add-on; operators for all of this equipment.
Ground Surveys with Manual Calculations	Middle cost; cost is generally less than aerial surveys for sites under 10 acres.	Depending on expertise and care of surveyors, map-makers, and whoever performs calculations, 10-20% accuracy.	Appropriate for all area-type landfills.	Best for landfills under 10 acres, or for larger landfills if it can be accomplished in-house at lower cost.	Manual surveying equipment, drafting equipment, planimeter or grid paper, calculator or computer spreadsheet; operators for all of this equipment.
Weight-Based	Low cost, particularly after first use of this method.	Accuracy of 20-25% is possible.	Appropriate for area-type landfills.	Appropriate for smaller and low-volume landfills.	Calculator or computer spreadsheet, accurate records of incoming material in volume or weight; care in performing calculations.
Trench Volume	Very low cost.	Accurate to within five percent.	Trench-type landfills with consistent trench dimensions, and area-type landfills with consistent cell dimensions.	Any size.	Calculator or computer spreadsheet; ability to perform basic geometric calculations.

Appendix A provides more detail on each methodology, including step by step instructions on how to use each method. Appendices B and C discuss methods for determining density of landfilled materials, and assessing the ratio of refuse:soil used in landfill. Appendix D discusses factors that may increase or decrease the ability to utilize remaining permitted capacity.

A. Topographical Survey Methods

Topographical surveys can be considered the most accurate and reliable method to determine the remaining capacity of a landfill. Topographic surveys are not, however, necessarily the most inexpensive method, and they require considerable surveying and engineering expertise to be done properly. The basic approach involves conducting a ground or aerial survey of the landfill and using the results to develop a map of the current topography of the site. This map is then compared to the base contours and the permitted final design contours of the landfill, and calculations are made to determine the total (gross) volume of airspace remaining in the fill. Gross airspace is then reduced by an estimate of the amount of space that will be taken up with daily, intermediate, and final cover material. The resulting figure is net airspace, or remaining refuse capacity. Net airspace may be used to report the remaining capacity in cubic yards, but if the landfill owner or operator wishes to express remaining capacity in tons, they must develop a density factor to use in converting volume to weight. The remaining capacity expressed in tons can then be used to project the remaining life of the landfill, based on existing and projected rates of disposal. Future settlement should also be taken into account in projecting the remaining lifespan of the facility.

One advantage of using periodic topographic surveys to assess remaining capacity is that the method provides a cross-check for determining in-place density of refuse, an otherwise problematic procedure. To determine in-place density, the current topography is compared to the topography at the time of the previous survey, to determine gross airspace used during that time period. Then total tons and total airspace are known, and one can easily calculate the space required for one ton of material by dividing cubic yards used by total tons landfilled. The volume of cover material used can be subtracted from total airspace used to determine the volume of refuse only. Settlement may also need to be factored in, since underlying lifts may have settled since the last survey and increased available airspace.

Survey methods are appropriate for area-type landfills, including canyon landfills, of any size. There are two different methods in common usage for conducting topographic surveys and two general approaches used for calculating the volume of refuse capacity used since the last computation, and the remaining capacity. Each of these is discussed in the following subsections.

Note that when surveys are used to gather volume data periodically, it is not always necessary to resurvey the entire landfill footprint. In order to save time and money, it is possible to conduct an interim survey of only the portions of the landfill active since the last survey. However, a focused survey may significantly limit the amount of valuable data available to planners, operators, and engineers while considering filling sequences, operational planning, and closure activities. Areas of landfills that are not currently being filled or have not been filled for a specific period of time are excellent field laboratories for settlement and displacement data collection. Consistent settlement monitoring may allow the operator to plan filling operations to maximize the life of the landfill. Horizontal displacement monitoring can provide the site engineer with an early warning of potential side slope or liner instability concerns.

1. Ground Surveys

This traditional method of gathering field topographic data for mapping is done through use of manual ground surveys conducted with a variety of instruments and techniques. While this approach has been practiced for centuries, it is no longer likely to be the most economical way to develop volume data, except under particular circumstances. It is, however, available practically anywhere either through internal staff or contracted consultant survey crews. Properly calibrated equipment, even instruments several decades old, can be used to gather accurate topographic data, although sophisticated modern instruments are generally significantly more efficient for field data collection.

Ground surveys are usable in essentially all situations where topographic, traverse, or boundary data is needed for landfill operations. Considerations in electing to use this basically manual method include availability of crews, equipment, timeframe, and technical expertise. Ground surveys are essential for setting ground control (targets) for aerial surveys, but are most likely to be cost effective for general surveys only for surveys of sites under 10 acres, or for small data needs (such as spot surveys) at any site. Methods for conducting ground surveys, along with other considerations to be evaluated in deciding whether and how to use ground survey and manual mapping methods, are discussed in Appendix A.

2. Aerial Surveys

While the data resulting from aerial surveys are similar to those from ground surveys, aerial techniques are much more highly automated. The per acre cost for aerial surveys is likely to be less than for ground surveys, especially for larger landfills, but the budget impact may be greater if the landfill owner or operator has to contract out for services. Ground surveys are required to set ground control (targets) for all aerial surveys.

The accuracy of aerial survey maps may be less than for maps made from ground surveys, if the actual ground surface is not clearly visible to the photo reader (a person or a computer). Any ground obscurities, such as snow, leaf, brush, or grass cover, can noticeably misrepresent the actual ground surface. A high level of accuracy is typically not needed for capacity calculations, however, unless actual construction is also to be based on that mapping effort. Where accuracy questions arise in the map use or development, ground spot surveys can often confirm data, but manually filling-in large data gaps can quickly eliminate any cost savings expected from using the automated approach. The steps for conducting aerial surveying (and related mapping) are discussed in detail in Appendix A.

3. Determining Remaining Volume of the Landfill Using Manual Techniques

Volume determinations from contours or cross-sections involve measurement of the area of each designated contour and conversion of those areas to volumes by multiplying times the contour spacing. The determination may be done by either internal staff or contracted service providers, although technical skills are required from either. Basic procedures for conducting volume estimates manually are described in Appendix A.

Landfill owners electing to perform volume calculations in-house must consider that small businesses or local government agencies are unlikely to have the skills or equipment for automated data derivations and computations. For manual methods, planimeters, including highly sophisticated electronic units, are probably available in offices doing road design or by rental from engineering supply stores (in urban areas). Grid counts require only a background grid and can be done by nearly anyone. [Note that if the grid is laid on the contours with the least area first, only the increment of area difference must be determined in moving to each larger contour.] Volume computations can be done quite rapidly once the area data is available; surveying and engineering consulting firms commonly use manual volume computations.

In order to compute airspace used to date and remaining capacity, it is necessary to measure the design plans, both the base plan and the approved final grades for the site. Once these measurements are done, they need not be repeated. Subsequent surveys are, therefore, greatly simplified.

In general, the degree of accuracy that can be achieved with manual volume calculations is influenced by several factors, including:

- Skill of the individual doing the measuring and calculating;
- Number and consistency of planimeter measuring repetitions; and
- Accuracy / calibration of the planimeter used.

All measurements and calculations should be checked for correct methodology and accuracy. Roughly measured dimensions of even irregularly shaped areas will provide some cross-checks of other computations. Measurement repetitions also improve accuracy and provide cross-checks.

4. Determining Remaining Volume of the Landfill Using Automated Techniques

Volume determinations from contours using automated techniques are described below and detailed in Appendix A. They may be performed by either internal staff or contracted service providers.

To complete the computations using automated techniques, the same processes as described for manual computations must be performed by automated means, typically with a computer system. The most effective systems perform both area measurements and volume computations using soft (electronic) topographic data taken directly from an automated map production process. If the soft data is not available, it can be developed by digitizing or possibly scanning the contours from the latest map. Area and volume computations can then be developed using existing specialty software, such as for surveying and/or road design applications, or by automating the processes described under manual computation methods. As with manual computations, automated volume determinations require digitizing of base and final grading plans the first time the calculations are performed.

The accuracy of the method is influenced by several factors, including:

- Skill of the individuals doing mapping, measuring, computer graphics, and calculating;
- Seasonal timeliness of the photography;

- Ability of the photo reader to see the true ground surface; and
- Accuracy of the mapped data used.

As with the manual method, all measurements and calculations should be checked for correct methodology and accuracy. Roughly measured dimensions of even irregularly shaped areas will provide some cross-checks of other computations.

5. Comparison of Methods

Ground surveys with manual data development and calculations are likely to be advantageous in these situations:

- A competent workforce is available at internal rates, especially if otherwise funded;
- Area to be surveyed is under 10 acres, or data collection needs are relatively small;
- Site topography is not so variable as to overly restrict foot-access to survey points;
- Survey, mapping, measuring, and/or computing equipment is available economically;
- Aerial survey vendors are not readily available;
- The combined time window for ground visibility and seasonal weather changes is too narrow to schedule aerial photography reliably;
- Cover soil management or other site operations considerations require closer (more frequent) fill rate monitoring than is practical with aerial photography;
- Waste flow quantities are small resulting in only minor topographic changes; and
- Data is needed before the aerial photography process could be completed.

Aerial surveys with automated data development and calculations are likely to be advantageous in these situations:

- Internal field workforces are not readily available;
- Site size and/or data collection needs are substantial;
- Site topography allows placement of ground control target points, but otherwise makes ground survey of the site impractical;
- Aerial survey vendors are available and affordable;
- The seasonal time window, if applicable, is adequate for aerial photography;
- Adequate lead time is available for completing the automated process;
- Automated photography, mapping, and/or computing equipment is available economically; and
- Skilled mapping, data extraction, and computational staff or contractors are available and affordable.

B. Weight to Volume Conversion and In-Truck Volume to Landfilled Volume Conversion Methods

Using weight to volume or compaction ratios to determine remaining capacity involves tracking the weight or volume of materials received at a landfill, converting these figures to landfilled volume, and calculating net and gross airspace used. This method requires no special expertise beyond careful record keeping and conducting basic mathematic calculations, and requires no special equipment beyond a scientific calculator or spreadsheet program (though a truck scale is an advantage). However, the method has several inherent problems:

- there are a relatively large number of variables in the calculations, and an error in one can compound into significant inaccuracies;

- there are no built-in cross-checks in the method; and

- the method involves developing several assumptions, some of which may require considerable field testing.

Nevertheless, weight to volume conversion can be a relatively simple and inexpensive method for determining remaining capacity, and, if performed carefully and diligently, can result in a reasonable degree of accuracy. Because of the relative ease and low cost of this method, it is recommended primarily for smaller area-type landfills, including canyon-type landfills (say, those receiving less than 10 TPD), or landfills receiving slightly higher volumes but which have a large amount of remaining capacity. Because of the inability to cross check results, the Board recommends that those using this method conduct occasional topographical surveys to provide a more accurate update of the benchmark capacity.

A variation on the weight to volume conversion method is the in-truck volume to landfilled volume conversion method. This method, which can be used by landfill operators who do not have a truck scale, involves measuring the volume of materials in trucks arriving at the facility, making assumptions about the density of these materials, and calculating the weight of the materials. The landfill operator then calculates or estimates the density of landfilled material and refuse:soil ratios to derive an estimate of the amount of landfill space used. This method requires tracking incoming loads by truck type, size, and fullness, then using density assumptions and a simple spreadsheet to convert volume to weight. Like the weight to volume method, this method also involves estimating or calculating refuse:soil ratios and taking into consideration design features and other contingencies.

The use of the weight to volume conversion method and the in-truck volume to landfilled volume method is facilitated by the existence of a number of studies that can be drawn upon to develop most of the crucial assumptions (in-place density, in-truck density, refuse:soil ratio). While sound landfill operating practices dictate that operators occasionally conduct field studies of these parameters, it is possible to estimate remaining capacity relying almost solely on desk-top calculations. Excerpts from Board-commissioned studies are included in Appendices A3 and B.

Depending on the size of the landfill, the time since the last topographical survey, and the completeness of records of in-coming material, daily and intermediate cover usage, and basic operating parameters (such as weight of equipment, average number of passes, depth of spread material, slope of working face), calculating remaining capacity using the weight-to-volume conversion method may take from several hours to several days. If an assessment of remaining capacity has not been performed for a number of years, then operators can assume that they will spend considerable time and effort the first time this method is employed. Thereafter, however, annual updates should be relatively simple and quick, particularly if operating parameters and the character of the waste stream do not change significantly, and if records are complete and accurate.

Costs of conducting an assessment of remaining capacity using weight to volume conversion include labor time for compiling records, developing assumptions, and making calculations; the cost of labor, equipment, and, if necessary, outside surveying or engineering expertise for conducting density studies or studies of refuse:soil ratios; and, to ensure accuracy, the cost of cross-checking and updating benchmark data by conducting occasional topographical surveys.

To keep costs of conducting occasional surveys to a minimum, landfill operators may be able to use existing equipment and expertise (e.g., having county road surveying crews conduct a ground survey), and using in-house expertise to perform volume calculations. The cost of conducting aerial surveys can be minimized if the photogrammetry of the landfill is conducted as an add-on to another aerial survey in the area, or if and when off-the-shelf (stereographic) commercial aerials become available. If no topographic survey has ever been performed on the fill, there will be the additional expense of digitizing the final contours or conducting manual area and volume calculations of the remaining planned lifts. These steps need not be repeated each time the topographic survey is conducted, unless design parameters change in the interim.

C. Trench Volume Method

A few landfills in the State are trench-type landfills. Operators of these facilities can easily determine their remaining capacity with simple field observations and mathematical calculations, if their trenches are of consistent dimensions. Determining remaining capacity of a trench-type fill involves measuring the cross section and length of each existing and planned trench to assess the volume of each. Site life, density of landfilled material, and refuse:soil ratio can all be calculated by measuring the length of trench used, the weight of incoming material, and the volume of cover material used. This method allows for cross-checking of remaining capacity by monitoring the rate of fill over time.

For the few operators of landfills that use trenches of consistent dimensions, this method of determining remaining capacity offers unparalleled ease and accuracy. Detailed formulas for performing trench volume calculations appear in Appendix A.

IV. CONCLUSION

The California Integrated Waste Management Act's mandate to reorganize the management of waste materials giving favor to reducing wastes at the source, then recycling or composting those that cannot be source reducted, then treating only the unrecoverable fraction through environmentally safe transformation or land disposal, is predicated on the necessity to conserve scarce resources, including landfill capacity. Having an accurate account of the capacity remaining in a particular landfill within a county or region, and within the State as a whole, is crucial information for managing this scarce resource, and for local governments to use in planning their transition to an integrated waste management system.

This report is intended as an initial step in assisting California's landfill owners and operators in improving their ability to gauge accurately their remaining permitted capacity, using techniques that are appropriate, reliable, and affordable. Through the establishment of informal standards for assessing remaining permitted capacity, and assistance in using standard methods, the Board hopes to encourage landfill operators to gauge periodically the capacity remaining in their own landfills and develop information that is accurate, that is comparable to data generated by other owners and operators, and that can be accomplished within a variety of situations and budgets.

V. BIBLIOGRAPHY AND CONTACTS

Brinker and Minnick, Editors, 1987, *The Surveying Handbook,* Van Nostrand Reinhold.

CalRecovery, Inc., (with Tellus Institute), 1993, *Conversion Factor Study, In-Vehicle and In-Place Waste Densities.* Final Report. Sacramento: the California Integrated Waste Management Board.

Jesitus, John, 1992, "Soil Substitutes Slash Daily-Cover Needs." *MSW Management,* Vol. 2, No. 2, pp. 34-36.

Magnuson, Anne, 1992; "The Economics of Landfill Compaction." *MSW Management,* Vol. 2, No.7, pp. 20-25.

Magnuson, Anne, 1993, "D-Day: Ready or Not." *MSW Management,* Vol. 3, No. 3, pp. 72-74.

Merritt, Editor, 1983, *Standard Handbook for Civil Engineers,* Third Edition, New York: McGraw-Hill, Inc.

Suprenant, Gene, and Lemke, James, 1994, "Setting a Density Standard." *Waste Age,* (August) pp. 43-52.

Tchobanoglous, George, Theisen, Hillary, and Vigil, Samuel, 1993, *Integrated Solid Waste Management, Engineering Principles and Management Issues.* New York: McGraw-Hill.

Zukerman, Ligon, and Ackerman, John, 1994, *Analysis of Techniques Used to Estimate Remaining Landfill Capacity in California,* for Environmental Science Associates/California Integrated Waste Management Board. Boston: Tellus Institute.

Contacts

Rich Doble, Central Landfill Manager, Sonoma County DPW

Chuck Post, Project Manager, RSS - West Contra Costa County Landfill in Richmond and Potrero Hills Landfill in Solano County

Kurt Hartog, Solid Waste Program Manager, Merced County

Al Thorson, Riverside Flood Control (Rfc)

Brian Gilmore, Surveyor, County of San Diego Field Surveys Department

Pat Lawrence, SCS Engineers, Santa Maria Refuse Disposal Site

Tom Wetherhill, SCS Engineers

Fred Cope, EMCON

Jim Greco, Program Manager, Waste Facility Engineering, HDR Engineering

Don Hoffman, Kings Co. Waste Management Authority

David Whitehead, P.E., City of Santa Monica

Lori Rising, L.A. County Sanitation District

Michael B. Wochnick and Darryl L. Petker, Board Closure and Remediation Branch

Kathi Davis & Mel Henson, State of Illinois Environmental Protection Agency

APPENDICES

APPENDIX A: METHODOLOGIES FOR DETERMINING REMAINING LANDFILL CAPACITY

APPENDIX A-1: SURVEY METHODS

Topographical survey methods are the preferred methods for determining the remaining permitted capacity of a sanitary landfill, and should be used if economically feasible. This method involves four main steps:

1. Conducting a ground or aerial survey of the site to ascertain current elevations and contours;
2. Mapping these elevations (creating a topographical map);
3. Calculating the volume difference between existing and permitted final grades (gross remaining air space); and
4. Adjusting the volume calculation to determine the amount of usable airspace remaining.

Surveying

Field or ground surveying methods consist of obtaining location and elevation data for a number of points on the ground and using this data to produce a surface model. The surface model may be in digital (electronic computer file) format, which will allow for automated volume calculations, or drawn manually. In either case, the model is used to produce a representation of the current topography of the site.

Ground surveys can be used efficiently to survey sites up to 10 acres. They are also practical for intermediate surveys to update current conditions such as borrow sites for cover volumes, intermediate lift heights, roadways, landfill settlement, etc. Aerial surveying can deliver the same products as field surveying but is usually much more cost-effective on sites over 10 acres. Aerial surveys also provide photographs of the site, which are an historic record of the area at a certain date.

Mapping

The two most important considerations in mapping are the size of the area to be mapped and the scale of the final mapping. The size of the area can determine whether ground surveys or aerial surveys are most efficient.

Volume Determinations

The current surface model or existing contours can be developed from field surveying, photogrammetric surveying, or a combination of both. Either way, an electronic data file can be produced. If volume calculations are to be performed with computer assistance, the final digital surface model file type must be compatible with the engineering software used for the volume calculations. Most recent software can use many types of files for input; however, it would be prudent to investigate and even ask for an example file from the surveyor in order to assure compatibility, as well as to practice. A number of engineering software programs can be used to generate and display surface models (terminology also used is topographic mapping and contour mapping). These surface models are computer files of location and elevation data which can be used by the software for display and to generate grading plans, volume studies, etc.

All permitted landfills should have a final grading plan. To calculate remaining airspace, the current surface model is subtracted from the final grading plan surface model, resulting in remaining airspace. This is a fairly straight-forward computer calculation, and can also be accomplished manually using either a planimeter or transparent grid paper.

Adjusting Volume Calculations

Once the volume between existing and final contours has been calculated, it is necessary to subtract from this gross volume figure the volume of material and features other than refuse, to determine the net capacity available for refuse placement. The primary considerations here are the volume of daily, intermediate, and final cover material; special design features that may limit net usable airspace, such as benching of slopes, drainage systems, methane collection systems, liners, and monitoring wells; and landfill characteristics that may increase apparent capacity, such as settlement of lower lifts and of substrate.

The following sections describe in detail the procedures and crucial considerations for conducting ground surveys, aerial surveys, and performing volume calculations using both manual and automated techniques.

A. Ground Surveys

The discussion below is presented as an explanation of the general steps to be followed, listed roughly in the order of likely progression.

1. Define all expected users, uses, and requirements

   Completion of this step prior to initiating the survey provides several benefits. Using this early planning information, the survey can be focused on gathering only the needed data and ensure that all of it is obtained. Related survey needs should also be identified at this time so that opportunities for consolidating surveys and funding can be utilized to reduce the cost for each application. This step may also define other surveys already done or planned that would provide the necessary data and preclude the need for a new survey.

   As data uses and users are identified, complete requirements for each application must also be defined so that correct and complete specifications for the survey and data are developed in the next step.

2. Define survey and data specifications

   The nature and extent of the surveys and data are identified in this step prior to sending the field crew(s) to the site. If multiple users with differing data needs are identified in Step 1, those needs must be consolidated in this step to provide for mutually acceptable survey, mapping, and data collection. The considerations in this step can be divided into these elements:

   a. Determine the extent, nature, and accuracy of data required

      - Determine nature of data required: elevations, point locations, traverses, feature definitions
      - Determine the contour interval and required associated survey data accuracy
      - Decide which features to note (structures, roads, ponds, ditches, fences, pipes)
      - Define area to be covered: whole site, or only partial (depends on whether portions of the site are unchanged since last survey; please note that even inactive portions of the landfill may be re-surveyed to check settlement)

b. Determine the field limits and methodology

- Extent/limits of survey and the layout
- Type of survey(s)
- Placement of survey data points (grids, set-up points)
- Location and number of benchmarks/datums (existing, new)
- Strategy for completing all facets of survey(s)

c. Equipment and crew requirements

- Matched to strategy and data requirements
- How many people/crews with what skills
- Equipment to be used (types, numbers, availability, expendable supplies)

d. Special requirements and limitations

- Weather and ground conditions (snow, dust, rain)
- Hazards on site (landfill gas [LFG], leachate, contact with refuse, heavy equipment and trucks, slippery surfaces, open ponds, hazardous materials or wastes, noise and other nuisance factors)
- Idiosyncrasies of landfill surveys (associated hazards, numerous irregular features, benchmark stability requirements)
- Field safety considerations/plan

The list above is not meant to be chronological, since the order of development of the listed information will vary with each survey.

3. Perform Survey

The survey itself may be performed by in-house staff or contracted out.

Considerations

- Seasonal affects/needs (snow, rain, hazardous conditions)
- Regular/consistent ongoing program
- Landfill surveying idiosyncrasies
- Field safety
- Survey methods (depends on data needs):
  - Elevation and contour data
  - Area grid with levels
  - Contour traversing
  - Polar (vertical and horizontal)
  - Horizontal location and perimeter definition data
  - Traversing
- Establish benchmarks/datums on "solid ground"
- Gather area data (elevations, notable features, other specifically needed data)

B. Aerial Surveys

Aerial surveys are typically contracted out to a surveying firm to perform the aerial photography. Depending on the arrangements with the contractor, deliverables may be any or all of the following:

- Aerial photographs

- Hard copy topographic map
- Digital file of topographic features

The steps to be taken in preparing for and performing an aerial survey include:

1. Define all expected users/uses and requirements

2. Set ground control

    - Field surveys
    - Ties to benchmarks/datums

3. Develop flight specifications: vertical/oblique; time frame; location; flight line; number of photos; who sets ground control; photo scale and altitude

4. Define data specifications, including photos: contour interval/accuracy; coverage area; features to note (e.g., structures, roads, ponds, ditches, fences)

5. Flight/photography (typically includes contracted services)

    Consider seasonal affects and restrictions, such as snow, leaves, and tall grass. The photogrammetrist must be able to "see" (define) the ground on the aerial photographs.

C. Contour Development and Mapping

The final grading plan for each landfill should include a topographic map of the final design of the landfill area. Current mapping should be accomplished in a manner that is consistent with the mapping on the final plan (see scale and contour interval below). If more modern mapping methods are going to be used, it would be useful to upgrade the final plan topographical map to the style of the current mapping. This can be accomplished in a variety of ways, including digitizing to a CAD program, or having the original photogrammetry remapped to digital output.

To produce a map from aerial photographs, a stereo plotter operator plots locations, contours, and desired features. This was formerly done to a hard copy, but it is now common practice to produce an electronic digital file that can be used by CAD programs for viewing, calculations, and hard copies.

Mapping scale and contour interval determine the accuracy of a map. Normal contract specifications for photogrammetric mapping simply states the resultant mapping scale. The two most common are:

1) 1" = 100' with two-foot contour intervals
2) 1" = 40' with one-foot contour intervals

Although the 1" = 40' scale results in a more accurate map, and therefore a more accurate volume calculation, it is considered impractical for sites over 50 acres.

An important consideration in photogrammetric mapping is the photo scale. Photo scale is directly related to above-ground flying height. Some photogrammetric equipment is more accurate than others, and different equipment may require different flying heights to achieve the same results. The following photo scale requirements were suggested by Al Thorsen of Riverside Flood Control as a general rule of thumb:

1) For mapping scale of 1" = 100' and two-foot contours, use a photo scale of 1" = 500'
2) For mapping scale of 1" = 40' and one-foot contours, use a photo scale of 1" = 200'

There are National Map Accuracy Standards which apply to photogrammetric mapping. Basically they say that if you were to use field surveying methods to check the elevation at 10 random points whose elevation was determined from the map, then 9 of these elevations should be no more than one half the contour interval from the elevations on the map (0.5 feet for a map with one-foot contours). While few surveyors will perform this cross-check routinely, this standard may be cited in the scope of work for a surveyor charged with producing a map of current landfill elevations.

D. Determining Remaining Volume of the Landfill Using Manual Techniques

In order to calculate volume between two surfaces using manual techniques, the topographical map of existing grades is used and the area of each contour between the highest point of the existing surface and the lowest point of the original grade is measured. Next, the area of each contour is added to that of the next contour, then divided by two to obtain the average area. This average is then multiplied by the contour interval to obtain a calculation in cubic feet of the volume between each of the two contours. The volumes between all of the contours are then totaled to obtain the total volume of the existing landfill. This figure is then subtracted from the original design capacity (which may be calculated in the same manner, comparing the design final grade to the base grade) to obtain gross remaining airspace.

Either of two methods may be used to measure the area of each contour:

Using a planimeter:

Planimeter each contour area at least twice; average the result; multiply times the conversion factor for the planimeter and map scale combination.

Using transparent graph paper:

Superimpose the grid; count the full squares; count the part squares and divide by two; add the part squares dividend to the full squares count; determine the area of each square using the map scale (e.g., if using 1/4 inch graph paper and the scale of the map is 1" = 100', then the area of each grid square is 25 * 25 = 625 square feet). Next, multiply the total number of squares by the area of one square. The result is the area of the contour.

Volume computation by end areas

For this computation, the average end area (average area of the two adjacent contours or cross-sections) is multiplied by the distance between those contours or cross-sections. The top and possibly the bottom of the landfill may be a point with zero area. In that instance, the average end area is the adjacent contour/cross-sectional area plus zero divided by two. The volumes for each layer are finally added to produce the total landfill volume. All volumes are computed in cubic yards.

It is very helpful to set up a columnar form or computer spreadsheet on which to do these computations. If such a format is developed from "scratch", note that all computations from the combining (totaling) of end areas must be on a line between the end areas source lines. Typical columns should include (from left to right):

1. Contour, expressed as an elevation (e.g., 195')
2. End areas (typically in square feet) of each contour; i.e., the area of each contour
3. Average end area between adjoining contours
4. Contour interval (in feet)
5. Volume in cubic feet: average end area ∗ contour interval = volume
6. Volume in cubic yards: volume in cubic feet ÷ 27
7. Gross volume: the sum of all of the volume in cubic yards calculations

Note 1: Contours are used for most landfill situations; however, cross-sections (similar to the situation for roads) can be used for some trench landfills.

Note 2: Some sources refer to double end areas which are simply the sum of the two adjacent end areas before division by two to obtain the average end area.

E. Determining Remaining Volume of the Landfill Using Automated Techniques

To complete the computations using automated techniques, the same processes as described for manual computations must be performed by automated means, typically with a computer system. The most effective systems perform both area measurements and volume computations using soft (electronic) topographic data taken directly from an automated map production process. If the soft data is not available, it can be developed by digitizing or possibly scanning the contours from the latest map. Area and volume computations can then be developed using existing specialty software, such as for surveying and/or road design applications, or by automating the processes described under manual computation methods.

There are three common methods for volume calculations. All three are based on the mathematical differences between two separate surface models: average end area method, grid method, and triangular surface method. Since the average end area and grid methods both work with cubic models, their answers will commonly be close to one another and will result in a slightly larger volume than the triangular method. The triangular method is generally more accurate for irregularly-shaped surfaces such as landfills, since triangles fit better into the irregularities than do squares.

F. Adjustments to Gross Volume Calculations

1. Calculate necessary earthworks (daily, intermediate, and final cover); see Appendix C.

2. Consider design parameters that may affect ability to use remaining airspace; see Appendix D.

3. Subtract volume of earthworks and other features from gross volume.

4. Using density factor, convert net remaining airspace to tons.

APPENDIX A-2: METHODOLOGY FOR DETERMINING REMAINING CAPACITY USING WEIGHT TO VOLUME CONVERSION (FOR LANDFILLS THAT TRACK WEIGHT OF IN-COMING MATERIALS)

The simplest and most useful method of converting from weight received at the gate of the landfill, to volume of airspace that the refuse will take up, is to develop and apply a single conversion factor that takes into account both in-place density and the refuse:soil ratio. Once this factor is developed, it can be applied to historic and projected disposal rates to determine how much capacity has been used, how much remains, and how long the remaining capacity is likely to last. This method requires occasional topographic surveys as a cross-check.

The method may be applied as follows:

1. Determine density of landfilled materials, either through field tests or using the desk-top technique described in Appendix B.

2. Determine refuse:soil ratio, as described in Appendix C.

3. To convert from landfilled tons to landfilled volume, use the following formula:

$$V = D * C$$

Where
V = the total volume of landfill space taken up by landfilling and covering one ton of refuse
D = the inverse of the density of in-place material, expressed in tons per cubic yards
C = the waste to soil cover factor, expressed at the total parts/waste parts.

For example, if the density of in-place material is determined to be 1,400 pounds per cubic yard, and the refuse:soil ratio is 5:1, then,
1,400 pounds = .7 tons; the inverse of .7 is 1/.7 = 1.43; use this for D.
5:1 ratio means total parts = 6, waste parts = 5, so C = 6/5, or 1.2.
Solving V = D * C,
V = 1.43 * 1.2
V = 1.71 cubic yards per one ton of refuse.

In other words, for each ton of refuse landfilled, 1.71 cubic yards of airspace is used.

4. From landfill records, determine net tons landfilled since last topographic survey or since site opened (be sure to adjust gate receipts by any salvage or diverted material).

5. Multiply net tons landfilled by the conversion factor (V) to ascertain total airspace used.

6. Subtract the result of Step 5 from the remaining airspace at the time of the last topographic survey, or the total design capacity of the site (whichever was used in Step 4). The result is total remaining airspace.
7. To determine net remaining airspace, subtract the projected volume of the final cover and intermediate cover from the result of Step 6.

8. To determine remaining site life, use projections of annual disposal rates, in tons, multiply by the conversion factor (V) and subtract from net remaining airspace (Step 7) for each future year until net remaining airspace = 0.

9. To cross-check total and net remaining airspace, conduct a topographical survey (see Appendix A-1) of the site.

APPENDIX A-3: METHODOLOGY FOR PERFORMING IN-TRUCK VOLUME TO WEIGHT CONVERSION (FOR LANDFILLS THAT TRACK INCOMING VOLUME)

Some landfills do not have scales for weighing incoming material. These landfills can use a variation on the weight-based method by tracking the volume of incoming material and converting to tons, then calculating the density of in-place material to arrive at a volume for landfilled materials. While it is possible to convert directly from in-truck density to in-place density, (by calculating a compaction ratio), recently adopted regulations (Title 14, Div.7, Chapter 9, Article 9) require landfill operators to report the tonnage of incoming material.

The method presented on the following pages is taken from the Board report *Conversion Factor Study In-Vehicle and In-Place Waste Densities* recently adopted by the Board (CalRecovery, et al, 1993). This method provides a relatively simple and accurate means for converting from volume of incoming material to weight. Once the weight of incoming materials since the last accurate capacity assessment is calculated, it is possible to use the steps presented in Appendix A2 to calculate remaining capacity.

EXAMPLE 1: THE SIMPLE MODEL

Imagine a small rural landfill operator who does not have truck scales and does not know the composition of the waste stream in his/her region, or desires a reasonably accurate estimation of incoming tonnage using a simple and easy to use model. Then, the easiest way for this person to determine the number of tons entering the facility in a given time period is to use the Simple Model. To use the Simple Model the following pieces of information are needed:

1. Truck or Vehicle Types Entering the Facility
2. Capacity of Trucks or Vehicles
3. Percent of Capacity Utilized
4. Average Density of Waste in each Truck Type

To obtain the first set of information it is necessary to have someone stationed at the facility entrance recording the type of vehicle entering, its capacity, and percent full, or to set up a system where the drivers would record this information themselves and put it in a common collection box. The driver is often the best source of information as to type of vehicle, capacity, and especially percent full. The estimation of percent full is important to the accuracy of the estimations of the model. These estimates should be performed by trained and knowledgeable personnel. The accuracy calculated for the model indicates that drivers of refuse collection equipment provide accurate estimates of percent of full capacity. As mentioned in Section 1, the error of the Simple Model based on field verification (where percent of capacity was reported) can be expected to be in the range of 8% to 14%.

Once the data is collected, the next step is to input the data into the Simple Model spreadsheet (e.g., as illustrated on page B-13). The first column allows the user to number the entry, i.e., 1, 2, 3. The second column asks for truck type. In this column it is essential that the proper code is entered for each truck since the model depends on recognizing the truck code in that cell and calculating by the correct in-truck density value. The third column requests that the volumetric capacity of the vehicle be entered in units of cubic yards. The fourth column requires the user to input the data describing how full the truck is as it enters the facility, i.e., for a 20-cu yd vehicle filled to 15 cu yd, 75% is entered in this column. After the user completes all the data input, the model calculates the estimated weight in the truck in the fifth and final column. The equation the model uses in doing this is as follows:

estimated in-truck weight = truck density value x truck capacity x percent full

Looking specifically at the Rural Landfill example, the following text examines four data entries and provides a step-by-step process for using the Simple Model. These data entry lines have been highlighted on the spreadsheet to make it easier to follow the example.

First, in the Rural Example, it is assumed that there are four types of vehicles entering the facility: mini-pickups, full-sized pickups, rear loaders, and front loaders. The legend to the model provides the average in-truck density values which are used to estimate the waste entering the facility. If one desires to change these values based on information which is specifically relevant to a particular landfill, one enters the new value in the value column of the legend box next to the appropriate truck code.

In the first example, enter the entry number (1), the truck type (i.e., RL), the truck capacity (20 cu yd), and the percent of the capacity utilized by the incoming truck (i.e., 100%). The model computes the weight of the waste in the vehicle. The following four equations describe the calculations for entries 1, 14, 26, and 39.

1. RL(525 lb/cu yd) x (20 cu yd) x (100%) = 10,500 lb

14. FL(480 lb/cu yd) x (30 cu yd) x (75%) = 10,800 lb

26. FP(316 lb/cu yd) x (2.5 cu yd) x (100%) = 790 lb

39. MP(294 lb/cu yd) x (1.25 cu yd) x (100%) = 367.5 lb

Table A3-1 Recommended In-Truck Density Values for Key Waste Sources and Truck Types in California

Waste Source/Truck Type	In-Truck Density (lb/cu yd)
Residential Rear Loaders	525
Commercial Front Loaders	480
Commercial Roll-Off Compactor	680
Industrial Roll-Off	400

Table A3-2 Marin County, California Field Study: Density Values for Self Haul Vehicles

Type of Hauler	Waste Category	Vehicle Type	Sample Size	Average Density lb/cy	% Error (a)
Residential					
	Yard Waste	**Mini-pickup**	**5**	**273.5**	**57.5**
	Misc.	**Mini-pickup**	**16**	**244.8**	**19.3**
	Yard Waste	**Full Size Pickup**	**7**	**193.3**	**35.2**
	Misc.	**Full Size Pickup**	**8**	**742.1**	**49.3**
Commercial					
	Misc.		**4**	**376.7**	**31.5**
	Yard Waste	**Mini-pickup**	**16**	**293.7**	**27.0**
	Misc.	**Mini-pickup**	**6**	**533.3**	**39.1**
	C & D	**Mini-pickup**	**5**	**574.4**	**33.8**
	Yard Waste	**Full Size Pickup**	**24**	**315.6**	**22.0**
	Misc.	**Full Size Pickup**	**9**	**295.0**	**39.9**
	Dirt/Rubble	**Full Size Pickup**	**8**	**2660.9**	**26.1**
	C & D	**Full Size Pickup**	**9**	**472.7**	**31.3**
	Yard Waste	**Flat Bed**	**4**	**354.0**	**93.2**
	Misc.	**Flat Bed**	**5**	**683.2**	**90.4**
	C & D	**Flat Bed**	**5**	**498.4**	**50.7**
	Yard Waste	**Dump truck**	**12**	**355.9**	**43.7**
	Misc.	**Dump truck**	**4**	**298.3**	**65.7**
	Dirt/Rubble	**Dump truck**	**3**	**1083.1**	**16.0**
	C & D	**Dump truck**	**4**	**623.6**	**111.2**

a) at 90% confidence

Figure A3-1
IN-TRUCK DENSITY MODEL:Simple Model
A Rural County: 50% Self Haul, 25% Rear Loaders, 25%Front Loaders(Commercial)

	Legend	Value
Truck Type	Code	lb/cu yd
Mini Pick-up	MP	294
Full Pick -up	FP	316
Rear Loader	RL	525
Front Loader	FL	480
Compacting Roll-Off	CRO	680
Open Compactor Top Roll-Off	OTR	400

Input Information In
The First Four Columns

Entry #	Truck Type	Capacity (cu yd)	% Full	Simple Model Estimated Weight (lb)
1	RL	20	100%	10,500
2	RL	20	75%	7,875
3	RL	25	60%	7,875
4	RL	18	75%	7,088
5	RL	16	100%	8,400
6	RL	15	80%	6,300
7	RL	18	100%	9,450
8	RL	10	100%	5,250
9	RL	18	80%	7,560
10	RL	20	80%	8,400
11	RL	15	100%	7,875
12	RL	20	100%	10,500
13	RL	25	80%	10,500
14	FL	30	75%	10,800
15	FL	30	95%	13,680
16	FL	35	50%	8,400
17	FL	35	60%	10,080
18	FL	39	80%	14,976
19	FL	39	100%	18,720
20	FL	39	25%	4,680
21	FL	40	100%	19,200
22	FL	39	100%	18,720
23	FL	35	100%	16,800
24	FL	2.5	90%	1,080
25	FL	40	90%	17,280

Simple

Entry #	Truck Type	Capacity (cu yd)	% Full	Model Estimated weight (lb)
26	FP	2.5	100%	790
27	FP	2	75%	474
28	FP	2.5	60%	474
29	FP	2.5	80%	632
30	FP	2	62%	392
31	FP	2	50%	316
32	FP	2	100%	632
33	FP	2.5	100%	790
34	FP	1.75	100%	553
35	FP	2.5	20%	158
36	FP	2	75%	474
37	FP	2	100%	632
38	FP	2	100%	632
39	MP	1.25	100%	368
40	MP	1.5	66%	291
41	MP	1.25	80%	294
42	MP	1.5	20%	88
43	MP	1.5	100%	441
44	MP	1.5	100%	441
45	MP	2.5	40%	294
46	MP	1.75	86%	442
47	MP	1.5	100%	441
48	MP	1.5	100%	441
49	MP	1.25	100%	368
50	MP	1.5	100%	441

Daily Total Weights **273,287**

Conversion Factor Study: In-Vehicle and In-Place Waste Densities

Data for this example was drawn from three sources, Redwood Sanitary Landfill, Bee Canyon Landfill, and self-haul data from the Marin County Transfer Station.

APPENDIX A-4: TRENCH VOLUME METHOD FOR DETERMINING REMAINING LANDFILL CAPACITY (FOR TRENCH-TYPE LANDFILLS)

Landfill trenches resemble inverted roads, so the volume formula and computations are based on cross-sections (as opposed to contours for other landfills), similar to conventional road design. In other words, volume is determined by multiplying the length of the trench by the area of the cross section of the trench. Since the floors of trenches typically slope upward at the ends, to allow for equipment access, the volume of the ends should be calculated separately.

The following general formula can be used to calculate total trench capacity, if the cross-sections are consistent:

$$V_{Total} = V_{Ends} + V_{Center}.$$

Where V_{Total} = the total volume of the trench;
V_{Ends} = the volume of the sloped ends; and
V_{Center} = the volume of the main portion of the trench

•V_{Ends} (Volume of the combined trench ends)

This is typically calculated for each end by multiplying the length of the sloped end, commencing from the beginning of the slope up to original grade, by the cross-sectional area of the trench, then dividing by two. The volume of the two ends is then added to give the answer for V_{Ends}.

•V_{Center} (Volume of the center portion of the trench)

To calculate the volume of the main body of the trench (V_{Center}), use which ever of the following formulas applies:

- With vertical sides: (V_{Center} = Length x $Factor_{Vertical}$) OR
- With sloped sides: (V_{Center} = Length x $Factor_{Sloped}$);

where: $Factor_{Vertical}$ = rectangular cross-sectional area of the trench
= (depth) x (base width)

$Factor_{Sloped}$ = trapezoidal cross-sectional area of the trench
= (depth) x (.5(base width + top width))

APPENDIX B: METHODOLOGY FOR PERFORMING LANDFILLED DENSITY STUDIES

The method presented on the following pages for determining the density of landfilled material is taken from the Board report *Conversion Factor Study In-Vehicle and In-Place Waste Densities*, recently adopted by the Board (CalRecovery, et al, 1993). This method provides a relatively simple and accurate means for estimating in-place density, based on several operating parameters.

APPENDIX B

IN-PLACE DENSITY MODEL

INTRODUCTION

General

This section of the report presents the methodology used to produce a mathematical model of in-place landfill density using primarily density data available from field studies. The development of the model is based on empiricism as well as certain fundamental governing principles. The model is presented both graphically and in terms of mathematical formulations. The impact of varying several landfill operating parameters is also discussed.

This model can be applied to predict the in-place volume of a known quantity (tonnage) of waste on the basis of fundamental parameters of weight of landfill compaction equipment, number of passes, and slope of the landfill working face. The model can also be used to estimate delivered quantity from the change in landfill volume over a known period as a function of the aforementioned parameters.

In-place landfill density has been reported by various investigators. Reports have included information on the density of mixed solid waste in landfills based on one of two principal estimating techniques:

- Annual change in topographic contours of the landfill and annual tonnage delivered.
- Specific tests designed to determine density, which usually include one to three days' landfilling operation with survey of final contours and test tonnage.

Based on previous studies and a literature review, the fundamental parameters that govern in-place solid waste density were initially identified as including variables grouped according to the following list:

A. MSW related parameters, including:

  - weight of waste delivered
  - composition
  - moisture content

B. Landform of the waste pile, including:

  - slope
  - waste depth

C. Equipment-related parameters, including:

  - compaction method
  - type of compaction equipment
  - number of equipment passes
  - equipment weight
  - pressure at the point of contact

MSW-Related Parameters

Of the MSW factors, most previous studies report the composition of the waste under consideration in only the most general terms. For example, Collord's December 1979 Orange County tests indicate that the test was conducted with "Group 2 wastes."[1] Two years later, at Stanislaus County, Collord reports commercially-collected "Group 2 wastes" with minor amounts of "Group 3" but with construction and demolition, tires, woody yard waste, septage, drilling muds, and cannery waste excluded. No water was added in any of the tests conducted by Collord.

In addition to the data reported by Collord, more recent data from studies conducted in Connecticut, Rhode Island, and Vermont are less specific with respect to composition. Waste is reported as "mixed waste, residential waste, or commercial waste" only.

Landform Parameters

Of the landform or topographic factors, isolation of the degree to which slope and waste depth affect in-place density has not been reported with great care in the previous investigations. Where slope has been reported, it has most commonly referred to the maximum slope that the inclined sides of the waste pile are permitted to achieve. Thus, in cases where the in-place density has been reported on the basis of annual data, as in New Milford, Connecticut and Johnston, Rhode Island, the slope should be understood to reflect the general sideslopes of the fill and not the density achieved by compacting directly on such a slope.

Based on in-house information and discussions with landfill managers, waste depth appears to influence compacted density in two ways. Waste that is compacted against the base of a landfill may achieve a slightly higher density upon initial compaction relative to upper lifts. Two factors may contribute to this effect: the unyielding nature of the prepared landfill base and the absence of voids that remain in waste after compaction. Thus, a difference could be expected between the data from test cells (i.e., Vermont and Collord) and annual data from Rhode Island and Connecticut. This potential difference is discussed further in a later subsection.

A second influence of waste depth on density is the consolidation of the lower levels of waste that occurs over time as additional upper lifts are added. The effect of the additional weight that is added to the landfill can be substantial. For example, a large, privately operated New Jersey landfill that is currently more than 100 ft high has periodically shown only 5 ft of elevation change after the completion of a 10-ft lift because of consolidation of the lower waste layers. Since, however, the Board's stated objective in this study is the determination of waste density in the upper layers of landfills, no further consideration has been given to consolidation of lower landfill layers.

Equipment-Related Parameters

Of the equipment related parameters cited above, compaction method and type of equipment affects density most directly. Thus, landfills that place and compact waste using bulldozer-type tracked equipment typically achieve the lowest in-place density because of the low bearing pressure exerted by the equipment. This observation is supported by reference to the design of tracked equipment in general, i.e., that it is designed to float on the surface of soft soils to avoid sinking that would result from compression of the soils. Alternatively, landfills that employ specially designed compactors generally achieve higher in-place densities than do those using dozers. Wheeled compactors (designed to achieve high bearing pressures) are usually equipped with steel wheels with cleats. Cleats are advertised as creators of high pressure at the point of contact with the waste.

---

[1] The category "Group 2 wastes," as defined by the California Solid Waste Management Board, the predecessor agency to the CIWMB, includes mixed municipal solid wastes.

Equipment weight is most obviously the critical variable once equipment type is selected. As shown in a later subsection of this report, within certain limits, increasing machine weight results in higher densities. For each generic machine type (i.e., landfill compactor), a value can be determined that represents the upper limit of density that can be achieved.

The number of passes of the equipment over a given section of waste has been shown in the literature to affect density up to approximately five passes. Beyond five passes, it is likely that the impact and the cost of the passes by the equipment is not offset by the incremental increases in in-place density.

The following section presents the mathematical relationship of the variables to in-place densities of wastes compacted in a landfill.

IN-PLACE DENSITY MODEL

In this section we present a mathematical model combining three of the most important, easily quantified influences on the in-place density of landfilled waste: weight of the compacting equipment, surface slope, and number of passes made by the compacting equipment. (Model parameters are estimated based on previously published quantitative field test data.) All three factors influencing in-place density are combined in a single equation at the end of this subsection, and are presented in an easy-to-use spreadsheet model. The following text describes the development and utilization of the models. Further discussion and examples of use are given in Appendix.

Model Description

Machine Weight

Figure B-1 and Table B-1 present the available information relating the weight of compacting equipment to the in-place density. The data are based on five passes by the vehicle over waste on a horizontal surface, i.e., zero slope. The data point at a machine weight of zero represents the uncompacted in-place density of 325 lb/cu yd, as reported in the literature (Diaz, Savage, Golueke, 1982).

As shown in Figure B-1, in-place density initially rises rapidly with machine weight; however, the rate of increase tapers off, and around 60,000 lb a plateau is reached. Such saturation effects are often modeled in the scientific literature by a logistic curve of the form

$$(4) \qquad Y = a / (1 + be^{-cX})$$

where a, b, and c are positive constants, and e = 2.718... is the base of natural logarithms. As X becomes very large, Y approaches a. At X = 0, Y = a/(1+b). The third parameter, c, affects the curvature of the graph.

A logistic curve fitted to the data presented in Table B-1 is also presented in Figure B-1, with a = 1450, b = 3.5, and $c = 6.3 \times 10^{-5}$. That is, if Y is in-place density and X is vehicle weight in pounds,

$$(5) \qquad Y = 1450 / (1 + 3.5 \text{ x } e^{-0.000063 \text{ x } X})$$

This suggests that as vehicle weight becomes large, in-place density (assuming five passes and zero slope) approaches 1450 lb/cu yd. Values for other vehicle weights can be calculated from equation (5) with a scientific calculator; equation (5) is also incorporated in the complete model presented below and in the accompanying spreadsheet model.

Slope

Either compacting waste on a sloping ground surface, or compacting to a sloping finished grade, results in a lower in-place density than compaction on a level surface. Modeling of the effect of slope is a simple matter of physics. On a level surface compaction depends on vehicle weight, as described above. However, on a slope, the effective weight of the compacting vehicle is reduced.

Compaction depends to a large degree on the weight that is exerted in a direction perpendicular to the working face of the landfill. If the surface is sloped at an angle A to the horizontal, then

(6) Effective weight perpendicular to surface = cos(A) x machine weight

where cos(A), the cosine function of trigonometry, is equal to 1 when A=0. A schematic representing the compaction conditions on a sloped surface is shown in Figure B-2. Values of cos(A) are shown for a number of angles in Table B-2.

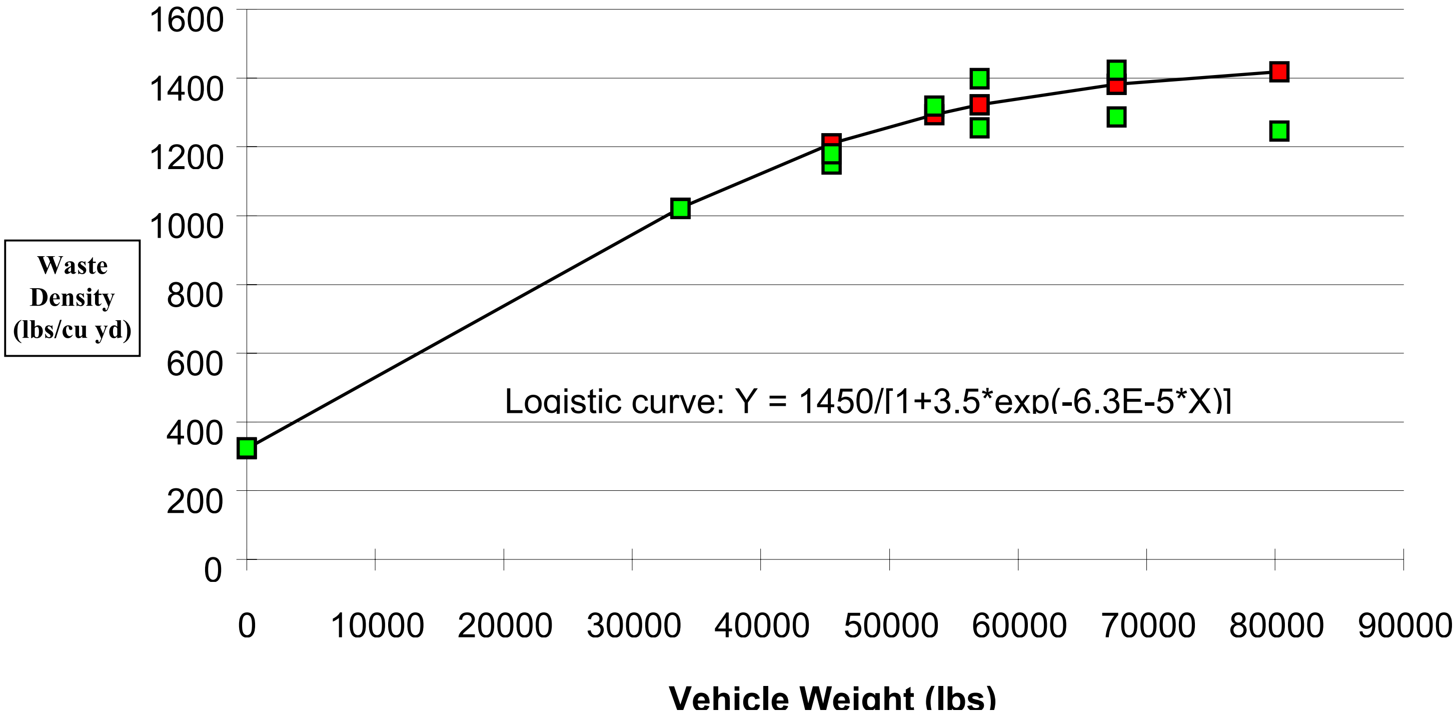


Figure B-1 Machine Weight vs. In-Place Model (Predicted) Data and Field (Observed)

Table B-1 Machine Weight and Density Data

Machine	Machine Weight lb	Density lb/cu yd	Notes	Reference
Slope: Flat				
Number of Passes: 5[a]				
Deere JD646-C	33746	1020.8		Collord, 1980a
Cat816B	45477	1151.1	Cat Blades	Collord, 1981
Cat816B	45477	1180.05	Caron Teeth	Collord, 1981
Rexnord 3-70	57000	1255.63		Collord, 1979
Rexnord 3-70	57000	1398.77		Collord, 1979
Cat826C	67670	1287.58		Collord, 1980b
Cat826C	67670	1423.57		Collord, 1980b
BomagK701	80325	1246.77		Collord, 1980b
Cat966	53490	1318		New Milford, Waste Management, Inc.1991

---

[a] Assumed to be five passes based on analysis of data.

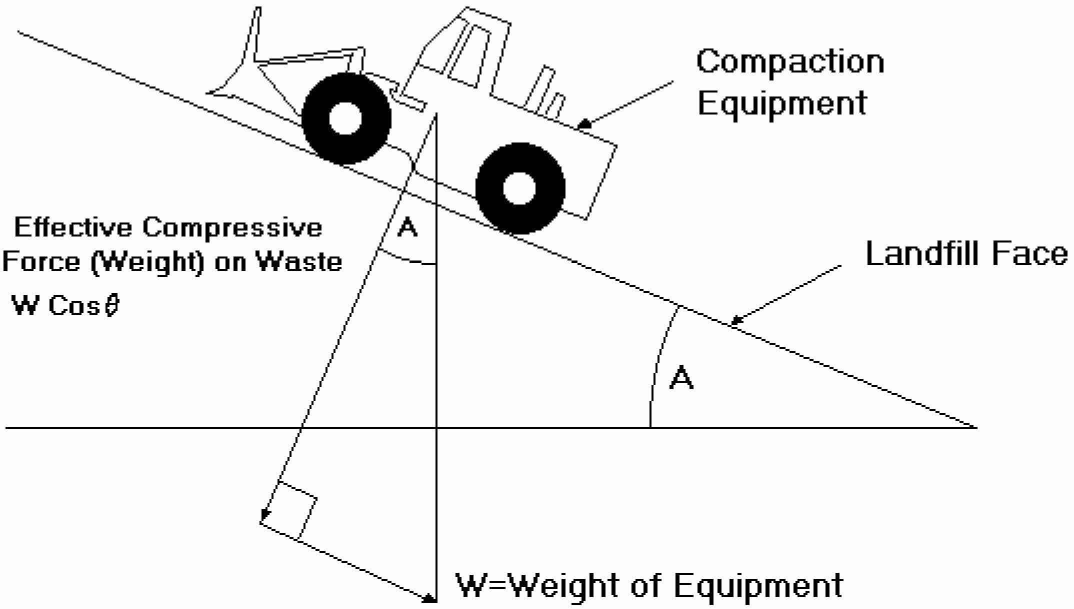


Figure B-2 **Compaction of Waste on a Sloped Surface**

Table B-2 Machine Weight Conversion Factors For Various Landfill Slopes

Slope	Conversion Factor (cos (A))
1%	1.00
5%	1.00
10%	1.00
5:1	0.98
4:1	0.97
3:1	0.95
2:1	0.89

At large angles, slippage of equipment on the surface will occur. This reduces the force exerted by the equipment on the surface by even more than equation (6) indicates. However, lacking empirical data on equipment slippage, equation (6) is used in the model. The implication of equation (6) is that vehicle weight, as used for example in equation (5), should be replaced by an effective weight = cos(A) x actual weight.

Number of Passes

Based on the literature (Waste Age, 1981), the number of passes made by landfill compacting equipment over waste affects its in-place density in a pronounced manner. Table 2-3 and Figure 2-3 illustrate this impact. As the number of passes increases, in-place density at first increases rapidly.

This relationship again suggests a logistic curve, based on equation (4). A logistic curve fitted to the data in Figure 2-2, with Y = index of in-place density (5-pass density = 100), and X = number of passes yields the equation:

$$(7) \qquad Y = 116 / (1 + 3 \times e^{-0.6 \times X})$$

The limit as the number of passes becomes large is 116% of the 5-pass density. As with equation (5), this can be estimated with a calculator; it is also incorporated into the general model presented in Section 3 and is included in the spreadsheet formulation.

Combining equations (5) and (7) and re-defining the set of parameters as:

D = in-place density in lb/cu yd

P = number of passes

W = weight of vehicle in pounds

A = slope angle of the surface or finished grade

the equation for in-place density becomes:

$$(8) \qquad D = 1680 / [(1 + 3.5 \times e^{-0.000063 \times W \times \cos(A)})(1 + 3 \times e^{-0.6 \times P})]$$

The numerator, 1680, is the estimated maximum achievable density via vehicle compaction alone. It is the product of 1450, the limit for 5 passes with heavy vehicles according to equation (5), multiplied by 116%, the maximum increase over the 5-pass density achievable with repeated passes according to equation (7).

Equation (8) does not hold in a physical sense in the limit where either W or P is zero, i.e., if there is no vehicle or number of passes is equal to zero. Equation (8) holds for positive values of W and P. In general equation (8) should apply to those situations where the number of passes is in the range of 2 to 9, the weight of the compaction equipment is 30,000 lb to 90,000 lb, and the slope of the working face is in the range of 6:1 to 2:1.

Table B-3 Effect of Equipment Passes Over Waste on In-Place Density (Flat Slope)

Number of Passes (p)	Density at Pass (p) D(p) (lb/cy)	Change in Density D(p) - D(p-1) (lb/cy)
0	350	-
1	565	215
2	775	210
3	970	195
4	1125	155
5	1225	100
6	1300	75
7	1350	50
8	1375	25
9	1395	20
10	1405	10

Reference: Waste Age, September 1981, Page 66.

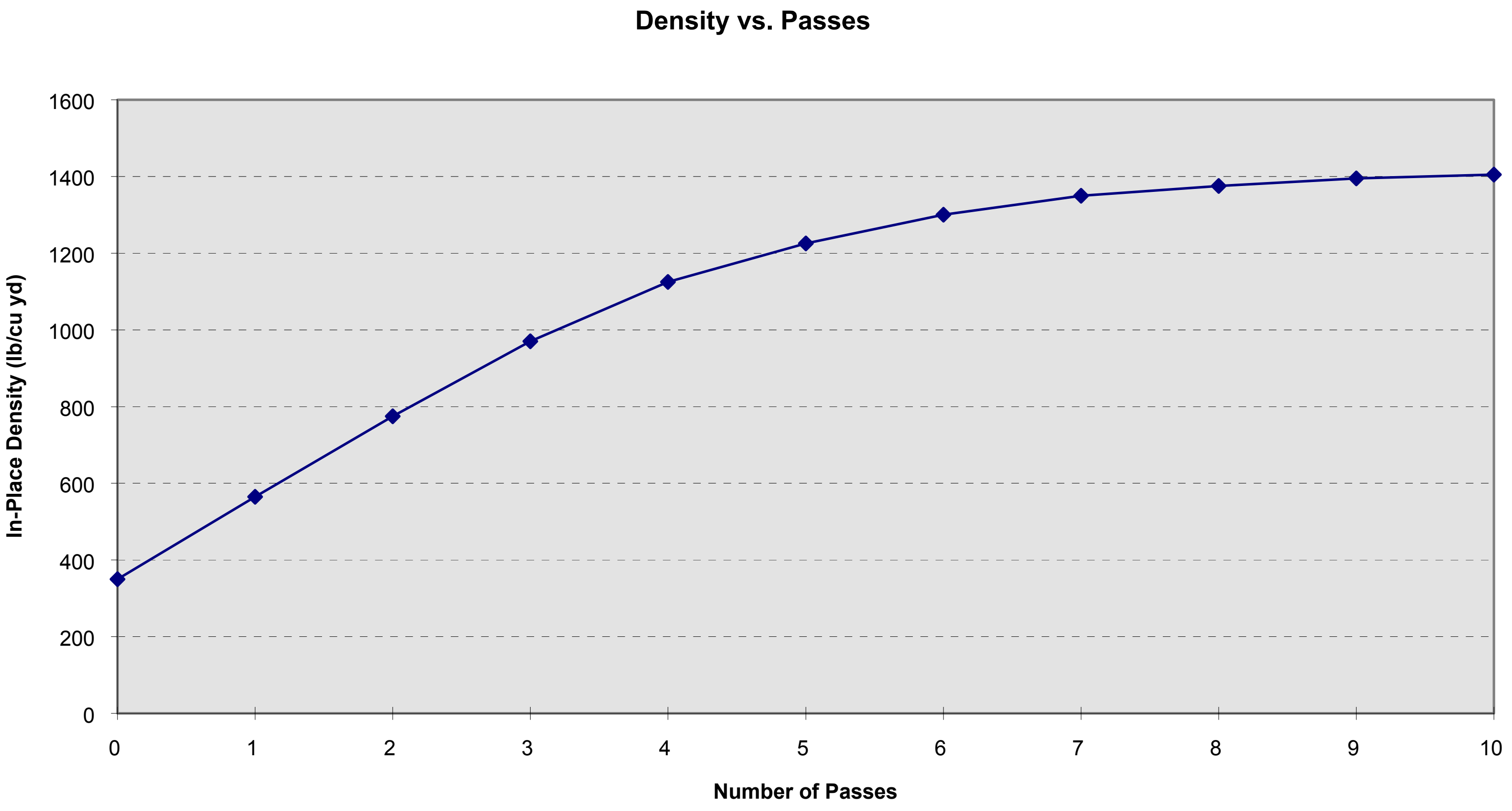


Figure B-3 Influence of Number of Passes on In-place Density

(zero slope)

Notice, also, that equation (8) does not allow for variation in the composition or as-delivered density of the waste stream. It was estimated based on published data, assuming average or default values for waste stream composition and density. Two further extensions of the model, allowing its integration with the in-truck model, and allowing for variation in the incoming waste stream composition, are presented in Section 3.

After the in-place density (in lb/cu yd) has been calculated, the user can use the density value to compute the volume of landfill occupied by a given weight of solid waste, i.e., volume (in cu yd) of a specified landfill space occupied = weight of solid waste (tons) divided by average in-place density (in lb/cu yd) multiplied by 2000 lb/ton.

Data Collection and Model Testing

A telephone survey of California landfills was conducted for the purpose of acquiring in-place compaction data. The landfills which reported on their compaction equipment, together with their responses, are listed in Table B-4. The 31 reported values for in-place density are reported in Table B-4. Data were incomplete or inferred from partial information for many of the reporting locations. Eighteen of the data were judged representative for the purpose of checking the validity of the model. As a point of information, the reported in-place densities were almost always rounded off to the nearest 100 lb/cu yd, introducing rounding errors of up to 5%.

For the 18 points, the average reported actual density was 1165 lb/cu yd, while the model represented by equation (8) predicted an average of 1375 lb/cu yd. The average error was 210, or 19%; the standard deviation of the errors was 181. A better fit can be obtained by modifying some of the parameters in equation (8) above.

A curve fit to the 18 points of data was performed in order to provide an alternative set of values of the constants used in the in-place density model. The alternative values are listed in the spreadsheet for the landfill compaction model described in Appendix (Examples of the Three Models). The alternative values of course yield more accurate results than the default values. The predicted in-place densities using the alternative values of the constants are compared to the reported densities in the results section of Appendix (Test Results of the Three Models). The average error using the in-place model with the alternative constants is about 9%. The alternative values are used in the in-place density modeling calculations in Appendix. However, the default values are included for reference in the model. (The default values represent curve fit constants based on rigorous landfill compaction tests.) The alternative values have been selected for use since they provided greater accuracy in the estimated in-place density based on the field survey than do the default values.

Table B-4. Summary Data from California Landfill Compaction Survey

	Compaction Equipment				Slope	In place density
LF - County	Model	Year	Weight	Passes	of Cell	(lb/cu yd)
Durham Rd - Alameda	D9H dozer	n/a	74,900	5	2.75:1	1350
Durham Rd - Alameda	Cat 826C			5	2.75:1	
Durham Rd - Alameda	I/R 750LF			5	2.75:1	
Altamont - Alameda	D9L dozer	n/a	109,200	5	3.0:1	1500
Altamont - Alameda	Cat 826C			5	3.0:1	
Amador Cty Sanitary - Amador	Cat D8	1968		3		
Rock Creek - Calaveras	Bomag BC601RB	1990	66,230	5	3.5:1	1200
West Contra Costa- Contra Costa	Cat 826B	1972	66,230	3.5	3.0:1	1000
West Contra Costa- Contra Costa	Cat 826C	1981		3.5	3.0:1	
West Contra Costa- Contra Costa	Cat 826C	1983		3.5	3.0:1	
West Contra Costa- Contra Costa	Intl TD25 dozer	1986		3.5	3.0:1	
West Contra Costa- Contra Costa	Kom 155A dozer	1984		3.5	3.0:1	
West Contra Costa- Contra Costa	Kom D65 P	1984		3.5	3.0:1	
West Contra Costa- Contra Costa	Kom TD 15E	1987		3.5	3.0:1	
Acme - Contra Costa	Rex	1971				1250

Table B-4. Summary Data from California Landfill Compaction Survey

	Compaction Equipment				Slope	In place density
LF - County	Model	Year	Weight	Passes	of Cell	(lb/cu yd)

Union Mine - El Dorado	Cat 816	1979	39,800	9	slope : "flat"	1200
Union Mine - El Dorado	Cat 826	1985		9	flat	
Chateau Fresno - Fresno	Cat 826			4.5	3.0:1	
American Ave - Fresno	Cat 826	1986	66,845	5	3.5:1	1200
Orange Ave - Fresno	Rex 350				flat	
Orange Ave - Fresno	Cat D9				flat	
Chestnut Ave - Fresno	Cat 826			4.5	3.0:1	
China Grade - Kern	Cat 826C	n/a	66,845	3.5	3.0:1	1200
China Grade - Kern	Cat D8K dozer	n/a		3.5	3.0:1	
China Grade - Kern	Kom D355 dozer	n/a		3.5	3.0:1	
China Grade - Kern	Cat 637D scraper	n/a		3.5	3.0:1	
Arvin Sanitary - Kern	Cat D9H dozer	n/a	74,900	3.5	3.0:1	1200
Arvin Sanitary - Kern	Cat 826B			3.5	3.0:1	
Arvin Sanitary - Kern	Cat 623B scraper			3.5	3.0:1	
Hanford Sanitary - Kings	I/R LS750	1987	79,000	6	3.0:1	1200
Western Regional - Placer	CAT826	n/a	66,845	5	3.0:1	1100
Highgrove Sanitary - Riverside	I/R LF750 300hp	1989	81,000	2.5	3.0:1	1200

Table B-4. Summary Data from California Landfill Compaction Survey

	Compaction Equipment				Slope	In place density
LF - County	Model	Year	Weight	Passes	of Cell	(lb/cu yd)
Western Regional - Placer	CAT826	n/a	66,845	5	3.0:1	1100
Highgrove Sanitary - Riverside	I/R LF750 300hp	1989	81,000	2.5	3.0:1	1200
El Sobrante - Riverside	Cat826C	1986	66,845	7	2.0:1	1224
El Sobrante - Riverside	REX390	1990	66,845	7	'2 to 1	
Sacramento County - Sacramento	Cat826	1991	66,845	4	5.0:1	1200

Sacramento County - Sacramento	Cat826	1988		4	'5 to 1	
Sacramento County - Sacramento	Cat826	1986		4	'5 to 1	
Sacramento City - Sacramento	Cat826	1983	66,845	6	0.13:1	1100
Milliken Sanitary - San Bernardino	Cat 826 w/spikes		66,845	6		1000
Colton Refuse - San Bernardino	Cat826	n/a	66,845	6	3.0:1	1000
Miramar - San Diego	Cat826	1988	66,845	2	3.0:1	1280
Miramar - San Diego	D9Trak Dozer	1988	66,845	2	3.0:1	
North County - San Joaquin	Cat826	1988	66,845	6	3.0:1	1100
Harney Lane - San Joaquin	Cat826	1988	66,845	6	2.0:1	1100
City of Paso Robles - San Luis Obispo	D9 dozer		66,845		'2 to 1	
Tajiquas - Santa Barbara	Cat826C	1989	66,845	9	2.5:1	1275

Table B-4. Summary Data from California Landfill Compaction Survey

						In place
	Compaction Equipment				Slope	density
LF - County		Year	Weight	Passes	of Cell	(lb/cu yd)
Tajiquas - Santa Barbara	Model	1990	84,900	9	2.5:1	1275
City of Lompoc - Santa Barbara	D9H doz w/caron	1988	81,000	4.5	3.0:1	1000
Newby Island - Santa Clara	Ingersoll	1988	66,845	5	3.0:1	1750
Buena Vista - Santa Cruz	Cat826	1990	74,900	3.5	3.0:1	1050
Buena Vista - Santa Cruz	D9 dozer	1990		3.5	'3 to 1	
Potrero Hills - Solano	Cat826C	1983	66,845	3.5	3.0:1	1300
Potrero Hills - Solano	C4 826C	1989		3.5	3.0:1	
Central - Sonoma	C5 826C	1990	66,845	5	3.0:1	1200
Central - Sonoma	Cat826	1990		5	3.0:1	
Fink Road - Stanislaus	Cat826	1980		5	3.0:1	1000
Tuolumne Cty - Tuolumne	Cat	n/a	39,800	5	3.0:1	1200
Simi Valley - Ventura	Cat816	1989	66,845	5	3.0:1	1200
U.C. Davis - Yolo	Cat 826	1982	42,230	6	3.0:1	898

APPENDIX C: METHODOLOGY FOR DETERMINING REFUSE:SOIL RATIOS

Many landfill operators assume their refuse:soil ratio is based on the required depth of daily and intermediate cover and the depth and area of refuse filled daily and within each area requiring an intermediate cover. The problem with such an assumption is that it does not account for variations in soil depth required to cover an uneven surface, nor for the soil that sifts down into the interstices between refuse components, nor for the voids in the filled materials. Several landfill operators interviewed commented on their experience assuming that their refuse to soil ratio was 4:1 or 5:1, only to find out after tracking the amount of soil used that the true ratio was 2:1 or even 1:1; one landfill owner discovered they were achieving a ratio of .9:1, in other words, more airspace was being used for soil than for refuse! Obviously, such disparities between actual and assumed use of soil as a cover material can greatly distort an assessment of remaining capacity.

Because of the basic properties of soil when used as a material to cover refuse, the most accurate means of measuring its use is to track the amount of material being excavated or emplaced, rather than trying to survey the material after it is in-place. Tracking may be accomplished at the borrow site, at the stock-pile site, or by counting the number of vehicle loads of soil being applied to the site, and multiplying this number by the average volume of the loads. Since the density of soil changes between its undisturbed condition, its condition after being excavated, and its condition after being landfilled and compacted, it is necessary to develop and apply soil swell or shrinkage factors, depending on where in the cycle of excavation and emplacement the volume of soil is calculated. This factor will be different for different soils, and may be accurately determined through standard laboratory tests, or by a qualified geotechnical engineer.

To determine the refuse:soil ratio, the density of in-place refuse should already be known (see Appendix B). A time frame for the test should be established (at least one month). Over the time frame, the total weight of refuse landfilled should be tracked and converted to volume, and the total volume of soil used to cover the refuse should also be tracked. The refuse:soil ratio is then determined by dividing total volume of refuse landfilled by the volume of soil used.

More detail on measuring soil follows.

SOIL MEASUREMENT

The volume of soil is more reliably estimated than that of refuse, because of soils' relative homogeneity. Several estimation points, described below, are possible for soils. A landfill placement compaction factor (in-place density) for the soil is needed in every instance. The same hauling-vehicle-to-in-place compaction factor should be usable for all of the measurement scenarios described below, since hauling is common to all scenarios and only one method relies on hauling volume for measurement.

Undisturbed volume measured at the source

The undisturbed (virgin) state is the most dense condition in which any soil is likely to be found. A virgin-soil swell factor to estimate the "fluffing" effect from initial excavation will be needed. The volume removed is typically measured using before-excavation and after-excavation surveys, mapping, and computation of the borrow area. Laboratory tests of undisturbed soil sample cores can provide a typical density for the undisturbed soil.

In-place volume measured at the stockpile

Stockpiled soil is measured similar to undisturbed soil with some degree of recompaction likely to have occurred during stockpiling and subsequent natural settlement. A stockpiled-soil swell factor to estimate the "fluffing" effect from re-excavation will be needed. The volume removed is typically measured using before-excavation and after-excavation surveys, mapping, and computation of the affected area of the stockpile. Laboratory tests of undisturbed stockpile soil sample cores can provide a typical density for the stockpiled soil.

Volume and weight per load (as it is hauled)

The volume of soil in a typical load for each hauling vehicle (or vehicle type) is measured or estimated. The number of loads hauled to the landfill multiplied by the volume per load is the volume of soil hauled in that vehicle type. The sum for all vehicle types is the total in-vehicle volume of soil used. The weight can be determined by weighing typical loads (for a per load weight factor) or by laboratory tests to determine an in-vehicle density factor. The in-vehicle total volume(s) converted with in-vehicle weights or density factors will provide the total weight of soil used for conversion to in-place soil volume.

SOIL DENSITY

Laboratory property tests

Standard field sampling and laboratory testing methodology and protocols are followed to determine such parameters as wet and dry densities, moisture content, and structural characteristics.

Field test fills

By this method, a test fill is constructed of a known weight and in-truck volume of soil. Before and after surveys, mapping, and computations are done to define in-place volume. The placement and compaction techniques used should duplicate actual landfill practice and conditions as closely as possible.

APPENDIX D: FACTORS AFFECTING UTILIZATION OF REMAINING CAPACITY

Several physical characteristics of landfilled refuse, and several features of sanitary landfill design and operations, can affect the ability to use remaining permitted capacity, either limiting or increasing the amount of refuse that can be placed in the fill. These include settlement, slope stability, environmental monitoring and control equipment, decomposition, and the sequence of construction of the landfill.

Post-Placement Settlement

Refuse placed in landfills compacts over time. Density increases throughout the existence of the refuse fill, due to two primary factors: surcharging compaction (from fill material added on top of it) and refuse decomposition. The result of the densification is some degree of settlement throughout that period. The settlement produces additional fill space that may be usable. The rate of settlement can be projected using previously published methods (see Tchobanoglous, et. al., 1993). A third factor in settlement is compaction of the substrate. This can be predicted based on the original geotechnical investigation of the site.

The longer the filling of each segment of base area takes, the more fill space will be recovered through settlement. Re-use of the recovered space can be managed where sufficient depth remains to add overlying lifts, as long as already constructed final covers, drainage features, gas collection systems, and monitoring wells do not preclude such use. Cost savings or increased revenues from re-using recovered space may be negated, however, if the fill has significant environmental or stability problems. Such problems may be aggravated if overlaid by additional lifts.

Some older landfills may reach a "steady state" for a time, when the rate of settlement equals the rate of new filling. In some cases, the site may stay open for years beyond the expected closure date. While prudent landfill operation would preclude a reliance upon realizing ever-more capacity through settlement, settlement does occur in all landfills, and in some cases may significantly increase the amount of refuse that can be placed in the apparent remaining airspace.

Settlement may also become a factor in trying to construct a landfill to specified final grades. Since the sides and top of the landfill may sag with settlement, settlement must be taken into account in order to achieve a top and sides with particular slopes. With regulatory approval, some degree of over-build may be appropriate to anticipate settlement likely to occur during the life and the afterlife of the landfill, especially in areas where additional lifts to make up for settlement are not practical. Over-build may consist of a slight increase in side slope angle, or building a portion of the landfill slightly above the approved grade.

If a landfill becomes unstable, it may be impossible to build it to its approved height.

Side Slopes

Several features of landfill side slope construction can have significant effects on capacity. These include design requirements to build benches in the side slopes, settlement of slopes, slope steepness and construction, and slope irregularity.

Benching

Most landfill sideslopes are designed with benches if the fill depth exceeds fifty feet. Each bench, likely to be ten feet or more wide, decreases the potential capacity by deleting the potential fill volume that could have rested on that bench. Simple geometrics can be used to estimate the lost volume. Each succeeding bench removes a parallel "slice" of volume.

Settlement and Overlying Fill Surcharging

The volume reductions discussed in the preceding section will apply to the sideslopes, as well as the landfill top area.

Slope Steepness and Constructibility

In some instances, cutslopes are designed so steeply as to preclude use of field equipment to place and compact liner soils while operating parallel to the slope. Construction can proceed with that equipment by building a road-like cross-section wide enough to support the equipment working on the horizontal top surface, but the resulting liner thickness will far exceed design thickness and potentially waste valuable fill space. Most of the lost space can be recovered during construction by building in lifts and shaving the over-depth off (such as with an excavator) to reach design depth after compaction is completed. The removed liner soil can then be reused when the next liner lift is constructed.

Slope Irregularity

Irregular sideslopes, such as may result from excavation of very coarse or bedrock subsoils, will require over excavation with placement of smoothing backfill or underexcavation with placement of bridging and smoothing backfill (to protect liners). The latter situation (bridging and smoothing) will infringe on the design capacity, but is sometimes preferable to avoid costly excavation of solid rock or stabilization of loose rocks.

Design Features

Design features that take up airspace include liners, landfill gas collection systems, and landfill gas and leachate monitoring wells, roads, and other public works. Many older landfills were designed without environmental protection features, and some must retrofit them to meet current regulatory requirements. New expansion areas may also require more advanced engineering in order to be permitted. The volume of these features should be subtracted from the total remaining capacity calculation, along with earthworks.

Use of Alternative daily cover (adc)

Alternative daily covers that consume little or no landfill space are becoming increasingly popular, and are being used more widely each year in California. A switch to an ADC (which requires regulatory approval) will require a reassessment of the landfill's remaining capacity.

Finishing the Fill

Operating space must be provided to allow operations near the final surfaces. Some designs, such as pyramids and ridged tops, may be difficult to operate on in their final stages.