# Lecture 23

# Requirements for Landfill Closure and Monitoring

# Solid waste landfill closure under RCRA

**SUBTITLE D**

**6.2 FINAL COVER DESIGN**

**40 CFR §258.606.2.1 Statement of Regulation**

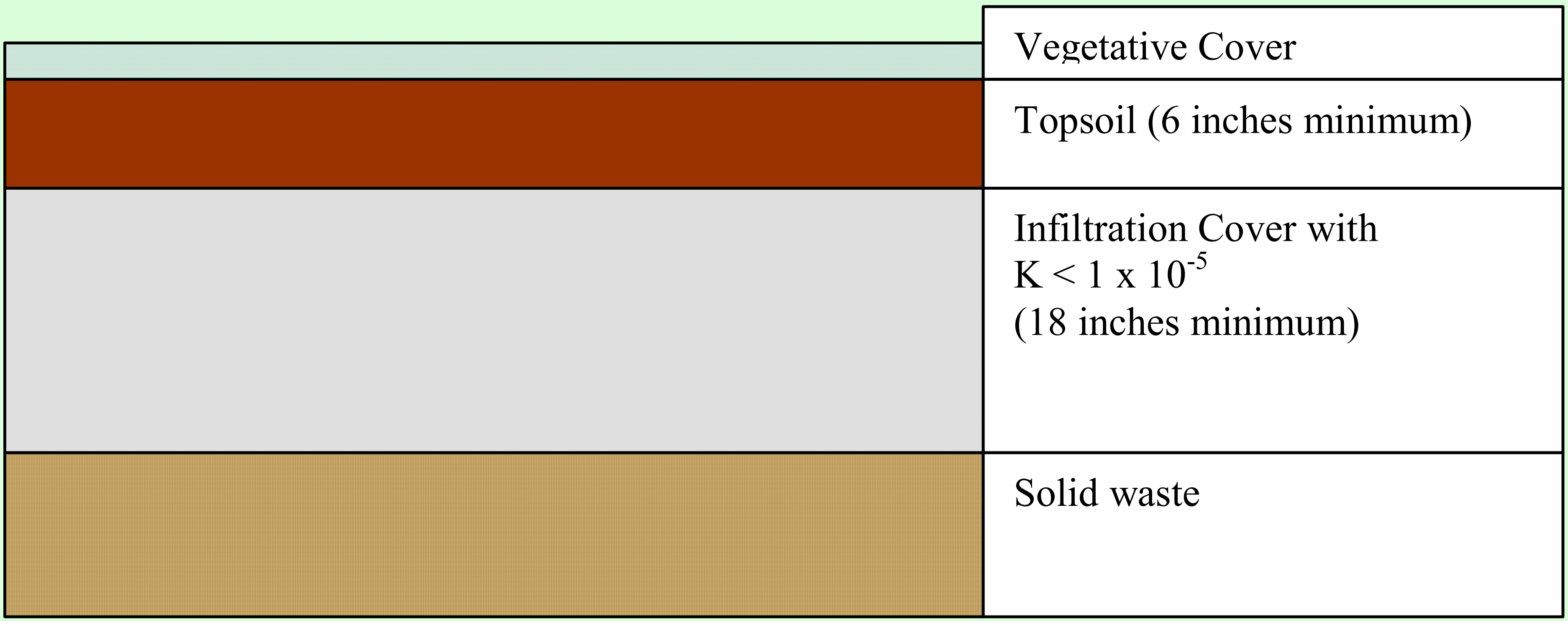
**(a) Owners or operators of all MSWLF units must install a final cover system that is designed to minimize infiltration and erosion. The final cover system must be designed and constructed to:**

**(1) Have permeability less than or equal to the permeability of any bottom liner system or natural subsoils present, or a permeability no greater than 1 x $10^{-5}$ cm/sec, whichever is less, and**

**(2) Minimize infiltration through the closed MSWLF unit by the use of an infiltration layer that contains a minimum of 18-inches of an earthen material, and**

**(3) Minimize erosion of the final cover by the use of an erosion layer that contains a minimum 6-inches of earthen material that is capable of sustaining native plant growth.**

# Solid waste landfill closure under RCRA



# Closure of hazardous waste landfill

Requirements for RCRA hazardous waste facilities (Subtitle C) are substantial:

- Includes multi-layer cap:
  - Low hydraulic conductivity soil/geomembrane layer
  - Drainage layer
  - Vegetation soil layer

Reference: U.S. EPA, 1991. Design and Construction of RCRA/CERCLA Final Covers. Report Number EPA/625/4-91/025. U.S. Environmental Protection Agency, Cincinnati, OH. May 1991.

# Closure of hazardous waste landfill

# Components of RCRA cap

- Vegetation layer
  - Provides vegetation growth
  - Provides erosion control
  - Reduces infiltration by plant transpiration
- Protection layer is optional but provides:
  - Freeze-thaw protection
  - Medium for root growth
  - Possibly rodent protection using cobbles

# Components of RCRA cap

- Drainage layer
  - Drains infiltrated water
  - Gravel or geonet
  - Designed based on results of HELP model (usually with factor of safety)
- Low-permeability barrier layer
  - Made of compacted clay, GCL, or composite
  - 60-cm (2-ft) clay liner is considered minimum
  - 40 mil minimum thickness

# Components of RCRA cap

- Gas vent layer
  - Usually coarse grained sand or geonet or thick geotextile
  - Provides stable layer for construction of barrier layer
- Maintenance issues (particularly for compacted clay liners):
  - Desiccation cracking
  - Freeze/thaw
  - Differential settlement of waste and tensile cracking of cover

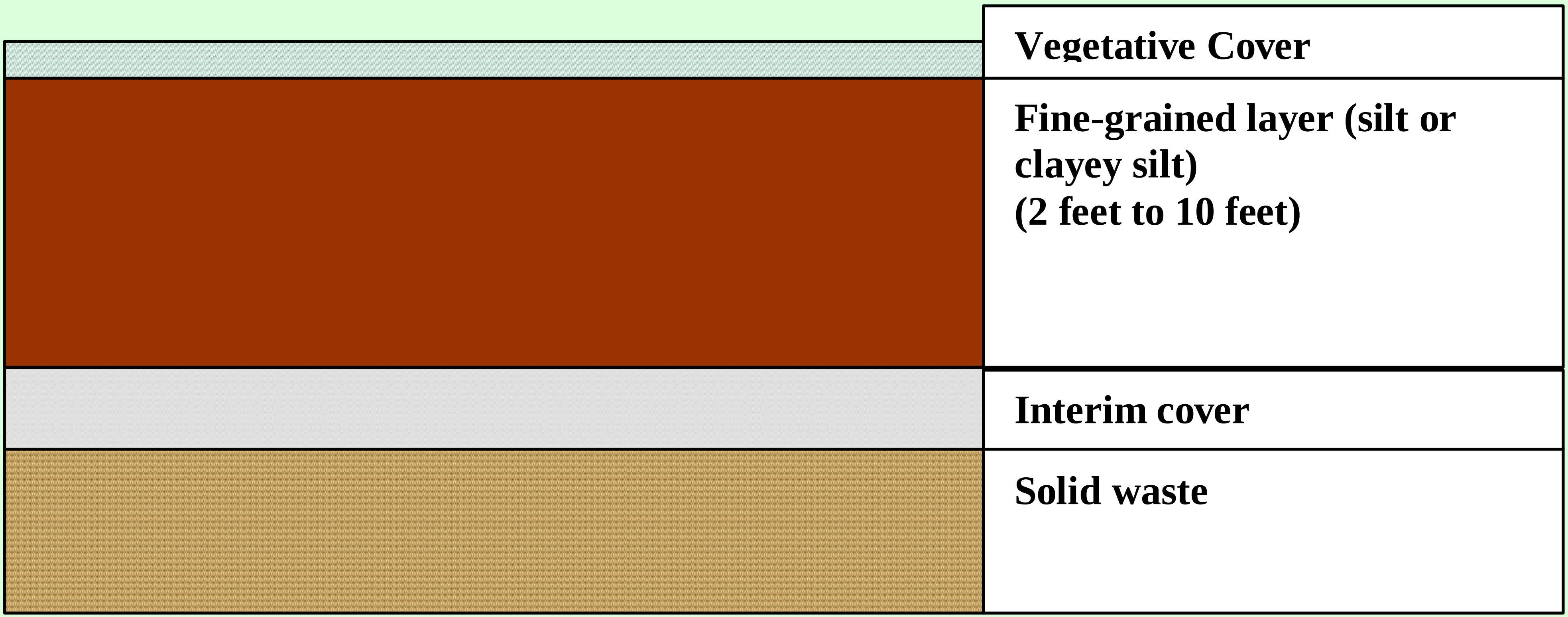
# Evapotranspiration landfill

Relatively new alternative for capping landfills in arid areas

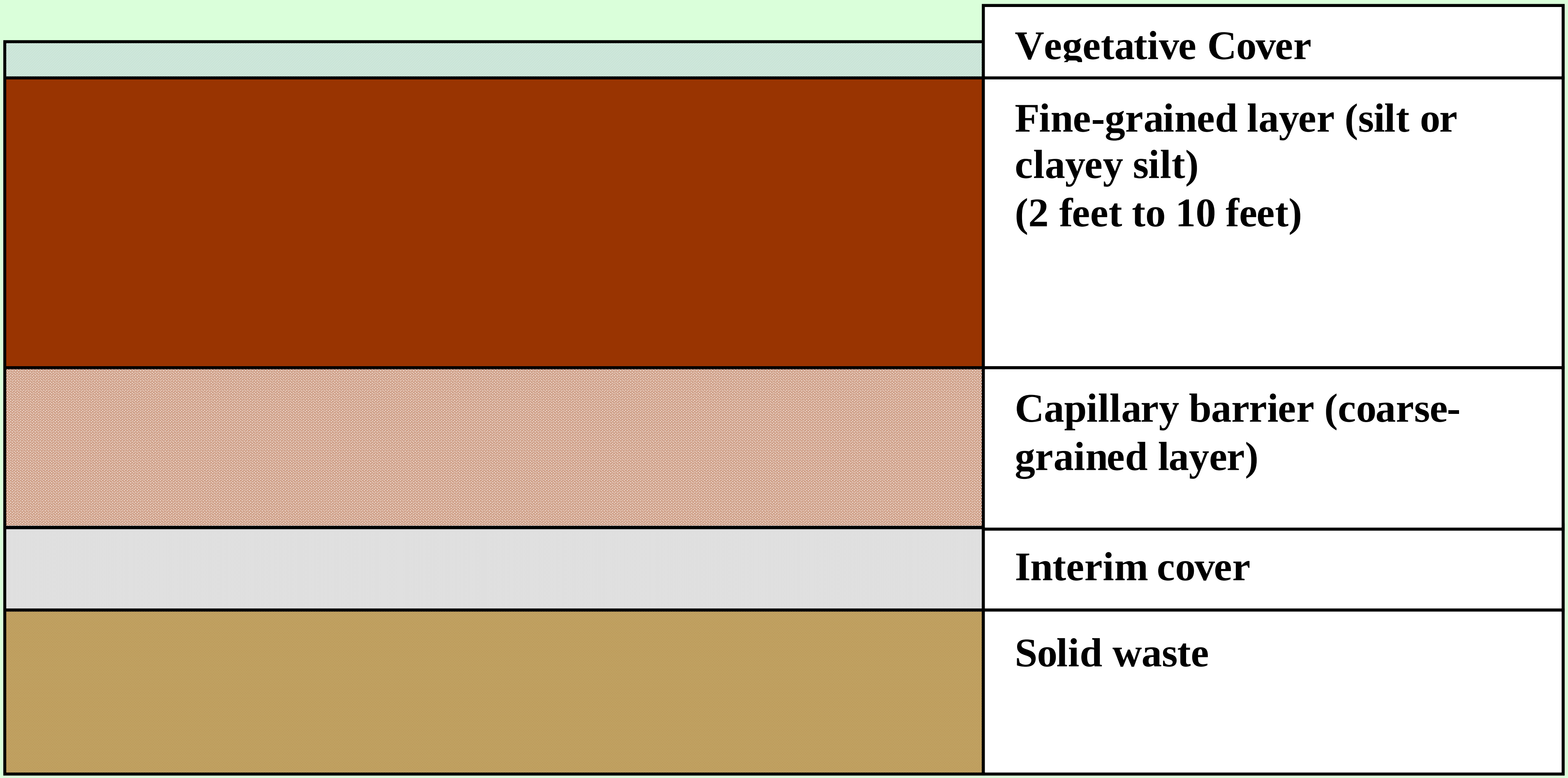
Relies on evapotranspiration to keep moisture out of waste

EPA Fact Sheet:
http://www.epa.gov/superfund/new/evapo.pdf

# Monolithic ET cover



# Capillary barrier ET cover



# ET cover design

Fine-grained layer stores water until evaporated or transpired

Capillary barrier minimizes downward percolation from fine-grained layer

Layers are designed using water-balance model like HELP to select proper soils and layer thicknesses for climate at the landfill

# Alternative Landfills Test Site

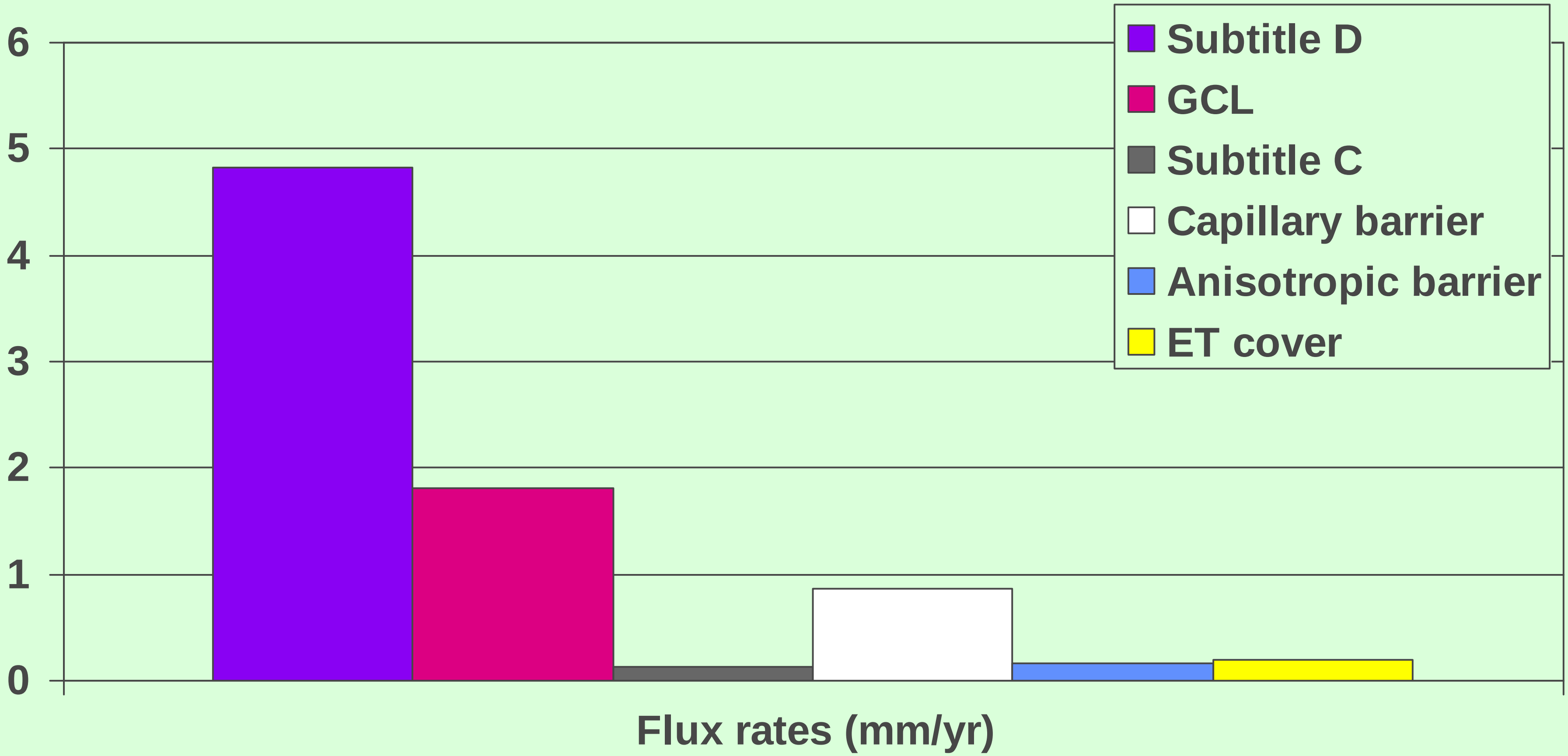
Source: DOE, 2000. Alternative Landfill Cover. Innovative Technology Summary Report No. DOE/EM-0558. U.S. Department of Energy, Office of Environmental Management, Office of Science and Technology, December 2000. http://apps.em.doe.gov/ost/pubs/itsrs/itsr10.pdf. Accessed May 1, 2004.

# Tested landfill cover designs

Table 1. Landfill cover design characteristics

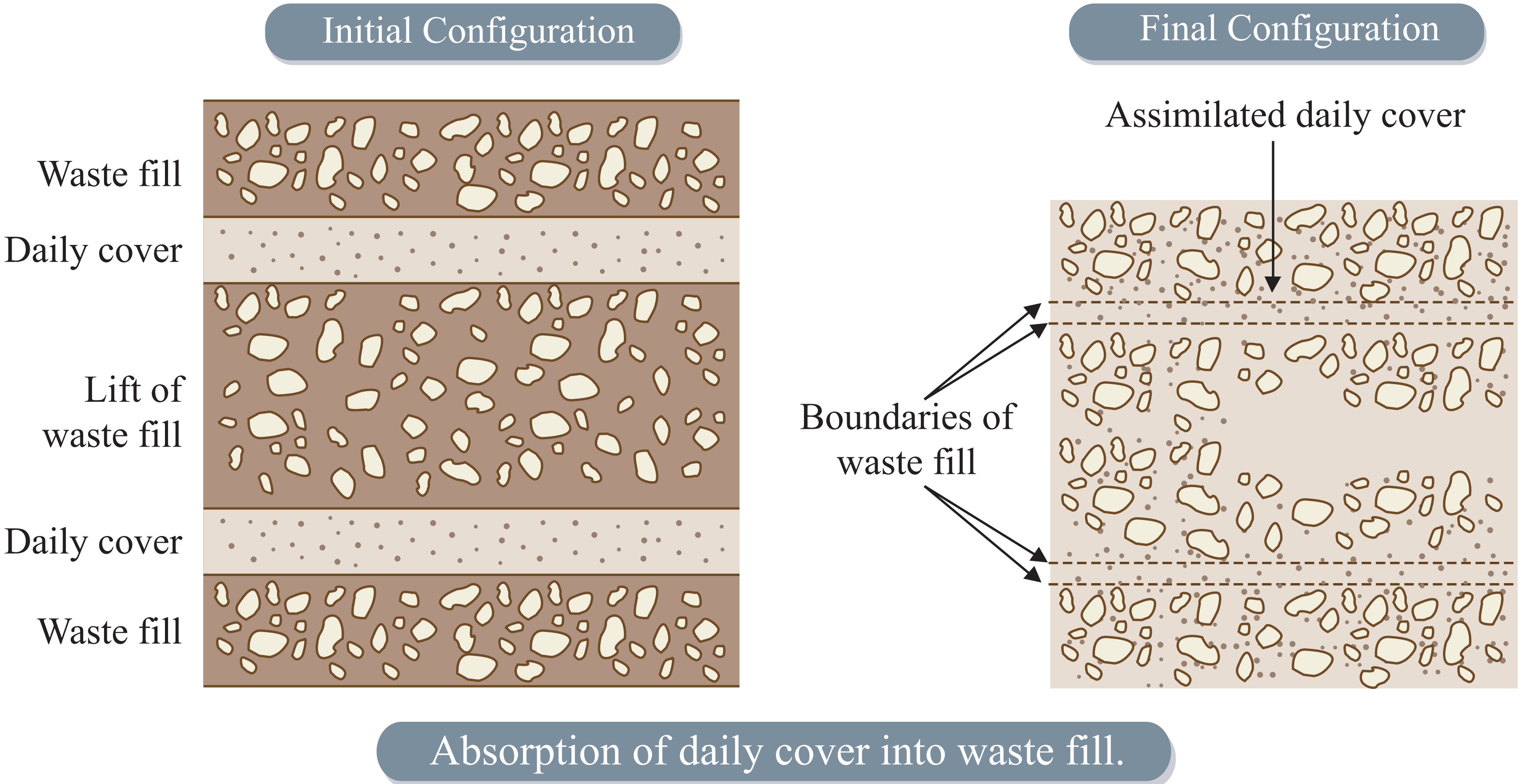
| Landfill Cover Design | Thickness | Layers | Components Description/Thickness |
|---|---|---|---|
| RCRA Subtitle D Cover | 60 cm | 2 | Top vegetation/soil layer – 15 cm<br>Compacted native soil -- 45 cm |
| RCRA Subtitle C Cover | 150 cm | 4 | Top vegetation/soil layer – 60 cm<br>Sand drainage layer – 30 cm<br>Geomembrane -- 40-mil<br>Compacted bentonite-amended soil – 60 cm |
| Geosynthetic Clay Liner (GCL) Cover | 90 | 4 | Top vegetation/soil layer – 60 cm<br>Geotextile filter fabric<br>Sand drainage layer – 30 cm<br>Geomembrane -- 40 cm<br>Geosynthetic clay liner |
| Capillary Barrier Cover | 140 | 4 | Top vegetation/soil layer – 30 cm<br>Upper sand drainage layer -- 15 cm<br>Upper gravel drainage layer -- 22 cm<br>Compacted barrier soil layer – 45 cm<br>Lower sand drainage layer -- 15 cm |
| Anisotropic Barrier Cover | 105 | 4 | Top vegetation/soil layer – 15 cm<br>Native soil cover layer -- 60 cm<br>Fine sand interface layer -- 15 cm<br>Pea gravel sublayer -- 15 cm |
| Evapotranspiration Soil Cover | 90 | 2 | Top vegetation/soil layer – 15 cm<br>Compacted native soil layer -- 75 cm |

# Cover performance



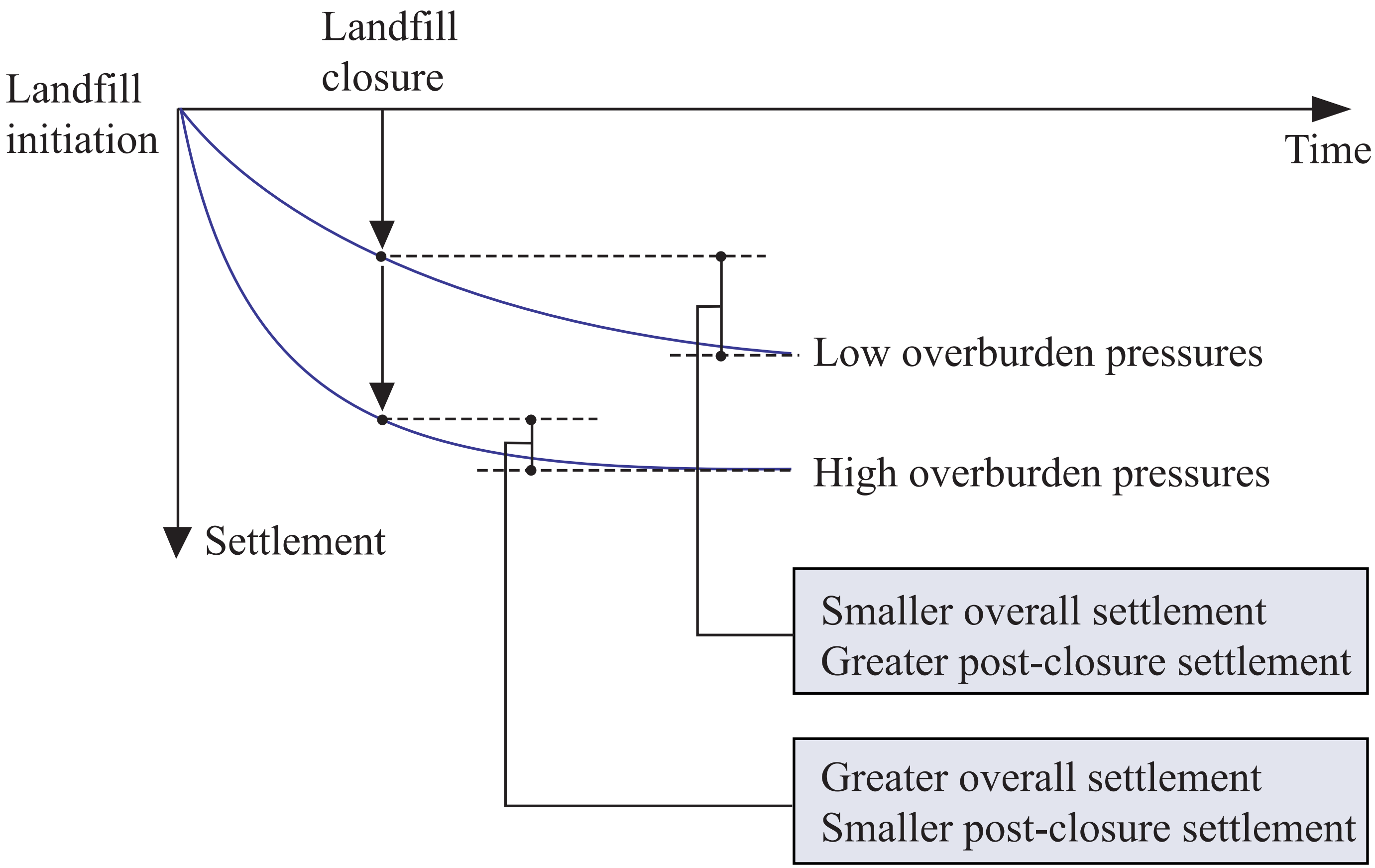

Source: DOE, 2000. Alternative Landfill Cover. Innovative Technology Summary Report No. DOE/EM-0558. U.S. Department of Energy, Office of Environmental Management, Office of Science and Technology, December 2000. http://apps.em.doe.gov/ost/pubs/itsrs/itsr10.pdf. Accessed May 1, 2004.

# Landfill settlement




Adapted from: Qian, X., R. M. Koerner, and D. H. Gray. *Geotechnical Aspects of Landfill Design and Construction*. Upper Saddle River, New Jersey: Prentice Hall, 2002.

# Landfill settlement




Possible settlement curves for dense and light fills.

Adapted from: Qian, X., R. M. Koerner, and D. H. Gray. *Geotechnical Aspects of Landfill Design and Construction*. Upper Saddle River, New Jersey: Prentice Hall, 2002.

# Landfill settlement

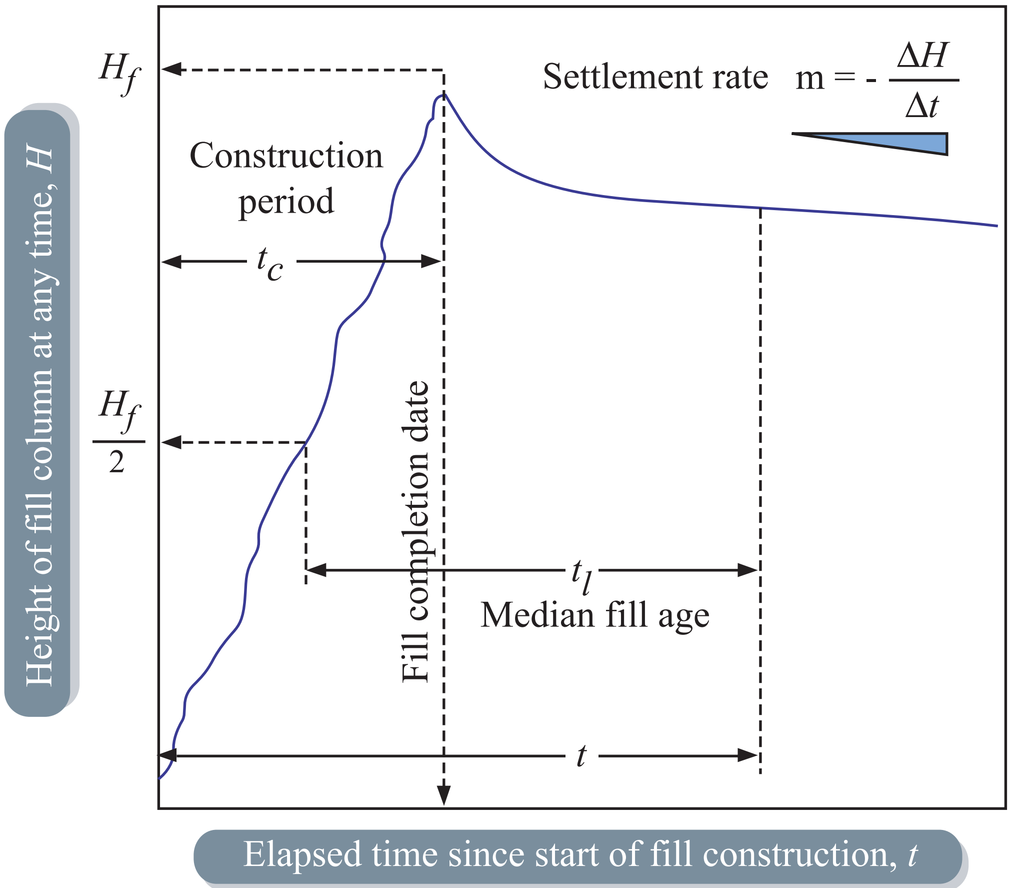


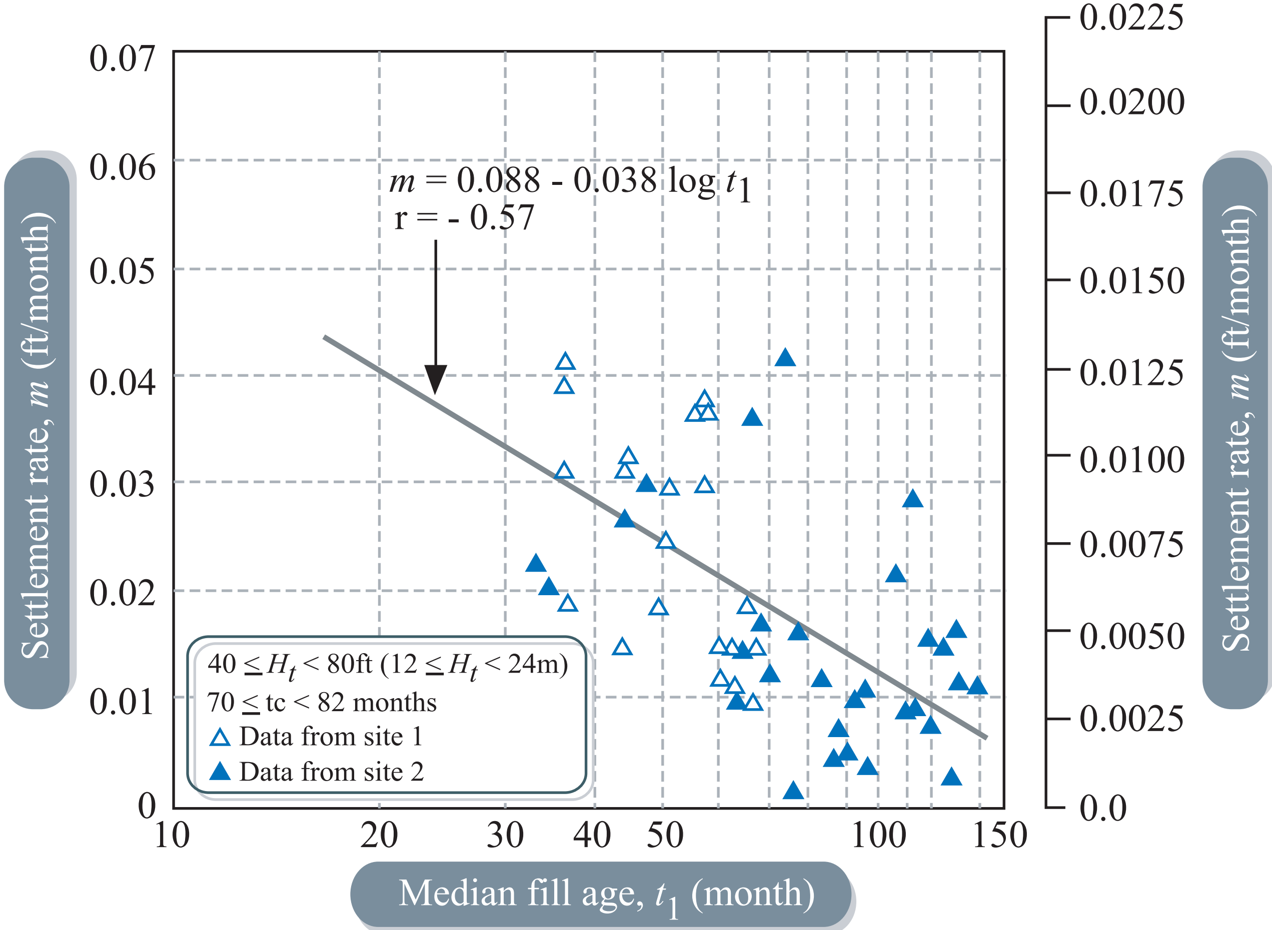

Diagram showing notations used in analysis.

Adapted from: Qian, X., R. M. Koerner, and D. H. Gray. *Geotechnical Aspects of Landfill Design and Construction*. Upper Saddle River, New Jersey: Prentice Hall, 2002.

Results of nine-year study of three landfills in Los Angeles

Yen, B.C. and B. Scanlon, 1975. Sanitary Landfill Settlement Rates. *Journal of Geotechnical Engineering, ASCE*. Volume 101, Number 5, Pages 475-487.

# Landfill settlement




Settlement rates versus time elapsed for fill depths between 40 ft and 80 ft (12 m and 24 m).

Adapted from: Qian, X., R. M. Koerner, and D. H. Gray. *Geotechnical Aspects of Landfill Design and Construction*. Upper Saddle River, New Jersey: Prentice Hall, 2002.

# Equations for landfill settlement

Qian et al. (2002) formula for long-term secondary settling:

$$\Delta H_{\alpha} = C_{\alpha} H_{o} \log(t_2/t_1)$$

where:

$\Delta H_{\alpha}$ = settlement (length units)

$C_{\alpha}$ = secondary compression index = 0.03 to 0.1

$H_o$ = initial waste thickness (length units)

$t_1$ = starting time

$t_2$ = ending time

# Equations for landfill settlement

Numerous empirical equations to predict settlement are in the literature—see Qian et al. (2002) for good summary

# Surface-water runoff & drainage control

Runoff-induced erosion can be an important factor in safe landfill closure

Control of stormwater runoff is an issue since capped landfill is likely to have greater runoff than pre-development condition and must be controlled to prevent effects on neighbors

# Stormwater design

Usually based on rational formula

In English units:

$Q = CiA$

$Q$ = peak rate of runoff ($ft^3$/sec)

$C$ = runoff coefficient

$i$ = rainfall intensity (inches) during time of concentration of drainage area (in/hr)

$A$ is basin area (acres)

# Stormwater design

In Metric units:

$Q = CiA / 360$

Q = peak rate of runoff ($m^3$/sec)

C = runoff coefficient

i = rainfall intensity (mm) during time of concentration of drainage area (mm/hr)

A is basin area (ha)

Rational formula recommended for basins up to 200 acres (81 hectares)

# Rainfall intensity

i comes from rainfall-frequency-duration data for location of landfill

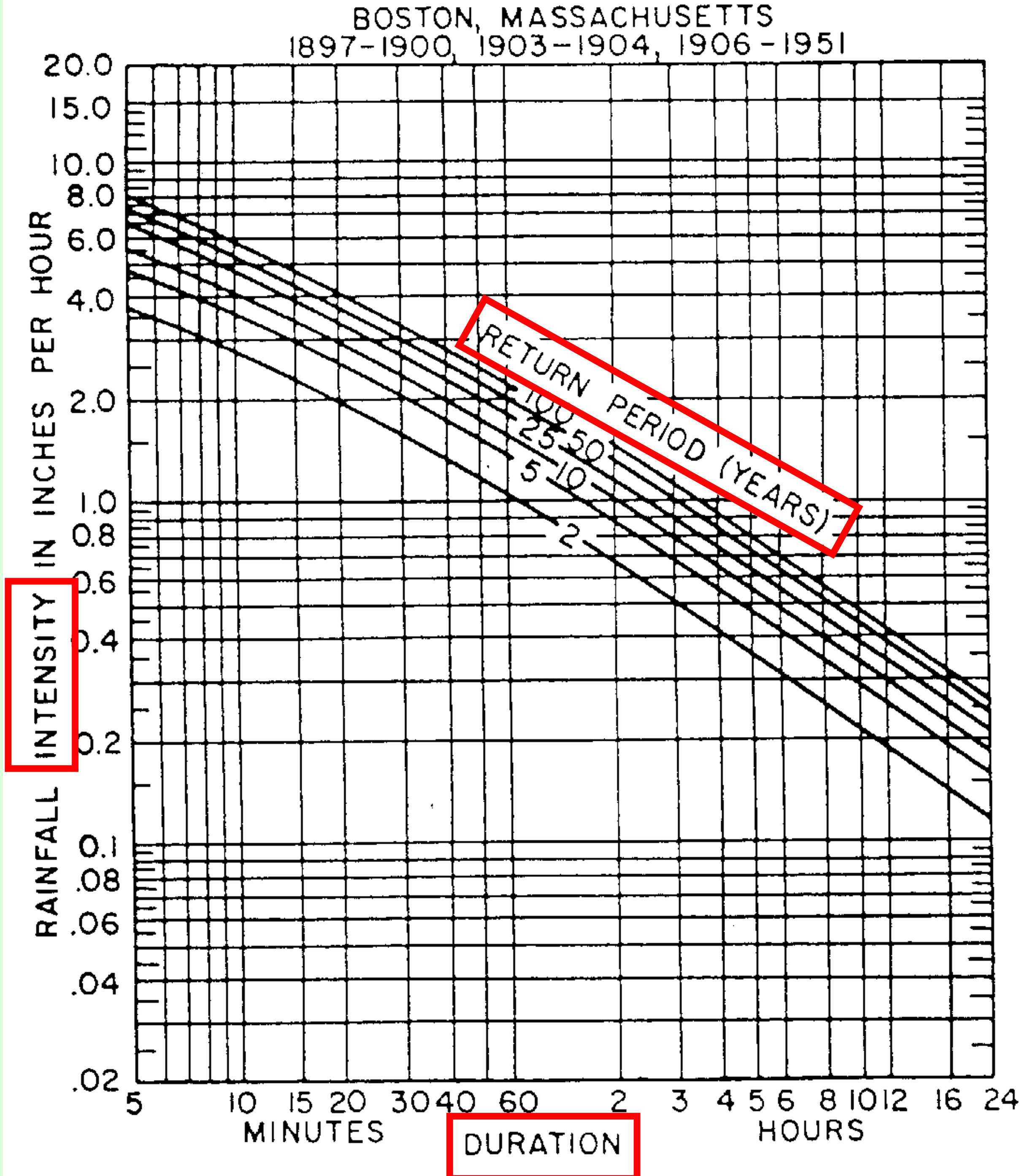
Rainfall-frequency-duration data come from long-term rainfall records

Usual source in US:

National Weather Service TP40

(Hershfield, D. M., 1961. Rainfall Frequency Atlas of the United States. Technical Paper 40. Weather Bureau, U.S. Department of Commerce, Washington, DC. May 1961.)

# IDF curve for Boston



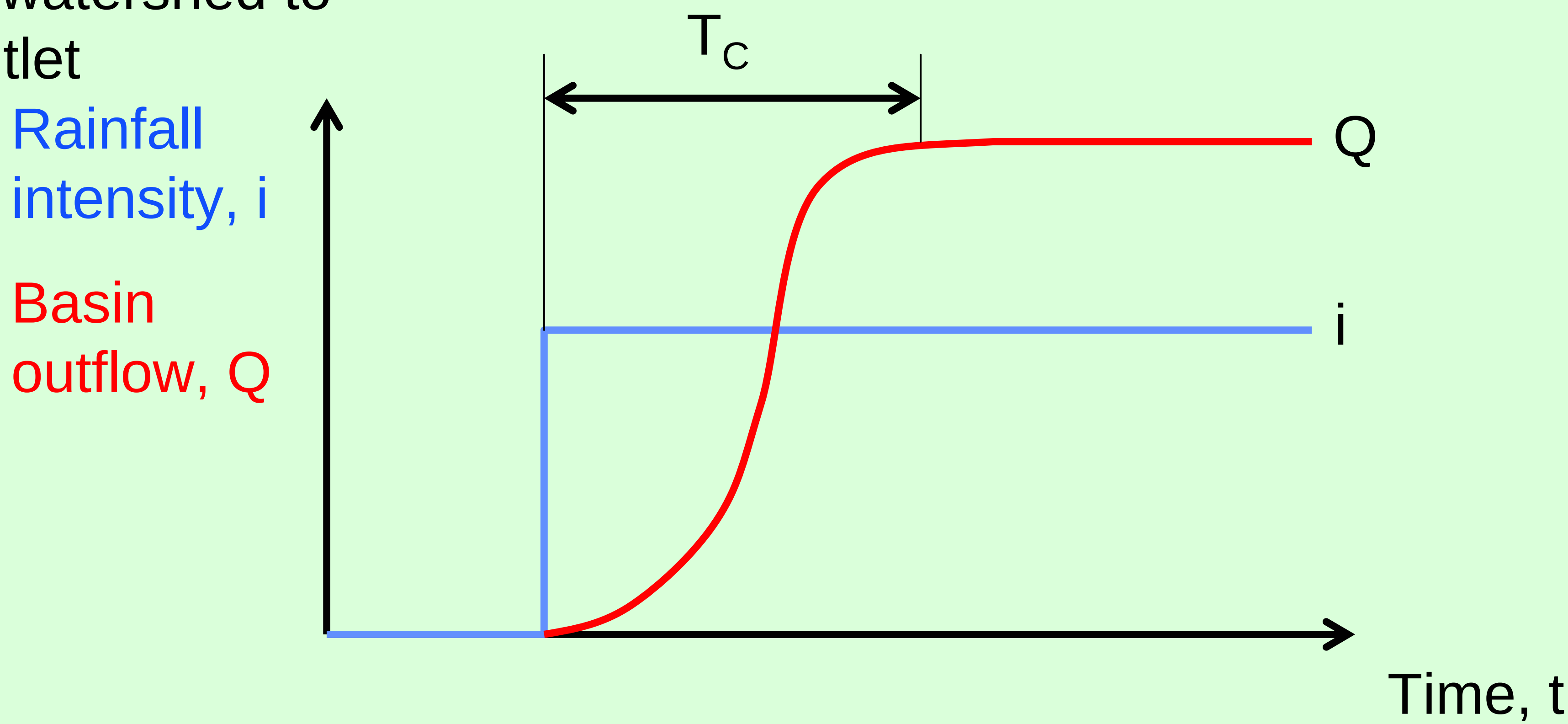
# Stormwater calculations

Pick i corresponding to basin time of concentration

(Note inconsistency in EPA requirements which specify 25-year, 24-hour storm.  This should apply only to basin with 24-hour time of concentration.)

# Time of concentration

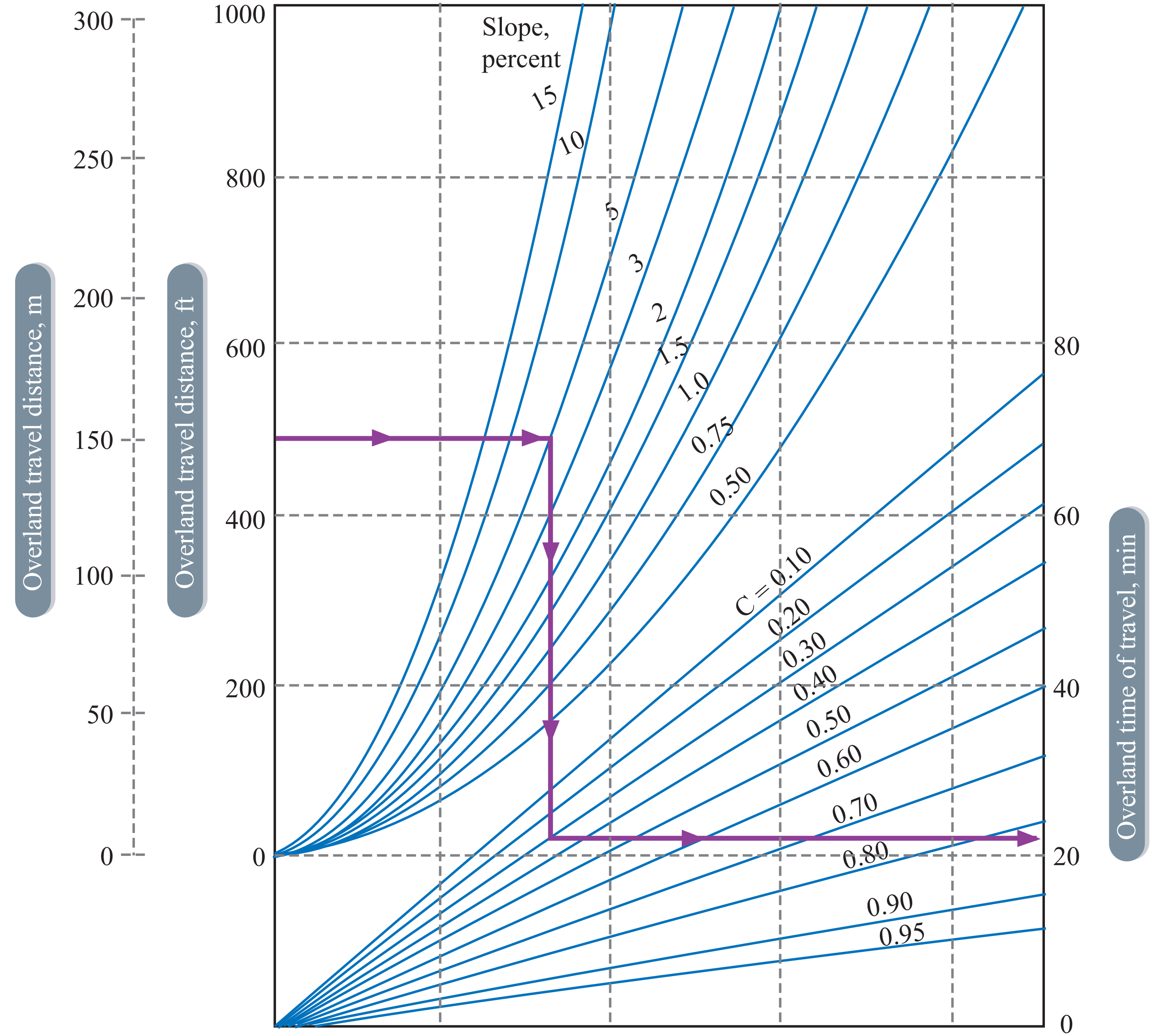
$T_C$ = travel time from hydraulically most distant point in watershed to outlet



# Time of concentration

- Time of concentration
  - Determined by routing flow over different portions of flow path:
    - Overland flow
    - Shallow concentrated flow
    - Channel flow
  - Use nomograph for small area like a landfill

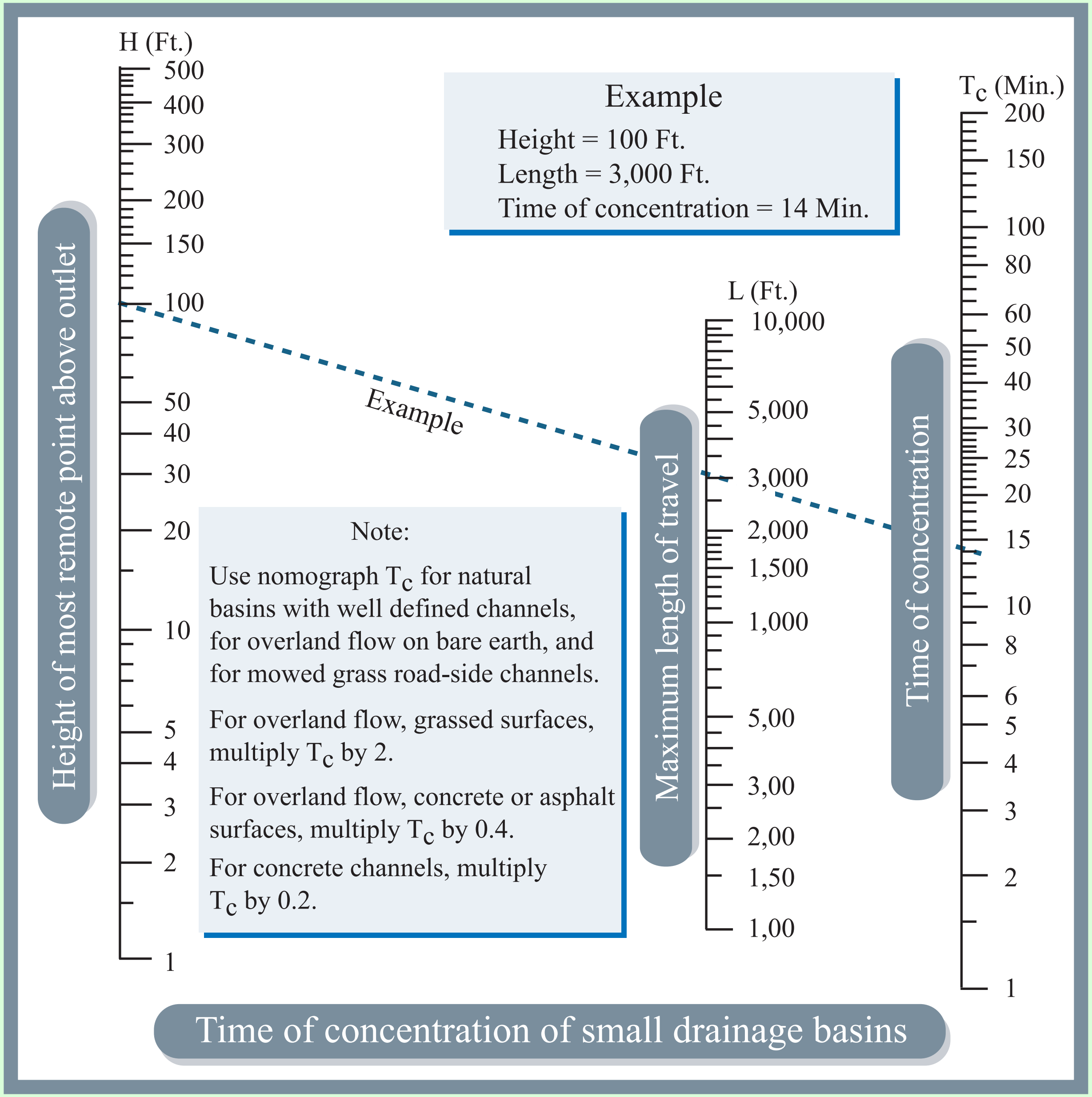
# Time of concentration nomograph for overland flow




A nomograph of overland flow time. (10) Enter left margin with slope length; move right to slope curve and down to *C* value; and find overland travel time on right margin.

Adapted from: Goldman, S. J., K. Jackson, and T. A. Bursztynsky. *Erosion and Sediment Control Handbook*. New York: McGraw-Hill, 1986.

# Time of concentration nomograph for small drainage basins



# Rational coefficient, C

James Dooge's rule of thumb:

C = sqrt(H)/10

where:
H = houses/acre

RATIONAL METHOD *C* VALUES (13)

| Land Use | *C* | Land Use | *C* |
|---|---|---|---|
| **Business** | | **Lawns** | |
| Downtown areas | 0.70-0.95 | Sandy soil, flat, 2% | 0.05-0.10 |
| Neighborhood areas | 0.50-0.70 | Sandy soil, average, 2-7% | 0.10-0.15 |
| **Residential** | | Sandy soil, steep, 7% | 0.15-0.20 |
| Single-family areas | 0.30-0.50 | Heavy soil, flat, 2% | 0.13-0.17 |
| Multi units, detached | 0.40-0.60 | Heavy soil, average, 2-7% | 0.18-0.22 |
| Multi units, attached | 0.60-0.75 | Heavy soil, steep, 7% | 0.25-0.35 |
| Suburban | 0.25-0.40 | **Agricultural land, 0-30%** | |
| **Industrial** | | Bare packed soil | |
| Light areas | 0.50-0.80 | Smooth | 0.30-0.60 |
| Heavy areas | 0.60-0.90 | Rough | 0.20-0.50 |
| **Parks, cemeteries** | 0.10-0.25 | Cultivated rows | |
| **Playgrounds** | 0.20-0.35 | Heavy soil, no crop | 0.30-0.60 |
| **Railroad yard areas** | 0.20-0.40 | Heavy soil with crop | 0.20-0.50 |
| **Unimproved areas** | 0.10-0.30 | Sandy soil, no crop | 0.20-0.40 |
| **Streets** | | Sandy soil with crop | 0.10-0.25 |
| | | Pasture | |
| Asphaltic | 0.70-0.95 | Heavy soil | 0.15-0.45 |
| Concrete | 0.80-0.95 | Sandy soil | 0.05-0.25 |
| Brick | 0.70-0.85 | Woodlands | 0.05-0.25 |
| **Drives and walks** | 0.75-0.85 | **Barren slopes, > 30%** | |
| | | Smooth, impervious | 0.70-0.90 |
| **Roofs** | 0.75-0.95 | Rough | 0.50-0.70 |

Note: The designer must use judgment to select the appropriate *C* value within the range. Generally, larger areas with permeable soils, flat slopes, and dense vegetation should have lowest *C* values. Smaller areas with dense soils, moderate to steep slopes, and sparse vegetation should be assigned highest *C* values.

Adapted from: Goldman, S. J., K. Jackson, and T. A. Bursztynsky. *Erosion and Sediment Control Handbook*. New York: McGraw-Hill, 1986.

# C for landfills:

| Soil | Slope | C |
|---|---|---|
| Sandy | Flat (≤ 2%)<br>Average (2-7%)<br>Steep (≥ 7%) | 0.05-0.10<br>0.10-0.15<br>0.15-0.20 |
| Clayey | Flat (≤ 2%)<br>Average (2-7%)<br>Steep (≥ 7%) | 0.13-0.17<br>0.18-0.22<br>0.25-0.35 |

Source: D.G. Fenn, K.J. Hanley and T.V. DeGeare, 1975, Use of the Water Balance for Predicting Leachate Concentration from Solid Waste Disposal Sites. Report No. EPA/530-SW-168. U.S. EPA, Washington, D.C.

# Example runoff calculation

One side of a landfill on the MIT campus has these characteristics:

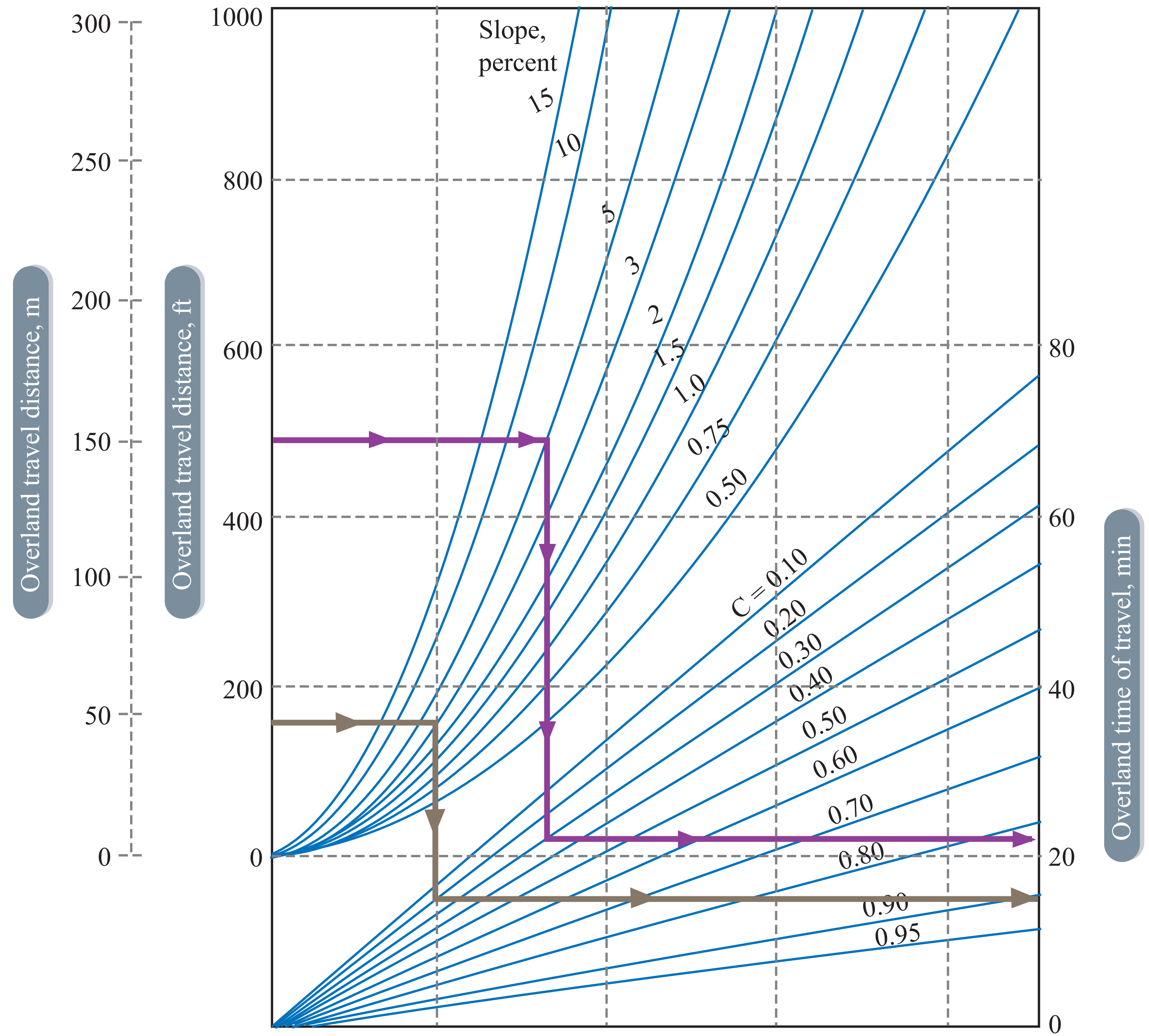
- Area of 2 acres
- Side slope of 3%
- Slope length of 150 feet
- Grassy cover on clayey topsoil

Want to design for 25-year storm

Estimate C = 0.2 from previous chart

# Example runoff calculation

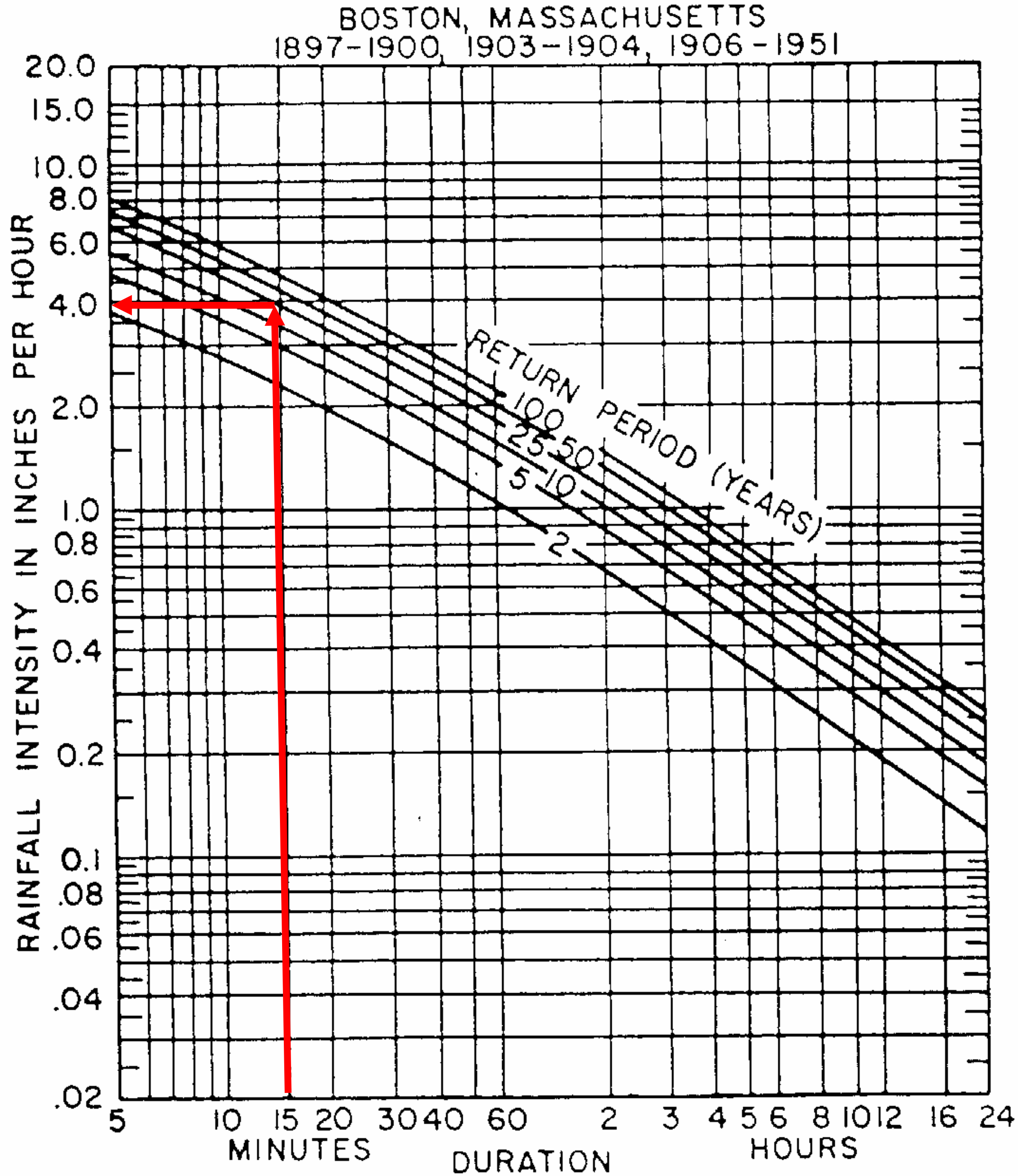
$T_C$ = 15 minutes




A nomograph of overland flow time. (10) Enter left margin with slope length; move right to slope curve and down to *C* value; and find overland travel time on right margin.

# Example runoff calculation

i = 4 inches/hour



# Example runoff calculation

A = 2 acres

C = 0.2

i = 4 inches/hour

Q = CiA = 0.2 x 4 x 2 = 1.6 cfs

# Alternative stormwater calculation method

SCS (NRCS) Method:

- Developed by U.S. Department of Agriculture Soil Conservation Service starting in the 1950s
- Now called Natural Resources Conservation Service
- Originally developed for agricultural basins, extended to urban land uses in 1970s

# SCS Method

Basis is the SCS Curve Number – an empirical measure of soil runoff characteristics

- An impervious surface such as roof or road has a curve number of 98
- Thick woods on sandy soil has CN = 30

**Table 2-2a** Runoff curve numbers for urban areas [1]

| Cover description | | Curve numbers for hydrologic soil group | | | |
|---|---|---|---|---|---|
| Cover type and hydrologic condition | Average percent impervious area [2] | A | B | C | D |
| *Fully developed urban areas (vegetation established)* | | | | | |
| Open space (lawns, parks, golf courses, cemeteries, etc.) [3]: | | | | | |
| Poor condition (grass cover < 50%) | | 68 | 79 | 86 | 89 |
| Fair condition (grass cover 50% to 75%) | | 49 | 69 | 79 | 84 |
| Good condition (grass cover > 75%) | | 39 | 61 | 74 | 80 |
| Impervious areas: | | | | | |
| Paved parking lots, roofs, driveways, etc. (excluding right-of-way) | | 98 | 98 | 98 | 98 |
| Streets and roads: | | | | | |
| Paved; curbs and storm sewers (excluding right-of-way) | | 98 | 98 | 98 | 98 |
| Paved; open ditches (including right-of-way) | | 83 | 89 | 92 | 93 |
| Gravel (including right-of-way) | | 76 | 85 | 89 | 91 |
| Dirt (including right-of-way) | | 72 | 82 | 87 | 89 |
| Western desert urban areas: | | | | | |
| Natural desert landscaping (pervious areas only) [4] | | 63 | 77 | 85 | 88 |
| Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders) | | 96 | 96 | 96 | 96 |
| Urban districts: | | | | | |
| Commercial and business | 85 | 89 | 92 | 94 | 95 |
| Industrial | 72 | 81 | 88 | 91 | 93 |
| Residential districts by average lot size: | | | | | |
| 1/8 acre or less (town houses) | 65 | 77 | 85 | 90 | 92 |
| 1/4 acre | 38 | 61 | 75 | 83 | 87 |
| 1/3 acre | 30 | 57 | 72 | 81 | 86 |
| 1/2 acre | 25 | 54 | 70 | 80 | 85 |
| 1 acre | 20 | 51 | 68 | 79 | 84 |
| 2 acres | 12 | 46 | 65 | 77 | 82 |
| *Developing urban areas* | | | | | |
| Newly graded areas (pervious areas only, no vegetation) [5] | | 77 | 86 | 91 | 94 |
| Idle lands (CN's are determined using cover types similar to those in table 2-2c). | | | | | |

Source: NCRS, 1986. Urban Hydrology for Small Watersheds. Technical Release 55. U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, DC. June 1986.

# SCS Method

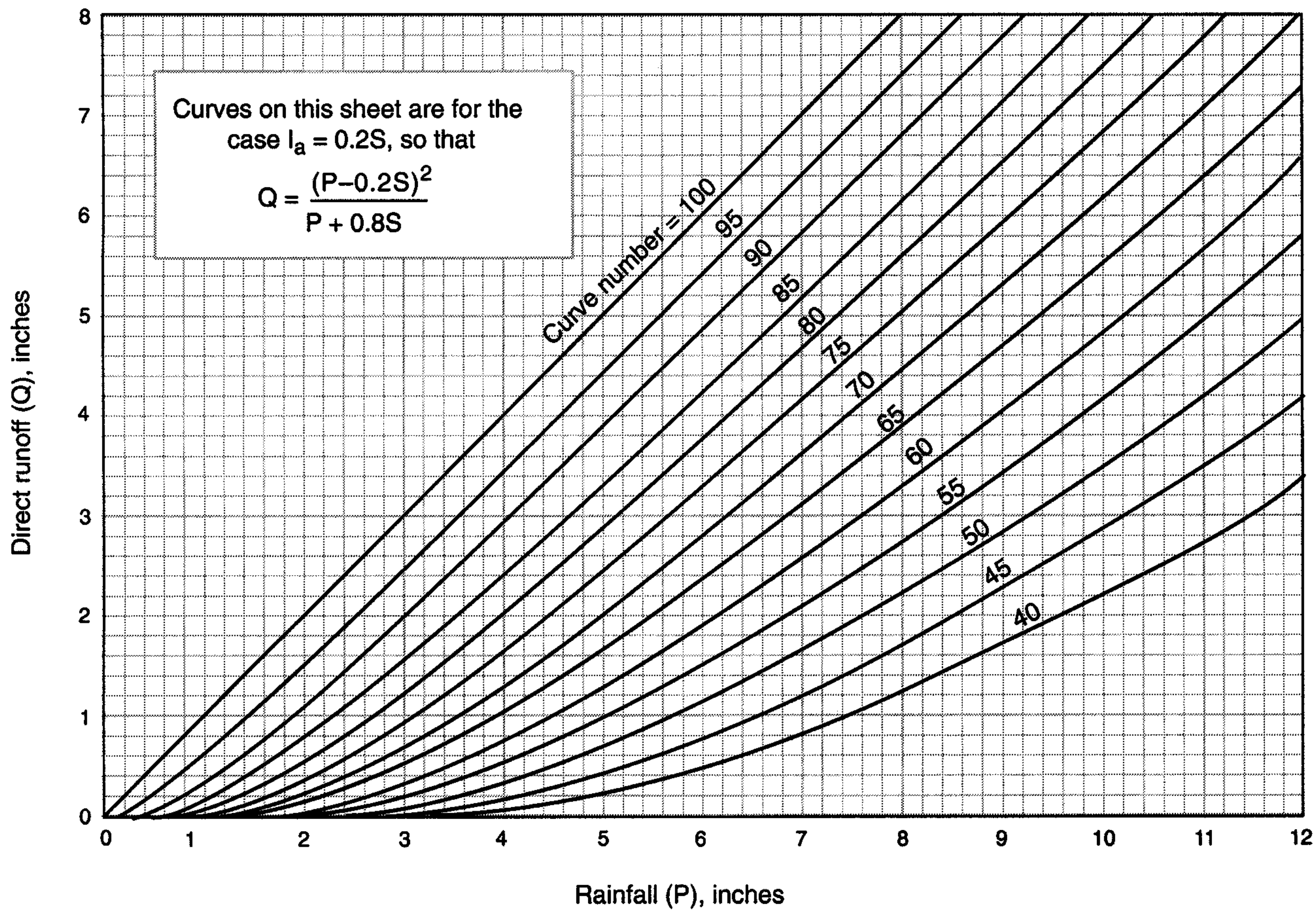
Predicts runoff as a function of precipitation

Provides standard rainfall design storm distributions

Provides procedure to compute hydrographs from runoff distribution over time

# SCS Method

**Figure 2-1** Solution of runoff equation.




Source: NCRS, 1986. Urban Hydrology for Small Watersheds. Technical Release 55. U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, DC. June 1986.

# References for SCS Method

SCS, 1986. Urban Hydrology for Small Watersheds, Second Edition. Technical Release 55. United States Department of Agriculture, Soil Conservation Service, Washington, D.C. June 1986. (http://www.wcc.nrcs.usda.gov/hydro/hydro-tools-models-tr55.html)

SCS, 1992. TR-20, Computer Program for Project Formulation Hydrology. Technical Release 20. U.S. Department of Agriculture, Soil Conservation Service, Lanham, Maryland. February 1992. (http://www.wcc.nrcs.usda.gov/hydro/hydro-tools-models-tr20.html)

SCS, 1972. National Engineering Handbook, Section 4, Hydrology. Report Number NEH-4. PB 744 463. Soil Conservation Service, U.S. Department of Agriculture, Washington, D.C. August 1972. (http://www.wcc.nrcs.usda.gov/hydro/hydro-techref-neh-630.html)

# Stormwater control

Typically landfills require drainage swales: grassed channels to convey flow to stormwater detention/retention ponds

Detention ponds release water slowly so as to reduce flow rates and potential for downstream flooding

Retention ponds retain water, recharging it into the ground

# To cap or not to cap?

Two alternative approaches:

Dry tomb – capped to keep waste dry

Digester (bioreactor) – kept moist to encourage biodegradation

# Dry tomb

- Prevalent U.S. practice
- Minimizes moisture, maximizes compression
- Capped to keep out moisture
- Advantages:
  - Low O&M cost
  - Low leachate volume and associated treatment costs
  - Established design procedure
- Disadvantages:
  - Encapsulates waste only—waste breakdown is minimal
  - Waste remains hazardous for a long time after closure

# Biodigestor

Popular in Europe

Maintains high moisture content (40 to 50%) to promote bacterial growth and waste biodegradation

Leachate recirculated to maintain moisture

Waste is not compacted in order to facilitate moisture migration

# Biodigestor

Advantages:

- Less leachate to be treated
- Increased methane production
- Biodegradation reduces contaminants in waste
- Waste settles more, creating room for more waste
- Eventual leachate will be much less contaminated or hazardous

# Biodigestor

Disadvantages:

- Design difficulties: less stable material and greater settlement
- Leachate lines more easily clogged as waste settles
- Greater capital and O&M costs
- Potential for vector problems

# Leachate recirculation

Concept: add supplemental water and/or recirculating leachate to enhance decomposition

First proposed in mid-1970s

Field implementation in US in late 1990s

# Side-by-side test of leachate recirc

Control cell

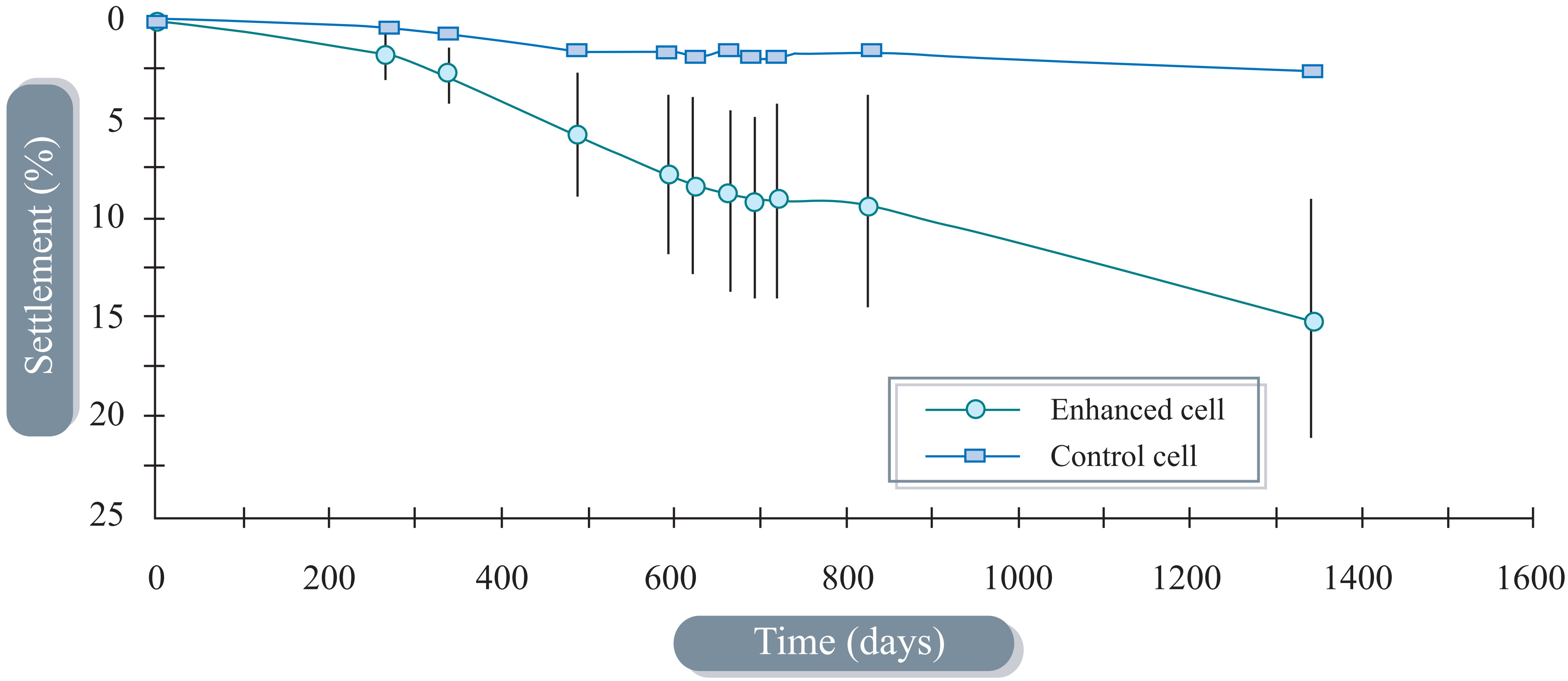
- 7932 metric tons MSW
- 930 $m^2$ area
- 12 m deep
- No addition of water or recirculation of leachate

Enhanced cell

- 7772 metric tons MSW
- 930 $m^2$ area
- 12 m deep
- 14 injection pits for water addition/leachate recirc
- 4430 $m^3$ leachate and clean ground water added over 1231 days

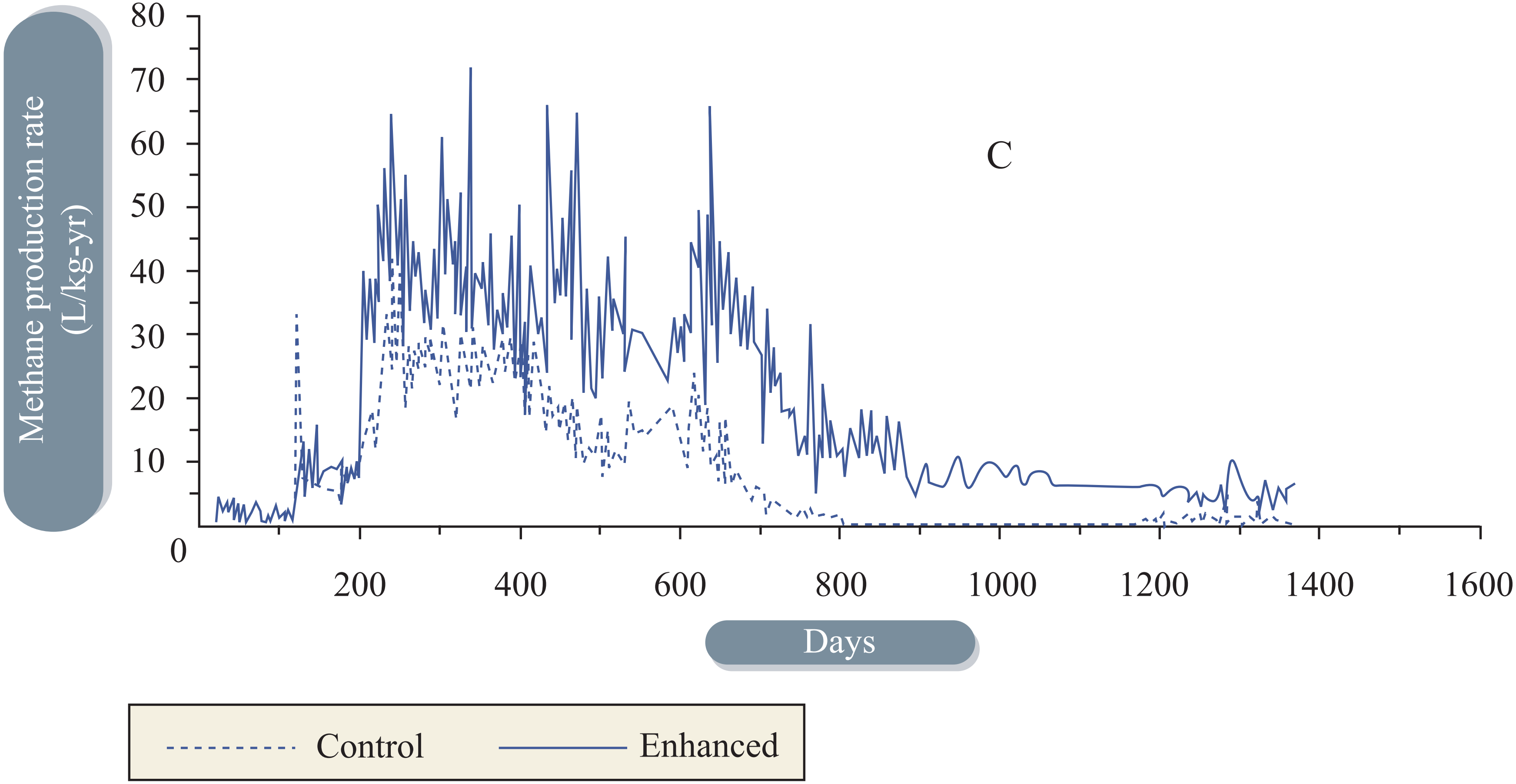
Source: Mehta, R., M. A. Barlaz, R. Yazdani, D. Augenstein, M. Bryars, and L. Sinderson, 2002. Refuse Decomposition in the Presence and Absence of Leachate Recirculation. *Journal of Environmental Engineering, ASCE*. Vol. 128, No. 3, Pg. 228-236. March 2002.

# Settlement with leachate recirculation



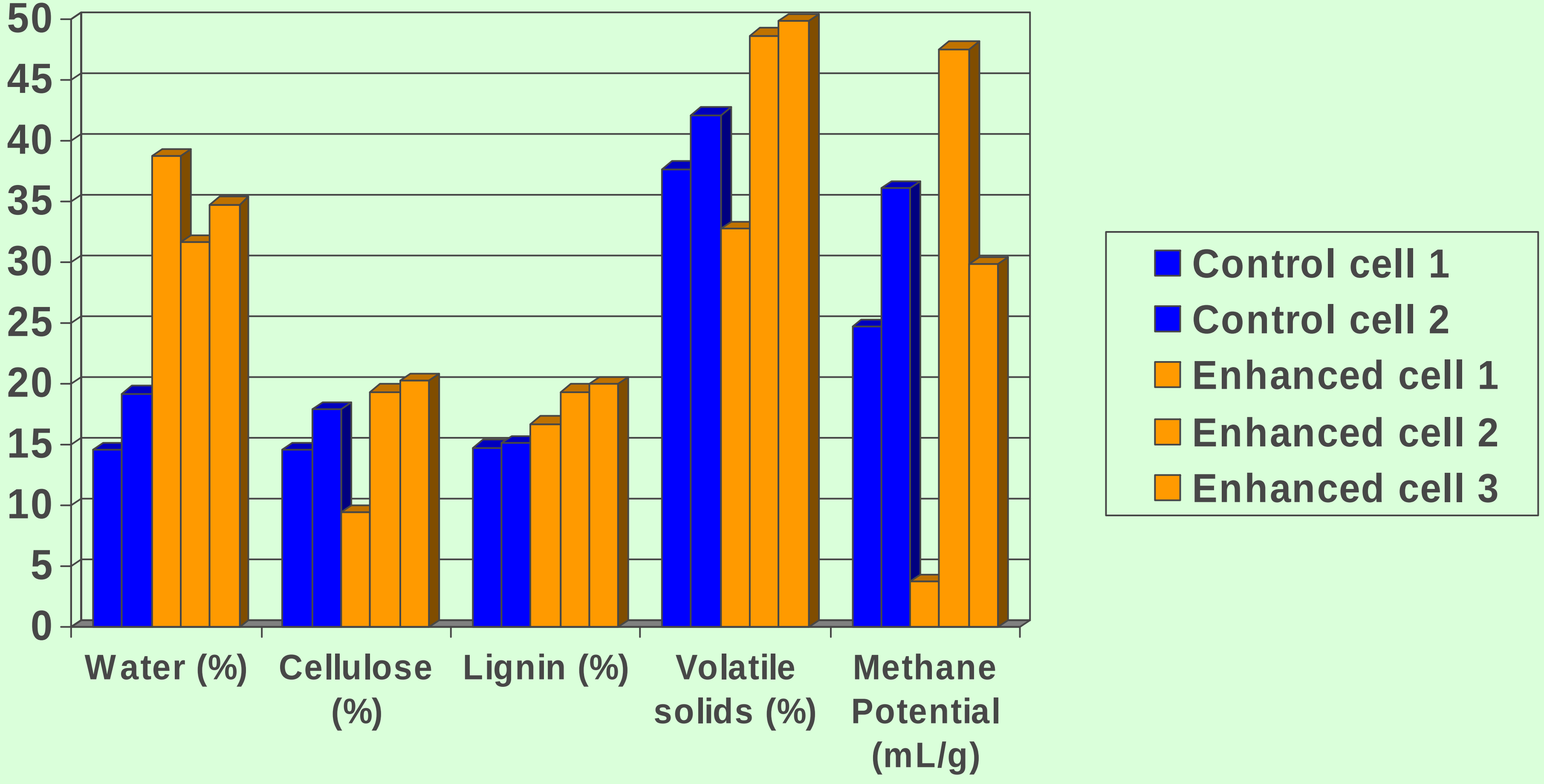

Adapted from: Mehta, R., M. A. Barlaz, R. Yazdani, D. Augenstein, M. Bryars, and L. Sinderson. "Refuse Decomposition in the Presence and Absence of Leachate Recirculation." *Journal of Environmental Engineering, ASCE* 128, no. 3 (March 2002): 228-236.

# Methane generation with leachate recirc




Adapted from: Mehta, R., M. A. Barlaz, R. Yazdani, D. Augenstein, M. Bryars, and L. Sinderson. "Refuse Decomposition in the Presence and Absence of Leachate Recirculation." *Journal of Environmental Engineering, ASCE* 128, no. 3 (March 2002): 228-236.

# Waste character from soil borings




Source: Mehta, R., M. A. Barlaz, R. Yazdani, D. Augenstein, M. Bryars, and L. Sinderson, 2002. Refuse Decomposition in the Presence and Absence of Leachate Recirculation. *Journal of Environmental Engineering, ASCE*. Vol. 128, No. 3, Pg. 228-236. March 2002.

# Landfill monitoring

Monitoring indicates:

whether facility is performing as intended (operational performance)

whether facility is polluting the environment (regulatory performance)

# Monitored parameters

Head in leachate collection systems
Leachate leakage
Ground-water quality around landfill
Gas content in landfill
Gas migration through liner
Gas in soil and air around landfill
Leachate quality and quantity
Condition of cover: erosion, etc.
Settlement

# Closure plans

Landfill operators are required to submit a closure plan as a part of their operating permit application

Closure plans primarily describe capping procedure

Operators are also required to provide post-closure care for period of 30 years

# Post-closure care

Primary requirements address:

- Cover
- Leachate collection
- Gas monitoring
- Ground-water monitoring

# Post-closure cover maintenance

Quarterly inspection of cap for cracks, erosion, settlement, and undesired vegetation

Repair of cover to maintain grades if needed

Inspection and repair of drainage and runoff control systems

# Post-closure leachate collection

Leachate collection system inspection and cleaning

Repair and replacement of pumps, etc.

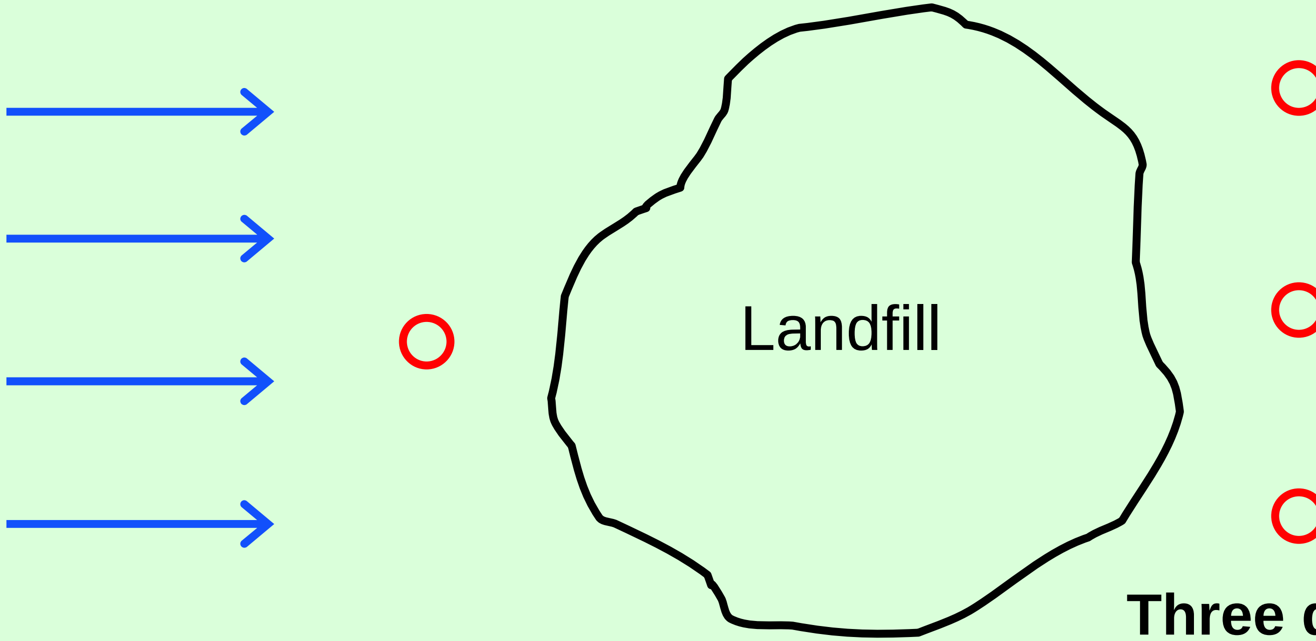
Leachate collection, pumping, and treatment must be continued until leachate quality does not pose a threat

# Post-closure monitoring

- Monitoring conducted on regular schedule established in the plan
- Both ground-water and gas
- Monitoring for COD, TDS, TOC, pH, various ions, metals, and VOCs
- Ground-water monitoring is a priority
  - Regulations require monitoring of the “uppermost aquifer” both upgradient and downgradient
  - Multiple downgradient wells required: enough to assess effect of entire facility

# “One-up, three-down” monitoring system

Minimum monitoring system:




**One upgradient well to monitor background water quality**

**Three downgradient wells to monitor background landfill effects on water quality**

# Post-closure

Post-closure care is a major expense since it continues for such a long time

Owner must demonstrate financial resources to provide long-term care as part of landfill licensing process

# Innovative post-closure

Reuse – capped landfills used for recreational or other low-development uses

Building on landfills is difficult: differential settlement and landfill gases create substantial impediments to building

# Cambridge landfill closure

Mid-1800s – 50-acre industrial center with clay pit, a kiln, and brick yard.

1952-1971 – City of Cambridge landfill.

1992 – Danehy Park opened.

# Landfill reclamation

Reclamation – landfill mining to recover recyclable or reusable materials

Reduces waste volume and creates more room for waste disposal

Process:

- Excavator digs up landfilled waste
- Waste is screened to remove metal, plastic, glass, and paper
- Combustible waste is sometimes sent to waste-burning facility

# Landfill reclamation

Disadvantages:

- Expensive
- Can release gases and cause odors
- Can uncover hazardous waste