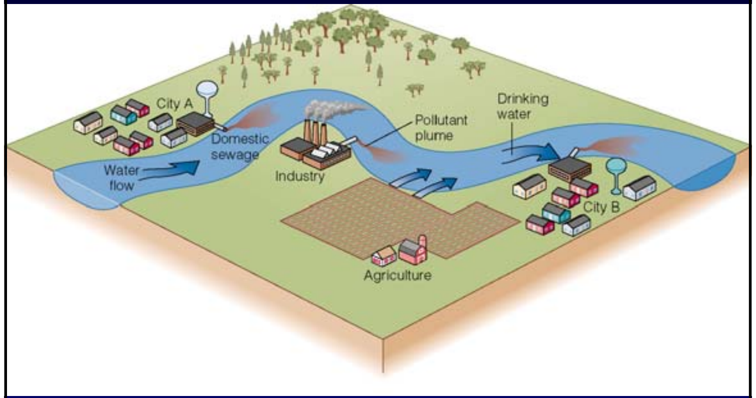
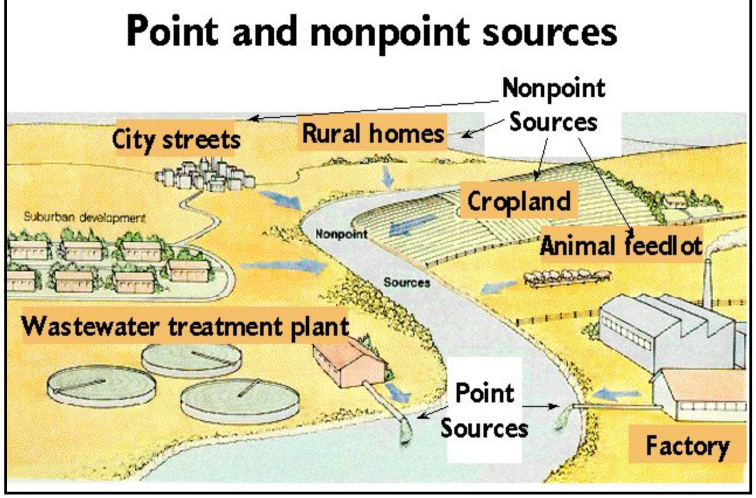
Module 7: Sanitary Sewer Design

Robert Pitt
University of Alabama
and
Shirley Clark
Penn State - Harrisburg

One City's Wastewater is Another City's Water Supply



McKinney and Schoch



Ancient temple drains at Knossos, Crete (Minoan 2600 to 1000 BC)

House drain at the Agora, Athens, Greece (1st to 4th century BC)

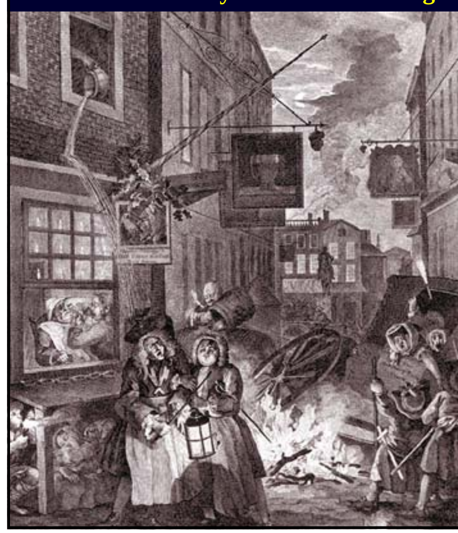
Child potty, ancient Greece (Agora Museum)

Roman community toilet, Athens, Greece (100 BC)

Coliseum sewage ditch, Rome (completed in 80 AD)

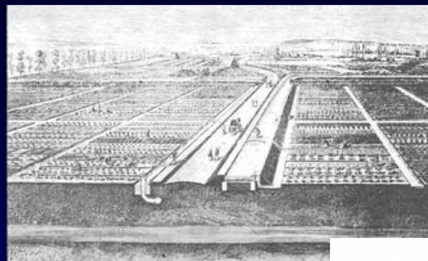
J. Harper photo

One Early Method of Getting Rid of Wastewater



Wastewater treatment has only been around since the late 1800s. People dumped wastes into gutters, ditches, and out open windows.

"Tout-a-la-rue“ (all in the streets), with the expectation that dogs, pigs, and rain would effectively remove wastes. This was the waste disposal policy in most western cities until the late 1800s.

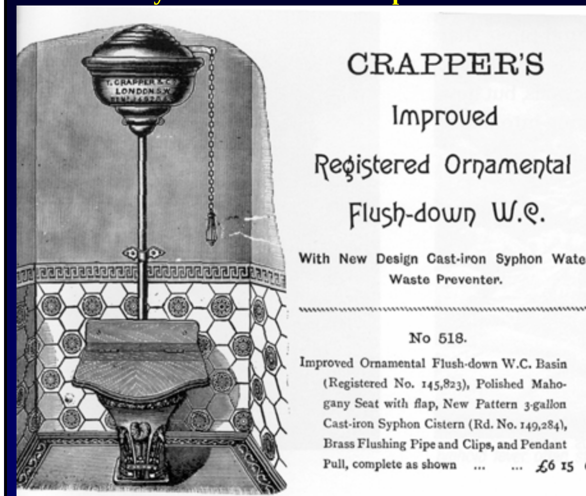


Several European cities transported wastewater to agricultural areas for fertilizer

At a later time in the USA, transporting wastewater to sewage farms was less common, but still practiced by some cities

Slide by Steve Burion, Univ. of Utah

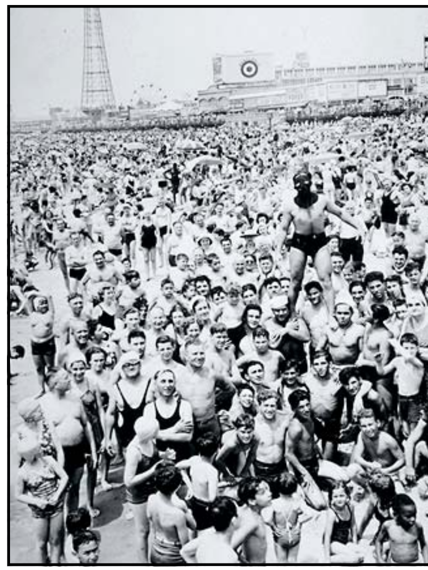
Early Flush Toilet Vast Improvement in Sanitation



More people were able to have a flush toilet, not just the rich. First US treatment plant built in NYC in 1886 to protect Coney Island beaches from vast increases in wastewater volume.

"Sewer" is from the early English meaning seaward.

Thomas Crapper's Toilet Tank and "Valveless Waste Preventer" (Underground Seattle Museum)



Coney Island, NY, summer 1940 by Weegee

Polluted New York Harbor in 1883

Coombs and Boucher

Polluted New York Harbor (Coney Island Creek) in 2000

London's drinking water, drawn unfiltered from the polluted Thames River, was home to many disease causing organisms and other nasty critters.

The anticontagionist, or miasmic, disease etiology belief held that putrefying organic matter in sewers exuded noxious disease causing gases; separate-sewer systems were advocated as the appropriate means to rapidly remove (< 2 or 3 days) human wastes from cities

Slide by Steve Burion, Univ. of Utah

In response to frequent disease outbreaks most large cities undertook massive sewer (both combined and separate) construction projects – the largest public works projects of the time period

Slide by Steve Burion, Univ. of Utah

Basic Wastewater Conveyance in Sanitary Condition not Always Achieved

McKinney and Schoch

Two Categories of Sewer Systems

- Separate Sewer Systems
- Combined Sewer Systems

Captured floatable debris from combined sewer outfalls at Brooklyn, NY, study area.

Separate sewer systems

- Two wastewater drainage systems exist in parallel:
  - Sanitary sewer system
    - Wastewater discharged to a treatment plant
  - Storm sewer system
    - Wastewater discharged to a receiving water

Sanitary Sewer Systems

- 3 types of sanitary wastewater collection systems based on hydraulic characteristics and purpose:
    - Gravity
    - Pressure
    - Vacuum

Gravity Sanitary Sewer

- Most common
- Wastewater transported by gravity
- Used to collect wastewater from residential, commercial, industrial, and institutional sources.
- Conveyance capacity allowances must be made for groundwater infiltration and unavoidable inflow

Pressure (Pumped) Sanitary Sewer

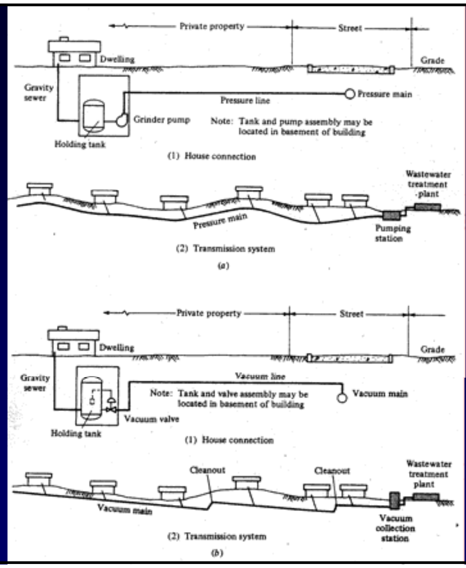
- Wastewater transported under pressure
- Used principally to collect wastewater from residential sources in locations unsuitable for the construction and/or use of gravity sewers
- They are also used to collect wastewater from commercial sources, but only rarely from industrial sources because of the large volumes that may be involved.
- These systems are usually small and are designed to exclude groundwater infiltration and stormwater inflow.

Vacuum Sanitary Systems

- Wastewater transported in a vacuum
- Otherwise, same as for pressure systems

Pressure Sewer System

Vacuum Sewer System



Industrial Wastewater Collection Options

- Discharge to sanitary sewer for treatment at a publicly owned wastewater treatment plant
- Partial treatment on site, followed by discharge to sanitary sewer for treatment at a publicly owned wastewater treatment plant (pre-treatment)
- Complete treatment to permit specifications on site, followed by release to receiving water

Storm Sewer Systems

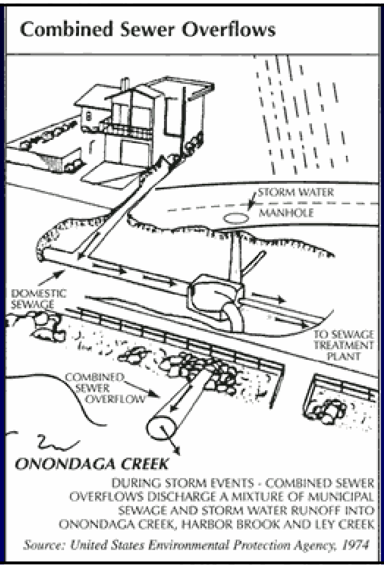
- Almost always gravity-flow systems due to large quantities of stormwater
- Collect stormwater from streets, roofs and other sources
- Sanitary wastewater is (in theory) totally excluded
  - Plumbing cross connection
  - Leaking sanitary sewers
  - Sanitary sewer overflows
  - Failing septic tanks

Storm drains flow directly to receiving waters

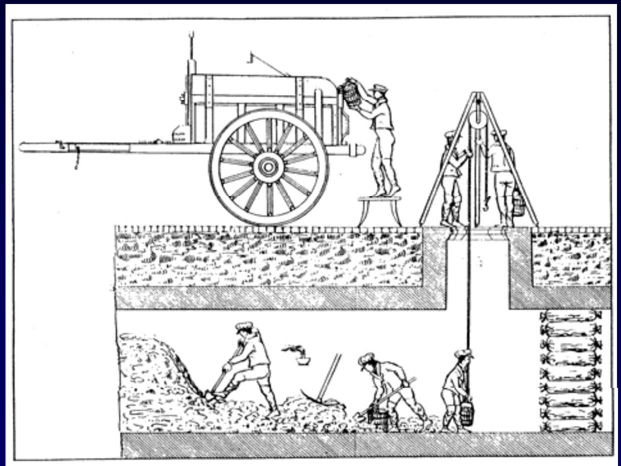
Combined Sewer Systems

- About 15% of communities in the U.S. have a single sewer system that handles both sanitary wastewater and stormwater in the same piping system.
- Most of these are found in older cities with populations of over 100,000.
- Most state regulations now permit the construction of separate sewers only, and expensive projects to separate, or provide partial treatment to combined sewage, is required.
- Combined systems still commonly constructed outside of the US, many include integrated storage and treatment systems

Location of Communities with Combined Sewer Systems



Early Sewer Maintenance and the Need for Large Diameter Sewage Pipes



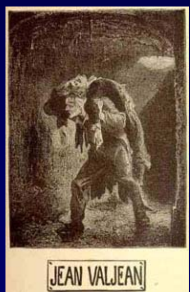
—Clearing drains in Paris, early nineteenth century.

Assignment

Write a short essay (about 2 double-spaced typed pages) comparing either the London or Paris water delivery and wastewater collection systems to modern systems in your community.

"... the great prodigality of Paris, her marvelous fête, her Beaujon folly, her orgy, her full-handed outpouring of gold, her pageant, her luxury, her magnificence, is her sewer." (*Les Miserables*; Jean Valjean, Book II, ch1, by Victor Hugo; *The Intestine of Leviathan*)

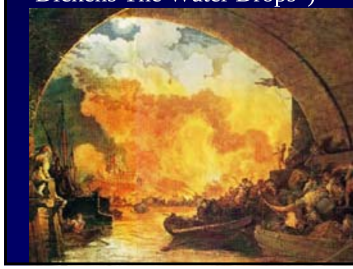
Freely available at:
http://www.readbookonline.net/read/177/5767/



A graphic description of the sewers of Paris in the mid 1800s, and the mystery of their construction and design.

(Read these sections only, not the entire novel, unless you have a really long rainy weekend available!)

Charles Dickens was a satirical journalist, besides a very popular novelist, who championed improved public health. *The Water Drops, a Fairy Tale*, is a little known story graphically describing the urban water system in London in the 1800s. I transcribed it several years ago from a old copy of the book and it is posted at: http://unix.eng.ua.edu/~rpitt/Class/Computerapplications/Module1/Dickens%20The%20Water%20Drops.PDF (or search Google for "Dickens The Water Drops")



The "Great London Fire" burned for 14 days in 1666, right after a plaque outbreak and provided an opportunity to rebuild the city's water system.

Design Approach to Wastewater

- Where does the wastewater come from?
- How much wastewater flow is there going to be?
- How is the wastewater going to be removed and treated?

Where does the wastewater come from?

- Two main categories:
  - Sanitary Wastewater
    Wastewater from residential, commercial, institutional and industrial sources.
  - Stormwater Runoff
    Wastewater resulting from rainfall running off streets, roofs, and other impervious surfaces.
- Today in the U.S., these wastewaters are generally handled separately and in very different ways.

Components of a Community's Wastewater

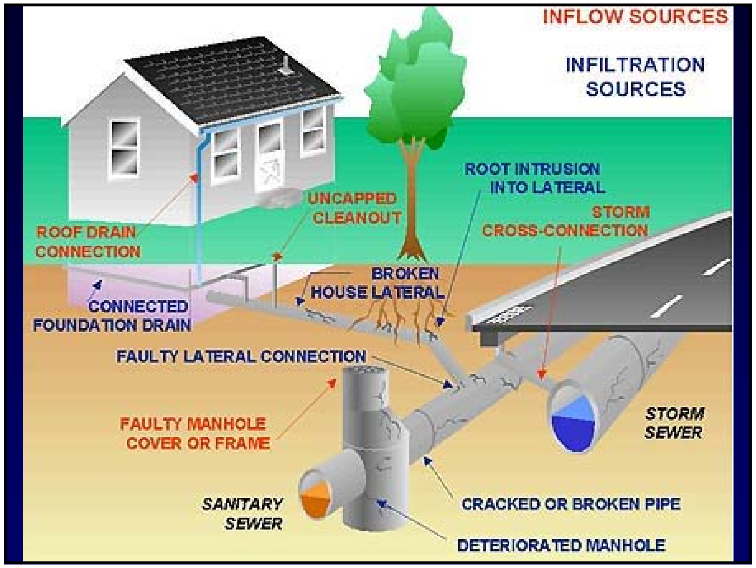
- *Domestic (sanitary) wastewater* – wastewater discharged from residences and from commercial, institutional and similar facilities.
- *Industrial wastewater* – wastewater in which industrial wastes predominate.
- *Infiltration/Inflow (I/I)* – extraneous water that enters the sewer system from the ground through various means, and storm water that is discharged from sources such as roof leaders, foundation drains, and storm sewers.
- *Stormwater* – runoff resulting from rainfall and snowmelt.

Infiltration to Sanitary Sewer Systems

- Groundwater/percolating water in the subsurface entering a sewer system through:
  - Defective pipes
  - Leaking pipe joints
  - Poor connections
  - Cracked manhole walls
  - etc.

Inflow to Sanitary Sewer Systems

- Water entering a sewer system from surface sources such as:
  - Leaking manhole covers
  - Directly connected roof gutters
  - Cellar or foundation drains
  - Cross connections from storm drains and combined sewers
  - Yard and area drains
  - Cooling-water discharges
  - Drains from springs and swampy areas
  - Street wash water
  - Etc.



Inflow and Infiltration Locations

Engineered by-pass in Five-Mile Creek, Birmingham, AL

Engineered Sanitary Sewer Overflows

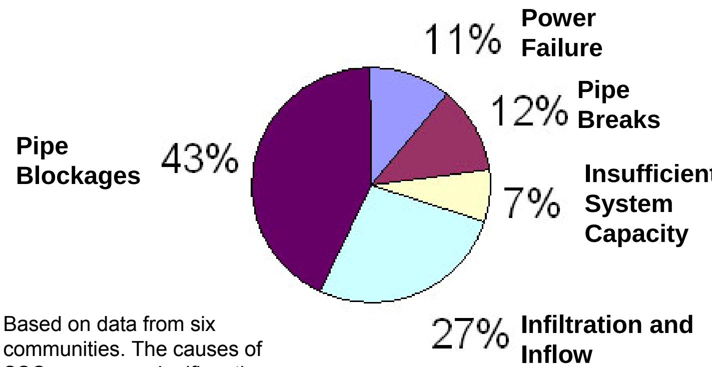
- In the Birmingham area, Jan.-March heaviest rain months of the year. In 1995, over 271 million gal of raw/untreated sewage discharged during these months. SSOs occur in many communities.
- Heavy rains overload the system though inflow and infiltration into cracks, ill-fitting joints, and leaky manholes.
- To prevent hydraulic overload of treatment plants, the excessive sewage bypasses the plant and is discharged without treatment.

Is this legal?

- The Clean Water Act of 1972 only allows bypasses in the cases of emergencies
- Typically, a rain storm is not considered an emergency
- Jefferson County lost a major lawsuit to the EPA, ADEM, and citizens and is required to correct the sanitary sewer system and expand treatment capacity, and spend about $30 million to purchase stream corridors buffers.

Sanitary Sewer Overflows (SSOs) in Separate Sanitary Sewer Systems

Causes of Sanitary Sewer Overflows (other than through engineered by-passes)



Based on data from six communities. The causes of SSOs can vary significantly for different communities.

Effects of SSOs

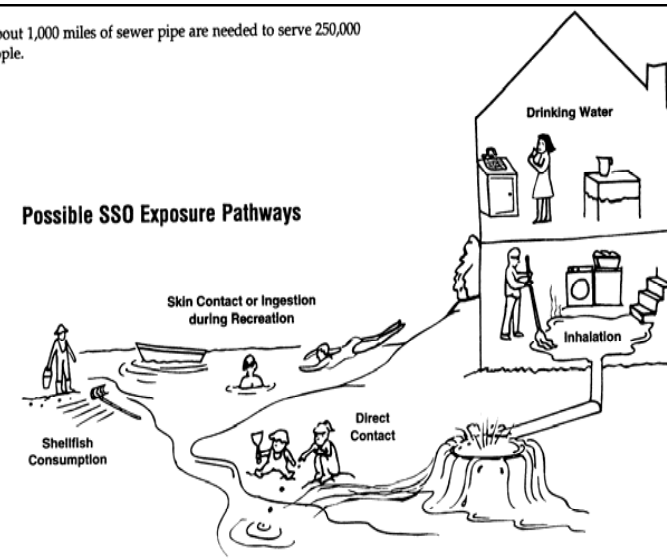
Environmental

- Nutrients and toxicants may cause algal blooms and harm wildlife. Algal blooms remove O_2 from water, smothering aquatic life.
- Decrease in water quality reduces number and range of plants and fish.

Public Health

- Direct contact with water containing sewage can cause skin and ear infections and gastroenteritis, and cuts become infected.
- Illnesses result from eating fish/shellfish that swim in sewage contaminated waters.
- Inhalation and skin absorption can also cause disease.

*About 1,000 miles of sewer pipe are needed to serve 250,000 people.

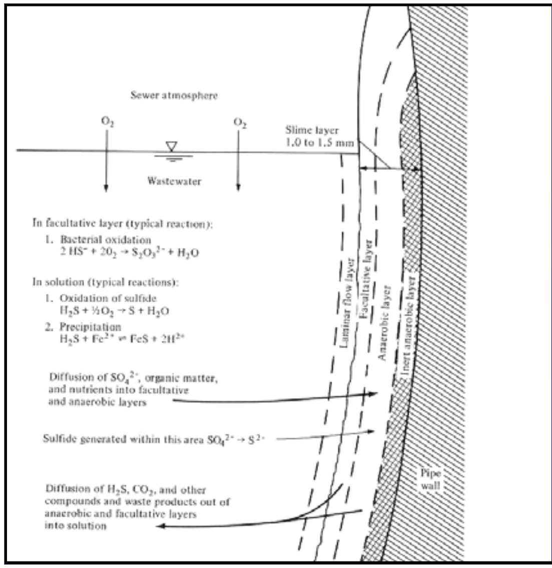


Sewer Corrosion is an Important Cause of Sewerage Failure – Acid Attack

- Takes place when low pH waste, usually industrial wastewater comes in contact with the concrete sewer structure.
- Corrosion is easily identifiable due to its propensity of attacking below the wastewater level or anywhere the wastewater contacts the cement structure on a regular basis.

Sewer Corrosion – Hydrogen Sulfide

- **Sulfide attack, hydrogen sulfide corrosion or simply sulfide corrosion**.
  - Extremely costly problem.
  - Closely related to acid attack in that they both involve sulfuric acid attacking the structures.
  - However, hydrogen sulfide corrosion can be found above the wastewater surface, usually in the crown of the pipe and is caused mainly by biological processes.
  - Slow moving sewage allows anaerobic bacteria to reduce sulfate ions to sulfide ions.
  - Corrosion occurs when the produced H_2S gas condenses on the sewer crown.
  - Condensate oxidized by aerobic bacterium into H_2SO_4.
  - The resulting sulfuric acid destroys the concrete above the normal wastewater level in the pipe.



Hydrogen sulfide generation in wastewater with more than 1 mg/L DO

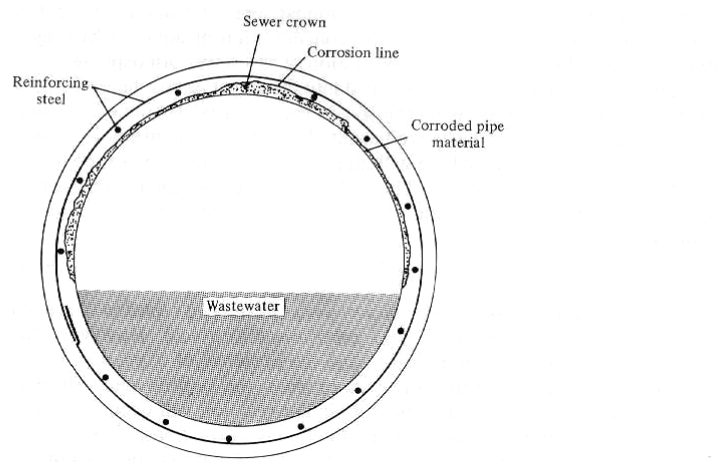


Figure 7-7 Schematic representation of typical corrosion pattern in reinforced-concrete sewer pipe.

- H_2S reacts with metals in the fittings and electronic equipment and all forms of iron and steel.
- If sewer pipes are made of these materials, they can be attacked from both sides.
  - These bacteria reduce the sulfate in the groundwater to precipitate iron (II) sulfides, which are key in the corrosion of the exterior of the pipes.
  - This type of corrosion is not exclusive to sewer pipes. This corrosion can affect any type of pipe exposed to soils containing sulfate.

Sulfide Generation based on Z values

$$Z = (0.308)\left(\frac{EBOD}{(S_o^{0.50})(Q^{0.33})}\right)\left(\frac{P}{B}\right)$$

EBOD is the effective BOD defined by: $EBOD = BOD_5(1.07)^{T-20}$

P/B is the ratio of the wetted perimeter to the top width of the flow

Z Values	Sulfide condition
$Z < 5{,}000$	sulfide rarely generated
$5{,}000 \le Z \le 10{,}000$	marginal condition for sulfide generation
$Z > 10{,}000$	sulfide generation common

Chin 2006

Example 3.31 (Chin 2006)

A 915 mm diameter concrete pipe has a slope of 0.9% and the flow is 1.7 m^3/s. If the BOD_5 is 300 mg/L, determine the potential for sulfide generation when the wastewater temperature is 25°C.

The P/B ratio can be calculated graphically after determining the d/D ratio, or by using the trial and error method using:

$$\frac{P}{B} = \frac{\theta}{2\sin(\theta/2)}$$

where θ is the angle from the center of the pipe to the edge of the water surface, in radians. The following equation can be solved by iteration to obtain θ:

$$\theta^{-2/3}(\theta - \sin\theta)^{5/3} - 20.16nQD^{-8/3}S_o^{-1/2} = 0$$

$$\theta^{-2/3}(\theta - \sin\theta)^{5/3} - 20.16(0.013)(1.7m^3/\sec)(0.915m)^{-8/3}(0.009)^{-1/2} = 0$$

simplifying: $\theta^{-2/3}(\theta - \sin\theta)^{5/3} = 5.95$

resulting in θ of 4.3 radians, therefore:

$$\frac{P}{B} = \frac{4.3\ radians}{2\sin(4.3\ radians/2)} = 2.57$$

$$EBOD = 300\ mg/L(1.07)^{25-20} = 421mg/L$$

$$Z = (0.308)\left(\frac{421mg/L}{(0.009)^{0.50}(1.7m^3/\sec)^{0.33}}\right)(2.57) = 2{,}948$$

Therefore, hydrogen sulfide will be rarely generated.

Sewer Corrosion Problems

– Biggest Problem: Loss of structural integrity. When the concrete is eroded more and more over time the walls can become very thin, and even disappear in some cases.
  - Vero Beach, FL (1990). Sulfide levels in the sewage were averaging 12-15 mg/L and gaseous H_2S readings in excess of 900 parts per million. A 12-ft vertical drop located in a wastewater-treatment-plant influent channel was constructed. In four months time this newly constructed structure lost four inches of concrete.
  - St. Louis (1987). "12 in. thick concrete baffle walls virtually disappeared".

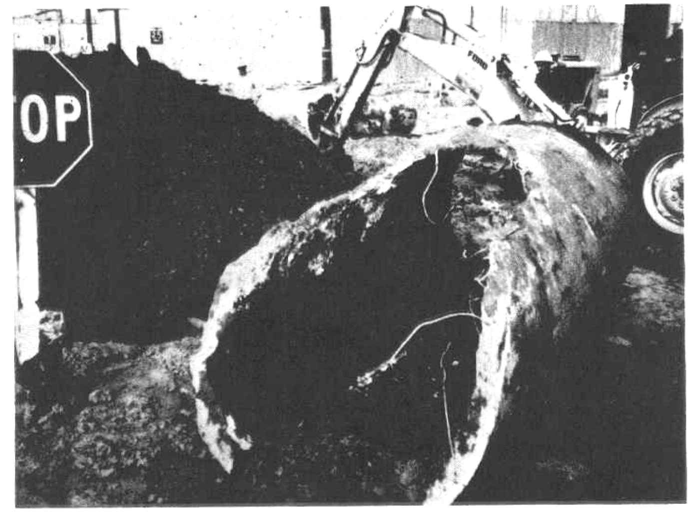


Figure 7-8 Sewer pipe corroded by hydrogen sulfide. (*Courtesy E. Rogers*)

Sewer Corrosion Causes Leaking Sewer Lines

- Poorly constructed/maintained collection lines allow large amounts of groundwater seepage.
- Amount of groundwater infiltration often enough to overload treatment plants.
- During storms, rainwater inflow also overloads a system.
- Surges in volume of wastewater from these inflows often enough to overload systems even when infiltration is relatively low.
- Combined effects of I&I may result in sustained flows far higher than plants were designed to handle and peak flows many times greater still.
- These usually cause some sort of bypass into a receiving water.
- I & I can cause raw sewage in collection systems to backup into homes, streets and yards.

Sewer Corrosion Causes Reduced Flow Capacity of Drainage Pipes

- Increased roughness of the pipe can greatly reduce a pipe's design flow rate and, during periods of heavy use, cause the system to back-up.
- In times of normal use, the lowered velocities can cause even more corrosion to take place as the bacterium will thrive in the stagnant conditions. In this case, the corrosion continues until some preventive measures are taken, or the sewer collapses and fails.

Calculation/Estimation of Infiltration/Inflow (I&I)

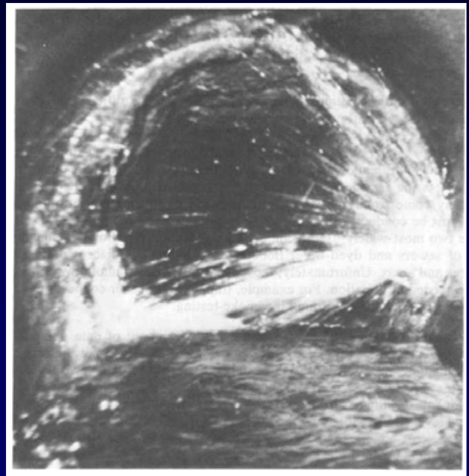


Figure 6-8 Photograph of sewer pipe interior taken during I/I analysis

Graphical Identification of I&I

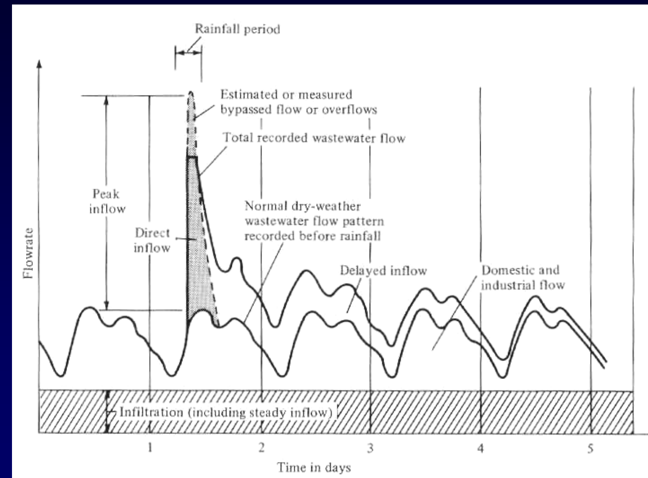


Figure 6-1 Graphic identification of infiltration/inflow.

Smoke Testing to Identify Inflow Locations

Calculation/Estimation of Infiltration/Inflow for New Construction

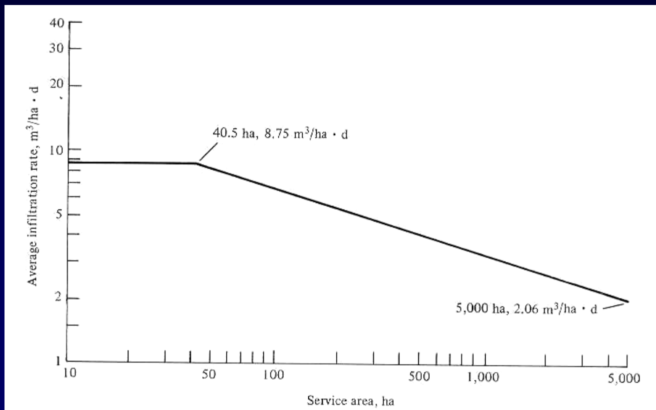


Figure 3-1 Average infiltration rate allowance for new sewers. Note: ha × 2.4711 = acre; m³/ha·d × 106.9 = gal/acre·d.

Design Approach to Wastewater

- Where does the wastewater come from?
- How much wastewater flow is there going to be?
- How is the wastewater going to be removed and treated?

Sources and Rates of Domestic Wastewater Flows

- Small residential districts – wastewater flows determined based on population density and average per capita contribution of wastewater.
- Large residential districts – wastewater flows developed based on land use areas and anticipated population density (typically rates are based on wastewater flows from nearby areas).
- If data is unavailable, estimate 70% of the domestic water-withdrawal rate is returned to the sanitary sewer system.
- In all cases, should try to obtain local wastewater flows for a similar area.

Example Relationship between Water and Wastewater Flows

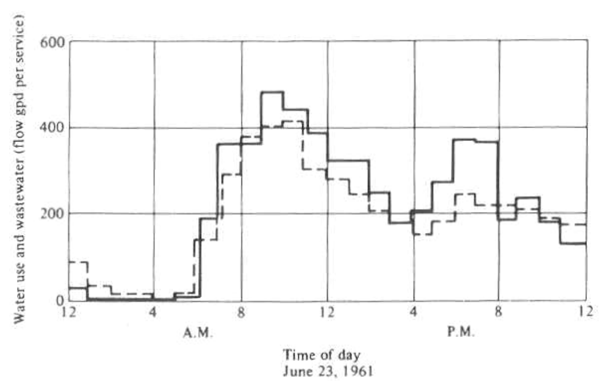
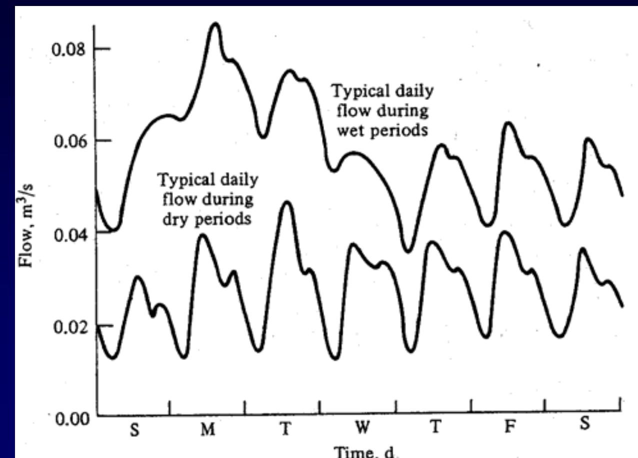
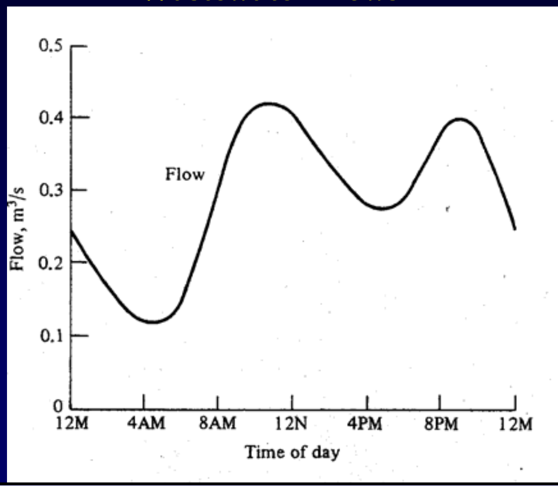


Figure 4.14 Comparison of water use (solid line) and wastewater flow (dashed lines) on days when little sprinkling occurred. (From Residential Water-Use Research Project, Johns Hopkins University and Federal Housing Administration, 1963.)

Example Daily/Weekly Variations in Residential Wastewater Flows for Dry and Wet Periods



Typical Hourly Variations in Residential Area Wastewater Flows



Example 3.29 (Chin 2006)

A trunk sewer is to be sized for a 25 km^2 (2,500 ha) city. It will be 60% residential, 30% commercial, and 10% industrial. The residential area will have 40% large lots, 55% small single-family lots, and 5% multi-story apartments. The average domestic wastewater flowrate is 800 L/d/capita (9.26×10^{-6} m^3/sec/person), the average commercial flowrate is 25,000 L/D/ha ($2.89\times10^{-4} m^3$/sec/ha), and the average industrial flowrate is 40,000 L/d/ha ($4.63\times10^{-4} m^3$/sec/ha). I&I is 1,000 L/d/ha for the entire area. Estimate the peak and minimum flows to be handled by the trunk.

The saturation densities for the residential areas are given in the adjacent table:

Type of area	Density (persons/ha)
Large lots	5–7
Small lots, single-family	75
Small lots, two-family	125
Multistory apartments	2,500

Source: American Concrete Pipe Association (1981).

The residential area will be 60% of 2,500 ha = 1,500 ha. The flowrates for each residential area will be:

Type	Area (ha)	Density (persons/ha)	Population	Flow (m^3/s)
Large lots	0.40(1500) = 600	6	3,600	0.03
Small single-family lots	0.55(1500) = 825	75	61,875	0.57
Multistory apartments	0.05(1500) = 75	2,500	187,500	1.74
Total			252,975	2.34

The commercial area will be 30% of 2,500 ha = 750 ha, with a flowrate of $2.89\times10^{-4} m^3$/sec/ha, the average flow for commercial areas will therefore be 0.22m^3/sec.

The industrial area covers 10% of 2,500 ha = 250 ha, with a flowrate of $4.63\times10^{-4} m^3$/sec/ha, the average flow for industrial areas will therefore be 0.12 m^3/sec.

The I&I for the entire area is: (1,000 L/ha)(2500 ha) = 2.5×10^6L/day = 0.03m^3/sec

The total city flow, excluding I&I, will therefore be: 2.34 + 0.22 + 0.12 = 2.68 m^3/sec. The total city population will be 252,975 (or 252.975 thousands of people). The peak and minimum flow rates can therefore be estimated:

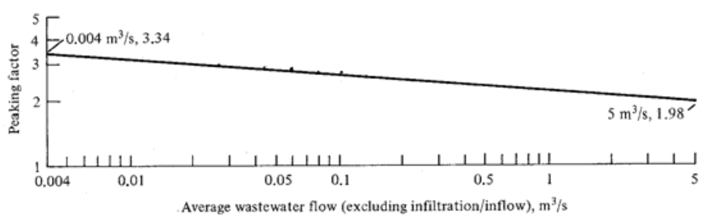
$$\frac{Q_{peak}}{Q_{ave}} = \frac{5.5}{p^{0.18}} = \frac{5.5}{(252.975)^{0.18}} = 2.0$$

$$\frac{Q_{\min}}{Q_{ave}} = 0.2\,p^{0.16} = 0.2(252.975)^{0.16} = 0.48$$

The peak flow is therefore estimated to be: 2.0 (2.68 m^3/sec) + 0.03 m^3/sec = 5.39 m^3/sec

The minimum flow is estimated to be: 0.48 (2.68 m^3/sec) + 0.03 m^3/sec = 1.32 m^3/sec

Peaking Factor for Residential Wastewater Flows



Average Wastewater Flows from Residential Sources

Source	Unit	Flow, L/unit-day	
		Range	**Typical**
Apartment	Person	200 – 340	260
Hotel, resident	Resident	150 – 220	190
Individual Dwellings			
Average Home	Person	190 – 350	280
Better Home	Person	250 – 400	310
Luxury Home	Person	300 – 550	380
Semimodern Home	Person	100 – 250	200
Summer Cottage	Person	100 – 240	190

Average per-capita wastewater domestic flowrates.

City	Flowrate (L/d/capita)	Comments
Berkeley, CA	350	
Boston, MA	380	includes infiltration; multiply by 3 when sewer is flowing full
Des Moines, IA	380× factor	factor = $\frac{18+\sqrt{P}}{4+\sqrt{P}}$ where P is the population in thousands
Detroit, MI	980	
Las Vegas, NV	950	
Little Rock, AR	380	
Milwaukee, WI	1,000	plus additional flow for inflow/infiltration
Orlando, FL	950	
Shreveport, LA	570	plus 5,600 L/d/ha infiltration

Source: ASCE. *Gravity Sanitary Sewer Design and Construction.* Copyright © 1982 by ASCE. Reprinted by permission.

Chin 2000

Average Wastewater Flows from Commercial Sources

Source	Unit	Flow, L/unit-day	
		Range	**Typical**
Airport	Passenger	8 – 15	10
Automobile Service Station	Vehicle served	30 – 50	40
	Employee	35 – 60	50
Bar	Customer	5 – 20	8
	Employee	40 – 60	50
Hotel	Guest	150 – 220	190
	Employee	30 – 50	40
Industrial Building (excluding industry & café)	Employee	30 – 65	55

Average Wastewater Flows from Commercial Sources (cont.)

Source	Unit	Flow, L/unit-day	
		Range	Typical
Laundromat	Machine	1800 – 2600	2200
	Wash	180 – 200	190
Motel	Person	90 – 150	120
Motel with Kitchen	Person	190 – 220	200
Office	Employee	30 – 65	55
Restaurant	Meal	8 – 15	10
Rooming House	Resident	90 – 190	150

Average Wastewater Flows from Commercial Sources (cont.)

Source	Unit	Flow, L/unit-day	
		Range	Typical
Store, Department	Toilet room	1600 – 2400	2000
	Employee	30 – 50	40
Shopping Center	Parking space	2 – 8	4
	Employee	30 – 50	40

Industrial Wastewater Estimation

- Industries without internal reuse programs: approximately 85 to 95% of water used will be returned to the sanitary sewer system.
- Large industries with internal-water-reuse programs: need data on how much water is re-used internally.

Reported commercial and industrial area wastewater flowrates.

City	Commercial	Industrial
Grand Rapids, MI	150–190 L/person/day, office buildings 1,500–1,900 L/day/room, hotels 750 L/d/bed, hospitals 750–1,150 L/d/room, schools	2.3×10^6 L/d/ha
Kansas City, MO	47,000 L/d/ha	94,000 L/d/ha
Memphis, TN	19,000 L/d/ha	19,000 L/d/ha
Santa Monica, CA	91,000 L/d/ha	127,000 L/d/ha

Source: American Concrete Pipe Association, 1981. Adapted by permission.

Chin 2000

Average Wastewater Flows from Institutional Sources

Source	Unit	Flow, L/unit-day	
		Range	Typical
Hospital, Medical	Bed	500 – 950	650
	Employee	20 – 60	40
Hospital, Mental	Bed	300 – 550	400
	Employee	20 – 60	40
Prison	Inmate	300 – 600	450
	Employee	20 – 60	40
Rest Home	Resident	200 – 450	350
	Employee	20 – 60	40

Average Wastewater Flows from Institutional Sources (cont.)

Source	Unit	Flow, L/unit-day	
		Range	Typical
School, Day			
w/ café., gym, showers	Student	60 – 115	80
w/ café., no gym or showers	Student	40 – 80	60
w/o café., gym, shower	Student	20 - 65	40
Schools, boarding	Student	200 – 400	280

Average Wastewater Flows from Recreational Sources

Source	Unit	Flow, L/unit-day	
		Range	Typical
Apartment, Resort	Person	200 – 280	220
Cabin, Resort	Person	130 – 190	160
Cafeteria	Customer	4 – 10	6
	Employee	30 – 50	40
Campground (Developed)	Person	80 – 150	120
Cocktail Lounge	Seat	50 – 100	75
Coffee Shop	Customer	15 – 30	20
	Employee	30 – 50	40

Average Wastewater Flows from Recreational Sources (cont.)

Source	Unit	Flow, L/unit-day	
		Range	Typical
Country Club	Member present	250 – 500	400
	Employee	40 – 60	50
Day Camp (no meals)	Person	40 – 60	50
Dining Hall	Meal served	15 – 40	30
Dormitory, Bunkhouse	Person	75 – 175	150
Hotel, Resort	Person	150 – 240	200
Laundromat	Machine	1800 – 2600	2200

Average Wastewater Flows from Recreational Sources (cont.)

Source	Unit	Flow, L/unit-day	
		Range	Typical
Store, Resort	Customer	5 – 20	10
	Employee	30 – 50	40
Swimming Pool	Customer	20 – 50	40
	Employee	30 – 50	40
Theater	Seat	10 – 15	10
Visitor Center	Visitor	15 – 30	20

Water Reduction Measures: Per Capita Wastewater Flows from Conventional Domestic Devices

Device	Wastewater Flow	
	L/capita-day	Percent
Bathtub Faucet	30.3	12
Clothes Washing Machine	34.1	14
Kitchen Sink Faucet	26.5	11
Lavatory Faucet	11.4	5
Shower Head	45.4	19
Toilet	94.6	39

Flow-Reduction Devices and Systems

Device/System	Description and/or Application
Batch-Flush Valve	Used extensively in commercial applications. Can be set to deliver between 1.9 L/cycle for urinals and 15 L/cycle for toilets.
Brick in Toilet Tank	A brick or similar device in a toilet tank achieves only a slight reduction in wastewater flow.
Dual-Cycle Tank Insert	Insert converts conventional toilet to dual-cycle operation. In new installations, a dual-cycle toilet is more cost effective than a conventional toilet with a dual-cycle insert.
Dual-Cycle Toilet	Uses 4.75 L/cycle for liquid wastes and 9.5 L/cycle for solid wastes.
Faucet Aerator	Increases the rinsing power of water by adding air and concentrating flow, thus reducing the amount of wash water used. Comparatively simple and inexpensive to install.

Flow-Reduction Devices and Systems (cont.)

Device/System	Description and/or Application
Level Controller for Clothes Washer	Matches the amount of water used to the amount of clothes to be washed.
Limiting-Flow Shower Head	Restricts and concentrates water passage by means of orifices that limit and divert shower flow for optimum use by the bather.
Pressure-Reducing Valve	Maintains how water pressure at a lower level than that of the water-distribution system. Reduces household flows and decreases the probability of leaks and dripping faucets.
Recirculating Mineral Oil Toilet System	Uses mineral oil as a water-transporting medium and requires no water. Operates in a closed loop in which toilet wastes are collected separately from other household wastes and are stored for later pickup by vacuum truck. In the storage tank, wastes are separated from the transporting fluid by gravity. The mineral oil is drawn off by pump, coalesced, and filtered before being recycled to the toilet tank.

Flow-Reduction Devices and Systems (cont.)

Device/System	Description and/or Application
Reduced-Flush Device	Toilet tank insert that either prevents a portion of the tank contents from being dumped during the flush cycle or occupies a portion of the tank volume so that less water is available per cycle.
Urinal	Wall-type urinal for home use that requires 5.7 L/cycle.
Vacuum-Flush Toilet System	Uses air as a waste-transporting medium and requires about 1.9 L/cycle.
Wash-Water Recycle System for Toilet Flushing	Recycles bath and laundry wastewater for use in toilet flushing.

Reductions Achieved by Flow-Reduction Devices and Systems (cont.)

Device	Wastewater Flow Reduction	
	L/capita-day	Percent
Level Control for Clothes Washer	4.5	2
Pressure-Reducing Valve	60.6	25
Recirculating Mineral Oil Toilet System	94.6	39
Shower		
Limiting-Flow Valve	22.7	9
Limiting-Flow Shower Head	28.4	12

Reductions Achieved by Flow-Reduction Devices and Systems (cont.)

Device	Wastewater Flow Reduction	
	L/capita-day	Percent
Toilet		
Reduced-Flush Device	37.9	16
Single-Batch-Flush Valve	28.4	12
Toilet and Urinal with Batch-Flush Valves	54.9	23
Urinal with Batch-Flush Valve	26.5	11
Water-Saver Toilet	28.4	12
Vacuum-Flush Toilet System	85.2	35
Washwater Recycle System for Toilet Flushing	94.6	39

Design Approach to Wastewater

- Where does the wastewater come from?
- How much wastewater flow is there going to be?
- How is the wastewater going to be removed and treated?

Types of Sewer Pipes in a Typical Separate Sanitary Collection System

- Sanitary sewers must be laid near all occupied buildings in order to collect wastewater.
- Building Connecting Pipes
  - Connects the building plumbing to the public sanitary wastewater collection system.
  - Convey wastewater from the buildings to lateral or branch sewer, or any other sewer except another building sewer.
  - Normally begins outside the building foundation

Types of Sewer Pipes in a Typical Separate Sanitary Collection System (cont.)

- Lateral or Branch Sewers
  - Forms the first element of a wastewater collection system.
  - Usually in streets or special utility easements.
  - Used to collect wastewater from one or more building sewers and convey it to a main sewer.
- Main Sewers
  - Main sewers are used to convey wastewater from one or more lateral sewers to trunk sewers or to intercepting sewers

Types of Sewer Pipes in a Typical Separate Sanitary Collection System (cont.)

- Trunk Sewers
  - Trunk sewers are large sewers that are used to convey wastewater from main sewers to treatment or other disposal facilities, or to large intercepting sewers.
- Interceptor Sewers
  - Intercepting sewers are large sewers that are used to intercept a number of main or trunk sewers and convey the wastewater to treatment or other disposal facilities

Sewer Pipe Types in a Collection System

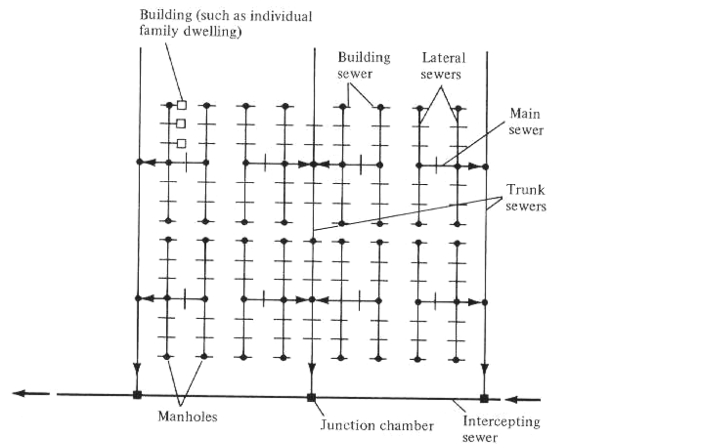


Figure 4-1 Definition sketch for various types of sewers in a typical collection system (See Table 4-2 for descriptions of sewers).

Design Approach to Wastewater Collection and Treatment Systems

- Where does the wastewater come from?
- How much wastewater flow will be in the pipes?
- How is the wastewater going to be removed and treated?
  - Treatment is the focus of another class!

Choice of Wastewater Collection System

- Wherever possible, use a gravity flow system.
- When the natural slopes are not sufficient to convey flow, a combination of gravity and pressure flow systems may be used.
  - The gravity sewer transports flows to a collection point, such as a wet well.
  - The wastewater is pumped from the wet well through a force main over some obstruction or hill to another gravity sewer, or directly to a wastewater treatment facility.

Combination Gravity and Pressure Sanitary Sewer System

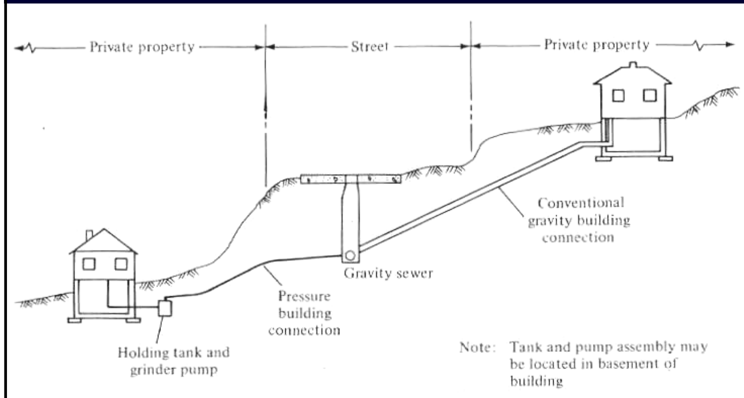


Figure 4-13 Typical pressure connection to gravity sewer from isolated low building site.

Wet Well Pumping Station for Pressure Sewer System

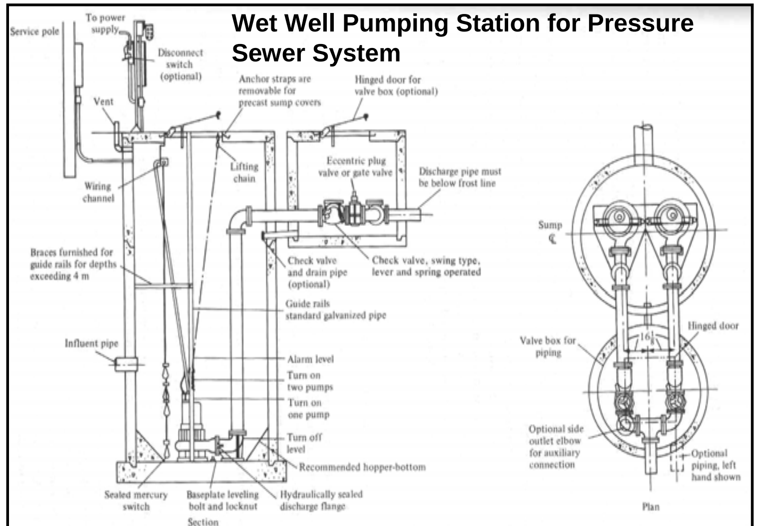


Figure 9-9 Wet-pit pumping station.

Design of Gravity-Flow Sanitary Sewers

- Conduct preliminary investigations
- Review design considerations and select basic design data and criteria
- Design the sewer

Preliminary Investigations

- Obtain pertinent maps
- Describe existing structures and utilities
- Determine groundwater conditions
- Determine character of the soil (and subsurface obstructions) in which sewers are to be constructed

Map Sources

- Site map prepared by land developer
- GIS information from city or county
- Municipal and county engineers and surveyors
- Regional planning agencies
- Local planning boards
- Tax assessment boards
- Land-title and insurance companies
- Public utility officials
- For larger projects: U.S.G.S., State Agencies, NRCS

Information from maps

- Location of streets, alleys, drainage ditches, public parks and railways
- Location of buildings
- Location of ponds and streams with surface water elevations
- Land elevation and contours
- Geologic conditions (sinkholes, bedrock, soil chemistry/acidity)

Information on existing structures and utilities

- Elevations of the sills of buildings and depths of their basements
- Character, age, and condition of the pavements of streets in which sewers will be laid
- Location of water and gas mains, electric conduits, drain lines, and other underground structures

Sanitary Sewer: Basic Design Considerations

- Wastewater flow
- Hydraulic-design equation
- Sewer pipe materials
- Minimum pipe sizes
- Minimum and maximum velocities
- Slopes and cover
- Evaluation of alternative alignments or designs
- Selection of appropriate sewer appurtenances

Hydraulic Design Equation

- The Manning equation is commonly used
- Manning n value not less than 0.013 recommended for new sewers
  - Assumes first class construction
  - Pipe sections not less than 5 feet long
  - True and smooth inside surfaces
  - Manholes, building connections, other flow-disturbing appurtenances
  - Uncertainties inherent in sewer design and construction

Sewer Pipe Materials

- Ductile Iron
- Reinforced Concrete
- Pre-stressed Concrete
- Polyvinyl Chloride
- Vitrified Clay

Ductile Iron Pipe

- Available sizes: 4 - 54 in (100-1350mm)
- Often used for river crossings and where the pipe must support unusually high loads
- Useful where unusually leakproof sewer is required or where unusual root problems are likely to develop
- Susceptible to acid corrosion and hydrogen sulfide attack
- Generally should not be used where groundwater is brackish

Reinforced Concrete Pipe

- Available sizes: 12-144 in (300-3600 mm)
- Readily available in most areas
- Susceptible to corrosion of interior if the atmosphere over wastewater contains hydrogen sulfide, or from outside if buried in an acid or high-sulfate environment

Pre-Stressed Concrete Pipe

- Available sizes: 16-144 in (400-3600 mm)
- Especially suited to long transmission mains without building connections and where precautions against leakage are required.
- Susceptibility to corrosion as in reinforced concrete

Polyvinyl Chloride Pipe

- Available sizes: 4-15 in (100-375 mm)
- Used as an alternative to asbestos-cement and vitrified-clay pipe.
- Light-weight but strong
- Highly resistant to corrosion

Vitrified Clay Pipe

- Available sizes: 4-36 in (100-900 mm)
- For many years the most widely used pipe for gravity sewers
- Still widely used in small and medium sizes
- Resistant to corrosion by both acids and alkalis
- Not susceptible to damage from hydrogen sulfide
- Brittle and susceptible to breakage

Pipe Sizes

- Minimum size 8 inches (200 mm)
- Smallest sewers should be larger than the building sewer connections in general use in the area
- Most common size of building connection is 6 inches
- Connections of 5 and 4 inches have been used successfully in some areas

Velocities

- Minimum velocity of 2.0 ft/sec (0.6 m/sec) with flow at ½ full or full depth
- Maximum average velocities of 8-10 ft/sec (2.5-3.0 m/sec) at design depth of flow
- Minimum and maximum velocities may be specified in state and local standards

Gravity Sewer Minimum Pipe Slopes

Size inches (mm)	Slope, m/m[a] n=0.013	Slope, m/m[a] n=0.015
8 (200)	0.0033	0.0044
10 (250)	0.0025	0.0033
12 (300)	0.0019	0.0026
15 (375)	0.0014	0.0019
18 (450)	0.0011	0.0015
21 (525)	0.0009	0.0012
24 (600)	0.0008	0.0010
27 (675)	0.0007[b]	0.0009
30 (750)	0.0006[b]	0.0008[b]
36 (900)	0.0004[b]	0.0006[b]

a. Based on Manning's equation with a minimum velocity of 0.6 m/s. Where practicable, steeper slopes should be used

b. The minimum practicable slope for construction is about 0.0008

Sewer Pipe Slopes

- Sewers with flat slopes may be required to avoid excessive excavation where surface slopes are flat or the changes in elevation are small.
- In such cases, the sewer sizes and slopes should be designed so that the velocity of flow will increase progressively, or at least will be steady throughout the length of the sewer.

Alternative Sewer Alignments and Designs

- It is generally not advisable to construct ordinary sewers outside public rights of way unless there is a significant advantage in cost or other condition.
- Interceptors are often constructed in private easements because the most favorable locations for interception are usually in valleys near natural drainage channels

Sewer Appurtenances

Primary appurtenances for sanitary sewers:

- Manholes
- Drop inlets to manholes
- Building connections
- Junction chambers

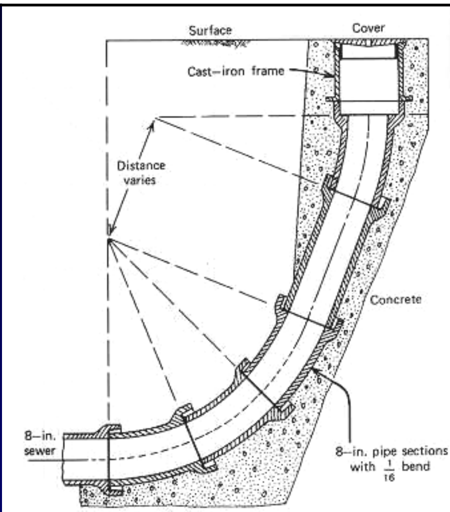
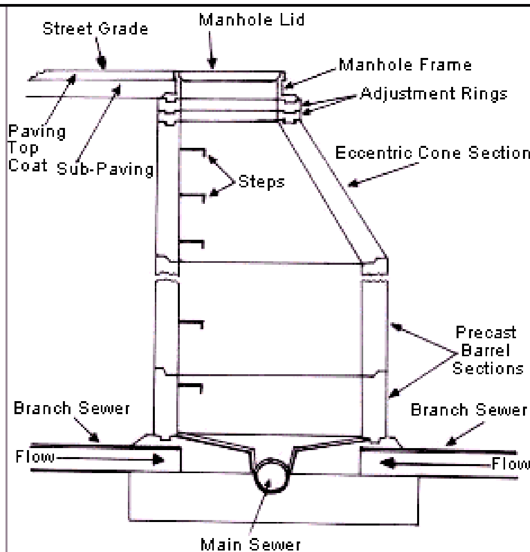


Figure 10-5 Terminal cleanout for ends of short branch or lateral sewers.

Manholes

- The number of manholes must be adequately spaced so that the sewers can be easily inspected and maintained.
- For sewers that are 48” and smaller, manholes should be located at changes in size, slope or directions.
- For larger sewers, these changes may be made without installing a manhole.



Typical Manholes. The drop manhole is needed when the invert of the inflow pipe is more than 0.6 m above the elevation that would be obtained by matching the crowns of the inflow and outflow pipes. This provides an acceptable workspace for maintenance and repair, instead of allowing sewage to cascade down from a large height.

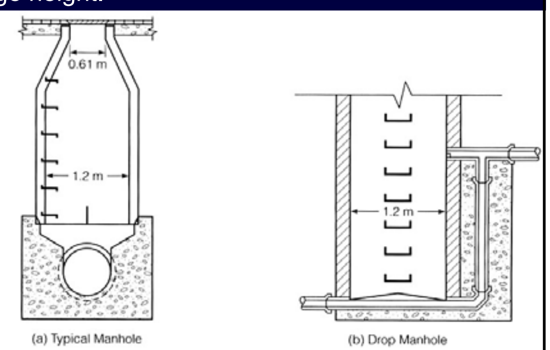
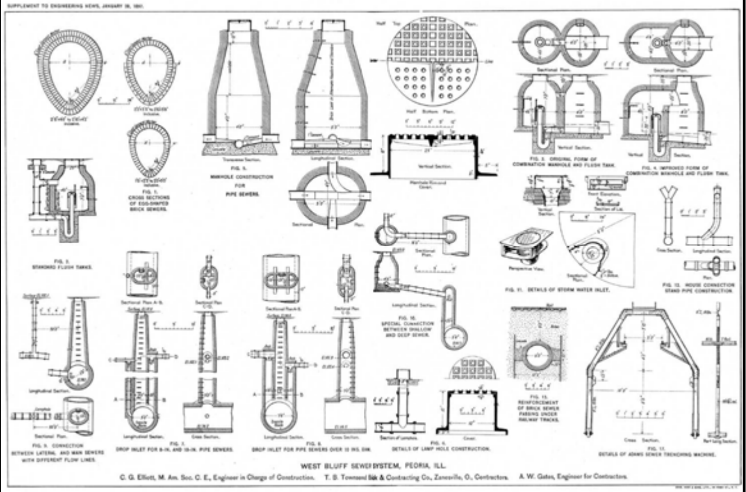


Figure 4.35 ■ Typical Manholes
ASCE. *Gravity Sewer Design and Construction.* Copyright © 1982 by ASCE. Reprinted by permission.

Chin 2000

Peoria, IL, Manholes as Published in 1897



Manhole Frames and Covers

Manhole Size

- Large enough to provide easy access to the sewer
- Room for a worker to handle a shovel
- Bottoms are usually concrete, sloping toward an open channel which is an extension of the lowest sewer. Bottom should provide footing for a person working in the manhole
- Manholes in small sewers are usually about 4 feet in diameter when the sewers have circular cross sections
- In large sewers, larger manholes may be required to accommodate larger cleaning devices

Manhole Spacing: General Guidance

- Sewers ≤ 24 in (600mm)
  Place manholes at intervals not greater than 350 ft (100m).
- Sewers 27 – 48 in (700-1200mm)
  Place manholes at intervals not greater than 400 ft (120m).
- Sewers > 48 in (1200 mm)
  Manholes may be placed at greater intervals depending on local conditions like breaks in grade, location of street intersections, etc.

Steps in the Design of a Sanitary Sewer System

1. Estimate the wastewater flow rates for the design period and any local conditions that may affect the hydraulic operation of the system.
   - Design for the expected peak flows (peak hourly flows from residential, commercial, institutional and industrial sources from the entire service area and add the peak infiltration and inflow allowance for the entire service area).

Steps in the Design of a Sanitary Sewer System (cont.)

2. Select the hydraulic design equation, sewer-pipe materials and minimum sizes, minimum and maximum velocities, slopes, and covers.
   1. Manning's n of 0.013 recommended when analyzing well-constructed new sewers and 0.015 for most older existing sewers. This value is based on the use of individual pipe sections (not less than 1.5 m, 5 ft long) with true and smooth inside surfaces, and on the assumption that only first-class construction procedures are used.
      - Minimum allowable velocity = 2 ft/sec (0.6 m/sec) at one-half full or full depth. If access for cleaning is difficult, the minimum velocity should be 3 ft/sec (1 m/sec).
      - Maximum allowable velocity = 8 to 10 ft/sec (2.5 to 3.0 m/sec) to prevent damage to the sewer.

Steps in the Design of a Sanitary Sewer System (cont.)

2. ASCE guidance specifies that sanitary sewers up to 375 mm (15 in) be designed to flow half full at the design flow rate, with larger sewers designed to flow three-quarters full. These guidelines reflect that small wastewater flows are much more uncertain than larger flows.
3. Minimum sanitary sewer pipe sizes are usually specified as 205 mm (8 in), laid on a 1% slope. Service connections are usually 150 mm (6 in) or 205 mm (8 in) pipes at a 2% slope.

- Evaluate alternative alignments or designs.
- Select the appropriate sewer appurtenances.
- Review the need for sewer ventilation to minimize H_2S formation.

Preliminary/Tentative Layout

- Locate lines along streets or utility easements (must be in front of all buildings!)
- Use arrows to show direction of flow (normally direction of ground slope)
- Should have sewer system leaving area at its lowest point (with flow coming to that point from areas with higher elevations)
- In flat areas, sewers should be sloped to common collection point
- WATCH OUT FOR PRE-EXISTING UTILITY LINES!!

Vertical Location

- Note where basement/below-ground service connections are required
- Want to have sewer below basement points so you don't have to pump!
- Also must have minimum required cover:
  - 3 m (10 ft) required in northern states
  - 0.75 m (2.5 ft) or more required in southern states

Manhole Locations

- Sewer intersections
- Abrupt changes in horizontal direction or slope
- Pipe size change locations
- Regular intervals along straight runs (for maintenance)
  - Less than, or equal to 100 m (300 ft) – general rule
  - 500 ft – maximum spacing
  - Exception: sewers that can be walked through
- Number manholes and use manhole numbers to identify sewers pipes

Vertical Profile

- Prepared for each sewer line
- Horizontal scale of 1:500 or 1:1000
- Vertical scale of 1:50 or 1:100
- Show following items:
  - Ground surface
  - Street surface (where applicable)
  - Tentative manhole locations
  - Elevations of important subsurface strata such as rock
  - Boring locations
  - Underground structures
  - Basement elevations
  - Cross streets
  - Plan of the sewer line

Design Principles Review

- Changes in direction in small sewers ALWAYS made at a manhole
- Head loss in manhole due to change in direction assumed to be 30 mm (0.1 ft). Drop down-gradient invert by this amount across manhole.
- Losses due to pipe size increases:
  - Provided for by matching the crowns or 0.8 depth points for sewer pipes on each side of manhole.
  - Drop in invert due to matching crowns greater than 30 mm, so head loss due to change in direction can be ignored.
  - Dropping invert of lower sewer (by matching crowns) also ensures that smaller sewer pipe not flowing full unless larger pipe is also full.
- Assume hydraulic grade line parallels invert if sewer line is fairly long and not surcharged (assume uniform flow).

Typical Sewer Design Problem

- Given: Flow
  Velocity
  Minimum pipe size
  Ground elevations and slope
  Pipe material and roughness
  Minimum pipe cover
- Calculate: Pipe slope
  Pipe size
  Pipe alignment
- WATCH COST OF EXCAVATION (slope of pipe versus slope of land)

Sanitary Sewer Design Example

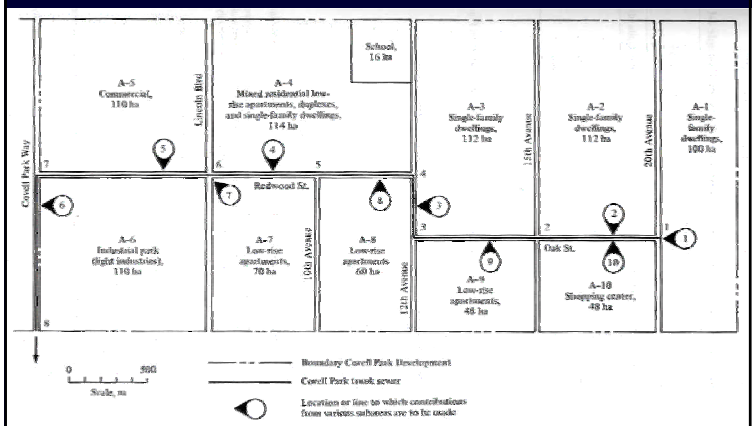


Figure 4-4 Location map for the design of the Covell Park trunk sewer for Example 4-1. (Only major streets are shown.) Note: ha × 2.4711 = acre; m × 3.2808 = ft.

Information for Sanitary Sewer Design Example

- Given:
  - Wastewater saturation densities and wastewater flows for the area.
  - Average wastewater flow from industrial areas = 30 m^3/ha-day (3200 gal/ac-day)
  - Peaking factor for wastewater flow from industrial areas = 2.1

Zoning	Type of development	Saturation population density		Wastewater flows	
		Persons/ha	Persons/ac	L/capita-day	Gal/capita-day
Resid.	Single-family houses	38	15	300	80
Resid.	Duplexes	60	24	280	75
Resid.	Low-rise apartments	124	50	225	60

Information for Sanitary Sewer Design Example (cont.)

- Average wastewater flow from commercial areas = 20 m^3/ha-day (2100 gal/ac-day)
- Peaking factor for wastewater flow from commercial areas = 1.8
- Average wastewater flow from the school = 75 L/student-day (20 gal/student-day)
- Peaking factor for wastewater flow from the school = 4.0
- Anticipated population of the school = 2000 students

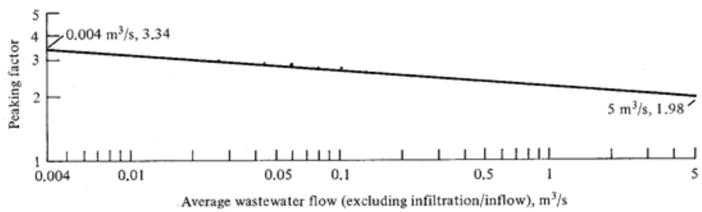


Figure 3-4 Peaking factor for domestic wastewater flows. Note: $m^3/s \times 22.8245$ = Mgal/d.

Calculation of average daily wastewater flows

Area Design.	Development type	Area (ha)	Sat. pop. density (persons/ha)	WW flows (L/cap.-day)	Average WW flow (m^3/day)
A-1	S-Family	100	38	300	1140
A-2	S-Family	112	38	300	1276.8
A-3	S-Family	112	38	300	1276.8
A-4	Mix Resid.	114	(38+60+124)/3 = 74	(300+280+225)/ 3 = 268.3	2263.7
A-4	School	16	2000	75	150
A-5	Comm.	110		20 m^3/ha-day	2200
A-6	Ind.	110		30 m^3/ha-day	3300
A-7	Low-rise Apart.	70	124	225	1953
A-8	Low-rise Apart.	60	124	225	1674
A-9	Low-rise Apart.	48	124	225	1339.2
A-10	Shopping Center	48		20 m^3/ha-day	960

Calculation of average daily wastewater flows (cont.)

Start at most upgradient location and work downgradient until intersection with another pipe, then go to upper end of that pipe and work down to intersection, then work down until next pipe intersection, etc. This example only has one main line, with no branching. More complex situations require care in setting up the calculation sheet.

Calculation of average daily wastewater flows (cont.)

Line Number	Up-stream Manhole	Down-stream Manhole	Feeder Areas	Cum. Av. WW Flow (Land Use) (m^3/day)	Peaking Factor	Peak WW Flow (Land Use) (m^3/day)
1	1	2	A-1 A-2 A-10	Res. 2417 Com. 960	2.9 1.8	R: 7009 C: 1728 Total: 8737
2	2	3	A-9	Res. 1339	3.0	4017
3	3	4	A-3	Res. 1277	3.0	3831
4	4	5	A-8	Res. 1674	3.0	5022
5	5	6	A-4	Res. 2264 School 150	2.9	R:6566 S: 600 Total: 7166
6	6	7	A-7 A-5	Res. 1953 Com. 2200	2.9 1.8	R: 5664 C: 3960 Total: 9624
7	7	8	A-6	Ind. 3300	2.1	6930

Infiltration and Inflow Allowances

- Use the new sewer curve to determine infiltration and inflow allowances. Assumption: Since industrial, commercial and institutional areas typically have a smaller density of sewer pipes, can assume that only a part of the area is contributing to infiltration.
- Assume 50% of area used for infiltration area for finding the infiltration allowance (which is assumed to include inflow) from the curve.

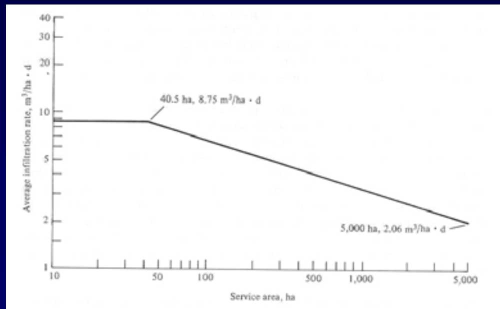


Figure 3-1 Average infiltration rate allowance for new sewers. Note: ha × 2.4711 = acre; m³/ha·d × 106.9 = gal/acre·d

Calculate Peak Daily Flows Entering Each Pipe Segment (with I&I)

Line #	Feeder Areas	Infiltration Area (ha)	Infiltration Allowance (m^3/ha-day)	Infilt. (m^3/day)	Peak WW Flow (m^3/day)	Peak Flow (m^3/day)
1	A-1 A-2 A-10	100 112 (0.5)48 Total: 236	5.4	1274	8737	10011
2	A-9	(0.5)48 Total: 24	8.75	210	4017	4227
3	A-3	112	7.6	8512	3831	12343
4	A-8	60	8.0	480	5022	5502
5	A-4	R: 114 S: (0.5)16 Total: 122	7.6	927	7166	8093
6	A-7 A-5	70 (0.5)110 Total: 125	7.6	950	9624	10574
7	A-6	(0.5)110	8.0	440	6930	7370

Calculate cumulative flows in each pipe segment

Line Number	Feeder Line	In-Pipe Flow (m^3/day)	Entering Flow (m^3/day)	Cumulative Flow (m^3/day)	Cumulative Flow (m^3/sec)
1	None	0	10011	10011	0.116
2	1	10011	4227	14238	0.165
3	2	14238	12343	26581	0.308
4	3	26581	5502	32083	0.371
5	4	32083	8093	40176	0.465
6	5	40176	10574	50750	0.587
7	6	50750	7370	58120	0.673

Pipe Diameter Calculations

- Calculate the pipe diameters assuming these peak flows are 'sewer flowing full conditions.' Assume Manning's n of 0.015 and slopes as shown in the table (slopes are typically determined from post-grading topographic maps of the area).

Example for line 1, using Manning's equation to solve for pipe diameter:

$$D = 1.548\left[\frac{nQ}{S^{0.5}}\right]^{0.375} = 1.548\left[\frac{(0.015)(0.116 m^3/\sec)}{(0.0019)^{0.5}}\right]^{0.375} = 0.462 m$$

The next larger commercial pipe size is 525 mm, which has a full flowing capacity of 10,011 m^3/day with this slope and roughness:

Line Number	Cumulative Flow (m^3/sec)	Slope (m/m)	Exact Diameter (m)	Pipe Diameter (mm)	Full Flow (m^3/day)
1	0.116	0.0019	0.462	525	10011

Pipe Diameter Calculations

- Calculate the pipe diameter assuming these peak flows are 'sewer flowing full conditions.' Assume Manning's n of 0.015 and slopes as shown in the table (slopes are typically determined from post-grading topographic maps of an area).

Line Number	Cumulative Flow (m^3/sec)	Slope (m/m)	Exact Diameter (m)	Pipe Diameter (mm)	Full Flow (m^3/day)
1	0.116	0.0019	0.462	525	13995
2	0.165	0.0015	0.528	600	17803
3	0.308	0.0012	0.667	675	26581
4	0.371	0.0011	0.716	750	32083
5	0.465	0.0010	0.779	900	40176
6	0.587	0.0007	0.849	900	50750
7	0.673	0.0009	0.894	900	58120

Velocity of Flowing Sewage

- Need to calculate the full-flowing velocities at the actual diameters (V_{full}) and the velocities at design flow (using the cumulative flow) through the partial-flow diagram.
  - If the velocity at design flow is greater than 2 ft/sec, the design should be sufficient to regularly achieve self-cleansing velocity. If not, increase the slope of the pipe, or anticipate increased maintenance.
  - If V > 10 ft/sec, need to lessen the slope to prevent erosion of the pipe interior.

Example for first pipe:

$$V_{full} = \frac{1}{n}\left(\frac{D}{4}\right)^{2/3} S^{0.5} = \frac{1}{0.015}\left(\frac{0.525m}{4}\right)^{2/3}(0.0019)^{0.5} = 0.75 m/\sec = 2.5\,ft/\sec$$

$$\frac{Q}{Q_{full}} = \frac{(0.116 m^3/\sec)(86{,}400 \sec/day)}{13{,}995 m^3/day} = 0.716$$

$$d/D = 0.72 \text{ from hydraulic elements figure}$$

$$\frac{V}{V_{full}} = 0.96 \text{ from hydraulic elements figure}$$

$$therefore,\ V = 0.96(2.5\,ft/\sec) = 2.4\,ft/\sec$$

Since this is greater than the desired 2 ft/sec goal, the pipe diameter is suitable for this slope. If the velocity was less than desired, then the slope should be increased (resulting in an increased trench depth at the lower end of the pipe) and the pipe size and resulting velocities re-calculated. This trial-and-error process would be repeated until the desired velocity outcome is achieved. This problem with velocity is most common for the upper pipe segments in residential areas that have little slope, and the minimum pipe diameter is used. In those cases, the slope may have to be significantly increased, which would result in unreasonable trench depths. Anticipated increased maintenance is usually a more reasonable solution.

Sewers Flowing Partly Full

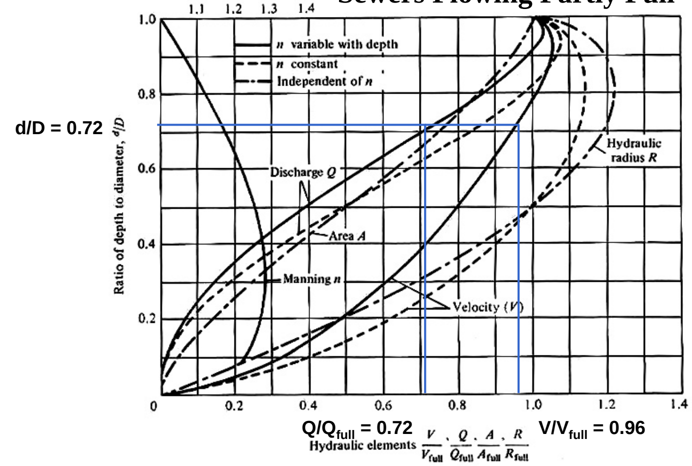


Figure 2-16 Hydraulic elements for circular sewers [10].

Metcalf and Eddy 1981

Example Sewer Profile

Once the final design is complete, need to draw profile maps of the sewer. An example profile map is shown here (it is not the same sewer as this example problem).

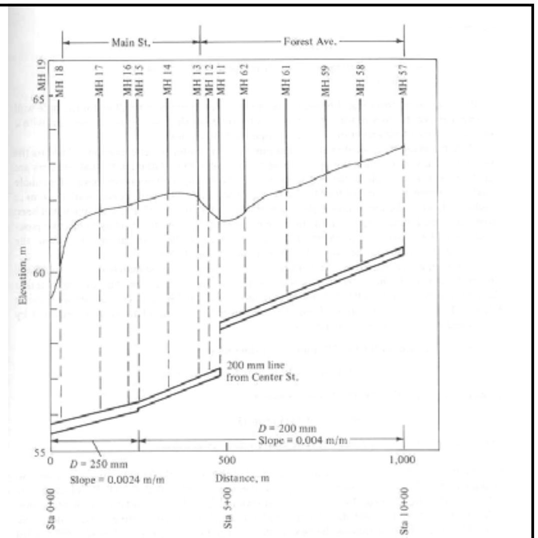


Figure 4-6 Sewer profile work sheet for Example 4-2. Note: m × 3.2808 = ft; mm × 0.03937 = in

Sewer Profile Example (Construction Drawings)

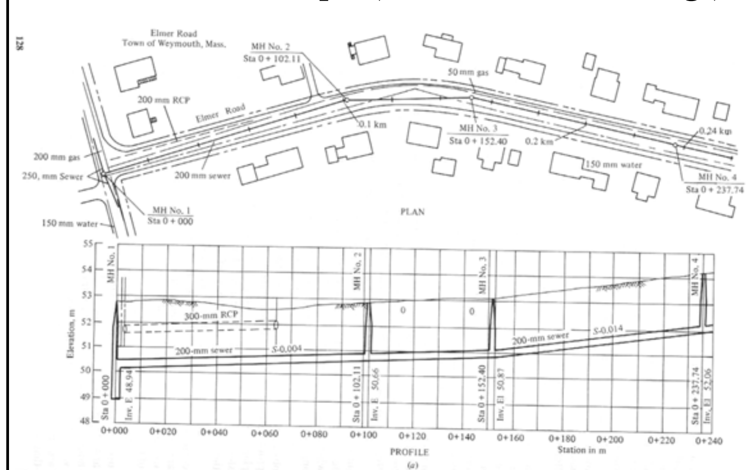
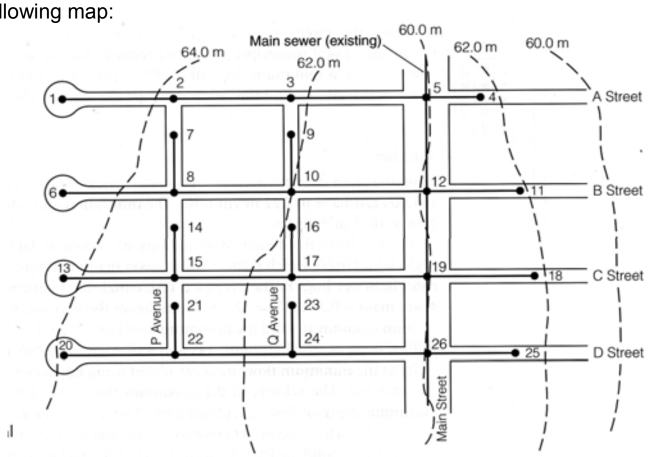


Figure 4-7(a) Typical sewer contract drawing in metric units.

Example 3.32 (Chin 2006)

A sewer system is to be designed to service the residential area shown on the following map:



The average per-capita wastewater flowrate is estimated to be 800 L/D/capita, and the I&I is estimated to be 70 m^3/d/km. This new sewer is to join an existing system at manhole #5, where the average wastewater flow is 0.37 m^3/sec, representing the contribution of about 100,000 people. The existing sewer at MH#5 is 1,065 mm in diameter, has an invert elevation of 55.35 m, and is laid on a slope of 0.9%. The flow will be along Main Street from MH#5 to MH#26. The following table lists the pipe lengths, contributing areas, and ground surface elevations. Design a sewer system between A Street and C Street for a saturation density of 130 persons/ha. Local regulations require:

- -minimum pipe cover of 2 m,
- -minimum slope of 0.08%,
- -peak flow factor of 3.0,
- -minimum flow factor of 0.5, and
- -minimum allowable pipe diameter of 150 mm.
- -the wastewater depth at peak flow must be less than half of the pipe diameter for pipes smaller than 375 mm and less than three-fourths full for larger pipes

Example 3.32 Sewer System Data (Chin 2006)

Line no. (1)	Location (2)	Manhole no. From (3)	Manhole no. To (4)	Length (m) (5)	Contributing area (ha) (6)	Ground surface elevation Upper end (m) (28)	Ground surface elevation Lower end (m) (29)
0	Main Street	—	5	—	—	—	60.04
1	A Street	1	2	53	0.47	65.00	63.80
2	A Street	2	3	91	0.50	63.80	62.40
3	A Street	3	5	100	0.44	62.40	60.04
4	A Street	4	5	89	0.90	61.88	60.04
5	Main Street	5	12	69	0.17	60.04	60.04
6	B Street	6	8	58	0.43	65.08	63.20
7	P Avenue	7	8	50	0.48	63.60	63.20
8	B Street	8	10	91	0.39	63.20	62.04
9	Q Avenue	9	10	56	0.88	62.72	62.04
10	B Street	10	12	97	0.45	62.04	60.04
11	B Street	11	12	125	0.90	61.88	60.04
12	Main Street	12	19	75	0.28	60.04	60.20
13	C Street	13	15	57	0.60	64.40	62.84
14	P Avenue	14	15	53	0.76	63.24	62.84
15	C Street	15	17	97	0.51	62.84	61.60
16	Q Avenue	16	17	63	0.94	62.12	61.60
17	C Street	17	19	100	0.46	61.60	60.20
18	C Street	18	19	138	1.41	61.92	60.20
19	Main Street	19	26	78	0.30	60.20	60.08

1) The average wastewater flow is 800 L/D/person x 130 persons/ha = 104,000 L/D/ha = 0.0722 m^3/min/ha. The I&I is 70 m^3/d/km = 4.86x10^{-5} m^3/min/m.

2) Computations begin with the existing line #0 which must be extended to accommodate the sewer lines in the new area. The average flow in the sewer main is 0.37 m^3/sec = 22.2 m^3/min. The maximum flow is 3x this flow, or 66.6 m^3/min, and the minimum flow is 0.5x this flow, or 11.1 m^3/min. With a slope of 0.009 and a diameter of 1,065 mm, the velocity at the minimum flow rate is calculated to be 1.75 m/s. The velocity at the maximum flow rate is calculated to be 2.88 m/sec, with a maximum depth of flow of 476 mm, or 45% of the pipe diameter. The velocity and depth values are acceptable (between 0.6 and 3.5 m/sec, and less than three-quarters full).

3) The design of the sewer system begins with line 1 (between MH#1 and 2) on A Street, and is 53 m long.

- The area contributing wastewater flow is 0.47 ha, and the average flow is 0.47 ha x 0.0722 m^3/min/ha = 0.0339 m^3/min
- The I&I is 4.86x10^{-5} m^3/min/m x 53 m = 0.0026 m^3/min.
- The peak wastewater flow is 3 x 0.0339 m^3/min = 0.102 m^3/min. Adding the I&I results in a total peak flow of 0.102 m^3/min + 0.0026 m^3/min = 0.105 m^3/min.
- The minimum wastewater flow is 0.5 x 0.0339 m^3/min = 0.0170 m^3/min. Adding the I&I results in a total minimum flow of 0.0170 m^3/min + 0.0026 m^3/min = 0.0196 m^3/min.
- Using the minimum pipe diameter of 150 mm and the ground slope of 0.047, the velocity at the minimum flow is 0.60 m/s, which is equal to the minimum acceptable velocity. If the velocity was less than this value, the slope would need to be increased, or permission obtained from the regulatory agency if an unusually deep pipe depth would result at the down-gradient manhole location.
- At the peak flow, the calculated velocity would be 0.99 m/sec, and the depth of flow is 23 mm. The velocity is less than the maximum permissible value of 3.5 m/sec and the depth is less than the half full goal.
- With a slope of 0.047 and a length of 53 m, the drop in elevation between the inverts at the ends of the pipes (in MH#1 to MH#2) would be 2.49 m. The elevation of the down-gradient invert is the elevation of the up-gradient invert minus this drop.

4) The designs of lines 2 and 3 are done in a similar manner, except that the flows are determined from the cumulative areas of all upslope pipes, plus the pipe being designed.

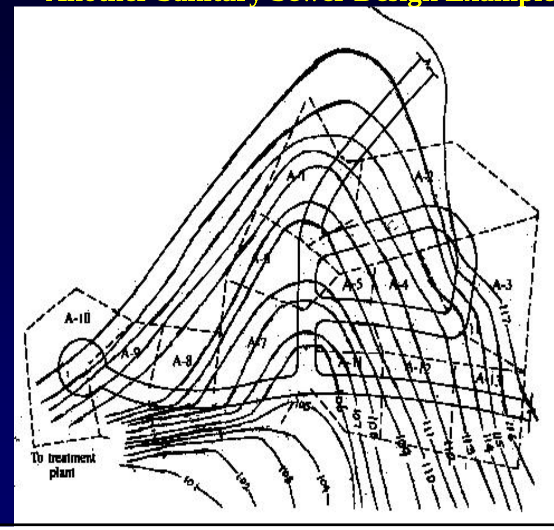
5) The crowns of the joining pipes must match, and the inverts must have a 30 mm drop, at least, when pipes are joined in a manhole at different directions.

6) Along Main Street (flat, with no ground slope), using the smallest pipe slope (0.001) that meets the depth of flow and velocity criteria minimizes excavation depths.

Table 4.27 Sewer Design Calculations

Line No. (1)	Location (2)	Manhole No. From (3)	Manhole No. To (4)	Length (m) (5)	Area Increment (ha) (6)	Area Total (ha) (7)	Maximum Flow I/I (m³/min) (8)	Maximum Flow Sewage (m³/min) (9)	Maximum Flow Total (m³/min) (10)	Minimum Flow I/I (m³/min) (11)	Minimum Flow Sewage (m³/min) (12)	Minimum Flow Total (m³/min) (13)	Slope of Sewer (14)	Diam (mm) (15)	Min Velocity (m/s) (16)	Max Velocity (m/s) (17)	Max Depth (mm) (18)	Invert Drop (m) (19)	Fall in Sewer (m) (20)	Sewer Invert Elevation Upper End (m) (21)	Sewer Invert Elevation Lower End (m) (22)	Ground Surface Elevation Upper End (m) (23)	Ground Surface Elevation Lower End (m) (24)
0	Main Street	–	5	–	–	–	–	–	66.6	–	–	11.1	0.009	1065	1.75	2.88	476	–	–	–	55.35	–	60.04
1	A Street	1	2	53	0.47	0.47	0.0026	0.102	0.105	0.0026	0.0170	0.0196	0.047	150	0.60	0.99	23	–	2.49	62.74	60.25	65.00	63.80
2	A Street	2	3	91	0.50	0.97	0.0070	0.210	0.217	0.0070	0.0350	0.0420	0.024	150	0.60	0.97	40	–	2.18	60.25	58.07	63.80	62.40
3	A Street	3	5	100	0.44	1.41	0.0120	0.305	0.317	0.0120	0.0509	0.0629	0.018	150	0.61	0.97	52	–	1.80	58.07	56.27	62.40	60.04
4	A Street	4	5	89	0.90	0.90	0.0043	0.195	0.199	0.0043	0.0325	0.0368	0.027	150	0.60	0.98	37	–	2.40	58.67	56.27	61.88	60.04
5	Main Street	5	12	69	0.17	309.96	0.0197	67.14	67.16	0.0197	11.19	11.21	0.001	1220	0.78	1.24	879	0.155	0.07	55.20	55.13	60.04	60.04
6	B Street	6	8	58	0.43	0.43	0.0028	0.0932	0.0960	0.0028	0.0155	0.0183	0.050	150	0.60	0.99	22	–	2.90	62.90	60.00	65.08	63.20
7	P Avenue	7	8	50	0.48	0.48	0.0024	0.104	0.106	0.0024	0.0173	0.0197	0.048	150	0.60	1.00	23	–	2.40	61.34	58.99	63.60	63.20
8	B Street	8	10	91	0.39	1.30	0.0097	0.282	0.292	0.0097	0.0469	0.0566	0.019	150	0.60	0.97	49	–	1.73	58.99	57.26	63.20	62.04
9	Q Avenue	9	10	56	0.88	0.88	0.0027	0.191	0.194	0.0027	0.0318	0.0345	0.029	150	0.60	1.00	36	–	1.62	60.44	58.82	62.72	62.04
10	B Street	10	12	97	0.45	2.67	0.0171	0.578	0.595	0.0171	0.0964	0.114	0.011	205	0.61	0.95	86	0.055	1.07	57.21	56.14	62.04	60.04
11	B Street	11	12	125	0.90	0.90	0.0061	0.195	0.201	0.0061	0.0325	0.0386	0.026	150	0.60	0.97	37	–	3.25	59.45	56.20	61.88	60.04
12	Main Street	12	19	75	0.28	313.81	0.0465	67.97	68.02	0.0465	11.33	11.38	0.001	1220	0.79	1.24	887	–	0.08	55.13	55.06	60.04	60.20
13	C Street	13	15	57	0.60	0.60	0.0028	0.130	0.133	0.0028	0.0217	0.0245	0.040	150	0.60	1.00	27	–	2.28	62.20	59.92	64.40	62.84
14	P Avenue	14	15	53	0.76	0.76	0.0026	0.165	0.168	0.0026	0.0274	0.0300	0.034	150	0.61	1.02	32	–	1.80	60.38	58.58	63.24	62.84
15	C Street	15	17	97	0.51	1.87	0.0101	0.405	0.415	0.0101	0.0675	0.0776	0.015	150	0.61	0.98	63	–	1.46	58.58	57.12	62.84	61.60
16	Q Avenue	16	17	63	0.94	0.94	0.0031	0.204	0.207	0.0031	0.0339	0.0370	0.028	150	0.60	1.01	37	–	1.76	59.90	58.21	62.12	61.60
17	C Street	17	19	100	0.48	3.27	0.0180	0.708	0.726	0.0180	0.1180	0.1360	0.010	205	0.60	0.96	83	0.055	1.00	57.07	56.07	61.60	60.20
18	C Street	18	19	138	1.41	1.41	0.0067	0.305	0.312	0.0067	0.0509	0.0576	0.019	150	0.60	0.99	51	–	2.62	58.75	56.13	61.92	60.20
19	Main Street	19	26	78	0.30	318.79	0.0750	69.05	69.13	0.0750	11.51	11.59	0.001	1220	0.79	1.25	900	–	0.08	55.06	54.98	60.20	60.08

Another Sanitary Sewer Design Example



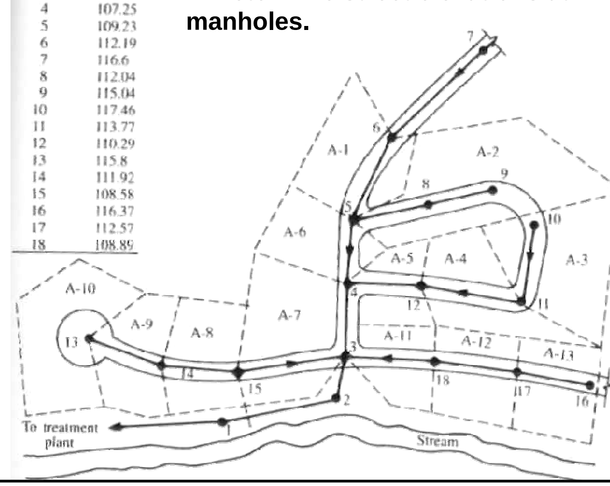
Example of Sewer Design

- Design a sanitary sewer system for the neighborhood assuming a population density of 40 people/acre, an average infiltration rate of 600 gal/acre/day, and a sanitary sewer flow of 100 gal/capita/day.

Manhole	Street El.
1	101.3
2	104.18
3	105.33
4	107.25
5	109.23
6	112.19
7	116.6
8	112.04
9	115.04
10	117.46
11	113.77
12	110.29
13	115.8
14	111.92
15	108.58
16	116.37
17	112.57
18	108.89

1. Determine manhole locations.

2. Determine street elevations at manholes.



3. Determine distance between manholes.
4. Determine slope of land/street.

$$Slope = \frac{\Delta Elevation}{Length}$$

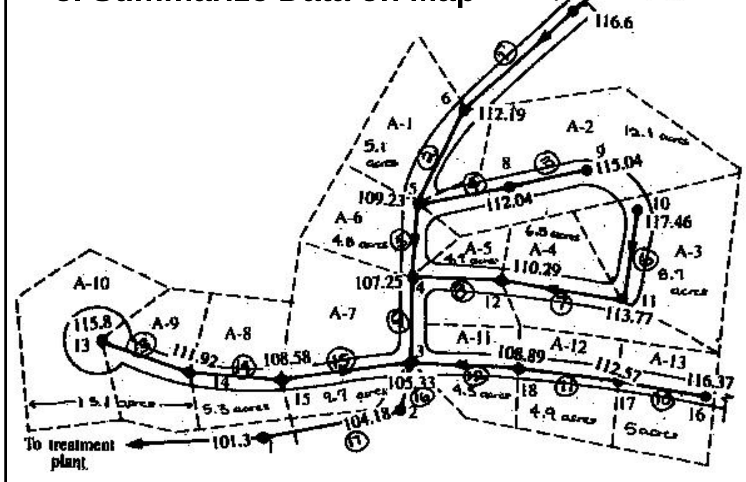
Example Solution: Summarize Data

Pipe No.	Upstream Manhole	Downstream Manhole	Street Elevation Up (ft)	Street Elevation Down (ft)	Pipe Length (ft)	Slope
1	7	6	116.60	112.19	630	0.007
2	6	5	112.19	109.23	470	0.006
3	9	8	115.04	112.04	390	0.008
4	8	5	112.04	109.23	385	0.007
5	5	4	109.23	107.25	330	0.006
6	10	11	117.46	113.77	410	0.009
7	11	12	113.77	110.29	400	0.009
8	12	4	110.29	107.25	380	0.008
9	4	3	107.25	105.33	370	0.005

Example Solution: Summarize Data (cont.)

Pipe No.	Upstream Manhole	Downstream Manhole	Street Elevation Up (ft)	Street Elevation Down (ft)	Pipe Length (ft)	Slope
10	16	17	116.37	112.57	380	0.010
11	17	18	112.57	108.89	400	0.009
12	18	3	108.89	105.33	405	0.009
13	13	14	115.80	111.92	400	0.010
14	14	15	111.92	108.58	380	0.009
15	15	3	108.58	105.33	411	0.008
16	3	2	105.33	104.18	230	0.005
17	2	1	104.18	101.30	600	0.005

5. Summarize Data on Map



6. Determine Infiltration Rate (given: 600 gal/acre/day)
7. Determine amount of infiltration to each pipe segment from its surrounding area.

Pipe No.	Contributing Area (ac)	Infiltration Rate (gal/acres/day)	Infiltration Amount (gal/day)
1	87	600	52200
2	5.1	600	3060
3	12.1	600	7260
4		600	0
5	4.8	600	2880
6	8.7	600	5220
7	6.3	600	3780
8	4.7	600	2820

Pipe No.	Contributing Area (ac)	Infiltration Rate (gal/acres/day)	Infiltration Amount (gal/day)
9		600	0
10	5	600	3000
11	4.9	600	2940
12	4.3	600	2580
13	13.1	600	7860
14	5.3	600	3180
15	9.7	600	5820
16		600	0
17		600	0

8. Determine population of sewered area (given: 40 persons/ac).
9. Determine average daily sewer flow rate (given: 100 gal/capita/day).
10. Calculate sewage contribution per pipe segment for its contributing area.

Pipe No.	Contributing Area (ac)	Number of People (persons/acre)	Sewage per Person (gal/cap./day)	Average Sewage per Pipe (gal/day)
1	87	40	100	348000
2	5.1	40	100	20400
3	12.1	40	100	48400
4		40	100	0
5	4.8	40	100	19200
6	8.7	40	100	34800
7	6.3	40	100	25200
8	4.7	40	100	18800

Pipe No.	Contributing Area (ac)	Number of People (persons/acre)	Sewage per Person (gal/cap./day)	Average Sewage per Pipe (gal/day)
9		40	100	0
10	5	40	100	20000
11	4.9	40	100	19600
12	4.3	40	100	17200
13	13.1	40	100	52400
14	5.3	40	100	21200
15	9.7	40	100	38800
16		40	100	0
17		40	100	0

12. Find peaking factor (given: peaking factor = 3.0).
13. Convert gallons/day to cubic feet per second (where 1 ft^3 = 7.48 gal and 1 day = 86,400 sec).
14. Cumulative Design Flow = Design Flow for Pipe Segment + Total Upstream Flow

Pipe No.	Up Manhole	Down Manhole	Avg Total Flow (gal/day)	Design Flow (gal/day)	Design Flow (ft^3/sec)	Cum Design Flow (ft^3/sec)
1	7	6	400200	1200600	1.86	1.86
2	6	5	23460	70380	0.11	1.97
3	9	8	55660	166980	0.26	0.26
4	8	5	0	0	0.00	0.26
5	5	4	22080	66240	0.10	2.23
6	10	11	40020	120060	0.19	0.19
7	11	12	28980	86940	0.13	0.32
8	12	4	21620	64860	0.10	0.42

Pipe No.	Up Manhole	Down Manhole	Avg. Total Flow (gal/day)	Design Flow (gal/day)	Design Flow (ft^3/sec)	Cum. Design Flow (ft^3/sec)
9	4	3	0	0	0.00	2.65
10	16	17	23000	69000	0.11	0.11
11	17	18	22540	67620	0.10	0.21
12	18	3	19780	59340	0.09	0.30
13	13	14	60260	180780	0.28	0.28
14	14	15	24380	73140	0.11	0.39
15	15	3	44620	133860	0.21	0.60
16	3	2	0	0	0	3.55
17	2	1	0	0	0	3.55

15. Determine Manning's n for each pipe segment (given n = 0.013).

16. Calculate exact pipe diameter for each pipe segment using Manning's equation.

17. Set actual pipe diameter equal to the commercial pipe size equal to or greater than the calculated exact pipe diameter.

18. Calculate full pipe flow rate using Manning's equation and pipe diameters from Step 17.

Pipe No.	Cumulative Design Flow (ft^3/sec)	Manning's n	Slope	Calculated Exact Diameter (in)	Actual Pipe Diameter (in)	Full Pipe Flow, Q_{full} (ft^3/sec)
1	1.86	0.013	0.007	10.04	12	2.99
2	1.97	0.013	0.006	10.46	12	2.84
3	0.26	0.013	0.008	4.71	8	1.06
4	0.26	0.013	0.007	4.75	8	1.04
5	2.23	0.013	0.006	11.06	12	2.77
6	0.19	0.013	0.009	4.04	8	1.15
7	0.32	0.013	0.009	4.98	8	1.13
8	0.42	0.013	0.008	5.61	8	1.08

Pipe No.	Cumulative Design Flow (ft^3/sec)	Manning's n	Slope	Calculated Exact Diameter (in)	Actual Pipe Diameter (in)	Full Pipe Flow, Q_{full} (ft^3/sec)
9	2.65	0.013	0.005	12.12	15	4.67
10	0.11	0.013	0.010	3.22	8	1.21
11	0.21	0.013	0.009	4.22	8	1.16
12	0.30	0.013	0.009	4.87	8	1.14
13	0.28	0.013	0.010	4.64	8	1.19
14	0.39	0.013	0.009	5.37	8	1.14
15	0.60	0.013	0.008	6.42	8	1.08
16	3.55	0.013	0.005	13.63	15	4.58
17	3.55	0.013	0.005	13.73	15	4.49

19. Calculate velocity in pipe flowing full ($V_{full} = Q_{full}/A_{full}$).
20. Calculate Q/Q_{full} where Q = design flow.

Pipe No.	Cumulative Design Flow (ft^3/sec)	Full Pipe Flow, Q_{full} (ft^3/sec)	Actual Diameter (in)	A_{full} (ft^2)	V_{full} (ft/sec)	Q_{design}/Q_{full}
1	1.86	2.99	12	0.785	3.81	0.62
2	1.97	2.84	12	0.785	3.61	0.69
3	0.26	1.06	8	0.524	3.04	0.24
4	0.26	1.04	8	0.524	2.97	0.25
5	2.23	2.77	12	0.785	3.52	0.80
6	0.19	1.15	8	0.524	3.29	0.16
7	0.32	1.13	8	0.524	3.24	0.28
8	0.42	1.08	8	0.524	3.11	0.39

Pipe No.	Cumulative Design Flow (ft^3/sec)	Full Pipe Flow, Q_{full} (ft^3/sec)	Actual Diameter (in)	A_{full} (ft^2)	V_{full} (ft/sec)	Q_{design}/Q_{full}
9	2.65	4.67	15	0.982	3.80	0.57
10	0.11	1.21	8	0.524	3.47	0.09
11	0.21	1.16	8	0.524	3.33	0.18
12	0.30	1.14	8	0.524	3.25	0.27
13	0.28	1.19	8	0.524	3.42	0.23
14	0.39	1.14	8	0.524	3.25	0.35
15	0.60	1.08	8	0.524	3.09	0.56
16	3.55	4.58	15	0.982	3.73	0.77
17	3.55	4.49	15	0.982	3.66	0.79

21. Using partial flow diagram, determine d/D and V/V_{full}.

Pipe No.	Q_{design}/Q_{full}	A_{full} (ft^2)	V_{full} (ft/sec)	D (in)	d/D	V/V_{full}
1	0.62	0.785	3.81	12	0.57	1.05
2	0.69	0.785	3.61	12	0.62	1.08
3	0.24	0.524	3.04	8	0.30	0.75
4	0.25	0.524	2.97	8	0.30	0.75
5	0.80	0.785	3.52	12	0.68	1.12
6	0.16	0.524	3.29	8	0.28	0.69
7	0.28	0.524	3.24	8	0.31	0.78
8	0.39	0.524	3.11	8	0.43	0.93

Pipe No.	Q_{design}/Q_{full}	A_{full} (ft^2)	V_{full} (ft/sec)	D (in)	d/D	V/V_{full}
9	0.57	0.982	3.80	15	0.56	1.03
10	0.09	0.524	3.47	8	0.20	0.56
11	0.18	0.524	3.33	8	0.24	0.68
12	0.27	0.524	3.25	8	0.36	0.84
13	0.23	0.524	3.42	8	0.34	0.81
14	0.35	0.524	3.25	8	0.41	0.89
15	0.56	0.524	3.09	8	0.55	1.03
16	0.77	0.982	3.73	15	0.67	1.12
17	0.79	0.982	3.66	15	0.68	1.12

22. Calculate design depth (d) and design velocity (V) from ratios from partial-flow diagram.

Pipe No.	A_{full} (ft^2)	V_{full} (ft/sec)	D (in)	d/D	V/V_{full}	Depth at Design Flow (in)	Velocity at Design Flow (ft/sec)
1	0.785	3.81	12	0.57	1.05	6.84	4.00
2	0.785	3.61	12	0.62	1.08	7.44	3.90
3	0.524	3.04	8	0.30	0.75	2.40	2.28
4	0.524	2.97	8	0.30	0.75	2.40	2.22
5	0.785	3.52	12	0.68	1.12	8.16	3.95
6	0.524	3.29	8	0.28	0.69	2.24	2.27
7	0.524	3.24	8	0.31	0.78	2.48	2.53
8	0.524	3.11	8	0.43	0.93	3.44	2.89

Pipe No.	A_{full} (ft^2)	V_{full} (ft/sec)	D (in)	d/D	V/V_{full}	Depth at Design Flow (in)	Velocity at Design Flow (ft/sec)
9	0.982	3.80	15	0.56	1.03	8.40	3.92
10	0.524	3.47	8	0.20	0.56	1.60	1.94
11	0.524	3.33	8	0.24	0.68	1.92	2.26
12	0.524	3.25	8	0.36	0.84	2.88	2.73
13	0.524	3.42	8	0.34	0.81	2.72	2.77
14	0.524	3.25	8	0.41	0.89	3.28	2.90
15	0.524	3.09	8	0.55	1.03	4.40	3.18
16	0.982	3.73	15	0.67	1.12	10.05	4.18
17	0.982	3.66	15	0.68	1.12	10.20	4.10

Last Steps!

23. Check velocities at the design flows to ensure that they are greater than 2 ft/sec. In this example, Pipe #10 has a calculated 1.9 ft/sec velocity. The slope of the pipe could be increased, with resulting trench depths, but this calculated value is close enough to the desired outcome considering the method used. Computerized design methods have smaller rounding errors and are more convenient when adjusting the slope to meet the targeted velocity value. Obviously, regulatory agency approval is needed if the minimum velocity criterion is not met, as increased maintenance may be needed.

24. Draw profiles, considering the final pipe depths and extra trench dimensions. Ensure that subsurface obstructions are cleared.

Trenching and Excavation

- Trench width must be great enough to provide room to join pipe sections and install required fittings.
- Clearance of about 150 mm (6 inches) on either side normally adequate.
- In rock excavations, the trench is typically cut at least 6 inches (150 mm) below the final grade of the pipe and sand or clean fill is placed between the rock and the pipe.

Sewer Construction

- Two types of sewer materials: flexible and rigid.
  - Rigid: asbestos-cement, cast iron, concrete, vitrified clay
  - Flexible: ductile iron, fabricated steel, corrugated aluminum, thermoset plastic (PE, PVC).

Sewer Construction

- Loads on sewer lines affected by conditions of flow, groundwater, adjacent earth, and superimposed situation.
- Loads include hydraulic loads, earth loads, groundwater loads, and superimposed loads.
- Therefore, crushing strength of sewer material, type of bedding and backfill load are all important.

Sewer Construction

- Marston's equation widely used to determine the vertical load on buried conduits caused by earth forces in all of the most commonly encountered construction conditions.

$$W = CwB^2$$

where
W = vertical load on pipe as a result of backfill, lb/linear foot
C = dimensionless load coefficient based on backfill and ratio of trench depth to width (often found using nomograph)
w = unit weight of backfill (lb/ft^3)
B = width of trench at top of sewer pipe (ft)

Sewer Construction

- Calculation of load coefficient

$$C = \frac{1 - e^{-2k\mu'(H/B)}}{2k\mu'}$$

where
k = Rankine's ratio of lateral pressure to vertical pressure
μ = tan Φ = coefficient of internal friction of backfill material
μ' = tan Φ' = coefficient of friction between backfill material and sides of trench ≤ μ
H = height of backfill above pipe (ft)

Sewer Construction

- Load on sewer conduit for trench condition is affected directly by soil backfill.
- Load varies widely over different soil types, from minimum of 100 lb/ft^3 (1600 kg/m^3) to maximum of about 135 lb/ft^3 (2200 kg/m^3).
- Design minimum of 120 – 125 lb/ft^3 (1900 or 2000 kg/m^3).

Unit weight, w	**Material description**
100 lb/ft^3 (1600 kg/m^3)	**Dry sand AND sand and damp topsoil**
115 lb/ft^3 (1840 kg/m^3)	**Saturated topsoil AND ordinary sand**
120 lb/ft^3 (1920 kg/m^3)	**Wet sand AND damp clay**
130 lb/ft^3 (2080 kg/m^3)	**Saturated Clay**

Sewer Construction

- Load also influenced by coefficient of friction between backfill and side of the trench (μ’) and by coefficient of internal friction in backfill soil (μ).
  - For design purposes, these are often set equal to each other.
  - But if the backfill is sharp sand and the sides of the trench are sheeted with finished lumber, μ may be substantially greater than μ’.
- Unless specific information is available and known, often assumed that kμ = kμ’ = 0.103.
- If backfill soil is slippery clay, kμ = kμ’ = 0.110.
- Specifically, kμ = 0.110 for saturated clay, 0.130 for clay, 0.150 for saturated top soil, 0.165 for sand and gravel, and 0.192 for cohesionless granular material.

Sewer Construction

- Common cuts for sewer pipe installations.

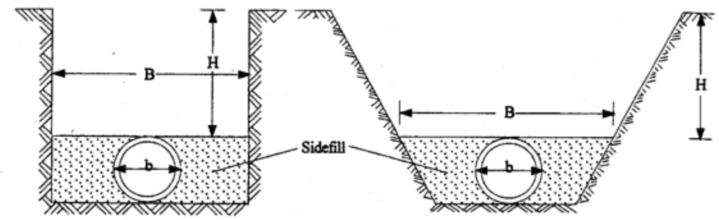


Figure 6.2 Common trench cuts for sewer pipes.

Sewer Construction Example

- A 18-in (457-mm) concrete pipe is to be installed in an ordinary trench of 10 ft (3.05 m) depth at the top of the pipe and 4 ft (1.22 m) wide. The cut will be filled with damp clay. Determine the load on the sewer pipe.

- Solution:
  - Compute the load coefficient, C:
    kμ’ = 0.11
    H/B = 3.05 m/1.22 m = 2.5 (or 10 ft/4 ft = 2.5)

$$C = \frac{1 - e^{-2k\mu'(H/B)}}{2k\mu'} = \frac{1 - e^{-2(0.11)(2.5)}}{2(0.11)}$$

$$C = 1.92$$

Sewer Construction Example (cont.)

- Compute load W by Marston’s formula:

$$w = 120 lb/ft^3 = 1920 kg/m^3$$

$$W = CwB^2 = (1.92)(1920 kg/m^3)(1.22m)^2$$

$$W = 5{,}487 kg/m = 3{,}687 lb/ft$$

For this load of 3.7 kips/ft, standard strength concrete pipe would require a bedding class of “A”, or extra strength concrete pipe could be used with a “B” class bedding. Alternatively, Class V reinforced concrete pipe could be used, as this load corresponds to 2458 lb/ft per ft diameter. These “extreme” pipe and bedding requirements are due to the great burial depth of the pipe in damp clay.

TABLE 14-10
Supporting strength of concrete pipe* per linear foot of pipe in thousands of pounds (kips)

ASTM spec. no.	Standard strength concrete sewer pipe, C 14, safety factor = 1.5				Extra strength concrete sewer pipe, C 14, safety factor = 1.5			
Bedding class	**D**	**C**	**B**	**A**	**D**	**C**	**B**	**A**
Load factor	**1.1**	**1.5**	**1.9**	**3.0**	**1.1**	**1.5**	**1.9**	**3.0**
Internal diameter of pipe, in								
6	0.8	1.1	1.4	2.2	1.5	2.0	2.5	4.0
8	0.9	1.3	1.6	2.6	1.5	2.0	2.5	4.0
10	1.0	1.4	1.8	2.8	1.5	2.0	2.5	4.0
12	1.1	1.5	1.9	3.0	1.6	2.2	2.8	4.5
15	1.2	1.7	2.2	3.5	2.0	2.8	3.5	5.5
18	1.4	2.0	2.5	4.0	2.4	3.3	4.2	6.6
21	1.6	2.2	2.8	4.4	2.8	3.8	4.9	7.8
24	1.7	2.4	3.0	4.8	2.9	4.0	5.1	8.0

* Supporting strengths are for concrete pipe meeting ASTM specifications (three-edge bearing test) and include safety and bedding factors as indicated (kips/ft × 14.6 = kN/m, in × 25.4 = mm).

Note: 21 inch concrete pipe not normally available

McGhee 1991

Bedding Conditions for Concrete Pipe

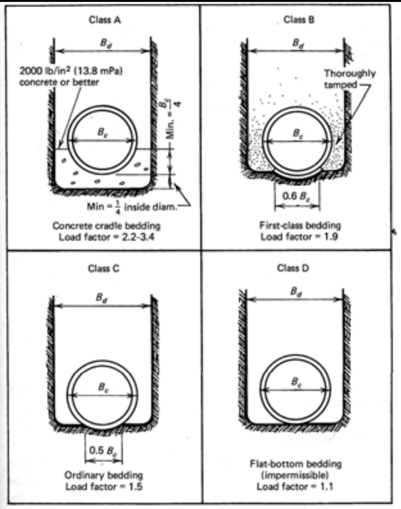


FIGURE 14-5
Methods of bedding concrete pipe and load factors applicable to strength.[6] (*Courtesy Portland Cement Association.*)

McGhee 1991

TABLE 14-11
Design loads for reinforced-concrete pipe (*reprinted by permission of the American Society for Testing and Materials*)

	Design load			
	To produce a 0.25-mm crack		Ultimate	
Class	**N/m per mm dia.**	**lb/ft per ft dia.**	**N/m per mm dia.**	**lb/ft per ft dia.**
I	38.3	800	57.4	1200
II	47.9	1000	71.8	1500
III	64.6	1350	95.8	2000
IV	95.8	2000	144.0	3000
V	144.0	3000	180.0	3750

Allowable loads based on cracking do not usually need a safety factor as the ratio of ultimate load to cracking load is approximately 1.5 for reinforced concrete pipes.

McGhee 1991

External Loads

- External loads are superficial loads on the soil produced by buildings, stockpiled materials, and vehicles.
- A portion of these loads will reach a buried pipe, depending on burial depth, soil characteristics, and load geometry.
- “Long” superficial loads are loads longer than the trench width, while “short” superficial loads are loads applied over lengths that are shorter than the trench width, or perpendicular to the trench.
- The proportion of the external loads reaching the pipe are determined using the following tables.

TABLE 14-8
Proportion of "long" superficial loads reaching pipe in trenches

Ratio of depth to width	Sand and damp topsoil	Saturated topsoil	Damp yellow clay	Saturated yellow clay
0.0	1.00	1.00	1.00	1.00
0.5	0.85	0.86	0.88	0.89
1.0	0.72	0.75	0.77	0.80
1.5	0.61	0.64	0.67	0.72
2.0	0.52	0.55	0.59	0.64
2.5	0.44	0.48	0.52	0.57
3.0	0.37	0.41	0.45	0.51
4.0	0.27	0.31	0.35	0.41
5.0	0.19	0.23	0.27	0.33
6.0	0.14	0.17	0.20	0.26
8.0	0.07	0.09	0.12	0.17
10.0	0.04	0.05	0.07	0.11

McGhee 1991

TABLE 14-9
Proportion of "short" superficial loads reaching pipe in trenches

Ratio of depth to width	Sand and damp topsoil		Saturated topsoil		Damp clay		Saturated clay	
	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
0.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.5	0.77	0.12	0.78	0.13	0.79	0.13	0.81	0.13
1.0	0.59	0.02	0.61	0.02	0.63	0.02	0.66	0.02
1.5	0.46		0.48		0.51		0.54	
2.0	0.35		0.38		0.40		0.44	
2.5	0.27		0.29		0.32		0.35	
3.0	0.21		0.23		0.25		0.29	
4.0	0.12		0.14		0.16		0.19	
5.0	0.07		0.09		0.10		0.13	
6.0	0.04		0.05		0.06		0.08	
8.0	0.02		0.02		0.03		0.04	
10.0	0.01		0.01		0.01		0.02	

McGhee 1991

Problem (from McGhee 1991):
A concrete structure 0.91 m wide with a weight of 1340 kg/m crosses a trench 1.22 m wide in damp clay. The structure bears on the soil 1.83 m above the top of the pipe. Determine the load transmitted to the pipe from this external superficial load.

Solution:
This is a "short" load as it crosses the trench. The load applied by the structure is:

F = 1340 kg/m (1.22 m) = 1635 kg

The pressure applied to the soil above the pipe is:

P = 1635 kg/0.91 m = 1795 kg/m

The ratio of depth to width is 1.83/1.22 = 1.5. From the table for short loads for this depth to width ratio and damp clay, the maximum proportion of the load reaching the pipe will be 0.51. Therefore, the load reaching the pipe will be:

P = 1795 kg/m (0.51) = 915 kg/m which must be added to the static load from the fill material.