Water Demand and Water Distribution System Design

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Distribution of per capita water demand

Range (liters/day)/person	Number of systems	Percent of systems
190–370	30	7.7
380–560	132	33.7
570–750	133	33.9
760–940	51	13.0
950–1130	19	4.8
> 1140	27	6.9

Source: Reprinted from *1984 Water Utility Operating Data*, by permission. Copyright © 1986 American Water Works Association.

(Chin 2000 Table 3.5)

Future Per Capita Estimates of Water Use

Projected Consumption of Water for Various Purposes in the Year 2000

From: *Water Supply and Sewerage, Sixth Edition*. Terence J. McGhee. McGraw-Hill Publishing Company. 1991.

Use	Gallons Per Capita/Day	Percentage of Total
Domestic	79.2	44
Industrial	42.24	24
Commercial	26.4	15
Public	15.84	9
Loss and Waste	13.2	8
TOTAL	176.88	100

System Design

- Can do estimates based on number and/or types of structures in design area and using existing data.
- Residential:

Residential Water Consumption

From: *On-Site Wastewater Treatment: Educational Materials Handbook*. National Small Flows Clearinghouse. West Virginia University, 1987.

Home Uses	Daily Water Use Per Person	
	Gallons	Percent
Toilet	32	45
Bathing/Personal Hygiene	21	30
Laundry/Dishes	14	20
Drinking/Cooking	3	5
TOTAL	70	100

From: *Water Resources Engineering, 1st Edition*. Larry W. Mays, John Wiley & Sons, Inc. 2001. (Table 11.1.4 page 346)

	Units	Average Use	Peak Use
Hotels	L/day/m^2	10.4	17.6
Motels	L/day/m^2	9.1	63.1
Barber shops	L/day/barber chair	207	1470
Beauty shops	L/day/station	1020	4050
Restaurants	L/day/seat	91.6	632
Night clubs	L/day/person served	5	5
Hospitals	L/day/bed	1310	3450
Nursing homes	L/day/bed	503	1600
Medical offices	L/day/m^2	25.2	202
Laundry	L/day/m^2	10.3	63.9

From: *Water Resources Engineering, 1st Edition*. Larry W. Mays, John Wiley & Sons, Inc. 2001. (Table 11.1.4 page 346)

	Units	Average Use	Peak Use
Laundromats	L/day/m^2	88.4	265
Retail space	L/day/sales m^2	4.3	11
Elementary schools	L/day/student	20.4	186
High schools	L/day/student	25.1	458
Bus-rail depot	L/day/m^2	136	1020
Car washes	L/day/inside m^2	194.7	1280
Churches	L/day/member	0.5	17.8
Golf-swim clubs	L/day/member	117	84
Bowling alleys	L/day/alley	503	503
Residential colleges	L/day/student	401	946

From: *Water Resources Engineering, 1st Edition*. Larry W. Mays, John Wiley & Sons, Inc. 2001. (Table 11.1.4 page 346)

	Units	Average Use	Peak Use
New office buildings	L/day/m^2	3.8	21.2
Old office buildings	L/day/m^2	5.8	14.4
Theaters	L/day/seat	12.6	12.6
Service stations	L/day/inside m^2	10.2	1280
Apartments	L/day/occupied unit	821	1640
Fast food restaurants	L/day/establishment	6780	20300

From: *Water Resources Engineering, 1st Edition*. Larry W. Mays, John Wiley & Sons, Inc. 2001. (Table 11.1.5 Page 347)

	Units	Average Use
Washing machine	L/load	130 – 270
Standard toilet	L/flush	10 – 30
Ultra volume toilet	L/flush	≤ 6
Silent leak	L/day	≥ 150
Nonstop running toilet	L/minute	≤ 20
Dishwasher	L/load	50 –120
Water-saver dishwasher	L/load	40 –100
Washing dishes with tap running	L/minute	≤ 20
Washing dishes in filled sink	L	20 – 40
Running garbage disposal	L/minute	10 – 20
Bathroom faucet	L/minute	≤ 20

From: *Water Resources Engineering, 1st Edition*. Larry W. Mays, John Wiley & Sons, Inc. 2001. (Table 11.1.5 Page 347)

	Units	Average Use
Brushing teeth	L	8
Shower head	L/minute	20 – 30
Low-flow shower head	L/minute	6 – 11
Filling bathtub	L	100 – 300
Watering 750-m^2 lawn	L/month	7600 – 16000
Standard sprinkler	L/hour	110 – 910
One drip-irrigation emitter	L/hour	1 – 10
½-Inch diameter hose	L/hour	1100
5/8-Inch diameter hose	L/hour	1900
¾-Inch diameter hose	L/hour	2300

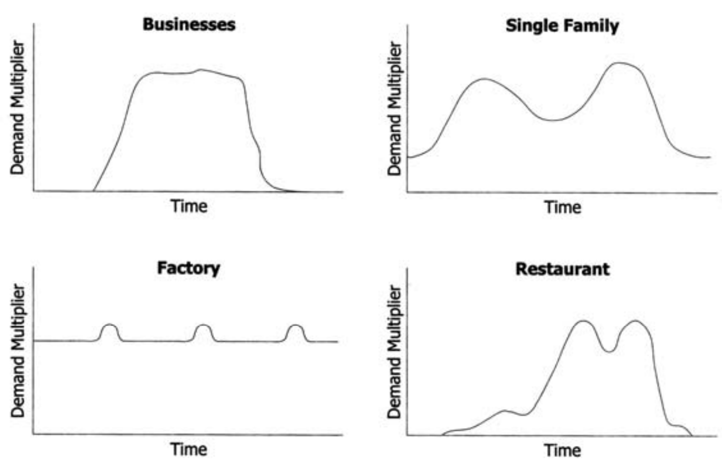
From: *Water Resources Engineering, 1st Edition*. Larry W. Mays, John Wiley & Sons, Inc. 2001. (Table 11.1.5 Page 347)

	Units	Average Use
Washing car with running water	L/20 minutes	400 – 800
Washing car with pistol-grip faucet	L/20 minutes	≥ 60
Uncovered pool	L lost/month	3000 – 11000+
Covered pool	L lost/month	300 – 1200

Given average annual consumption rates, still need to estimate peak demand because

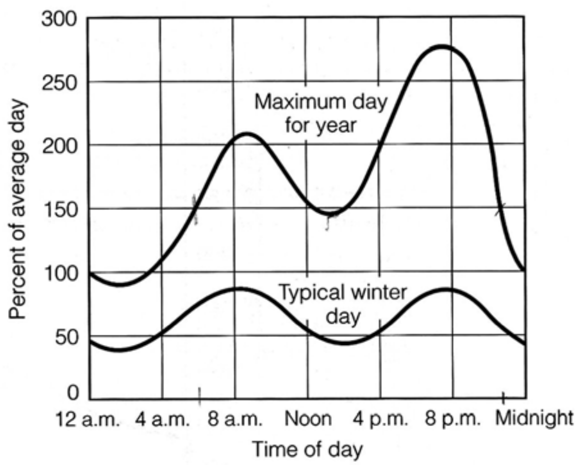
- Water use varies during the day
- Water use varies from day to day
- Water use varies weekly and seasonally

Diurnal curves for different user categories



(Walski, *et al.* 2001 figure 4.8)

Typical daily cycles in water demand



(Chin 2000 Figure 3.23)

Peak Water Use Estimation: Estimation of Average Daily Rate Based on a Maximum Time Period

Goodrich Formula:

- Estimates maximum demand (expressed as daily water demand based on time period for which maximum water demand is desired) for community when given annual average per capita daily water use rate:

$$p = 180 \cdot t^{-0.10}$$

where p = percentage of average annual rate (volume/day) used in period of time of interest

t = length of period for which peak demand is required (days) (valid time periods – 2 hours to 360 days)

- **Daily rate based upon a maximum hour is approximately equal to 150 percent of average annual daily rate.

Peak Water Use Estimation

- Consumption rate for max day = 180% of the annual average daily consumption
- Consumption rate for max week = 148% of the annual average daily consumption
- Consumption rate for max month = 128% of the annual average daily consumption
- Consumption rate for max hour = 150% of the max day, or 270% of the annual average daily consumption

Typical demand factors

Condition	Range of demand factors	Typical value
Daily average in maximum month	1.10–1.50	1.20
Daily average in maximum week	1.20–1.60	1.40
Maximum daily demand	1.50–3.00	1.80
Maximum hourly demand	2.00–4.00	3.25
Minimum hourly demand	0.20–0.60	0.30

Source: Velon and Johnson (1993). Reprinted by permission of The McGraw-Hill Companies.

(Chin 2000 Table 3.6)

Fire Demand

In metric units (AWWA 1992):

$$NFF_i = C_i O_i (X+P)_i$$

C is the construction factor based on the size of the building and its construction,

O is the occupancy factor reflecting the kinds of materials stored in the building (ranging from 0.75 to 1.25), and

(X+P) is the sum of the exposure factor and the communication factor that reflect the proximity and exposure of the other buildings.

$$C_i = 220 F \sqrt{A_i}$$

C (L/min),

A (m^2) is the effective floor area, typically equal to the area of the largest floor plus 50% of all other floors,

F is a coefficient based on the class of construction

Construction coefficient, F

Class of construction	Description	F
1	frame	1.5
2	joisted masonry	1.0
3	noncombustible	0.8
4	masonry, noncombustible	0.8
5	modified fire resistive	0.6
6	fire resistive	0.6

Source: AWWA (1992).

(Chin 2000 Table 3.7)

Occupancy factors, O_i

Combustibility class	Examples	O_i
C-1 Noncombustible	steel or concrete products storage	0.75
C-2 Limited combustible	apartments, churches, offices	0.85
C-3 Combustible	department stores, supermarkets	1.00
C-4 Free burning	auditoriums, warehouses	1.15
C-5 Rapid burning	paint shops, upholstering shops	1.25

Source: Reprinted from *Distribution System Requirements for Fire Protection* (M31), by permission. Copyright © 1992 American Water Works Association.

(Chin 2000 Table 3.8)

Needed fire flow for one- and two-family dwellings

Distance between buildings (m)	Needed fire flow (L/min)
> 30	2,000
9.5–30	3,000
3.5–9.5	4,000
< 3.5	6,000

Source: Reprinted from *Distribution System Requirements for Fire Protection* (M31), by permission. Copyright © 1992 American Water Works Association.

(Chin 2000 Table 3.9)

Table 4.3 Needed fire flow for residences two stories and less

Distance Between Buildings (ft)	Fire Flow (gpm)
More than 100	500
31-100	750
11-30	1000
Less than 11	1500

(Walski, *et al.* 2001)

Required fire flow durations

Required fire flow (L/min)	Duration (h)
< 9000	2
11,000–13,000	3
15,000–17,000	4
19,000–21,000	5
23,000–26,000	6
26,000–30,000	7
30,000–34,000	8
34,000–38,000	9
38,000–45,000	10

Source: Reprinted from *Distribution System Requirements for Fire Protection* (M31), by permission. Copyright © 1992 American Water Works Association.

(Chin 2000 Table 3.10)

Example 3.16 from Chin 2000

Estimate the flowrate and volume required to provide adequate protection to a 10-story noncombustible building with and effective floor area of 8,000 m^2.

$$NFF_i = C_i O_i (X+P)_i \qquad C_i = 220F\sqrt{A_i}$$

The construction factor is calculated as (F=0.8 for class 3 noncombustible construction and the floor area is 8,000 m^2):

$$C_i = 220(0.8)\sqrt{8000m^2} = 16{,}000 L/\min$$

The occupancy factor C is 0.75 (C-1 noncombustible) and the (X+P) is estimated using the median value of 1.4. Therefore, the required fire flow is:

$$NFF_i = (16{,}000 L/\min)(0.75)(1.4) = 17{,}000 L/\min$$

The flow must be maintained for a duration of 4 hours, and the required volume is therefore:

$$V = 17{,}000 L/\min(4\,hours)(60\min/hr) = 4.08x10^6 L = 4{,}080 m^3$$

Design periods and capacities in water-supply systems

Component	Design period (years)	Design capacity
Sources of supply:		
River	indefinite	maximum daily demand
Wellfield	10–25	maximum daily demand
Reservoir	25–50	average annual demand
Pumps:		
Low-lift	10	maximum daily demand, one reserve unit
High-lift	10	maximum hourly demand, one reserve unit
Water-treatment plant	10–15	maximum daily demand
Service reservoir	20–25	working storage plus fire demand plus emergency storage
Distribution system:		
Supply pipe or conduit	25–50	greater of (1) maximum daily demand plus fire demand, or (2) maximum hourly demand
Distribution grid	full development	same as for supply pipes

Source: Reprinted by permission of Waveland Press, Inc. from R. S. Gupta, *Hydrology and Hydraulic Systems.* (Prospect Heights, IL; Waveland Press, Inc., 1989 [reissued 1995]). All rights reserved.

(Chin 2000 Table 3.11)

Methods of Water Distribution

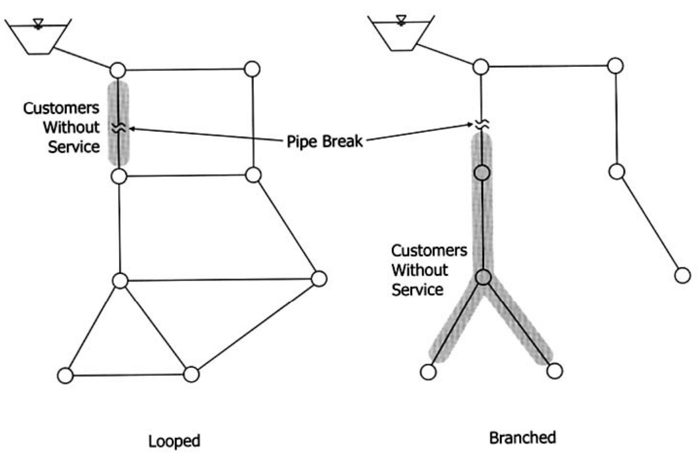
- Pumping with Storage
  - Most common
  - Water supplied at approximately uniform rate
  - Flow in excess of consumption stored in elevated tanks
  - Tank water provides flow and pressure when use is high
    - Fire-fighting
    - High-use hours
    - Flow during power failure
  - Storage volume throughout system and for individual service areas should be approximately 15 – 30% of maximum daily rate.

Water Distribution System Components

- Pumping Stations
- Distribution Storage
- Distribution System Piping

Other water system components include water source and water treatment

Looped and branched networks after network failure



(Walski, *et al.* 2001 figure 1.2)

The Pipe System

- Primary Mains (Arterial Mains)
  - Form the basic structure of the system and carry flow from the pumping station to elevated storage tanks and from elevated storage tanks to the various districts of the city
    - Laid out in interlocking loops
    - Mains not more than 1 km (3000 ft) apart
    - Valved at intervals of not more than 1.5 km (1 mile)
    - Smaller lines connecting to them are valved

The Pipe System, Cont.

- Secondary Lines
  - Form smaller loops within the primary main system
  - Run from one primary line to another
  - Spacings of 2 to 4 blocks
  - Provide large amounts of water for fire fighting with out excessive pressure loss

The Pipe System, Cont.

- Small distribution lines
  - Form a grid over the entire service area
  - Supply water to every user and fire hydrants
  - Connected to primary, secondary, or other small mains at both ends
  - Valved so the system can be shut down for repairs
  - Size may be dictated by fire flow except in residential areas with very large lots

Pipe sizes in Municipal Distribution Systems

- Small distribution lines providing only domestic flow may be as small as 4 inches, but:
  - < 1300 ft in length if dead ended, or
  - < 2000 ft if connected to system at both ends.
- Otherwise, small distribution mains > 6 in
- High value districts – minimum size 8 in
- Major streets – minimum size 12 in

- Fire-fighting requirements
  > 150 mm (6 in.)
- National Board of Fire Underwriters
  > 200 mm (8 in.)

Velocity in Municipal Distribution Systems

(McGhee, *Water Supply and Sewerage, 6th Edition*)

- Normal use ≤ 1m/s, (3 ft/s)
- Upper limit = 2 m/s (6 ft/s) (may occur in vicinity of large fires)

(Viessman and Hammer, *Water Supply and Pollution Control, 6th Edition*)

$1 \leq V \leq 1.7$ m/s $(3 \leq V \leq 5$ ft/s)

Pressure in Municipal Distribution Systems (American Water Works Association)

AWWA recommends normal static pressure of 400-500kPa, 60-75lb/in^2

- supplies ordinary uses in building up to 10 stories
- will supply sprinkler system in buildings up to 5 stories
- will provide useful fire flow without pumper trucks
- will provide a relatively large margin of safety to offset sudden high demand or closure of part of the system.

Pressure in Municipal Distribution Systems (McGee)

- Pressure in the range of 150 – 400kPa (20 to 40 lb/in^2) are adequate for normal use and may be used for fire supply in small towns where building heights do not exceed 4 stories.

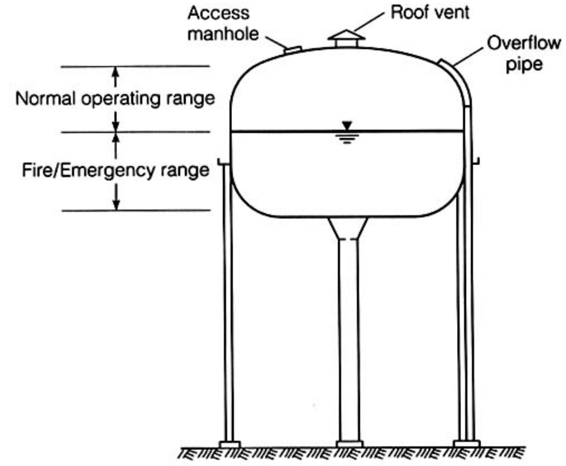
Minimum acceptable pressures in distribution systems

Demand condition	Minimum acceptable pressure (kPa)
Average daily demand	240–410
Maximum daily demand	240–410
Maximum hourly demand	240–410
Fire situation	> 140
Emergency conditions	> 140

Source: GLUMB (1987).

(Chin 2000 Table 3.12)

Typical elevated storage tank



(Chin 2000 Figure 3.24)

Hardy Cross Method

- Used in design and analysis of water distribution systems for many years..
- Based on the hydraulic formulas we reviewed earlier in the term.

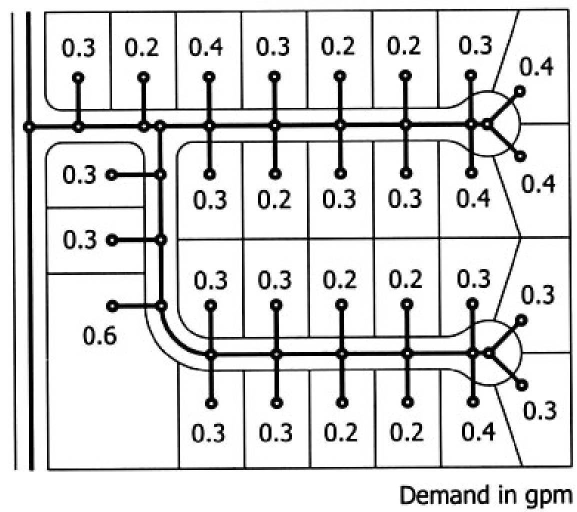
For Hardy-Cross Analysis:

- Water is actually removed from the distribution system of a city at a very large number of points.
- Its is not reasonable to attempt to analyze a system with this degree of detail
- Rather, individual flows are concentrated at a smaller number of points, commonly at the intersection of streets.
- The distribution system can then be considered to consist of a network of nodes (corresponding to points of concentrated flow withdrawal) and links (pipes connecting the nodes).
- The estimated water consumption of the areas contained within the links is distributed to the appropriate nodes

Network model overlaid on aerial photograph

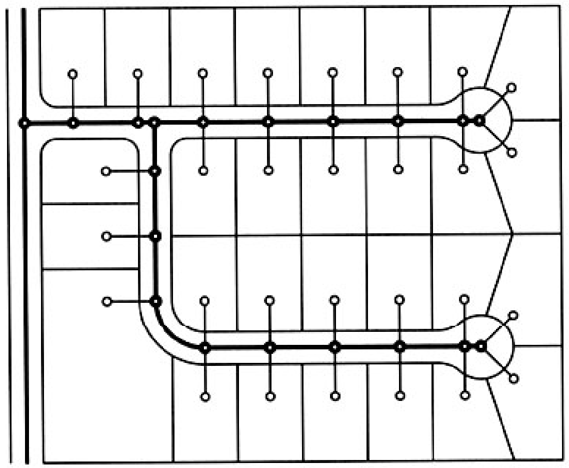
(Walski, *et al.* 2004 figure 3.4)

Skeletonization - An all-link network



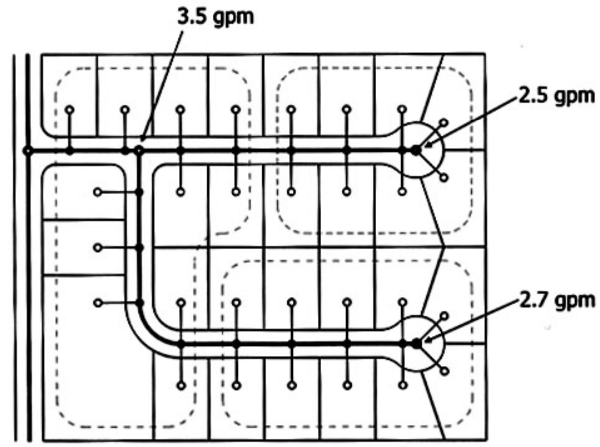
(Walski, *et al.* 2004 figure 3.32)

Minimal skeletonization



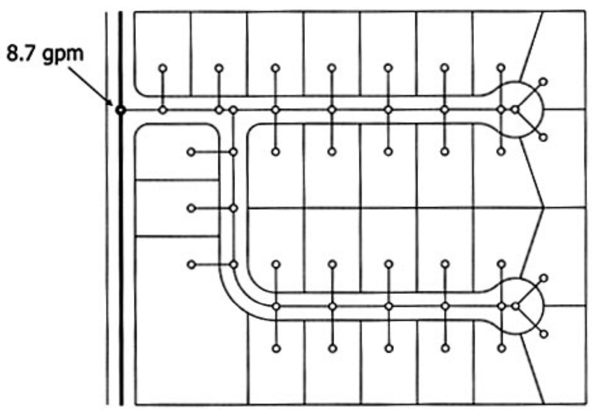
(Walski, *et al.* 2004 figure 3.33)

Moderate skeletonization



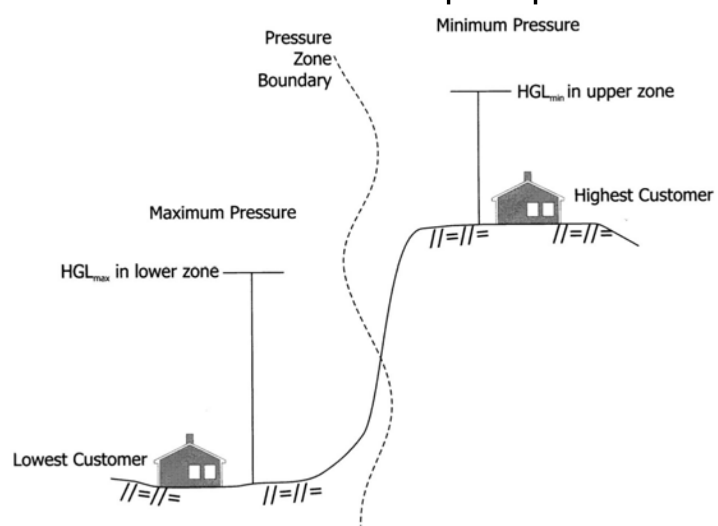
(Walski, *et al.* 2004 figure 3.34)

Maximum skeletonization



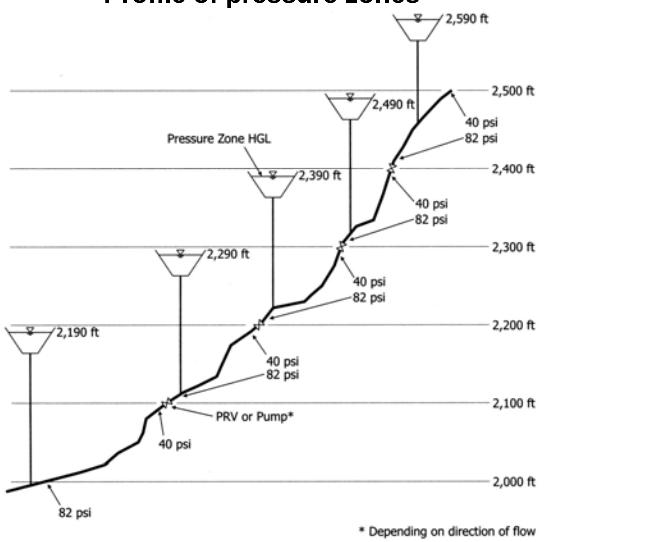
(Walski, *et al.* 2004 figure 3.35)

Customers must be served from separate pressure zones



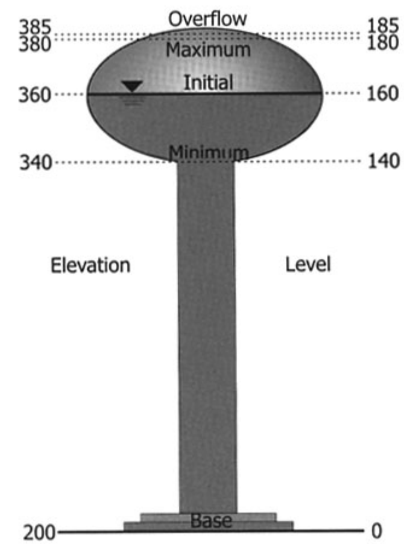
(Walski, *et al.* 2001 figure 7.17)

Profile of pressure zones



(Walski, *et al.* 2001 figure 7.20)

Important tank elevations



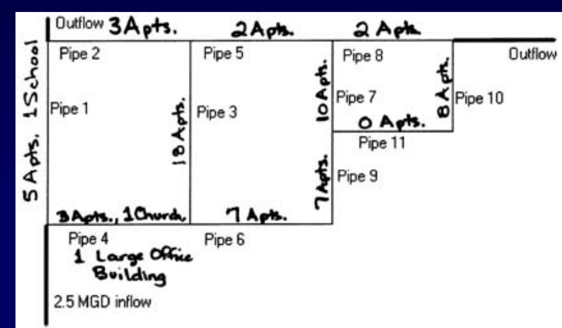
(Walski, *et al.* 2001 figure 3.10)

Hardy-Cross Method of Water Distribution Design

- Definitions
  - *Pipe sections or links* are the most abundant elements in the network.
    - These sections are constant in diameter and may contain fittings and other appurtenances.
    - Pipes are the largest capital investment in the distribution system.
  - *Node* refers to either end of a pipe.
    - Two categories of nodes are *junction nodes* and *fixed-grade nodes*.
    - Nodes where the inflow or outflow is known are referred to as junction nodes. These nodes have lumped demand, which may vary with time.
    - Nodes to which a reservoir is attached are referred to as fixed-grade nodes. These nodes can take the form of tanks or large constant-pressure mains.

Steps for Setting Up and Solving a Water Distribution System using the Hardy-Cross Method

1. Set up grid network to resemble planned flow distribution pattern.



Steps for the Hardy-Cross Method

2. Calculate water use on each street (including fire demand on the street where it should be located).

Street Number	Building Description	Without Fire Demand		With Fire Demand (worst building)	
		MGD	ft^3/sec	MGD	ft^3/sec
1**	5 A, 1 S	0.059	0.092	2.00	3.10
2	3 A	0.019	0.030	0.019	0.030
3	18 A	0.12	0.18	0.12	0.18
4	3 A, 1 O, 1 C	0.056	0.086	0.056	0.086
5	2 A	0.013	0.020	0.013	0.020
6	7 A	0.045	0.070	0.045	0.070
7	10 A	0.065	0.100	0.065	0.100
8	2 A	0.013	0.020	0.013	0.020
9	7 A	0.045	0.070	0.045	0.070
10	8 A	0.052	0.080	0.052	0.080
11	No buildings	0.0	0.0	0.0	0.0

Steps for the Hardy-Cross Method

3. Add up the flow used in the neighborhood without fire demand and distribute it out the nodes where known outflow is required. Repeat for fire demand.

Total without Fire Demand = 0.75 cfs

Influent = 2.5 MGD = 3.87 cfs

Left Over to Other Neighborhoods = 3.12 cfs

Distribute 50/50 to two outflow nodes = 1.56 cfs (arbitrary for this problem – would be based on known “downstream” requirements).

Steps for the Hardy-Cross Method

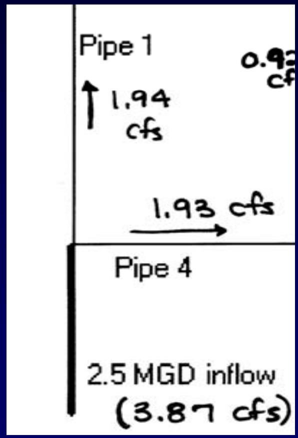
4. Assume internally consistent distribution of flow, i.e., at any given node and for the overall water distribution system:

$$\Sigma \text{ flow entering node} = \Sigma \text{ flow leaving node}$$

Steps for the Hardy-Cross Method

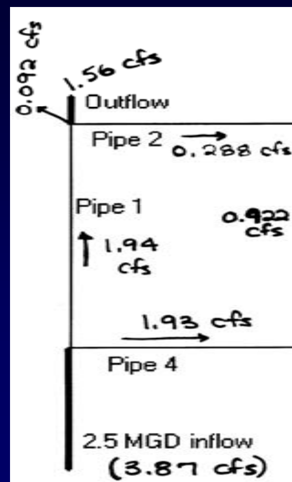
5. For the inflow node, split the flow among the pipes leaving that node (there will be no additional outflow since no water has been used by the neighborhood as yet).

Inflow = Σ Outflows



Steps for the Hardy-Cross Method

6. For each of the pipes leaving the inflow node, put the water demand for that street at the node at the end of the pipe.



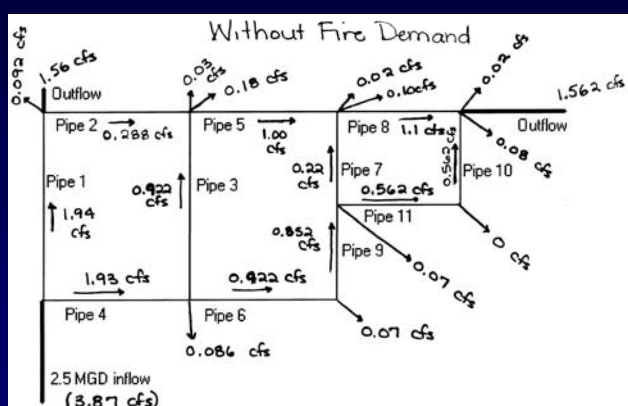
Steps for the Hardy-Cross Method

7. For the above node and the next pipes in the distribution system, subtract the water used on the street (and aggregated at the node) from the water flowing down the pipe. Pass the remaining water along to one or more of the pipes connected to that node.

8. Repeat Steps 6 and 7 for each pipe and node in the distribution system. The calculation can be checked by seeing if the total water outflow from the system equals the total inflow to the system, as well as checking each node to see if inflow equals outflow.

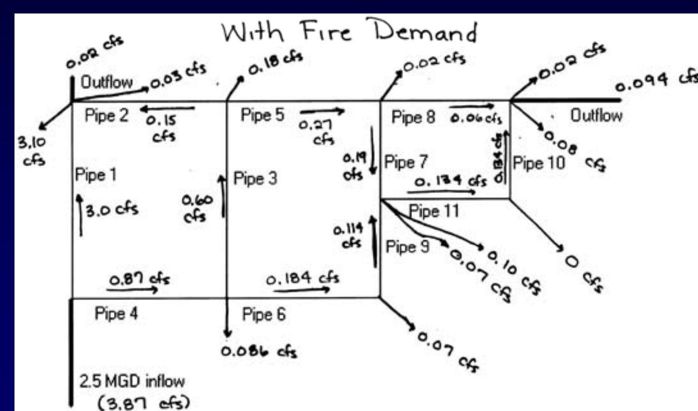
Steps for the Hardy-Cross Method

9a. Check each node to see if inflow equals outflow.



Steps for the Hardy-Cross Method

9b. Check each node to see if inflow equals outflow.



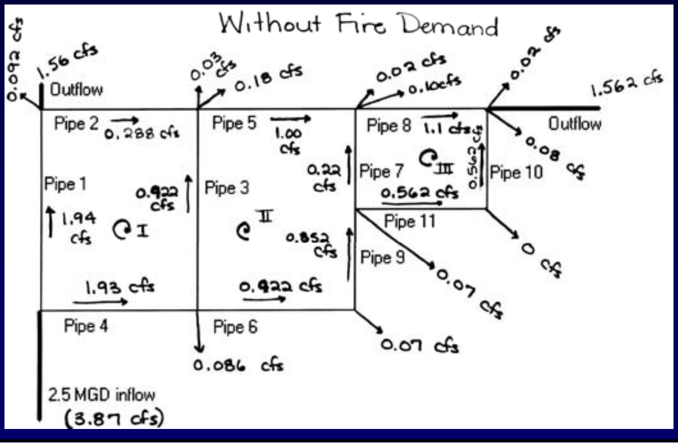
Steps for the Hardy-Cross Method

10. Select initial pipe sizes (assume a velocity of 3 ft/sec for normal flow with no fire demand). With a known/assumed flow and an assumed velocity, use the continuity equation (Q = VA) to calculate the cross-sectional area of flow. (when conducting computer design, set diameters to minimum allowable diameters for each type of neighborhood according to local regulations)

Pipe Number	Flow (ft^3/sec)	Velocity (ft/sec)	Area (ft^2)	Diameter (ft)	Diameter (in)	Actual D (in)
1	1.94	3.0	0.65	0.91	10.9	12
2	0.288	3.0	0.10	0.35	4.2	6
3	0.922	3.0	0.31	0.63	7.5	8
4	1.930	3.0	0.64	0.91	10.9	12
5	1.000	3.0	0.33	0.65	7.8	8
6	0.922	3.0	0.31	0.63	7.5	8
7	0.220	3.0	0.07	0.31	3.7	4
8	1.100	3.0	0.37	0.68	8.2	10
9	0.852	3.0	0.28	0.60	7.2	8
10	0.562	3.0	0.19	0.49	5.9	6
11	0.562	3.0	0.19	0.49	5.9	6

Steps for the Hardy-Cross Method

11. Determine the convention for flow. Generally, clockwise flows are positive and counter-clockwise flows are negative.



Steps for the Hardy-Cross Method

12. Paying attention to sign (+/-), compute the head loss in each element/pipe of the system (such as by using Darcy-Weisbach or Hazen-Williams).

Hazen – Williams

$$h_L = L\left(\frac{Q}{0.432CD^{2.63}}\right)^{1.85}$$

Darcy – Weisbach

$$h_L = f\,\frac{L}{D}\left(\frac{V^2}{2g}\right)$$

Steps for the Hardy-Cross Method

13. Compute the sum of the head losses around each loop (carrying the appropriate sign throughout the calculation).

14. Compute the quantity, head loss/flow (h_L/Q), for each element/pipe (note that the signs cancel out, leaving a positive number).

15. Compute the sum of the (h_L/Q)s for each loop.

Steps for the Hardy-Cross Method

16. Compute the correction for each loop.

$$\Delta Q = \frac{-\sum_{loop} h_L}{n \sum_{loop} \frac{h_L}{Q}}$$

where n = 1.85

Steps for the Hardy-Cross Method

17. Apply the correction for each pipe in the loop that is not shared with another loop.

$$Q_1 = Q_0 + \Delta Q$$

18. For those pipes that are shared, apply the following correction equation (continuing to carry all the appropriate signs on the flow):

$$Q_1 = Q_0 + \Delta Q_{loop\ in} - \Delta Q_{shared\ loop}$$

Steps for the Hardy-Cross Method

19. Reiterate until corrections are sufficiently small (10 – 15% or less of smallest flow in system), or until oscillation occurs.

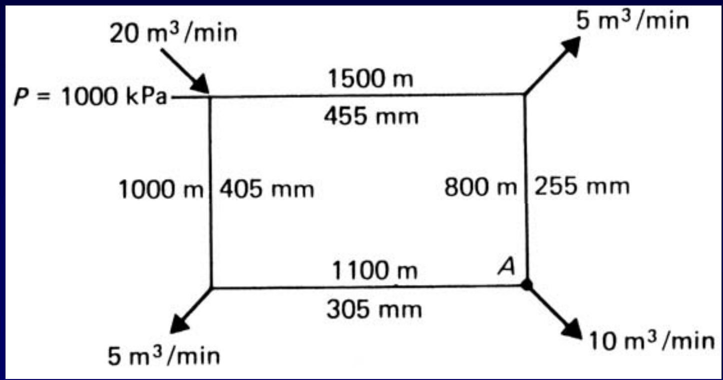
20. Calculate velocities in each pipe and compare to standards to ensure that sufficient velocity (and pressure) are available in each pipe. Adjust pipe sizes to reduce or increase velocities as needed.

21. Repeat all the above steps until a satisfactory solution is obtained.

22. Apply fire flow and other conditions that may be critical and reevaluate.

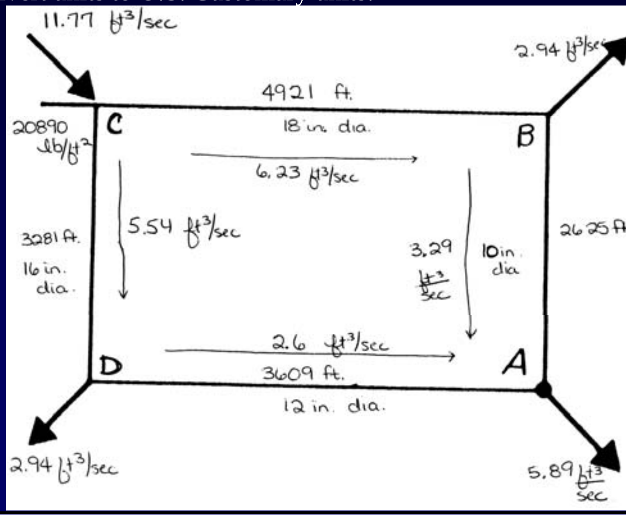
Example for the Hardy-Cross Method

(From McGhee, *Water Supply and Sewerage, Sixth Edition*)



Example for the Hardy-Cross Method

Convert units to U.S. Customary units:



Example for the Hardy-Cross Method

- Insert data into spreadsheet for Hardy-Cross (solve using Hazen-Williams).
- ASSUME: Pipes are 20-year old cast iron, so C = 100.

Pipe Section	Pipe Length (ft)	Pipe Diameter (in)	$Flow_0$ (ft^3/sec)
BC	4921	18	6.23
CD	3281	16	-5.54
DA	3609	12	-2.6
AB	2625	10	3.29

Steps for the Hardy-Cross Method

- Paying attention to sign (+/-), compute the head loss in each element/pipe of the system by using Hazen-Williams (check that the sign for the head loss is the same as the sign for the flow).

Hazen – Williams

$$h_L = L\left(\frac{Q}{0.432CD^{2.63}}\right)^{1.85}$$

Example for the Hardy-Cross Method

- Calculate head loss using Hazen-Williams.

Pipe Section	Pipe Length (ft)	Pipe Diameter (in)	$Flow_0$ (ft^3/sec)	h_L (ft)
BC	4921	18	6.23	19.03
CD	3281	16	-5.54	-18.11
DA	3609	12	-2.6	-19.93
AB	2625	10	3.29	54.39

Example for the Hardy-Cross Method

- Calculate h_L/Q for each pipe (all of these ratios have positive signs, as the negative values for h_L and Q cancel out).

Pipe Section	$Flow_0$ (ft^3/sec)	h_L (ft)	h_L/Q (sec/ft^2)
BC	6.23	19.03	3.05
CD	-5.54	-18.11	3.27
DA	-2.6	-19.93	7.66
AB	3.29	54.39	16.53

Example for the Hardy-Cross Method

- Calculate head loss using Hazen-Williams and column totals:

Pipe Section	h_L (ft)	h_L/Q (sec/ft^2)
BC	19.03	3.05
CD	-18.11	3.27
DA	-19.93	7.66
AB	54.39	16.53
	$\Sigma h_L = 35.38$	$\Sigma(h_L/Q) = 30.51$

Example for the Hardy-Cross Method

- Calculate the correction factor for each pipe in the loop.

$$\Delta Q = \frac{-\sum_{loop} h_L}{n \sum_{loop} \frac{h_L}{Q}}$$

where n = 1.85

= -(35.38)/1.85(30.51) = -0.627

Example for the Hardy-Cross Method

- Calculate the new flows for each pipe using the following equation:

$Q_1 = Q_0 + \Delta Q$

Pipe Section	$Flow_0$ (ft^3/sec)	ΔQ (ft^3/sec)	$Flow_1$ (ft^3/sec)
BC	6.23	-0.627	5.60
CD	-5.54	-0.627	-6.17
DA	-2.6	-0.627	-3.23
AB	3.29	-0.627	2.66

Example for the Hardy-Cross Method

HARDY CROSS METHOD FOR WATER SUPPLY DISTRIBUTION

Trial 1

Pipe Section	Pipe Length (ft)	Pipe Diameter (in)	Flow $_0$ (ft^3/sec)	H_L (ft)	H_L/Q (sec/ft^2)	$n\Sigma(H_L/Q)$ (sec/ft^2)	$\Sigma(H_L)$ (ft)	ΔQ (ft^3/sec)	Flow $_1$ (ft^3/sec)
BC	4921	18	6.2	19.03	3.05	56.46	35.38	-0.627	5.60
CD	3281	16	-5.5	-18.11	3.27			-0.627	-6.17
DA	3609	12	-2.6	-19.93	7.66			-0.627	-3.23
BA	2625	10	3.3	54.39	16.53			-0.627	2.66

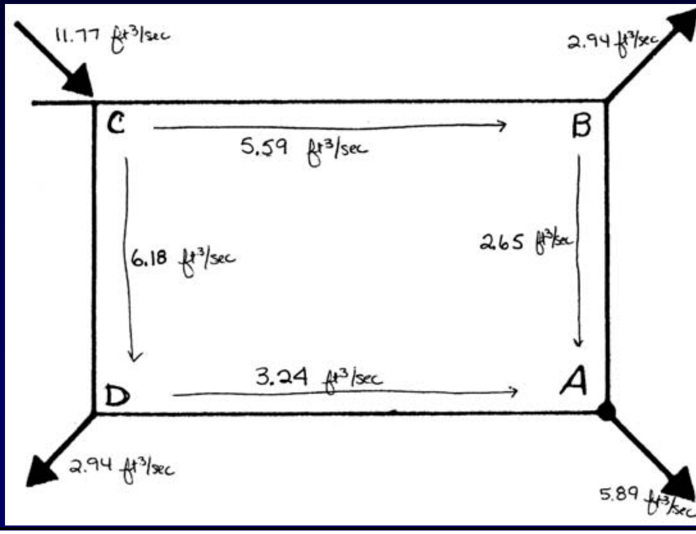
Trial 2

Pipe Section	Pipe Length (ft)	Pipe Diameter (in)	Flow $_1$ (ft^3/sec)	H_L (ft)	H_L/Q (sec/ft^2)	$n\Sigma(H_L/Q)$ (sec/ft^2)	$\Sigma(H_L)$ (ft)	ΔQ (ft^3/sec)	Flow $_2$ (ft^3/sec)
BC	4921	18	5.60	15.64	2.79	54.38	0.64	-0.012	5.59
CD	3281	16	-6.17	-22.08	3.58			-0.012	-6.18
DA	3609	12	-3.23	-29.71	9.21			-0.012	-3.24
BA	2625	10	2.66	36.79	13.81			-0.012	2.65

Trial 3

Pipe Section	Pipe Length (ft)	Pipe Diameter (in)	Flow $_2$ (ft^3/sec)	H_L (ft)	H_L/Q (sec/ft^2)	$n\Sigma(H_L/Q)$ (sec/ft^2)	$\Sigma(H_L)$ (ft)	ΔQ (ft^3/sec)	Flow $_3$ (ft^3/sec)
BC	4921	18	5.59	15.58	2.79	54.34	0.00	0.000	5.59
CD	3281	16	-6.18	-22.16	3.59			0.000	-6.18
DA	3609	12	-3.24	-29.91	9.24			0.000	-3.24
BA	2625	10	2.65	36.49	13.76			0.000	2.65

Final Flows for the Hardy-Cross Example



Pressure Water Distribution System

The pressure at any node can be calculated by starting with a known pressure at one node and subtracting the absolute values of the head losses along the links in the direction of flow.

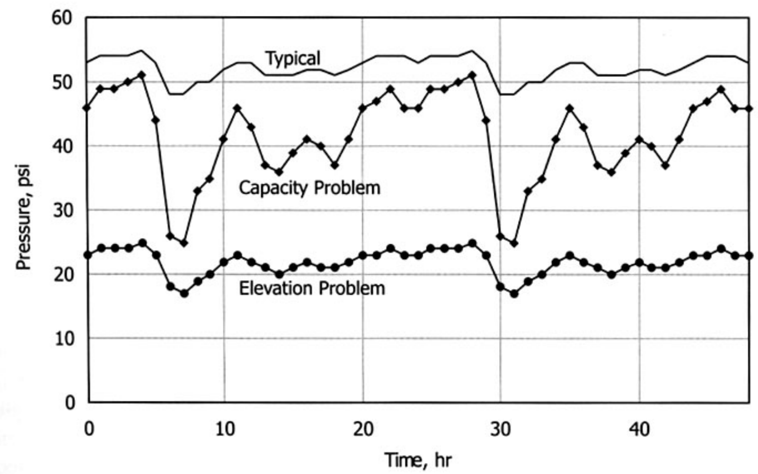
In this example, assume that the pressure head at node C is 100 ft. and the pressure head at node A is desired.

There are two paths between the known and unknown nodes for this example and both should be examined: CB and BA or CD and DA.

In the first case: 100 ft. – 15.58 ft. – 36.49 ft. = 47.93 ft.

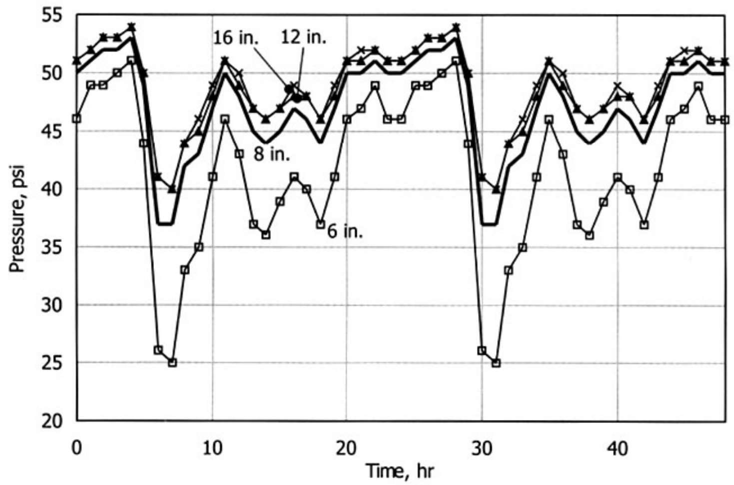
And in the second: 100 ft. – 22.16 ft. – 29.91 ft. = 47.93 ft.

Extended period simulation (EPS) runs showing low pressure due to elevation or system capacity problem



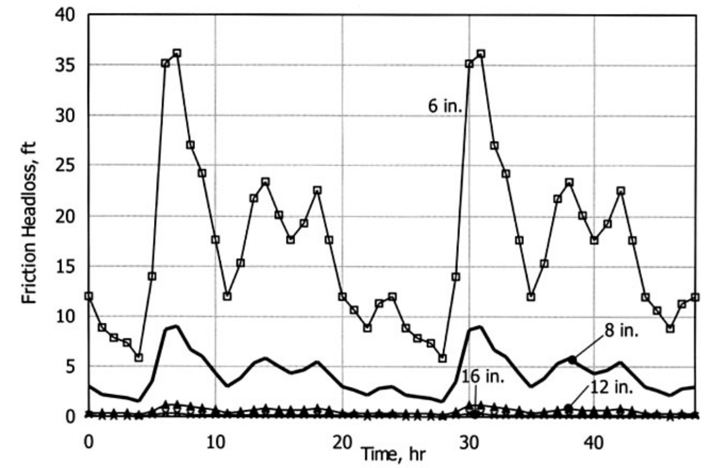
(Walski, *et al.* 2001 figure 7.3)

Pressure comparison for 6-, 8-, 12-, and 16- inch pipes



(Walski, *et al.* 2001 figure 7.4)

Head loss comparison for 6-, 8-, 12-, and 16- inch pipes



(Walski, *et al.* 2001 figure 7.5)

EPANet Water Distribution Model