Module 1

Introduction, Theory, History and Basics of Water Distribution System Modeling

Introduction to EPANET Water Distribution Modeling

EWRI WORLD ENVIRONMENTAL AND WATER RESOURCES CONGRESS
June 5, 2018
Minneapolis, MN

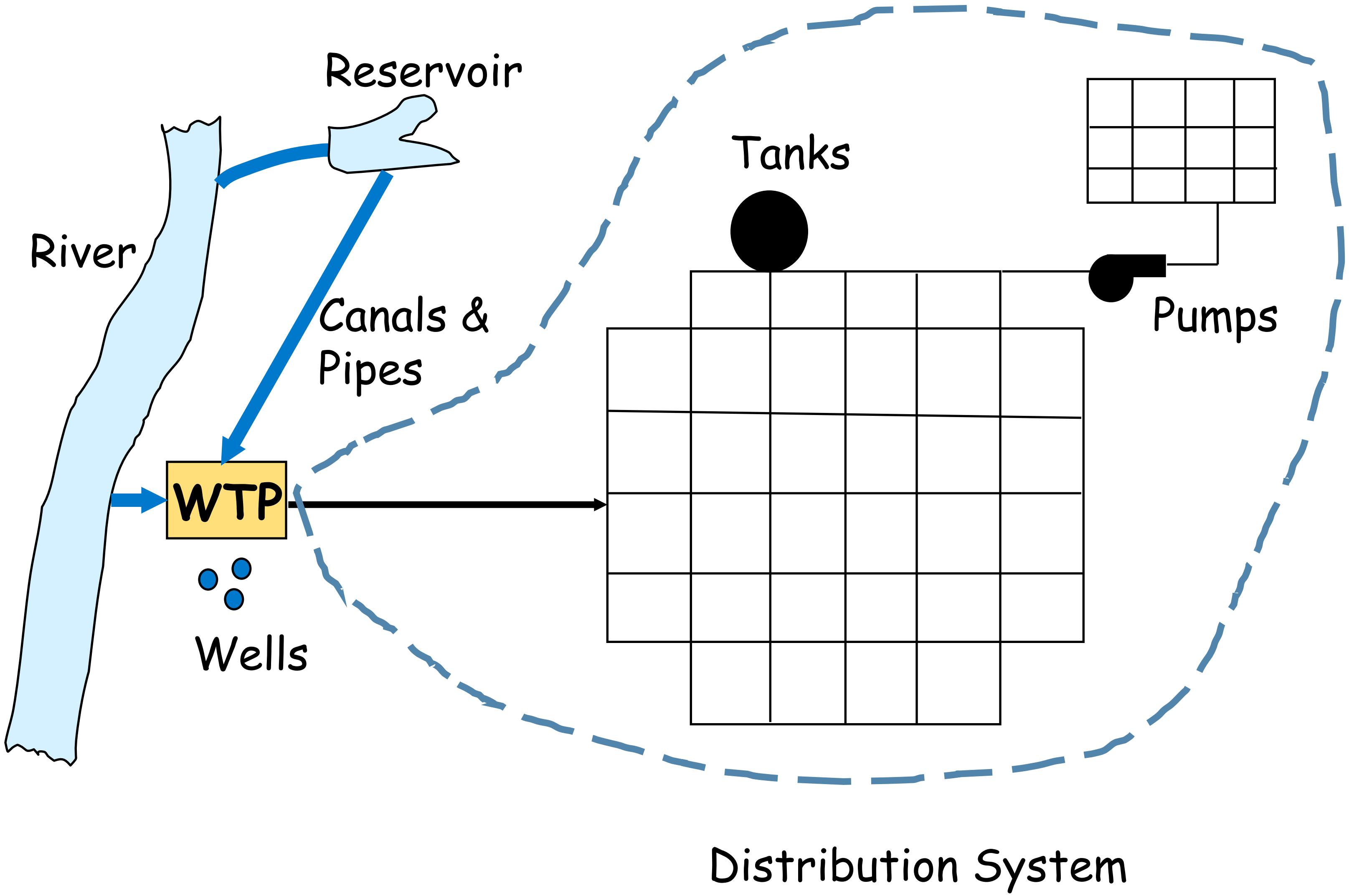
Curriculum

Module 1:	Lecture on Introduction, theory, history, and basics of water distribution system modeling
Module 2:	Hands-on demo of building and running a basic steady state model
Module 3:	Lecture on Extended Period Simulation (EPS) and water quality modeling
Module 4:	Hands-on demo of extended period simulation and water quality modeling

What is a Water Distribution System?

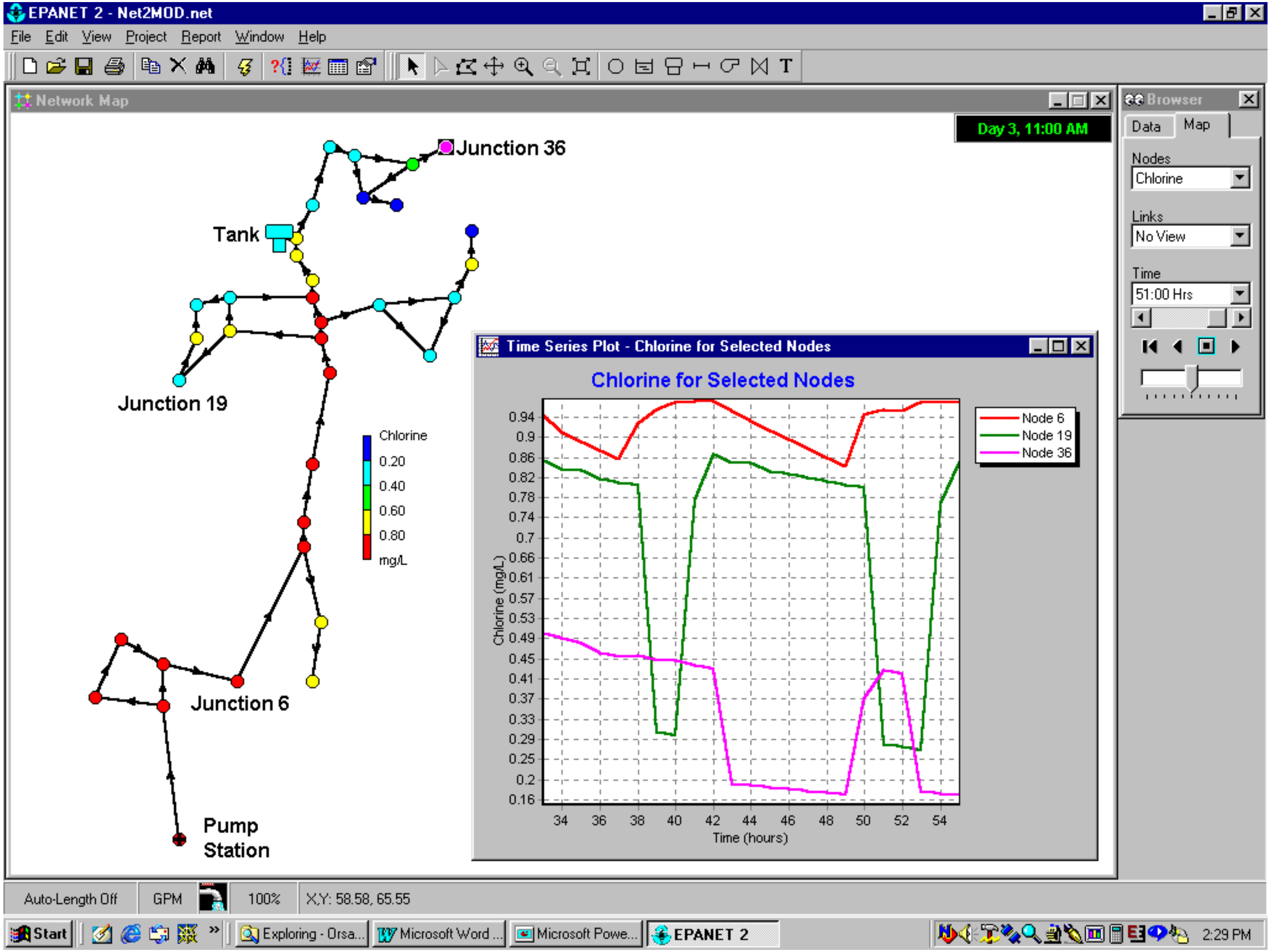
A collection of pipes, tanks, pumps, valves control systems and other appurtenances that together are used to move water from a water source or treatment plant to individual water users

Elements of a Water Supply System

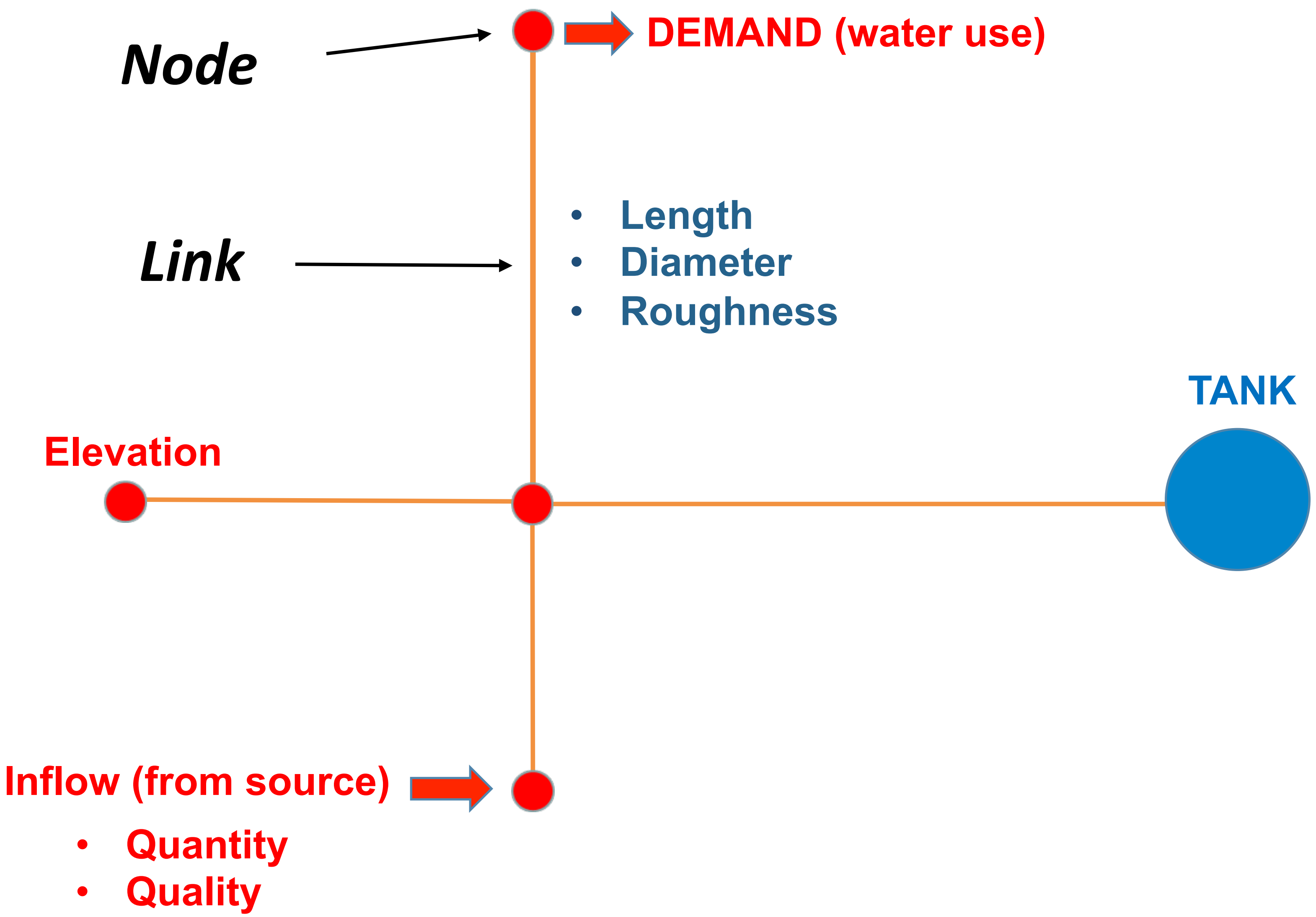


What is a Water Distribution System Hydraulic Model?

- It’s a computer program (software)
- that takes as input
    - pipe network layout
    - water demands (consumption)
    - information on system operation
- and produces as output
    - flows and pressures (heads) in the network
        - Steady-state: at a single point in time
        - Extended period simulation: at each time step


EPANET 2 - Net2MOD.net
File
Edit
View
Project
Report
Window
Help
Network Map
Day 3, 11:00 AM
Junction 36
Tank
Junction 19
Junction 6
Pump Station
Chlorine
0.20
0.40
0.60
0.80
mg/L
Browser
Data
Map
Nodes
Chlorine
Links
No View
Time
51:00 Hrs
Time Series Plot - Chlorine for Selected Nodes
Chlorine for Selected Nodes
Chlorine (mg/L)
0.94
0.9
0.86
0.82
0.78
0.74
0.7
0.66
0.61
0.57
0.53
0.49
0.45
0.41
0.37
0.33
0.29
0.25
0.2
0.16
34
36
38
40
42
44
46
48
50
52
54
Time (hours)
Node 6
Node 19
Node 36
Auto-Length Off
GPM
100%
X,Y: 58.58, 65.55
Start
Exploring - Orsa...
Microsoft Word ...
Microsoft Powe...
EPANET 2
2:29 PM

Model Input



Node

DEMAND (water use)

Link

- **Length**
- **Diameter**
- **Roughness**

TANK

Elevation

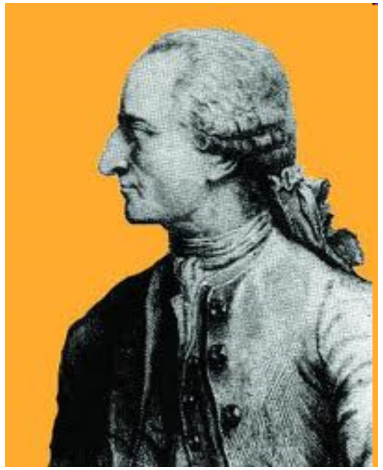
Inflow (from source)

- **Quantity**
- **Quality**

A Little History of Water Distribution

Pioneers of Water Flow Analysis

Bernoulli



Chezy

St. Venant

Darcy

Weisbach

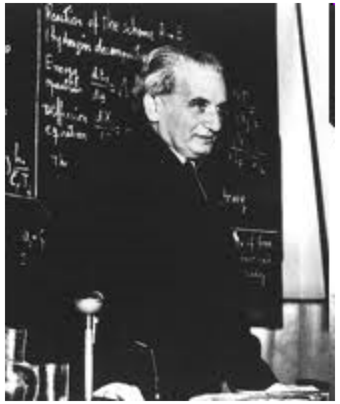
Pitot

Newton

Reynolds

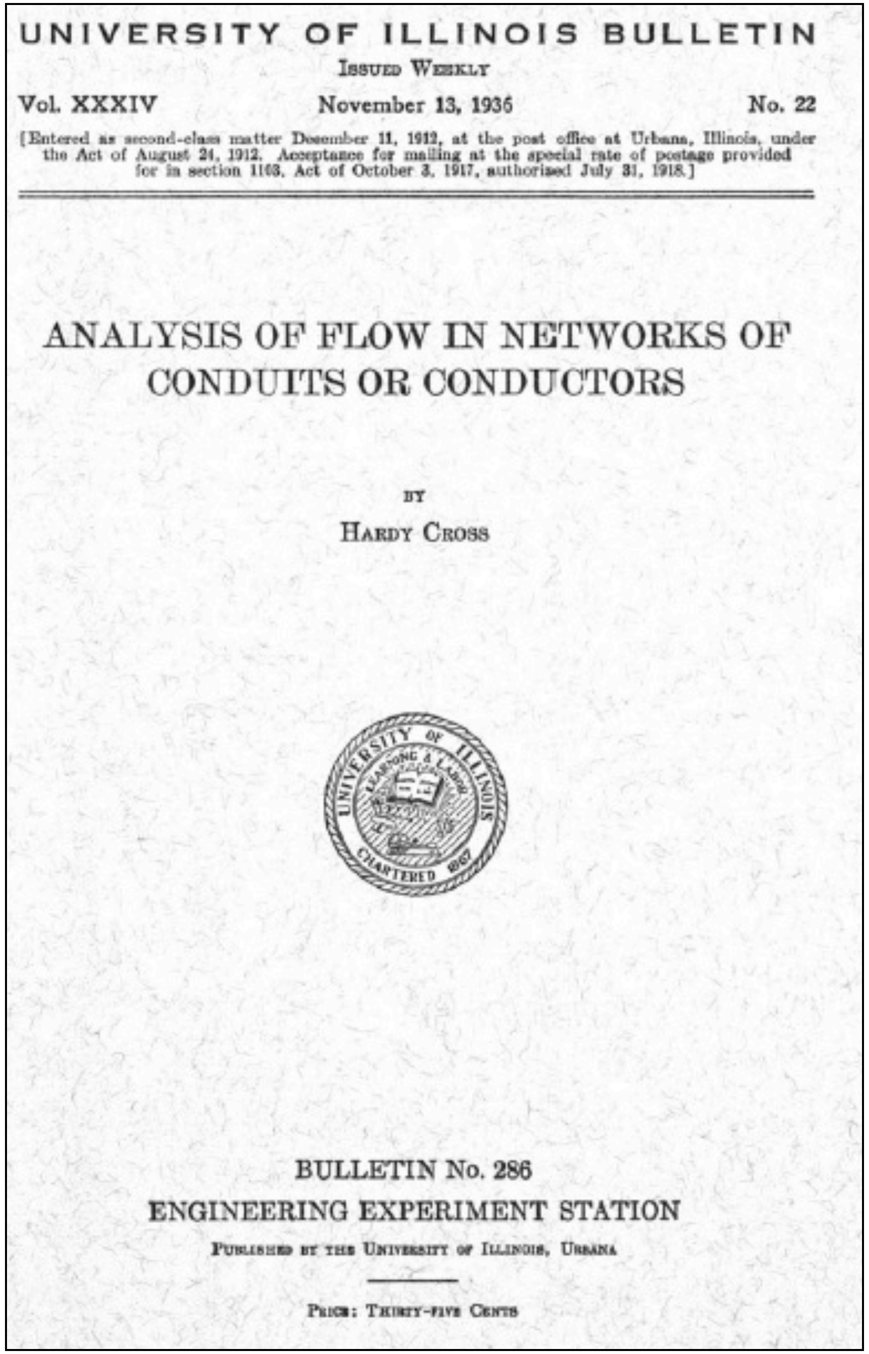
Hazen

Williams



Von Karmen

Hardy Cross
(1885 – 1959)



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ANALYSIS OF FLOW IN NETWORKS OF CONDUITS OR CONDUCTORS

by

Hardy Cross

BULLETIN No. 286

ENGINEERING EXPERIMENT STATION

Published by the University of Illinois, Urbana

Price: Thirty-five Cents

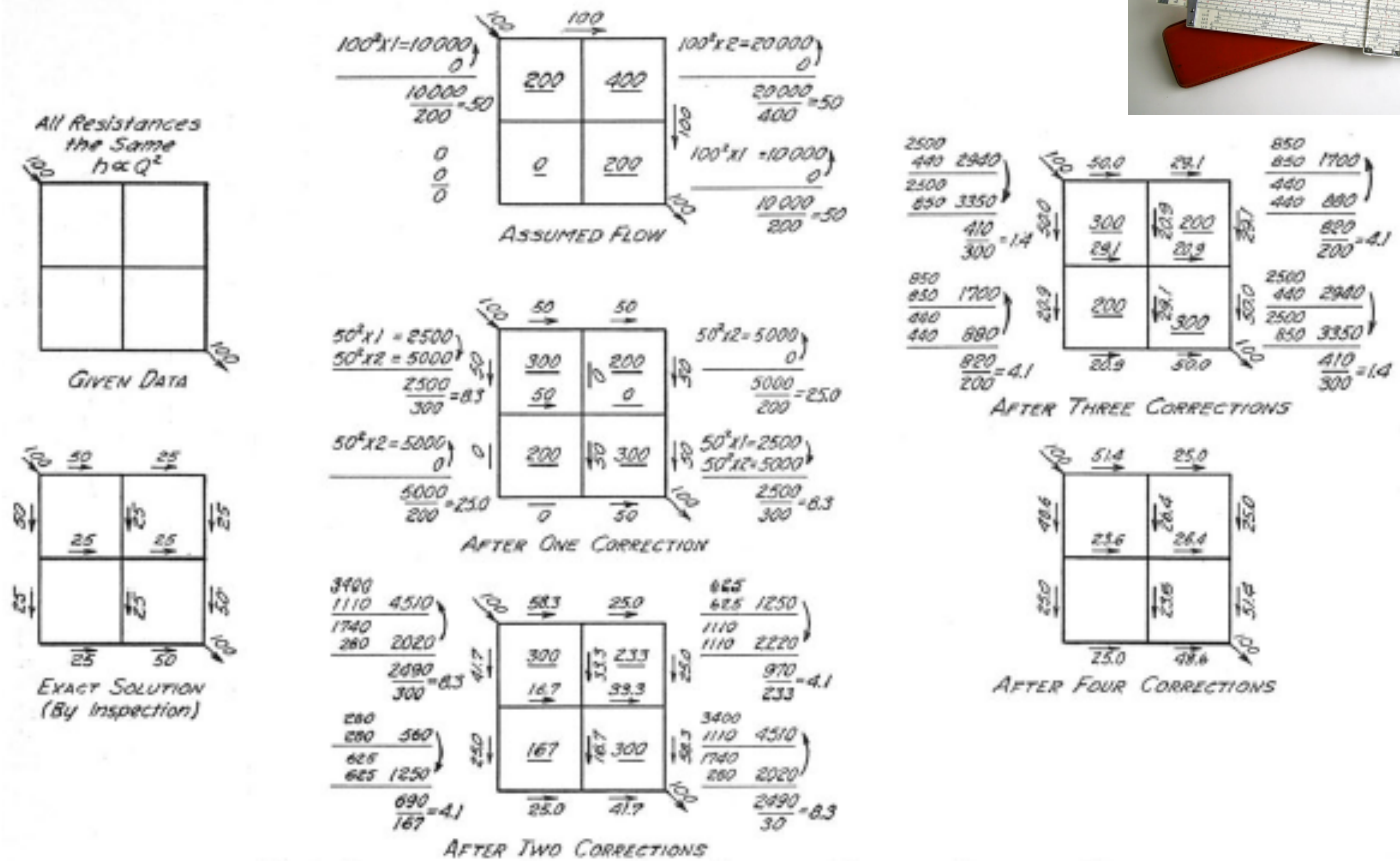
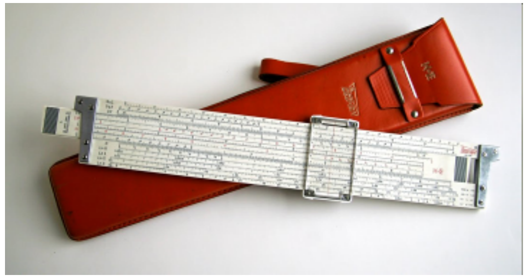
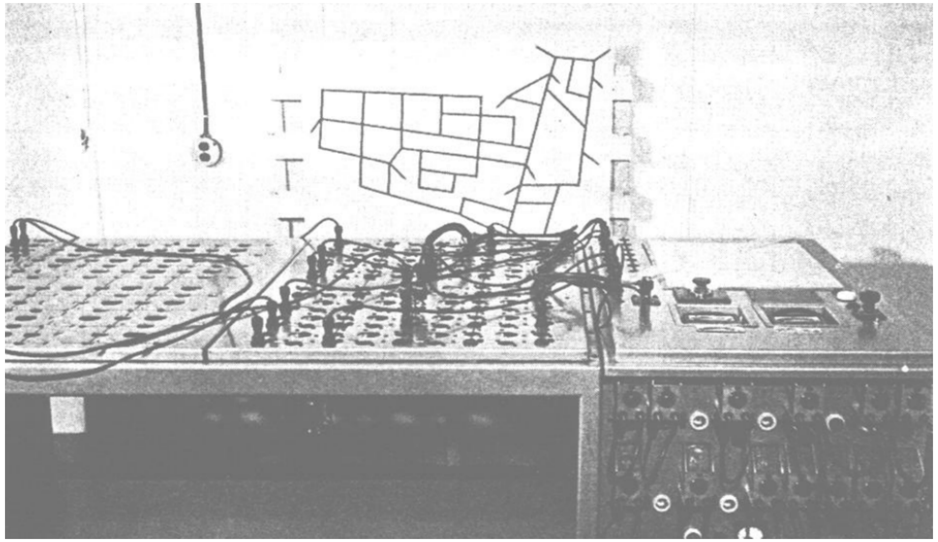


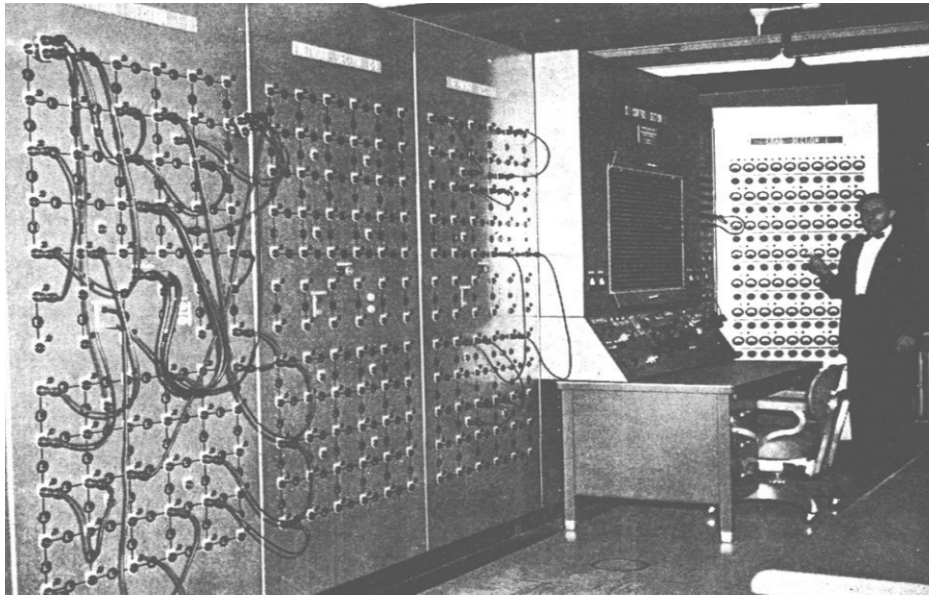
FIG. 2. DISTRIBUTION OF FLOW IN SIMPLE NETWORK; METHOD OF BALANCING HEADS



Analog Pipe Flow Analyzers

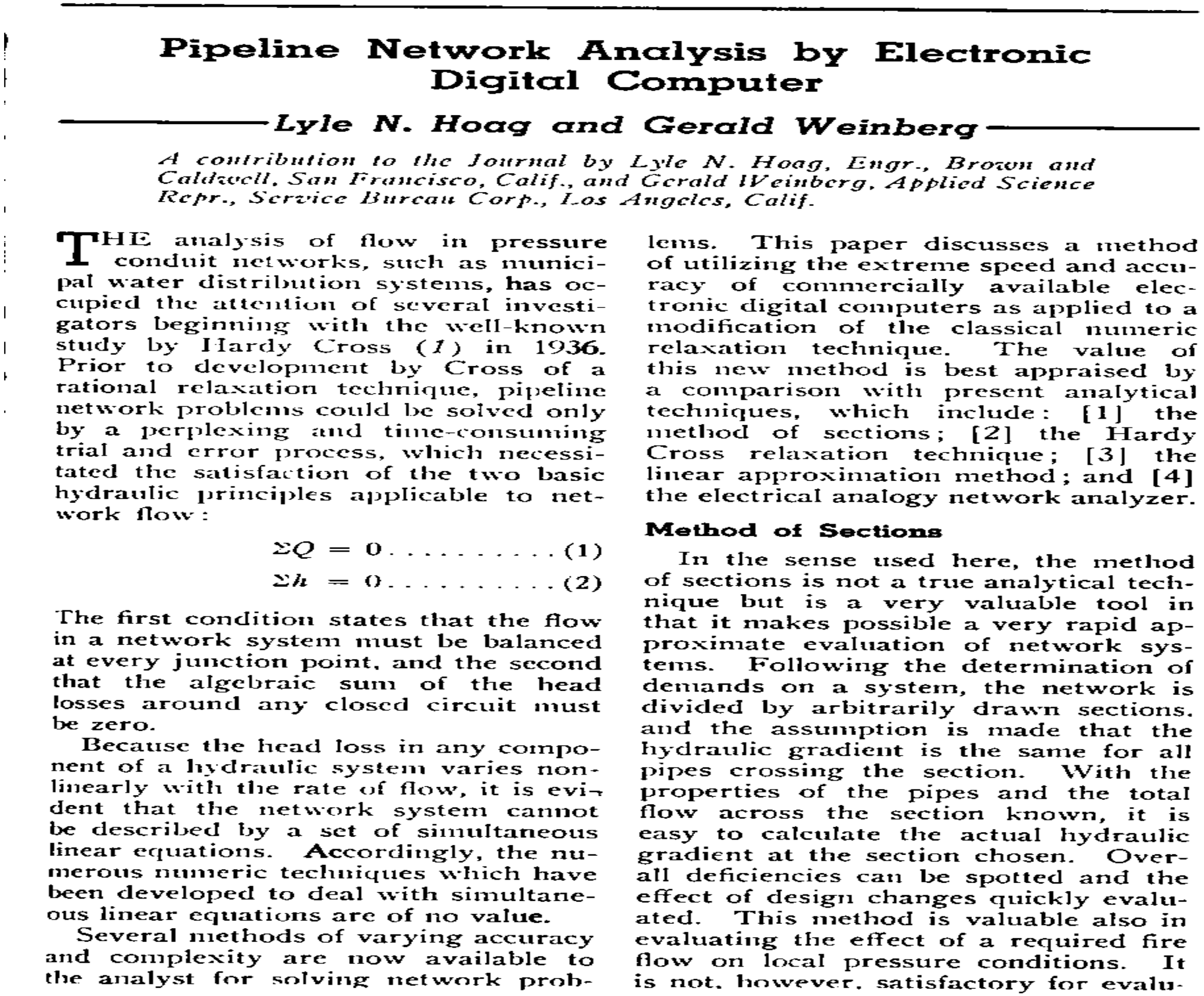


Thomas Camp's analog system in the early 1940s



Malcom McIlroy's analog nonlinear vacuum tube design in the late 1940s. This model was installed in Philadelphia.

Early Computer Analysis (1957)



Pipeline Network Analysis by Electronic Digital Computer

Lyle N. Hoag and Gerald Weinberg

A contribution to the Journal by Lyle N. Hoag, Engr., Brown and Caldwell, San Francisco, Calif., and Gerald Weinberg, Applied Science Repr., Service Bureau Corp., Los Angeles, Calif.

THE analysis of flow in pressure conduit networks, such as municipal water distribution systems, has occupied the attention of several investigators beginning with the well-known study by Hardy Cross (*1*) in 1936. Prior to development by Cross of a rational relaxation technique, pipeline network problems could be solved only by a perplexing and time-consuming trial and error process, which necessitated the satisfaction of the two basic hydraulic principles applicable to network flow:

$$\Sigma Q = 0 \,.\,.\,.\,.\,.\,.\,.\,.\,.\,.\,. \quad (1)$$

$$\Sigma h = 0 \,.\,.\,.\,.\,.\,.\,.\,.\,.\,.\,. \quad (2)$$

The first condition states that the flow in a network system must be balanced at every junction point, and the second that the algebraic sum of the head losses around any closed circuit must be zero.

Because the head loss in any component of a hydraulic system varies nonlinearly with the rate of flow, it is evident that the network system cannot be described by a set of simultaneous linear equations. Accordingly, the numerous numeric techniques which have been developed to deal with simultaneous linear equations are of no value.

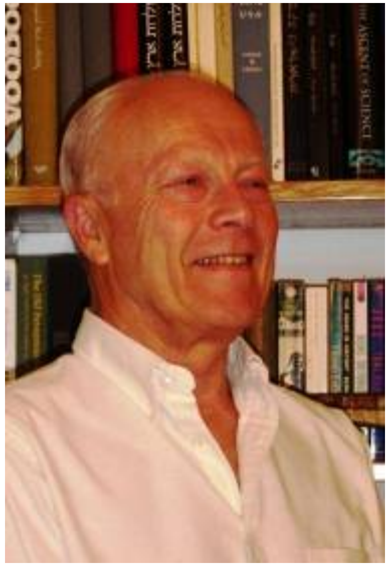
Several methods of varying accuracy and complexity are now available to the analyst for solving network problems. This paper discusses a method of utilizing the extreme speed and accuracy of commercially available electronic digital computers as applied to a modification of the classical numeric relaxation technique. The value of this new method is best appraised by a comparison with present analytical techniques, which include: [1] the method of sections; [2] the Hardy Cross relaxation technique; [3] the linear approximation method; and [4] the electrical analogy network analyzer.

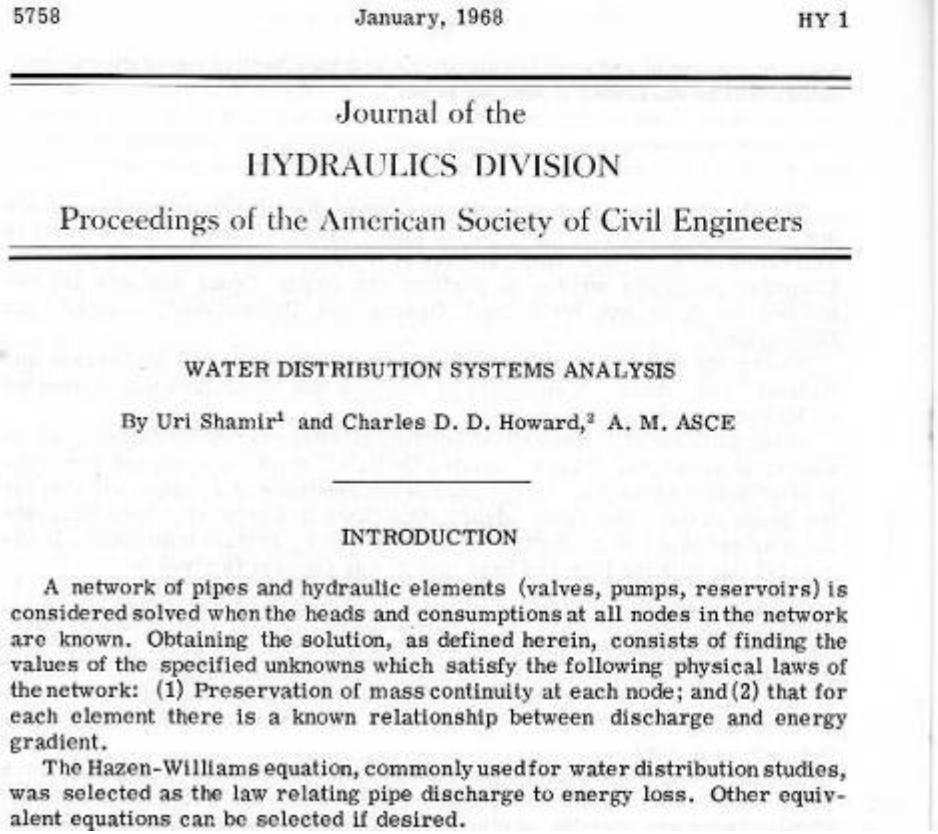
Method of Sections

In the sense used here, the method of sections is not a true analytical technique but is a very valuable tool in that it makes possible a very rapid approximate evaluation of network systems. Following the determination of demands on a system, the network is divided by arbitrarily drawn sections, and the assumption is made that the hydraulic gradient is the same for all pipes crossing the section. With the properties of the pipes and the total flow across the section known, it is easy to calculate the actual hydraulic gradient at the section chosen. Overall deficiencies can be spotted and the effect of design changes quickly evaluated. This method is valuable also in evaluating the effect of a required fire flow on local pressure conditions. It is not, however, satisfactory for evalu-

Steady-State Models

- Network analyzed at a snapshot in time
- No temporal variation





5758 January, 1968 HY 1

Journal of the
HYDRAULICS DIVISION
Proceedings of the American Society of Civil Engineers

WATER DISTRIBUTION SYSTEMS ANALYSIS

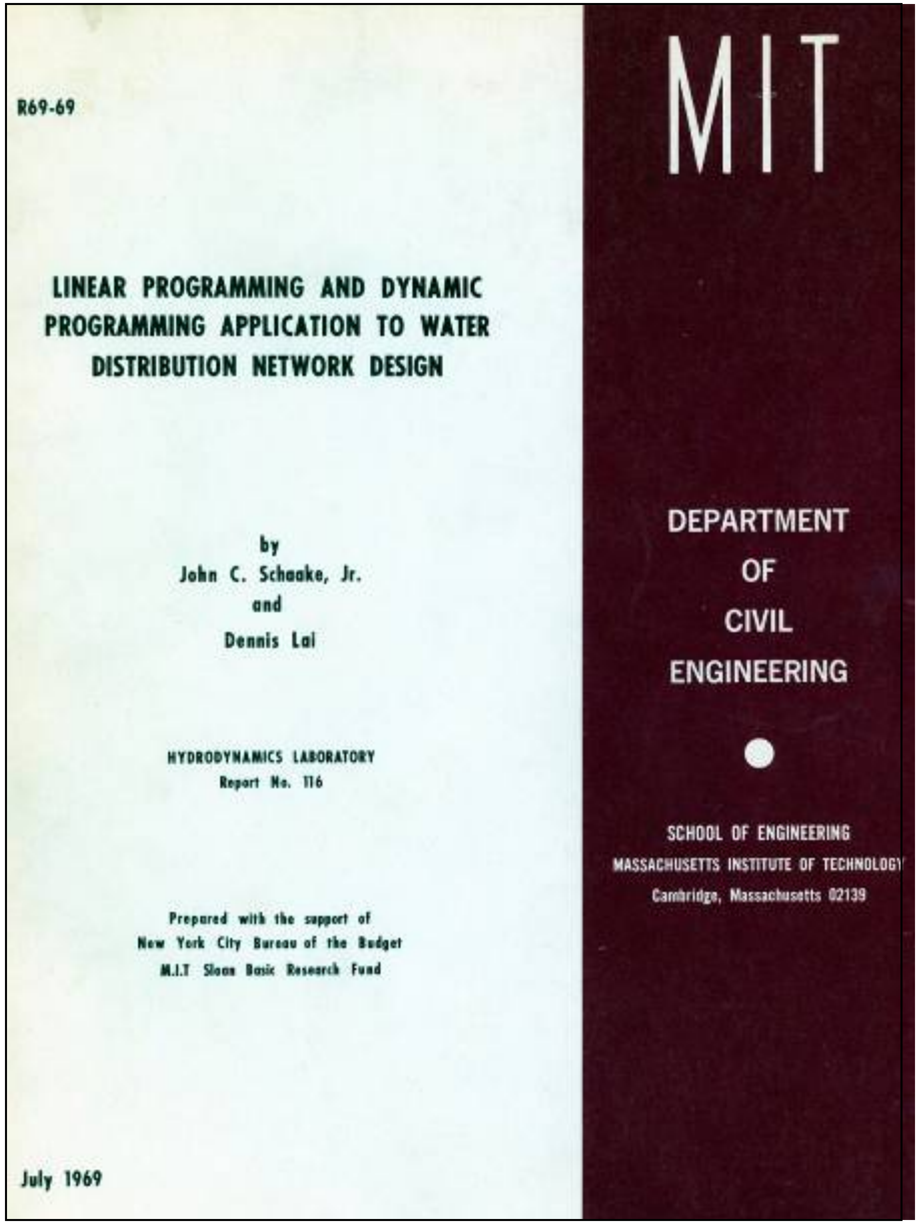
By Uri Shamir[1] and Charles D. D. Howard,[2] A. M. ASCE

INTRODUCTION

A network of pipes and hydraulic elements (valves, pumps, reservoirs) is considered solved when the heads and consumptions at all nodes in the network are known. Obtaining the solution, as defined herein, consists of finding the values of the specified unknowns which satisfy the following physical laws of the network: (1) Preservation of mass continuity at each node; and (2) that for each element there is a known relationship between discharge and energy gradient.

The Hazen-Williams equation, commonly used for water distribution studies, was selected as the law relating pipe discharge to energy loss. Other equivalent equations can be selected if desired.

Optimization of Water System Design



R69-69

LINEAR PROGRAMMING AND DYNAMIC PROGRAMMING APPLICATION TO WATER DISTRIBUTION NETWORK DESIGN

by
John C. Schaake, Jr.
and
Dennis Lai

HYDRODYNAMICS LABORATORY
Report No. 116

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New York City Bureau of the Budget
M.I.T Sloan Basic Research Fund

July 1969

MIT

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Cambridge, Massachusetts 02139

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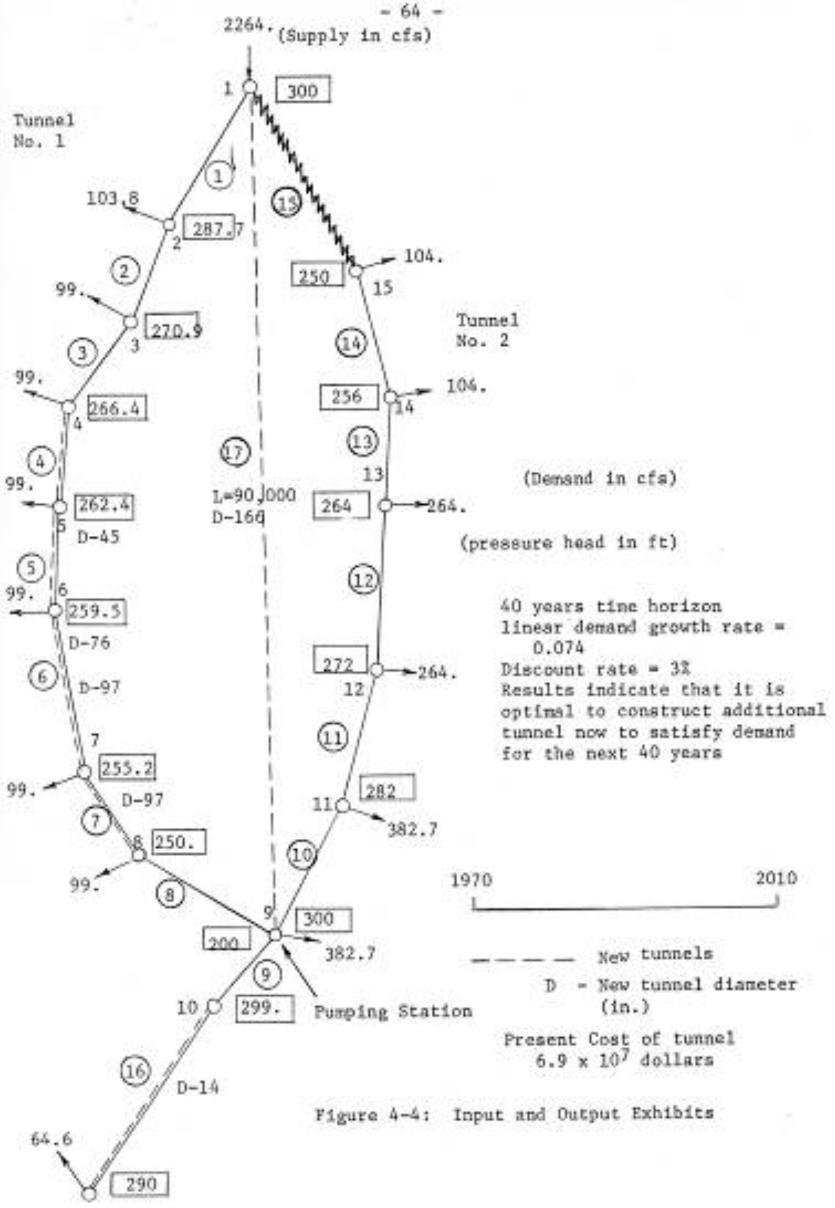


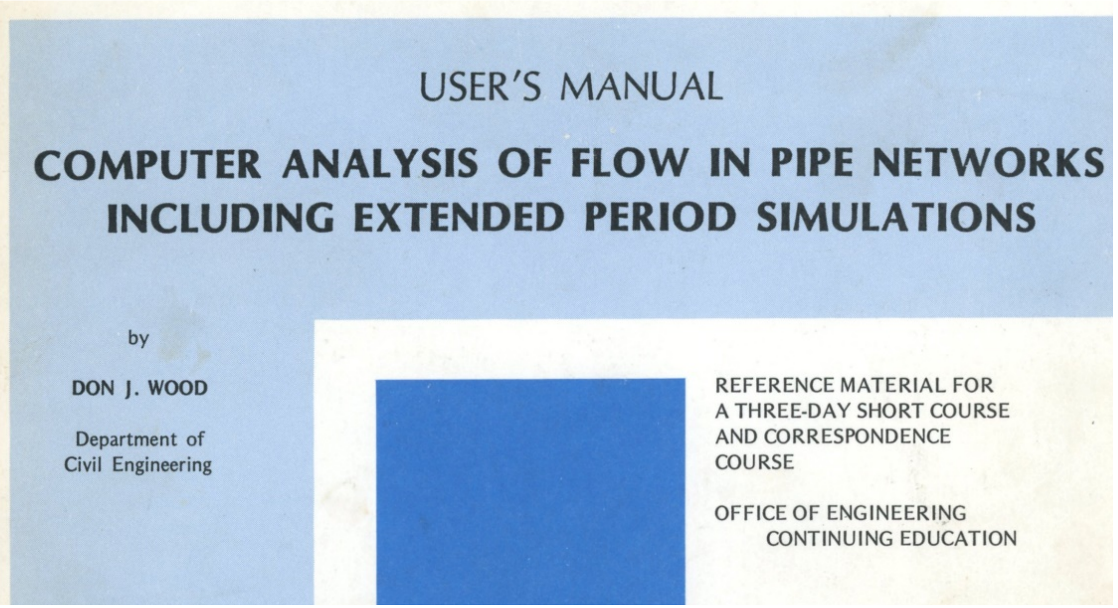
40 years time horizon
linear demand growth rate =
0.074
Discount rate = 3%
Results indicate that it is
optimal to construct additional
tunnel now to satisfy demand
for the next 40 years

Present Cost of tunnel
6.9×10^7 dollars

Figure 4-4: Input and Output Exhibits

EPS Models

- Extended Period Simulation (EPS) introduced in 1970s
- Models distribution system over time as a series of linked steady state runs
- First proposed by Don Wood (KYPipe)



USER'S MANUAL

COMPUTER ANALYSIS OF FLOW IN PIPE NETWORKS INCLUDING EXTENDED PERIOD SIMULATIONS

by

DON J. WOOD

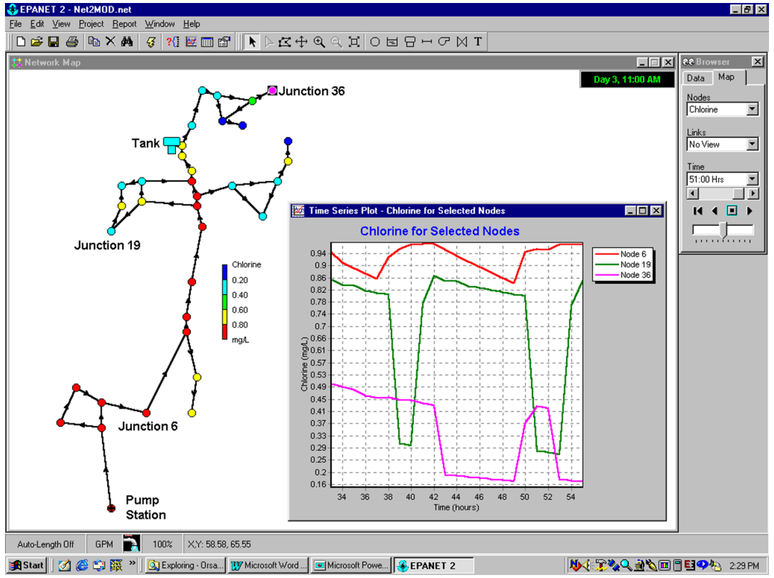
Department of
Civil Engineering

REFERENCE MATERIAL FOR
A THREE-DAY SHORT COURSE
AND CORRESPONDENCE
COURSE

OFFICE OF ENGINEERING
CONTINUING EDUCATION

EPANET

- Initially developed in 1993 by Lew Rossman
- EPANET engine used in most commercial software packages
- Version 2 in 2000: improved engine & features
- New GIS-GUI version with improved functionality to be introduced in 2017 and beyond



Nodes: Chlorine

Links: No View

Time: 51:00 Hrs

Hydraulics Review

- Fundamental factors
  - Flow & Velocity
  - Pressure
- Governing principles
  - Continuity
  - Energy
- Headloss equations
- Formulations and solution methods

Basic Assumptions about Flow

- Software represents flow as:
  - Incompressible flow (not gas)
  - Turbulent flow (not laminar)
  - Closed pipe (not open channel)
  - Full pipe (no intermittent flow)
  - Newtonian flow
  - Single phase flow

Common Units of Flow

- English units (adapted for U.S.)
  - Gallons per minute (GPM)
  - Million gallons per day (MGD)
  - 1 MGD = 646 GPM
- Metric
  - Liters per second (l/s)
  - Cubic meters per second (m^3/s)
  - 1 m^3/s = 1000 l/s
- EPANET supports both units but we will use U.S. (English) units in this course

Velocity

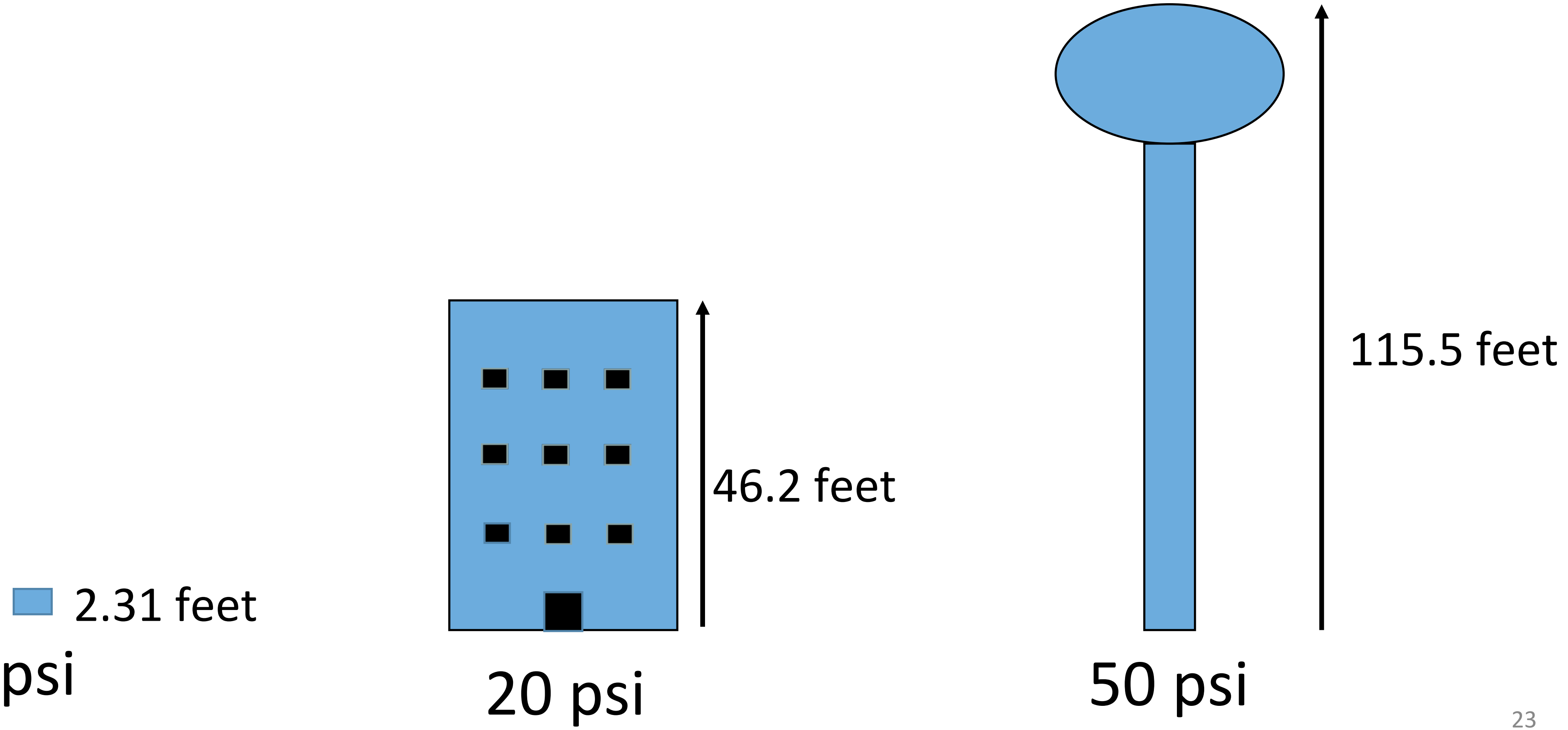
- Velocity = Flow/Area ($V = Q/A$)
  - Area of a pipe is $\pi D^2/4$ (D is pipe diameter)
  - $V = 4Q/\pi D^2$
- Common units:
  - English: feet per second (fps)
  - Metric: meters per sec (m/s)
- Typical pipe velocities
  - Small neighborhood pipes (< 1 fps)
  - Transmission lines (1 to 4 fps)
  - Maximum velocities (10 fps)

Pressure

- Pressure = Force/Area
- Typical units:
  - Pounds per square inch (psi) U.S.
  - Pascal (Pa) = Newton/ square meter. Metric
- Normal range of allowable pressures
  - 20 psi (minimum)
  - 80 to 100 psi (maximum)

Pressure: psi to feet

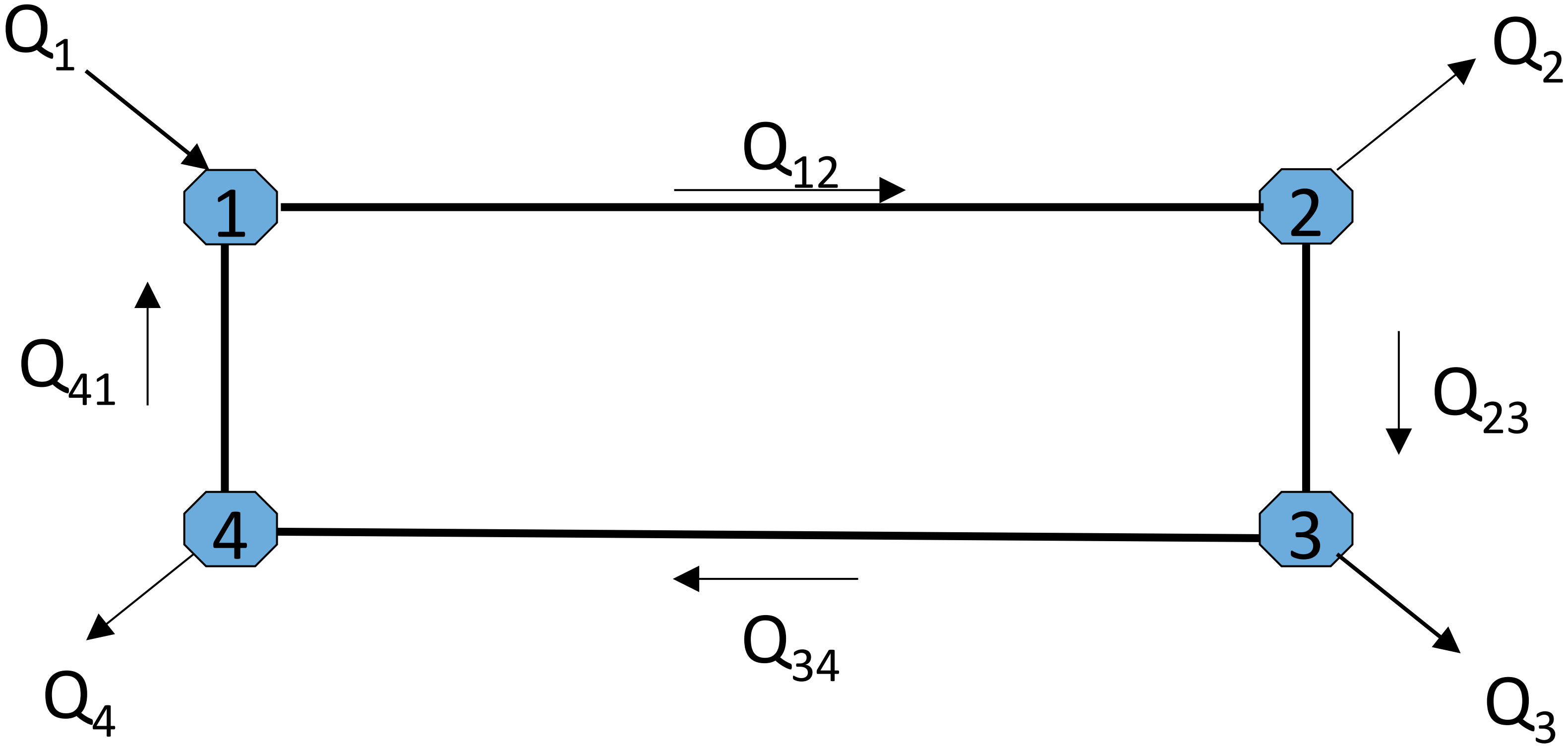
How far will water rise for different pressures at the base?



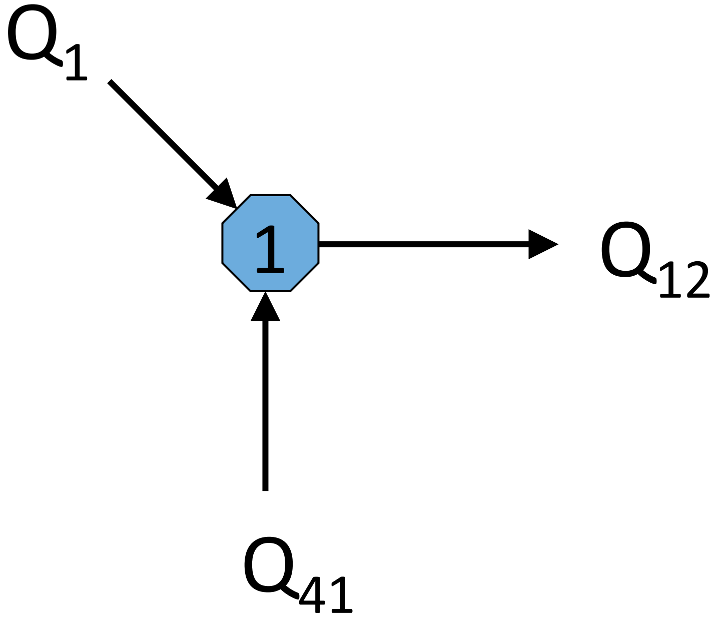
Governing Principles

Basic Laws of Physics

- Continuity (Mass Balance)
- Energy conservation



Continuity Equation
(Mass Balance)



$$Q_1 + Q_{41} - Q_{12} = 0$$

or $Q_1 + Q_{41} = Q_{12}$

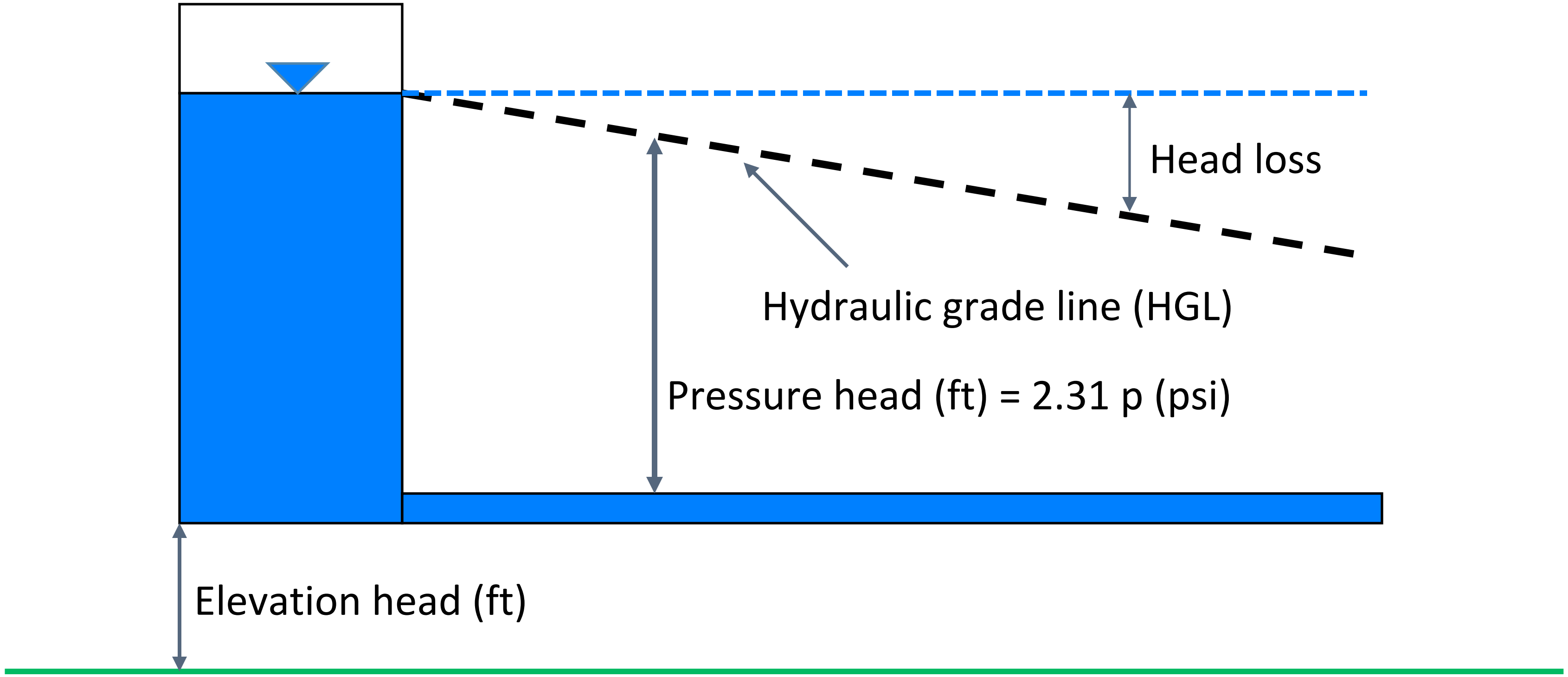
Energy Principle

In hydraulic analysis, we refer to **Head** as a measure of energy of water. Head is reported in units of length (feet in the U.S.).

Energy can take three forms:

- Pressure head
- Elevation head
- Velocity head

Hydraulic Grade Line



Static head = Pressure head + Elevation head

Hydraulic grade line (HGL) connects static head points

Total head = Static head + velocity head

Headloss Equations

- ***Empirical*** equations describing headloss in a pipe or other means of conveyance.
- Common methods for pipe headloss
  - Hazen Williams: Primarily used in U.S.
  - Darcy Weisbach: Rest of the world.
    - modified by Colebrook White and Swamee Jain
  - Minor headloss equations for fittings in pipes (e.g., bends, gates valves, etc.)
- Headlosses associated with valves and pumps.

Hazen Williams Equation

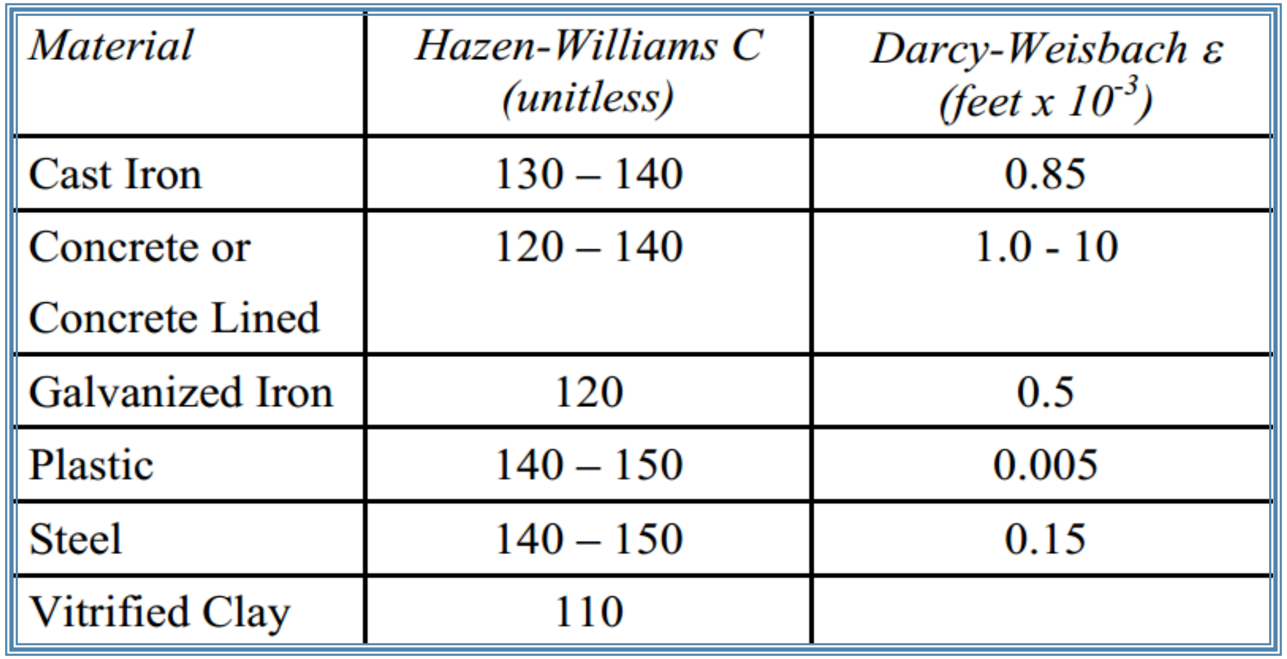
$$h_f = \frac{4.72 Q^{1.852} L}{C^{1.852} D^{4.87}}$$

$$V = 1.318 C r^{0.63} s^{0.54}$$

V = mean velocity (ft/sec)
C = Hazen Williams coefficient (decreases with increasing roughness)
r = hydraulic radius (feet) [area/wetted perimeter]
S = slope of energy line
h_f= head loss (ft)
Q = discharge (CFS)
L = length of pipe (ft)
D = inside diameter of pipe (in)

Equation of same form available for metric calculation

Typical Roughness Coefficients



Material	*Hazen-Williams C (unitless)*	*Darcy-Weisbach ε (feet x 10^{-3})*
Cast Iron	130 – 140	0.85
Concrete or Concrete Lined	120 – 140	1.0 - 10
Galvanized Iron	120	0.5
Plastic	140 – 150	0.005
Steel	140 – 150	0.15
Vitrified Clay	110	

EPANET 2 User’s Manual

For
new
pipes

As pipes age, coefficients change. For older pipes, Hazen-Williams roughness coefficient decreases and Darcy-Weisbach roughness coefficient increases

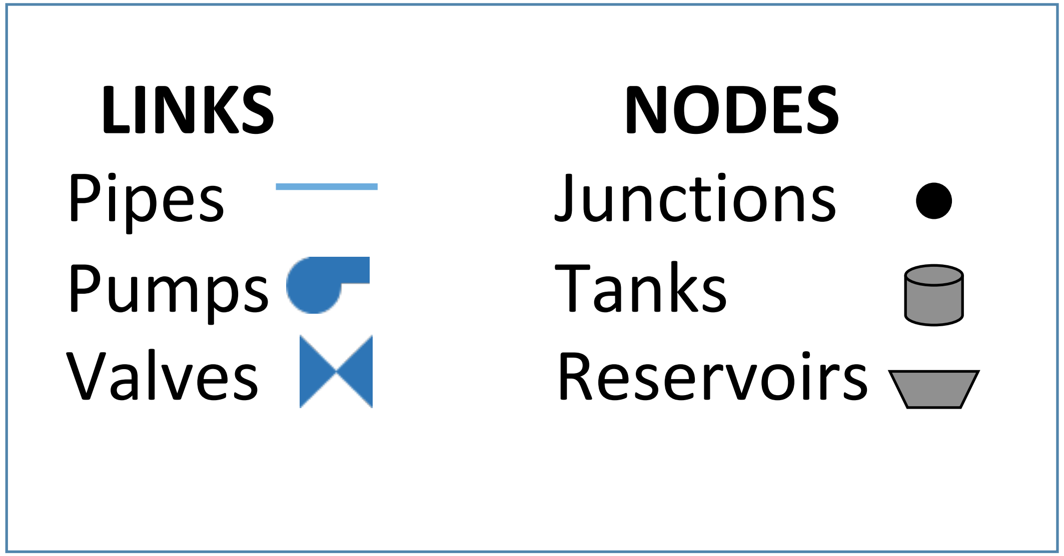
Formulations & Solutions

- General formulation:
  - N Conservation of mass equations (linear)
  - L Conservation of energy equations (non linear)
- Several different iterative, numerical solution techniques are available
  - Hardy Cross, Linear theory, gradient algorithm
- EPANET uses the Todini gradient algorithm

Types of Hydraulic Models

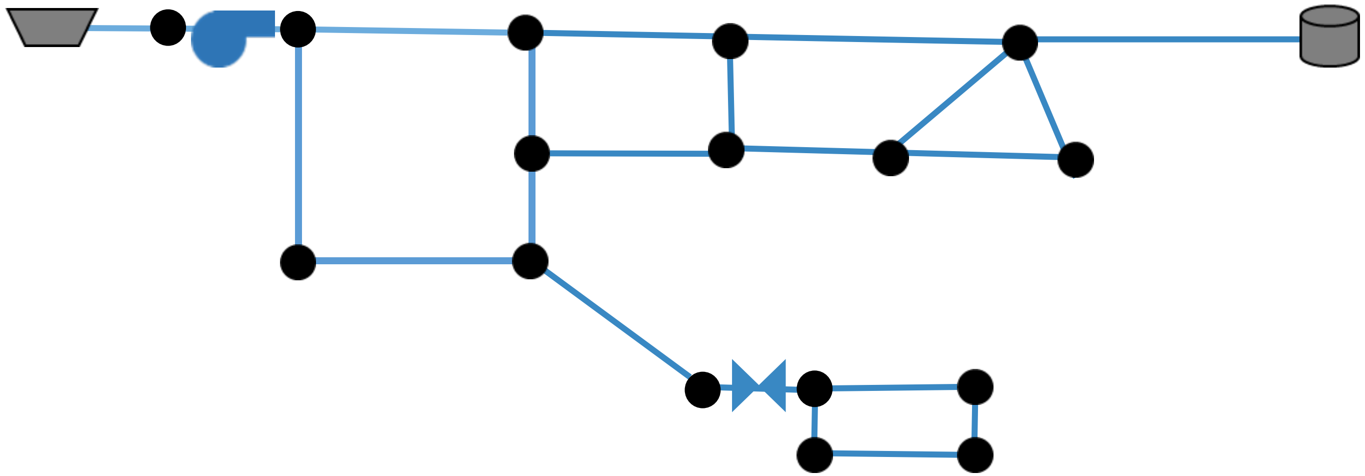
- **Steady State (SS)**
  - Snapshot of the distribution system at a given point in time
  - Could represent an average condition (e.g., average day), an extreme condition (e.g., peak hour), or at any point in time
  - Used for some fire flow analysis, design criteria, planning, etc.
- **Extended Period Simulation (EPS)**
  - Time varying analysis, 24 hours or longer
  - Used for water quality, energy and many other types of analyses

Representing a system as a link-node network

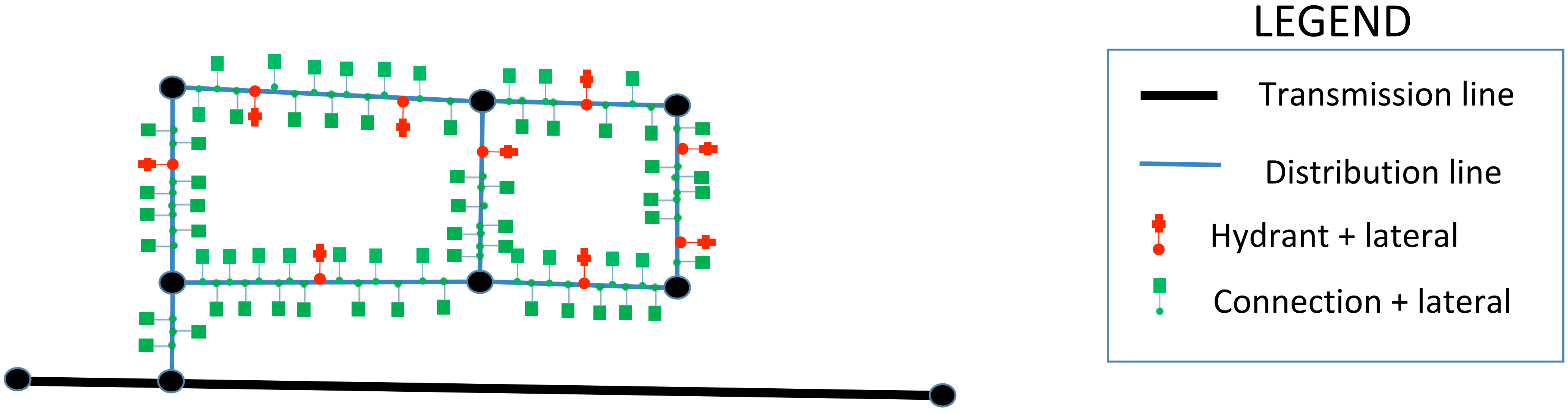


LINKS	**NODES**
Pipes	Junctions
Pumps	Tanks
Valves	Reservoirs

- Links and nodes are generic names.
- Pipes, pumps, junctions, tanks, etc. are specific types of links and nodes.
- A link connects two nodes
- The specified direction of a link depends on the specific type of link.



A detailed (complete) representation of network



A skeletonized representation of network

Major Components in a Water System

PIPES

JUNCTIONS

PUMPS

TANKS

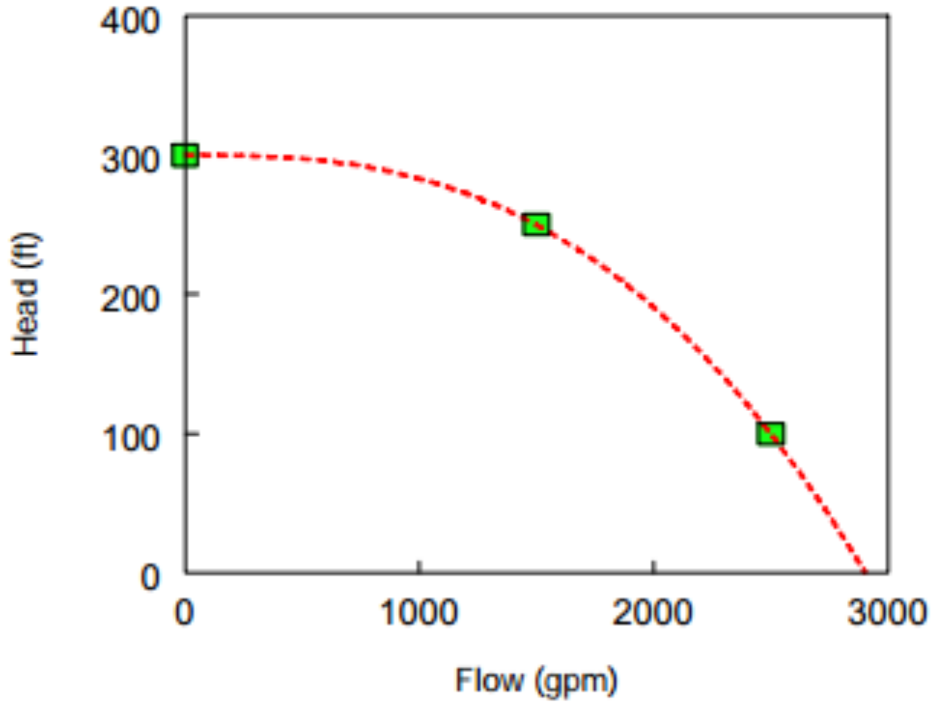
VALVES

SOURCES

Pumps

- Pumps are links that impart energy to a fluid thereby raising its hydraulic head
- A pump (head-flow) curve represents the relationship between the head and flow rate that a pump can deliver. Pump operates on a curve.
- A pump efficiency curve shows the efficiency of a pump at different pump rates.

Three Point Pump Curve



- Standard pump curve defined by:
  - Low Flow point (flow and head at low or zero flow condition),
  - Design Flow point (flow and head at desired operating point)
  - Maximum Flow point (flow and head at maximum flow).
- EPANET fits a function of the form:

h_G = head gain
q = pump flow rate
A,B,C are constants

$$h_G = A - Bq^C$$

Pump Operation

- Flow through a pump is unidirectional.
- If system conditions require more head than the pump can produce, EPANET shuts the pump off.
- If more than the maximum flow is required, EPANET extrapolates the pump curve to the required flow, even if this produces a negative head.
- In both cases a warning message will be issued.

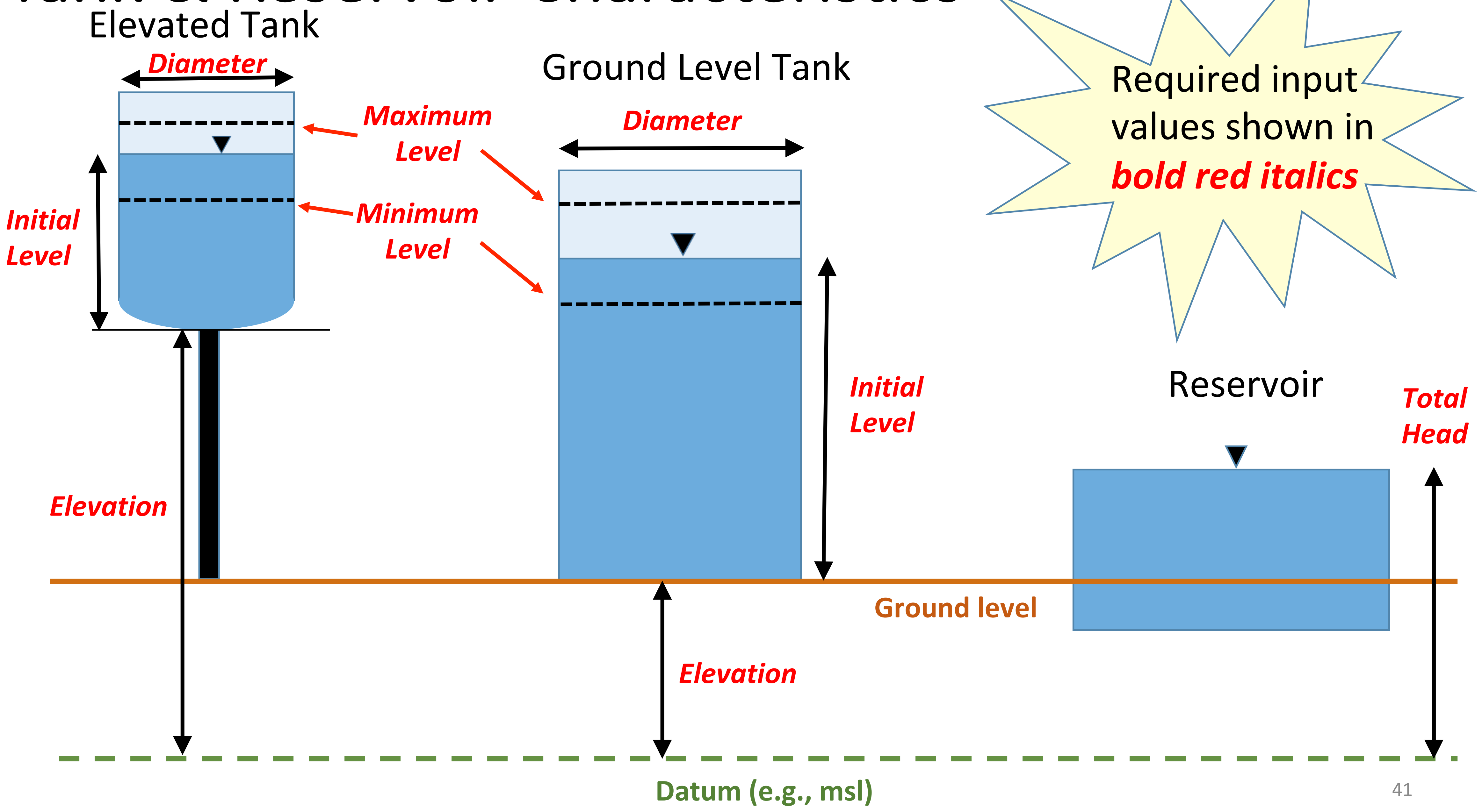
Tanks and Reservoirs

- Tanks and reservoirs store water and provide head
- They come in all shapes, sizes and configurations

What is the difference between a Tank & Reservoir?

- In a water system?
  - Depends on local terminology
- In a model?
  - There are a clear set of rules that differentiate the two.
    - A reservoir is of infinite volume and the water level does not change (a fixed grade node)
    - A tank has finite volume and the water level can change over time
    - In steady-state runs, tanks and reservoirs operate the same way with a fixed water level

Tank & Reservoir Characteristics



Required input values shown in ***bold red italics***

Valves

- Valves are devices that limit the pressure or flow at a specific point in the network
- Control valves are represented as links in EPANET with the following input requirements
  - Start and end nodes
  - Diameter
  - Setting
  - Fixed status (none, open, closed)
- Some “special” valves are represented in different ways

Types of Valves in EPANET

- Pressure Reducing Valve (PRV)
- Pressure Sustaining Valve (PSV)
- Pressure Breaker Valve (PBV)
- Flow Control Valve (FCV)
- Throttle Control Valve (TCV)
- General Purpose Valve (GPV)

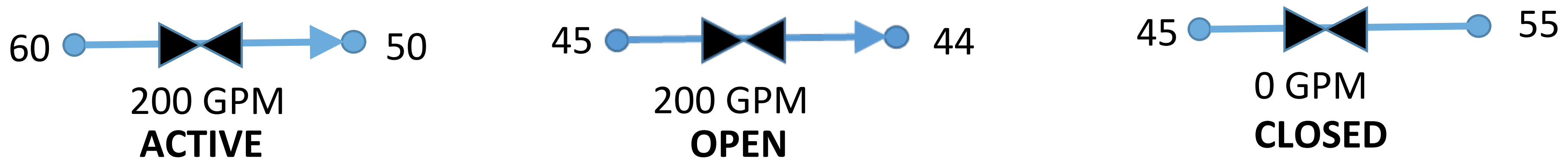
Explicitly represented as control valves in EPANET

- Check Valve
- Shutoff Valve
- Altitude Valve

Represented in other ways in EPANET

Pressure Reducing Valve (PRV)

- PRVs limit the pressure at the node downstream of the valve in the pipe network.
- Setting for PRV is in terms of pressure
- EPANET allows one of three different states for PRV:
    - partially opened (i.e., active) to achieve its pressure setting on its downstream side when the upstream pressure is above the setting
    - fully open if the upstream pressure is below the setting
    - closed if the pressure on the downstream side exceeds that on the upstream side (i.e., reverse flow is not allowed)
- Example: SETTING = 50 psi DEMAND = 200 GPM



Sources

- Sources of water flow into the distribution system
  - Wells, treatment plants or transfers from other systems
- There are no designated simple components to represent sources
- Common ways of representing sources
  - Reservoirs with or without a pump (and other appurtenances)
  - Negative demands
- Note that models must have at least one fixed grade node (tank or reservoir) to operate.

Representing Wells

- Composite element
    - Reservoir = groundwater level
    - Pump
    - Pipe losses
    - Surface node
- Issue:
    - Actual pump creates a cone of depression when it is on
    - What do we use as the water level in reservoir in model?