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Tennessee Water Resources Research Center

THE UNIVERSITY OF TENNESSEE
KNOXVILLE

Introduction to Water Distribution System Modeling (Part 1)

April 30, 2026

www.efcnetwork.org

This program is made possible under a cooperative agreement with US EPA.

Instructor

- Steven W.H. Hoagland, Research Assistant Professor
  Tennessee Water Resources Research Center
  - Manage technical assistance and training projects for water and wastewater utilities, specializing in:

Geographic Information Systems (GIS)

Asset Management Plans

Hydraulic Modeling (WDS and CS)

  - **Always looking for utilities to work with**
  - Email: hoagland@utk.edu
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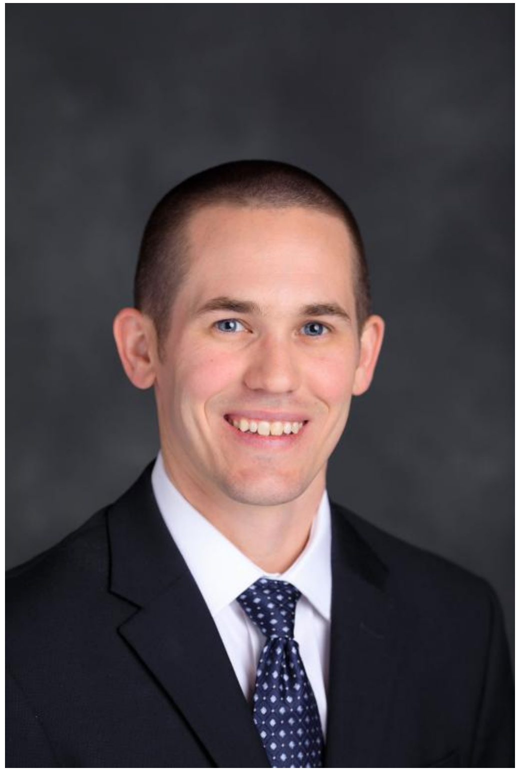

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Webinar Outline

Introduction to WDS Modeling (30 minutes)

- What is a WDS model?
- Why is a WDS model useful?
- How does a WDS model work?

WDS Model Development (20 minutes)

- Select modeling software
- Determine model scale
- Create the network
- Add node information
- Add link information

Save the date!

Introduction to WDS Modeling Webinar (Part 2)

May 28, 2026

Registration link coming soon

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Introduction to WDS Modeling

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What is a WDS Model?

- A water distribution system (WDS) model is **a computational tool** that can be used to help engineers, managers, and operators with the planning, design, analysis, and operation of their system.
- A WDS model **uses scientific laws, empirical relationships, and mathematics** to predict system information (e.g., pressures and flowrates) through simulations.

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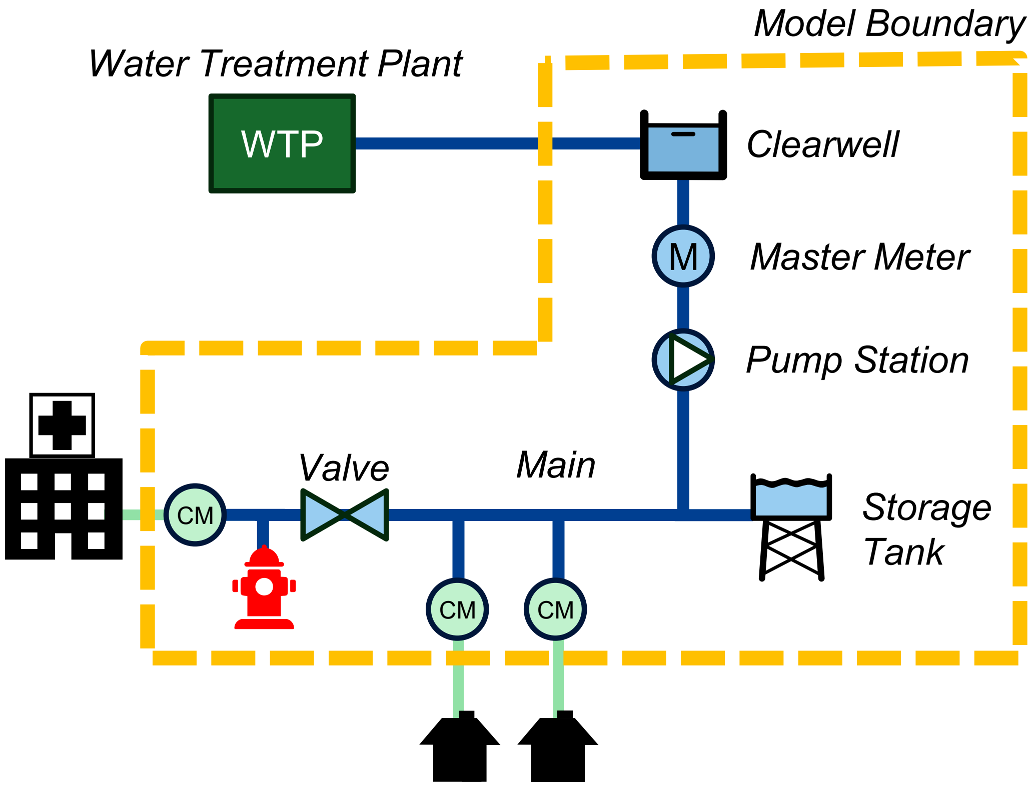
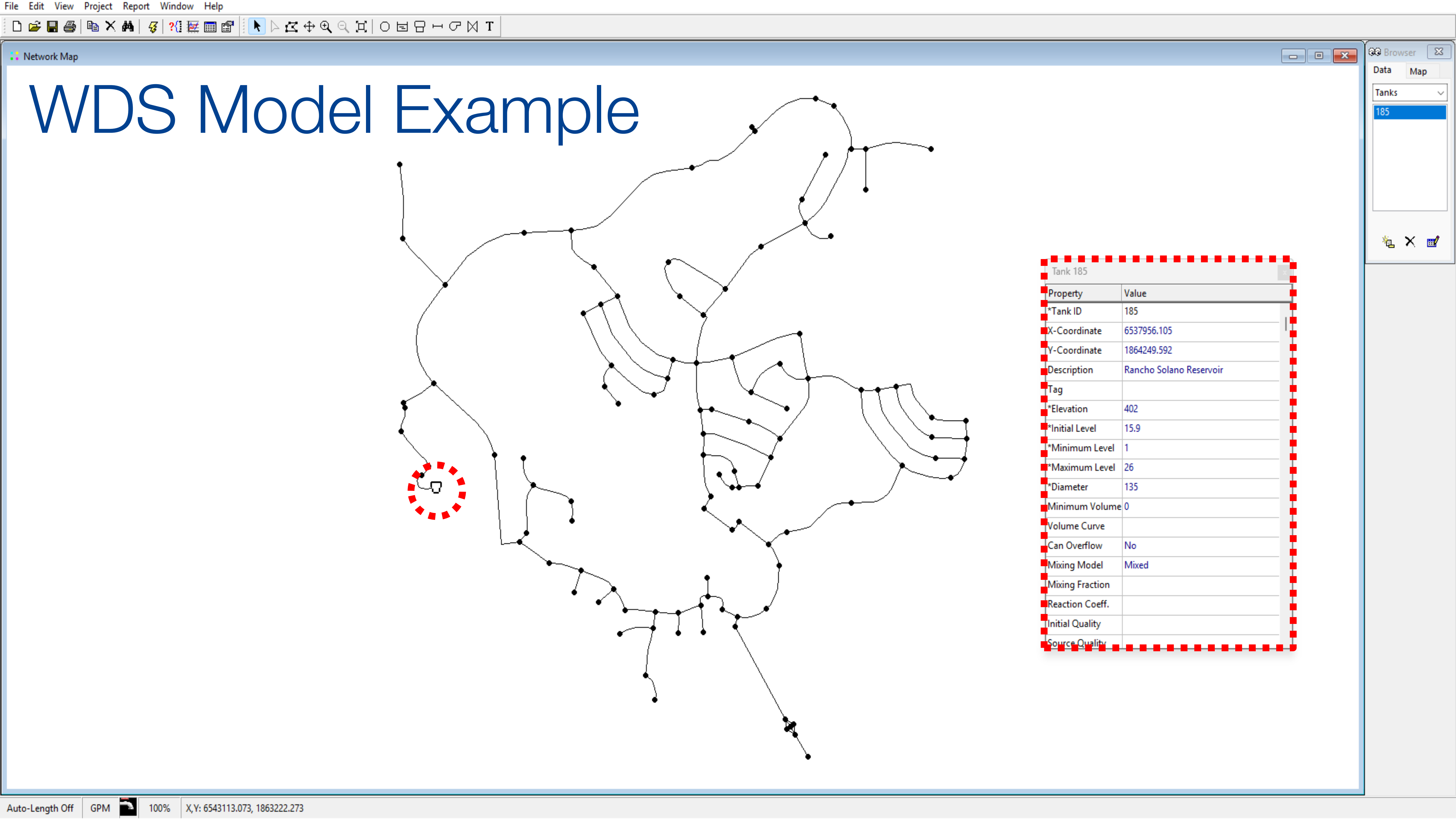
Water Distribution Systems

- Water distribution systems convey (typically potable) water through a pressurized network that extends from a clearwell to customer meters

- Water flow is driven by pressure difference between the network and discharge locations

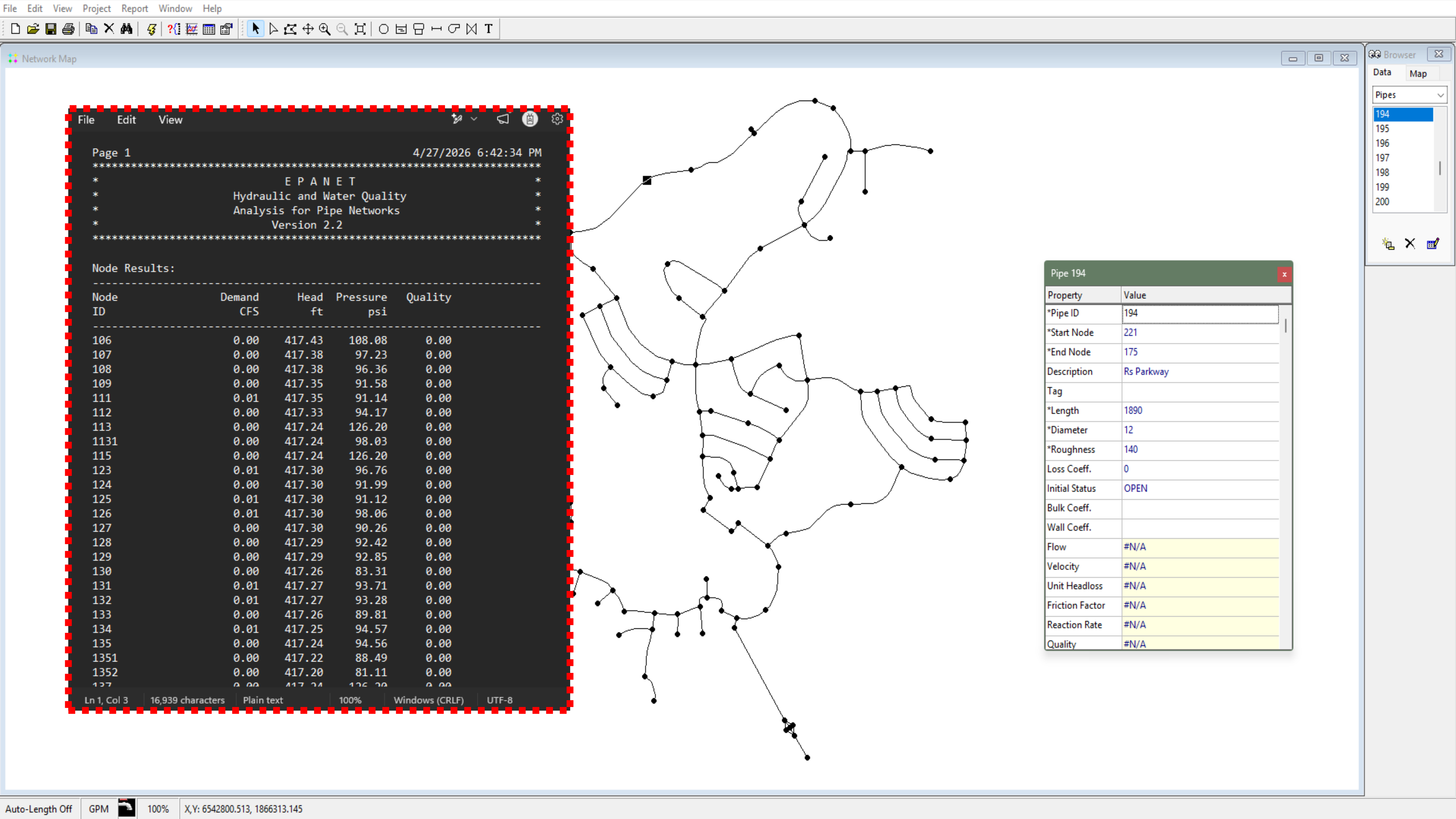


WDS Model Example



Property	Value
*Tank ID	185
X-Coordinate	6537956.105
Y-Coordinate	1864249.592
Description	Rancho Solano Reservoir
Tag	
*Elevation	402
*Initial Level	15.9
*Minimum Level	1
*Maximum Level	26
*Diameter	135
Minimum Volume	0
Volume Curve	
Can Overflow	No
Mixing Model	Mixed
Mixing Fraction	
Reaction Coeff.	
Initial Quality	
Source Quality	

Auto-Length Off
GPM
100%
X,Y: 6543113.073, 1863222.273

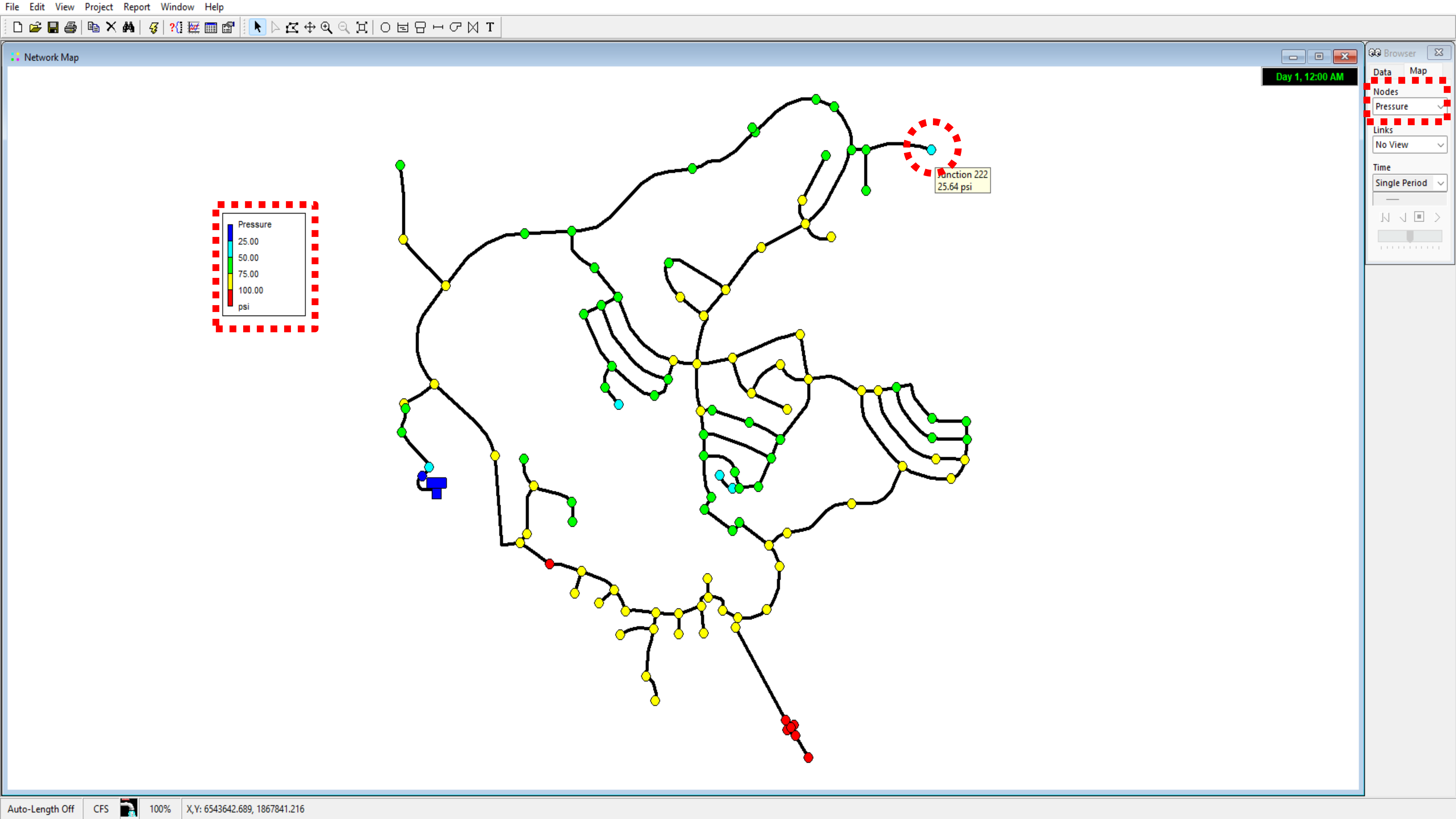


```
Page 1                                       4/27/2026 6:42:34 PM
**********************************************************************
*                           E P A N E T                              *
*                Hydraulic and Water Quality                         *
*                Analysis for Pipe Networks                          *
*                          Version 2.2                               *
**********************************************************************

Node Results:
----------------------------------------------------------------------
Node                  Demand      Head   Pressure    Quality
ID                       CFS        ft        psi
----------------------------------------------------------------------
106                     0.00    417.43     108.08       0.00
107                     0.00    417.38      97.23       0.00
108                     0.00    417.38      96.36       0.00
109                     0.00    417.35      91.58       0.00
111                     0.01    417.35      91.14       0.00
112                     0.00    417.33      94.17       0.00
113                     0.00    417.24     126.20       0.00
1131                    0.00    417.24      98.03       0.00
115                     0.00    417.24     126.20       0.00
123                     0.01    417.30      96.76       0.00
124                     0.00    417.30      91.99       0.00
125                     0.01    417.30      91.12       0.00
126                     0.01    417.30      98.06       0.00
127                     0.00    417.30      90.26       0.00
128                     0.00    417.29      92.42       0.00
129                     0.00    417.29      92.85       0.00
130                     0.00    417.26      83.31       0.00
131                     0.01    417.27      93.71       0.00
132                     0.01    417.27      93.28       0.00
133                     0.00    417.26      89.81       0.00
134                     0.01    417.25      94.57       0.00
135                     0.00    417.24      94.56       0.00
1351                    0.00    417.22      88.49       0.00
1352                    0.00    417.20      81.11       0.00
```

Pipe 194

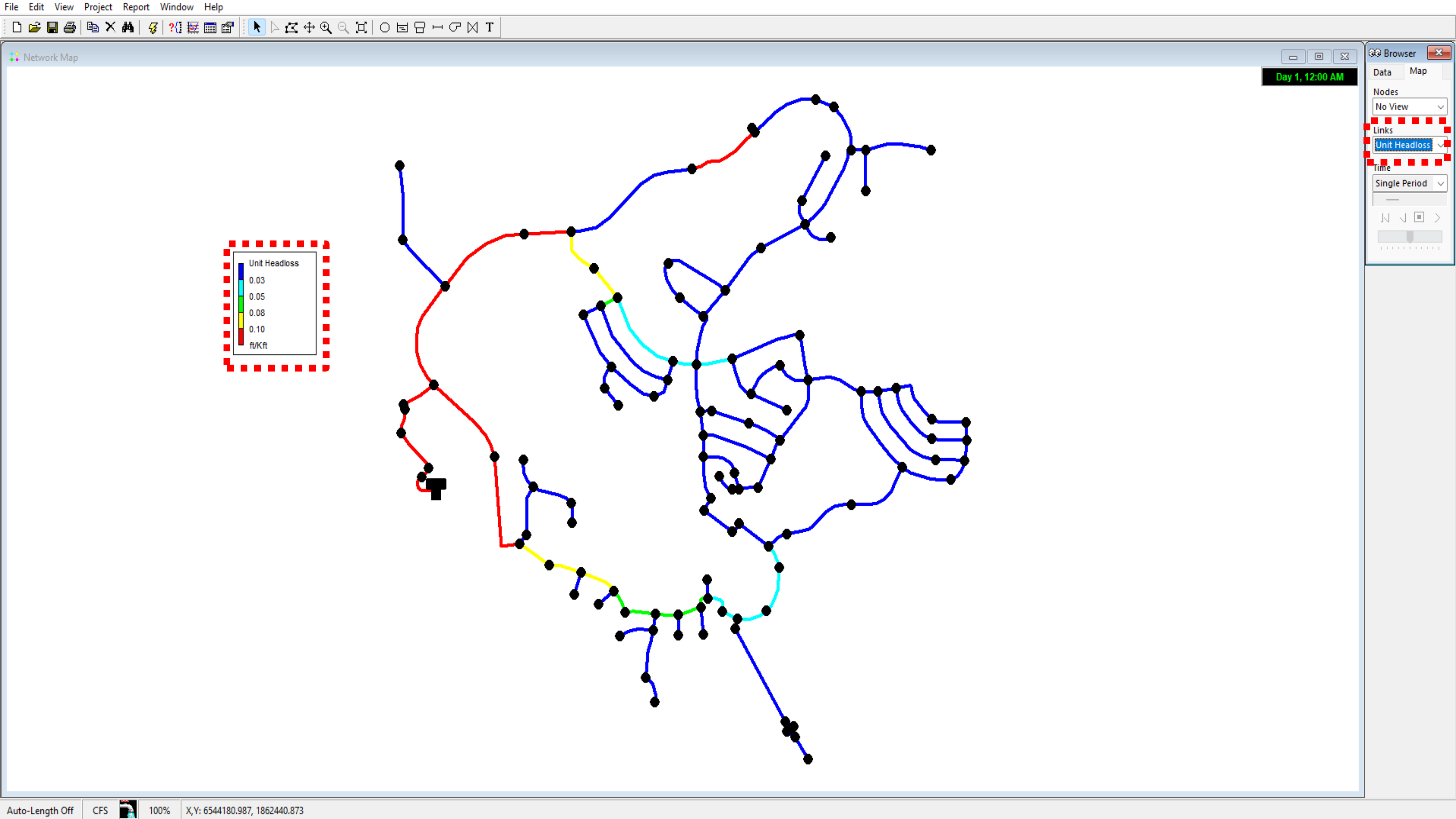
Property	Value
*Pipe ID	194
*Start Node	221
*End Node	175
Description	Rs Parkway
Tag	
*Length	1890
*Diameter	12
*Roughness	140
Loss Coeff.	0
Initial Status	OPEN
Bulk Coeff.	
Wall Coeff.	
Flow	#N/A
Velocity	#N/A
Unit Headloss	#N/A
Friction Factor	#N/A
Reaction Rate	#N/A
Quality	#N/A



Nodes: Pressure

Links: No View

Time: Single Period



Nodes: No View

Links: Unit Headloss

Time: Single Period

Auto-Length Off

CFS

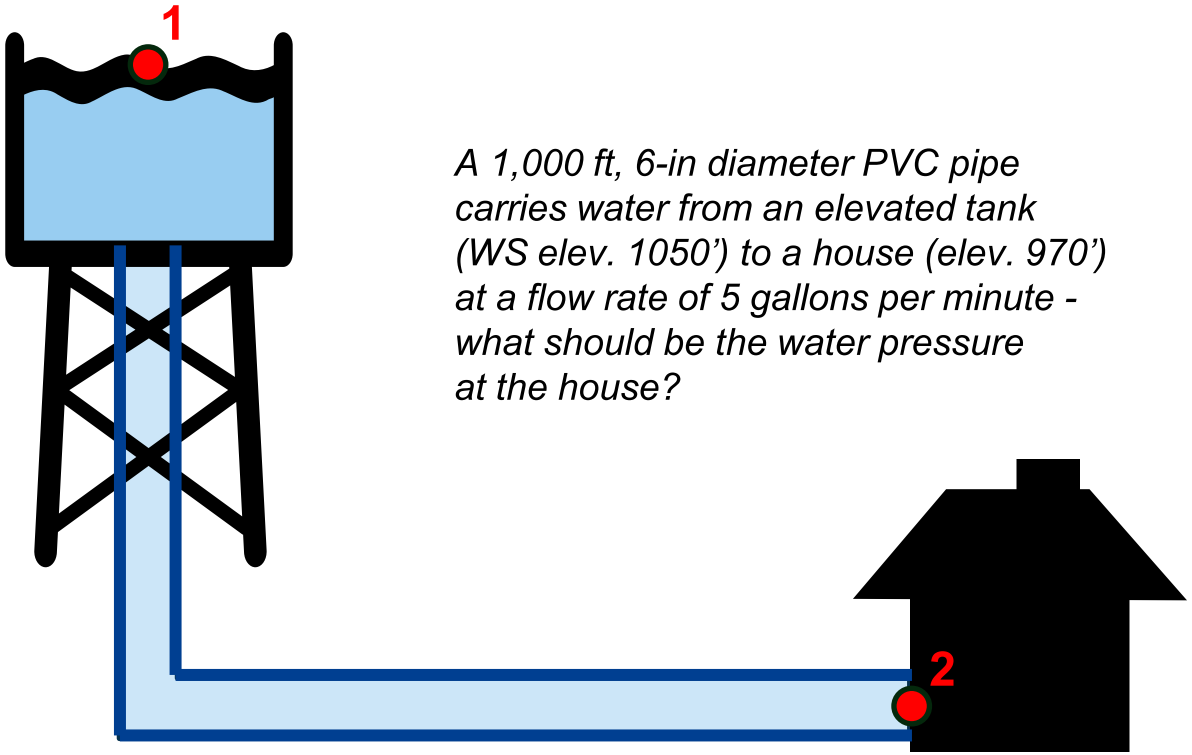
100%

X,Y: 6544180.987, 1862440.873

Why is a WDS model useful?

- Hydraulic Analysis and Design
- System Operations
- Planning
- Water Quality and Transient Analysis
- Operator Training and Knowledge Transfer

Hydraulic analysis and design



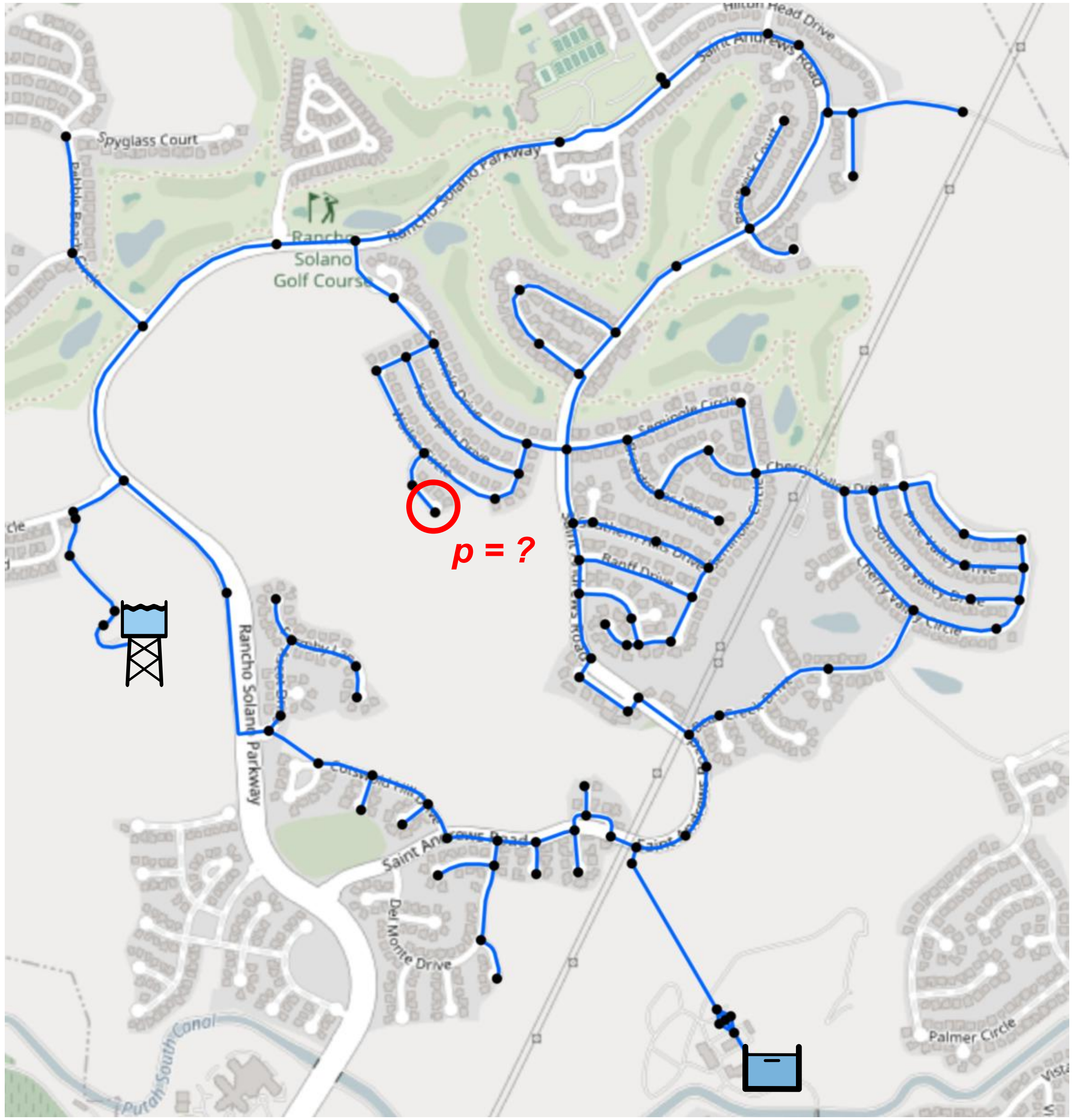
A 1,000 ft, 6-in diameter PVC pipe carries water from an elevated tank (WS elev. 1050') to a house (elev. 970') at a flow rate of 5 gallons per minute - what should be the water pressure at the house?

Bernoulli Equation

$$z_1 + \cancelto{0}{\frac{p_1}{\gamma}} + \cancelto{0}{\frac{v_1^2}{2g}} + \cancelto{0}{h_G} - \cancelto{f\frac{L}{D}\frac{v^2}{2g}}{h_L} = z_2 + \frac{p_2}{\gamma} + \frac{v_2^2}{2g}$$

$$\boxed{\gamma\left(z_1 - z_2 - \frac{v_2^2}{2g} - f\frac{L}{D}\frac{v_2^2}{2g}\right)} = p_2$$

Hydraulic analysis and design



(Relatively) Simple Network

- 111 Junctions
- 126 Pipes
- 1 Tank
- 1 Clearwell and Pump Station

Increased calculation complexity due to:

- Various pipe diameters, lengths, materials
- Varied customer locations and demands
- Elevation changes across the system
- Multiple flow paths and sources

Models handle this complexity well!

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System Operations

- Operational “what-if” scenarios
- Troubleshooting problems (e.g., low pressures)
- Emergency scenarios (e.g., main break isolation)
- Water loss calculations after main break
- Impact of planned outages
- Planning and impact of flushing program
- Optimal pump scheduling and energy management

Other reasons

- Planning
  - Asset management (risk analysis, CIP)
  - Water conservation
- Water quality analysis
  - Water age
  - Source analysis
  - Chlorine residuals
- Transient analysis
- Operator training and knowledge transfer

How does a WDS model work?

It solves a system of non-linear equations that represent the application of mass and energy conservation laws and empirical relationships to a distribution network to predict pressure, velocity, and other associated metrics.

System of Equations

$$y = x - 1$$

$$y = -x^{2} + 3$$

Non-Linear Equation

**Here we have 2 equations and 2 unknowns (y and x), so we can solve for both.*

How does a WDS model work?

It solves a system of non-linear equations that represent the application of mass and energy conservation laws and empirical relationships to a distribution network to predict pressure, velocity, and other associated metrics.

Law of Conservation of Mass (Continuity)

In a closed system, mass is neither created nor destroyed.

$$Q_{in} = Q_{out}$$

Q = *flowrate*

How does a WDS model work?

It solves a system of non-linear equations that represent the application of mass and energy conservation laws and empirical relationships to a distribution network to predict pressure, velocity, and other associated metrics.

Law of Conservation of Energy

In a closed system, energy is neither created nor destroyed.

$$z + \frac{p}{\gamma} + \frac{v^2}{2g}$$

z = *elevation head*
p/γ = *pressure head*
$v^2/2g$ = *velocity head*

How does a WDS model work?

It solves a system of non-linear equations that represent the application of mass and energy conservation laws and empirical relationships to a distribution network to predict pressure, velocity, and other associated metrics.

Law of Conservation of Energy

In a closed system, energy is neither created nor destroyed.

$$z_1 + \frac{p_1}{\gamma} + \frac{v_1^2}{2g} + h_G - h_L = z_2 + \frac{p_2}{\gamma} + \frac{v_2^2}{2g}$$

z = *elevation head*
p/γ = *pressure head*
$v^2/2g$ = *velocity head*
h_G = *head gained (pump)*
h_L = *head loss*

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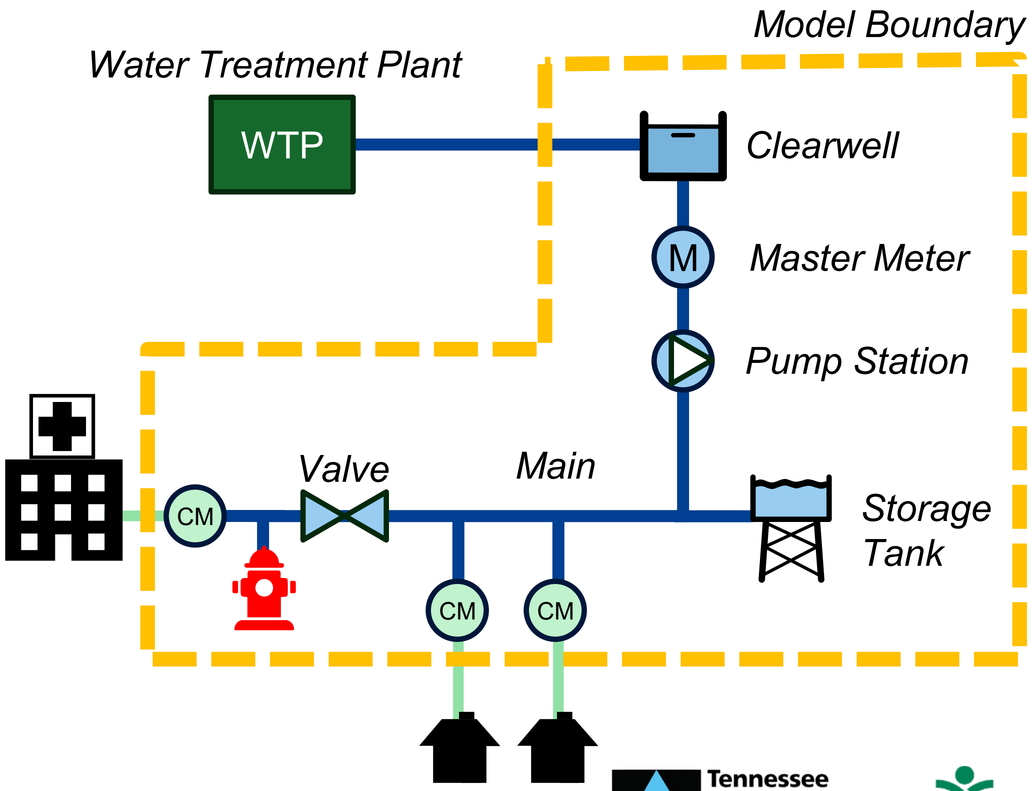
How does a WDS model work?

It solves a system of non-linear equations that represent the application of mass and energy conservation laws and empirical relationships to a distribution network to predict pressure, velocity, and other associated metrics.

Real World System



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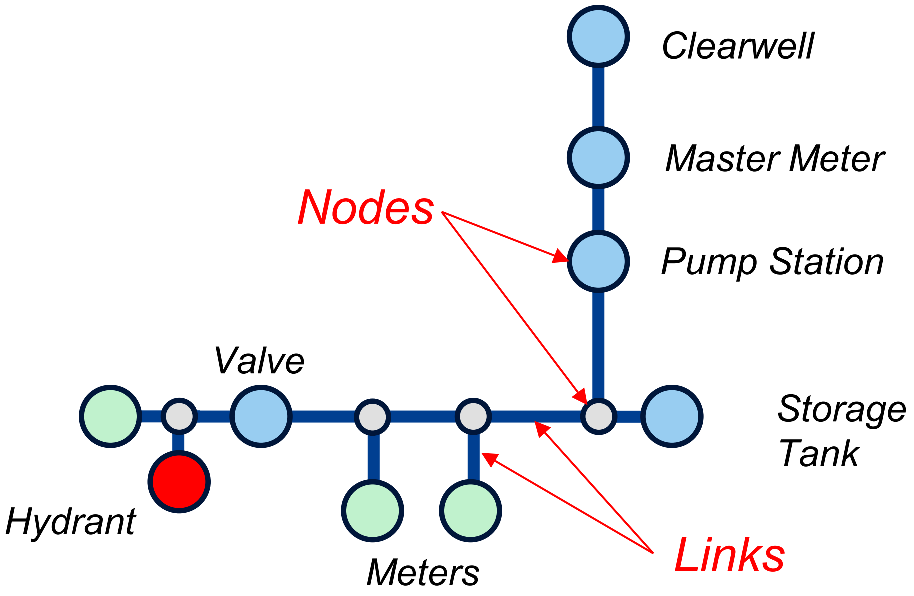
How does a WDS model work?

It solves a system of non-linear equations that represent the application of mass and energy conservation laws and empirical relationships to a distribution network to predict pressure, velocity, and other associated metrics.

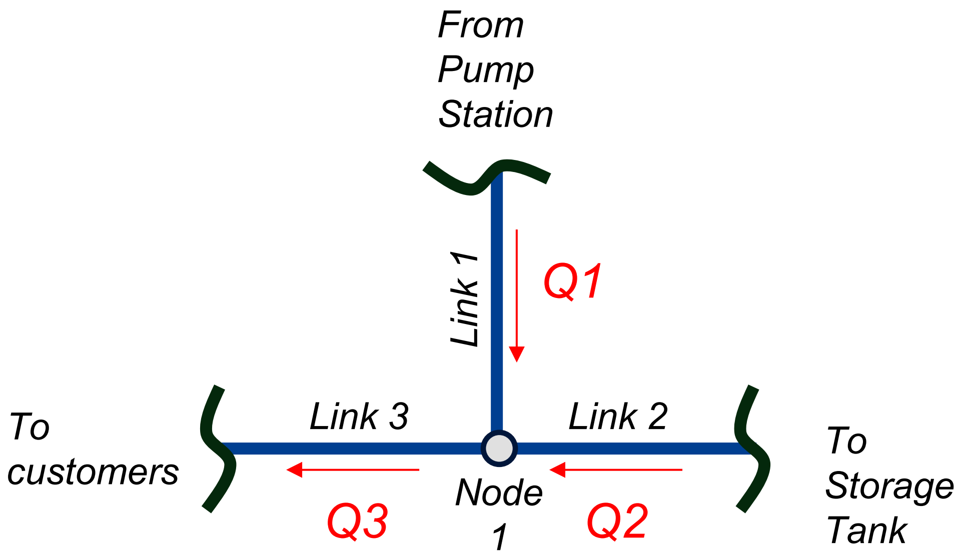
Distribution Network



How does a WDS model work?

It solves a system of non-linear equations that represent the application of mass and energy conservation laws and empirical relationships to a distribution network to predict pressure, velocity, and other associated metrics.

Node Zoom-In



Continuity for Node 1: $Q1 + Q2 - Q3 \boxed{- Usage} = 0$

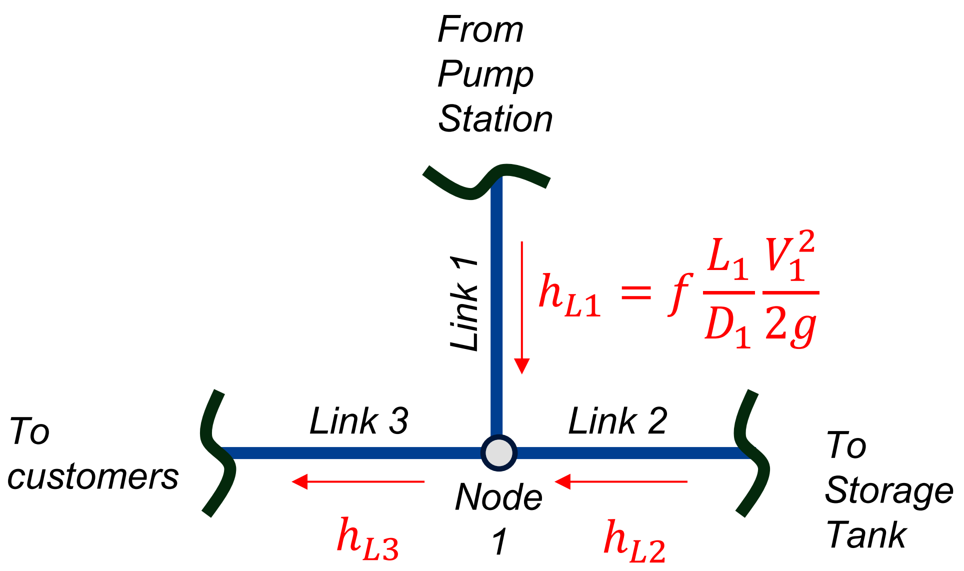
*write continuity equation for every node

*If customer usage at node

How does a WDS model work?

It solves a system of non-linear equations that represent the application of mass and energy conservation laws and empirical relationships to a distribution network to predict pressure, velocity, and other associated metrics.

Node Zoom-In



**Sum energy losses around closed loops and paths throughout the system; must equal 0 to conserve energy*

How does a WDS model work?

It solves a system of non-linear equations that represent the application of mass and energy conservation laws and empirical relationships to a distribution network to predict pressure, velocity, and other associated metrics.

$Q = VA$

System of Non-Linear Equations

(Node 1 Eq.) $Q_1 + Q_2 - Q_3 = 0$

(Node 2 Eq.) $Q_3 - Q_4 - Q_5 = 0$

(Node 3 Eq.) $Q_5 - Q_6 - Q_7 = 0$

$\vdots$

(Path 1 Eq.) $z_{CW} + h_{L1} - h_{L2} - \Delta z_{CW,ST} = 0$

How does a WDS model work?

It solves a system of non-linear equations that represent the application of mass and energy conservation laws and empirical relationships to a distribution network to predict pressure, velocity, and other associated metrics.

System of Non-Linear Equations

(Node 1 Eq.) $\enclose{circle}{V_1}A_1 + \enclose{circle}{V_2}A_2 - \enclose{circle}{V_3}A_3 = 0$

(Node 2 Eq.) $\enclose{circle}{V_3}A_3 - \enclose{circle}{V_4}A_4 - \enclose{circle}{V_5}A_5 = 0$

(Node 3 Eq.) $\enclose{circle}{V_5}A_5 - \enclose{circle}{V_6}A_6 - \enclose{circle}{V_7}A_7 = 0$

$\vdots$

(Path 1 Eq.) $z_{CW} + h_{L1} - h_{L2} - \Delta z_{CW,ST} = 0$

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How does a WDS model work?

It solves a system of non-linear equations that represent the application of mass and energy conservation laws and empirical relationships to a distribution network to predict pressure, velocity, and other associated metrics.

System of Non-Linear Equations

(Node 1 Eq.) $V_1A_1 + V_2A_2 - V_3A_3 = 0$

(Node 2 Eq.) $V_3A_3 - V_4A_4 - V_5A_5 = 0$

(Node 3 Eq.) $V_5A_5 - V_6A_6 - V_7A_7 = 0$

$$\vdots$$

(Path 1 Eq.) $z_{CW} + h_{L1} - h_{L2} - \Delta z_{CW,ST} = 0$

Rewrite in terms of V1 and V2

$$h_{L1} = f\frac{L_1}{D_1}\frac{V_1^2}{2g} \qquad h_{L2} = f\frac{L_2}{D_2}\frac{V_2^2}{2g}$$

Then solve for all velocities; pressure is subsequently calculated

How does a WDS model work?

It solves a system of non-linear equations that represent the application of mass and energy conservation laws and empirical relationships to a distribution network to predict pressure, velocity, and other associated metrics.

For a modest system…

- *325 pipes*
- *300 junctions*
- *3 tanks*

…you will need to solve a system of approximately ***325 equations****!*
(multiple times)

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Early modeling efforts

Hardy Cross Method (1936)

- Equations solved by hand (often using slide rule)
- Required small number of pipes and loops

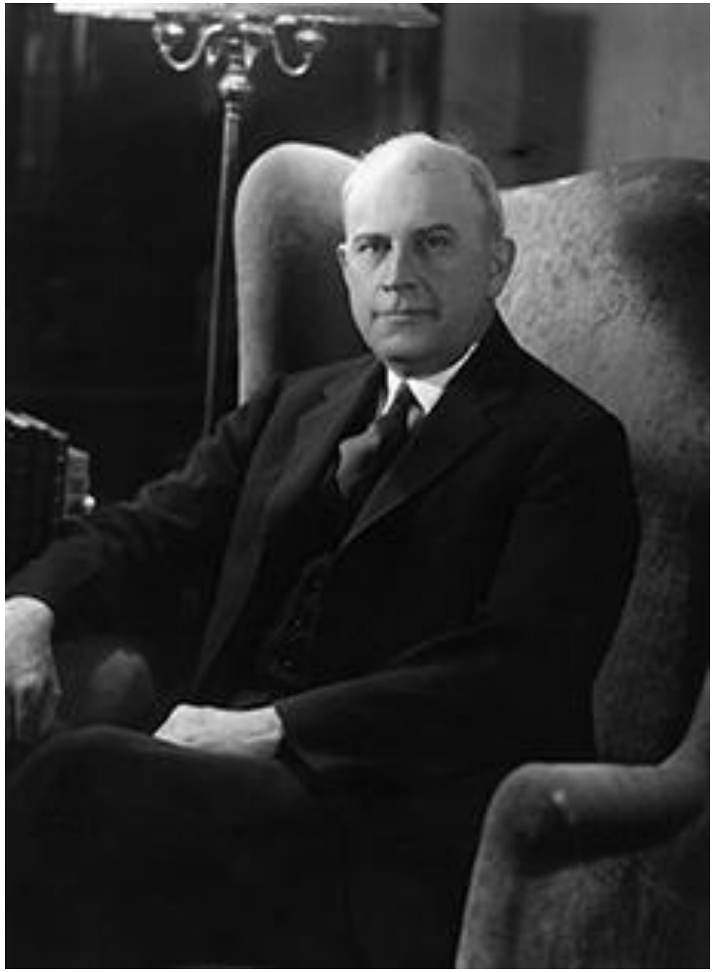
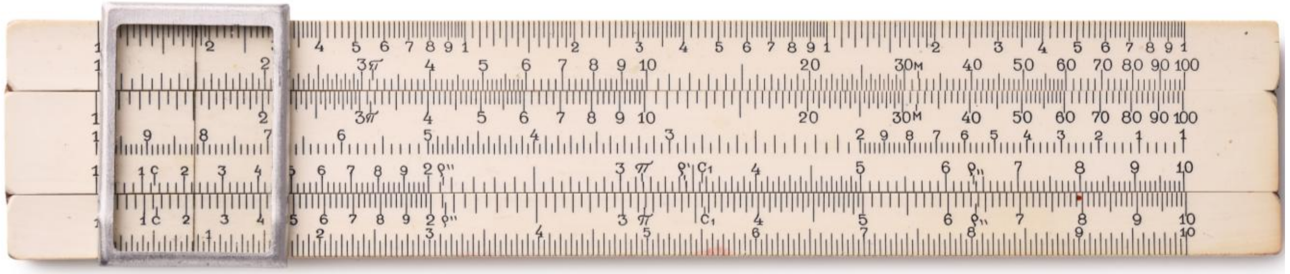


Image from the University of Illinois Archives: https://archives.library.illinois.edu/2013/04/10/thomas-clark-shedd-hardy-cross-and-broad-aspects/



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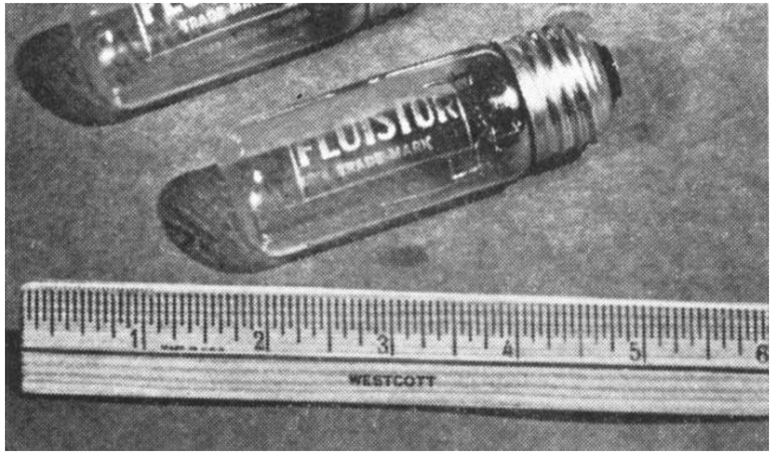
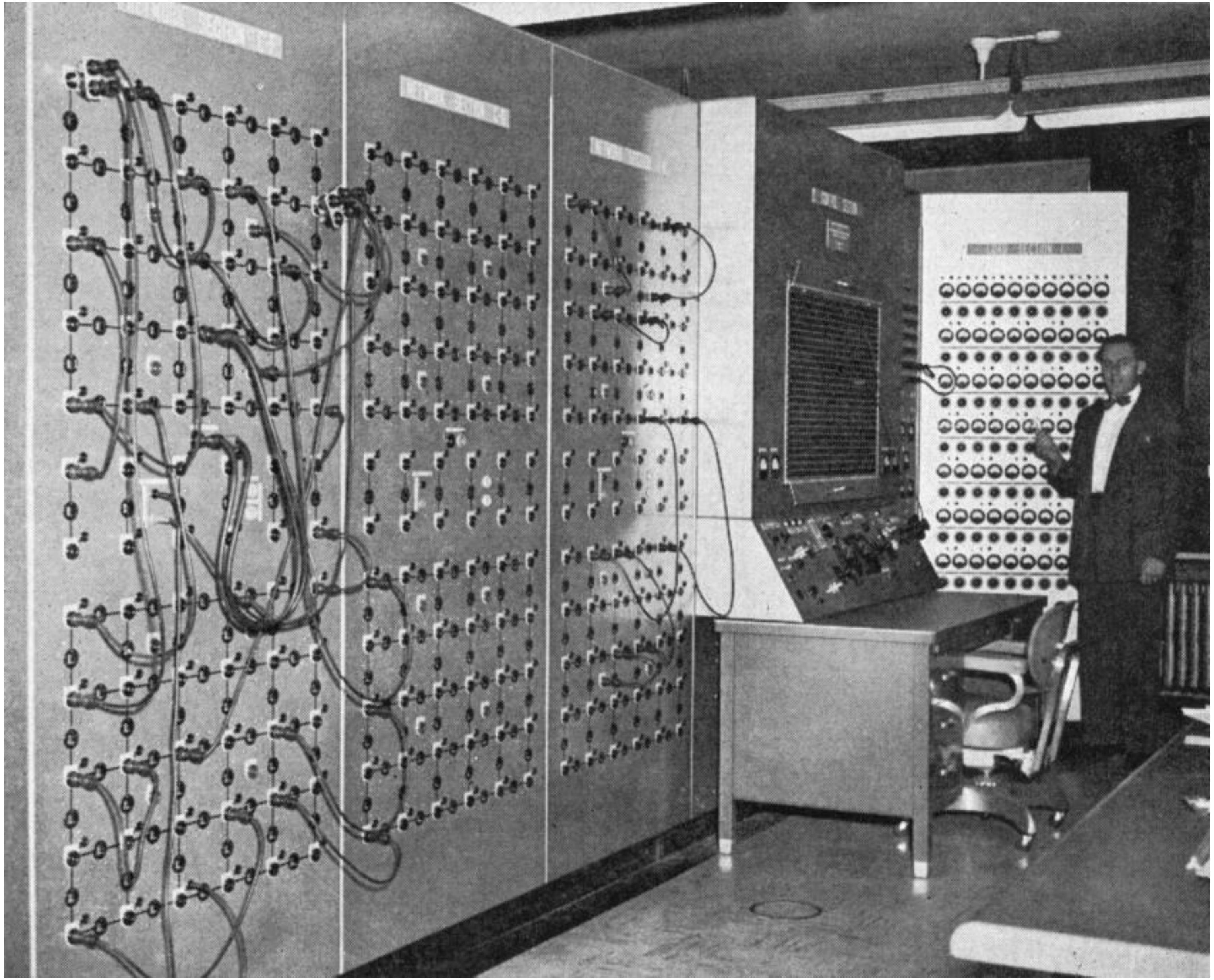
Early modeling efforts

Images from Appleyard, V.A. and Linaweaver Jr., F.P. (1957) The McIlroy Fluid Analyzer in Water Works Practice. J. AWWA, Vol. 49, No. 1

McIlroy Electric
Network Analyzer
(1950)

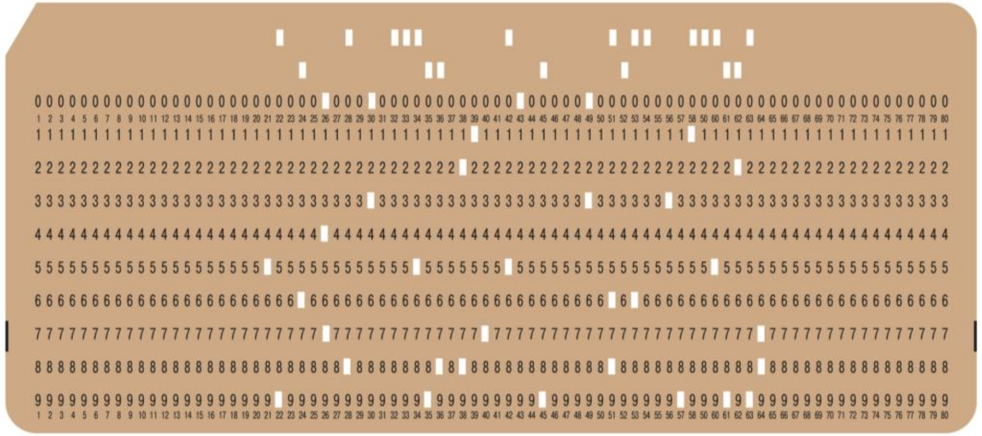




Early modeling efforts

Early computational methods

- Hardy Cross Method on punch cards
- More advanced algorithms developed for network analysis



By NASA - Great Images in NASA Description, Public Domain, https://commons.wikimedia.org/w/index.php?curid=6455009

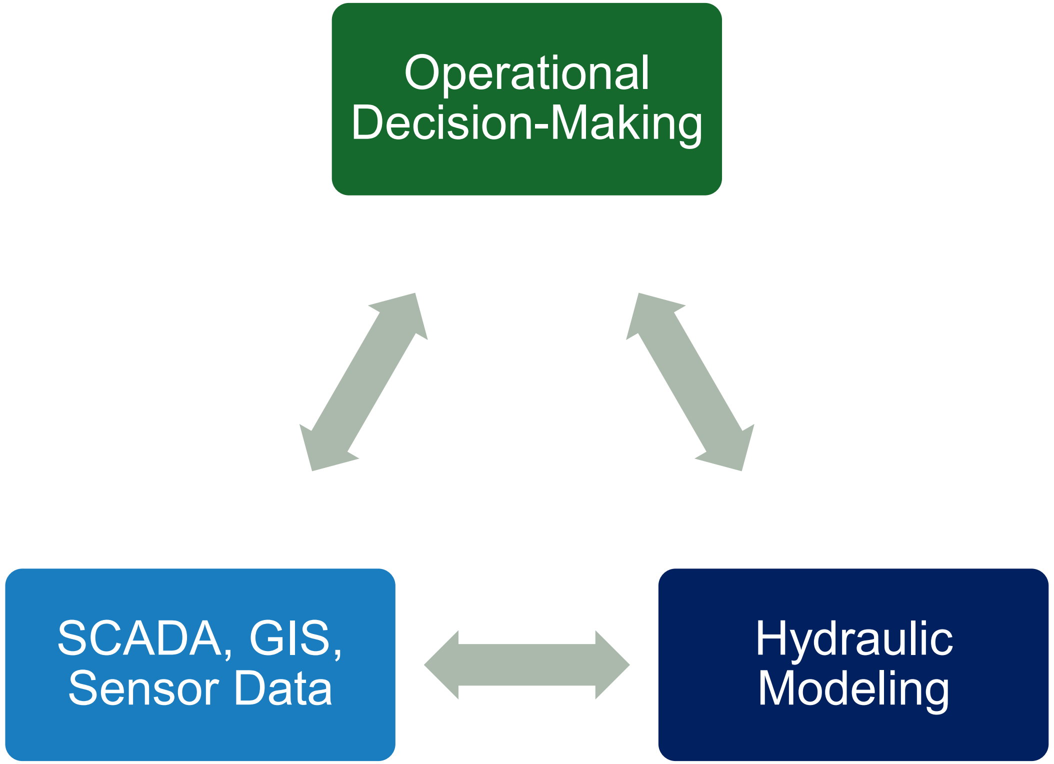
Modeling Advancements

- 1980s – Extended period simulation & water quality analysis; founding of many commercial modeling software companies
- 1990s – EPANET released (1993) by USEPA; commercial software companies integrate modeling software with CADD and GIS
- 2000s – Continued integration with GIS; optimization and calibration tools added

EPANET

Present Day Modeling

- Commercial and free, open-source programs
- Integration with GIS and other utility software
- More advanced water quality modeling (e.g., EPANET-MSX or multi-species extension)
- Real time modeling and the creation of digital twins



Operational Decision-Making

SCADA, GIS, Sensor Data

Hydraulic Modeling

WDS Model Development

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How to develop a preliminary model

1. Select modeling software
2. Determine model scale
3. Create the network
4. Add node information
5. Add link information

1. Select modeling software

A few things to consider:

- **Your Purpose**
- **Software Integration**
- **License Costs**
- **Technical Support**

How much experience do you have with hydraulic modeling? Are you starting with a basic, steady state model, or are you creating a real-time digital twin?

What will be your primary use of the model?

Are you primarily developing and using the model in-house?

1. Select modeling software

A few things to consider:

- **Your Purpose**
- **Software Integration**
- **License Costs**
- **Technical Support**

Will the model integrate with (your existing) GIS or other software packages?

Can the modeling software import other data sources?

What other tools/features are available with the modeling software?

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1. Select modeling software

A few things to consider:

Your Purpose

Software Integration

License Costs

Technical Support

How much does an annual license subscription cost? Is other software required?

Is their tiered pricing based on the number of pipes in the model?

Does the subscription include multiple license seats?

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1. Select modeling software

A few things to consider:

- **Your Purpose**
- **Software Integration**
- **License Costs**
- **Technical Support**

How will technical support be available to you?

Is technical support included in your subscription cost?

1. Select modeling software

If you are just getting started, consider starting with **free** and open-source software.

EPANET

QGIS

QGISRed

2. Determine model scale

What assets will be included/represented in the model?

What level of model skeletonization?

- ☑ Mains
- ☑ Tanks
- ☑ Pump Stations

- ☐ Hydrants?
- ☐ Valves?
- ☐ Connections?

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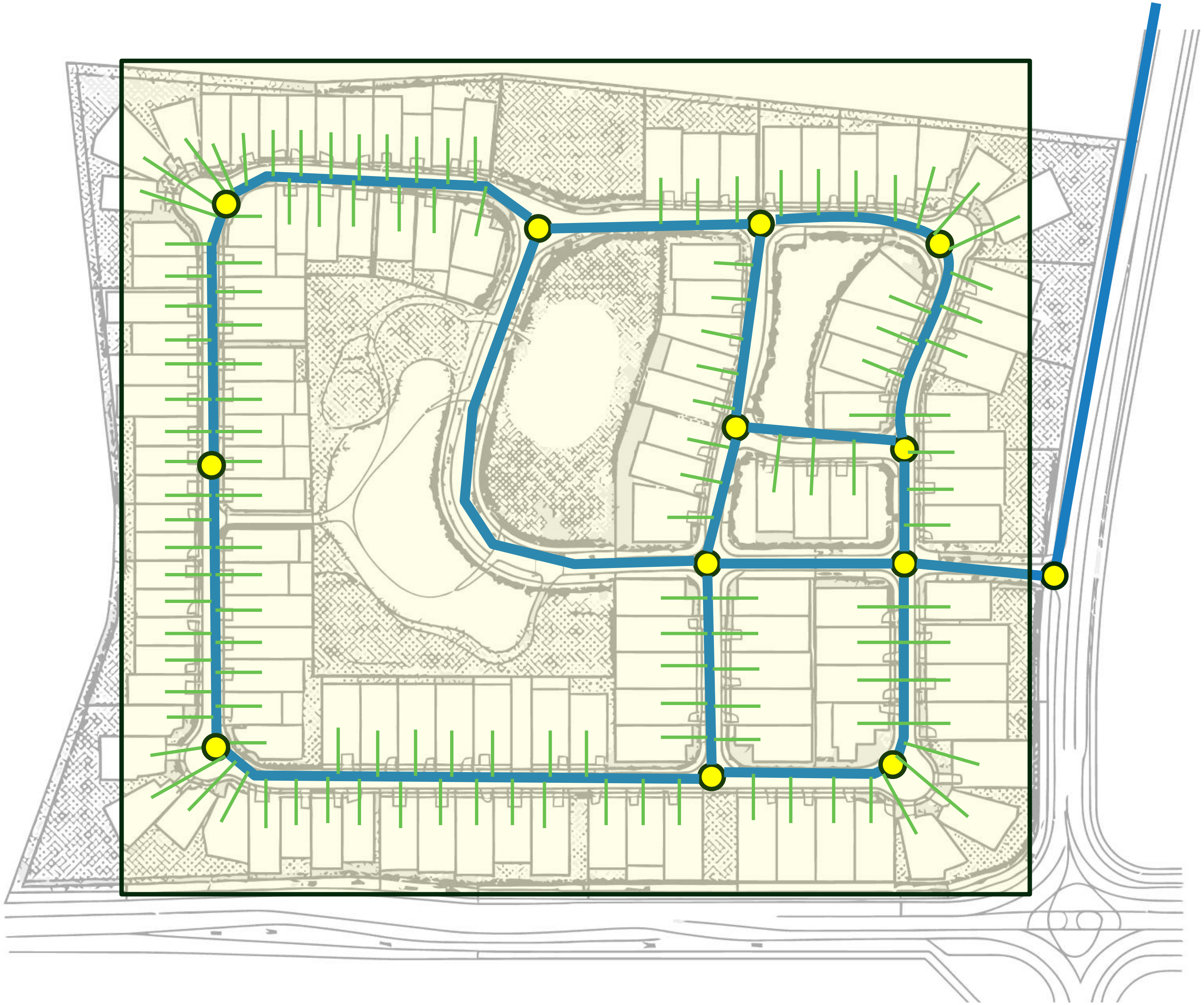
2. Determine model scale

What assets will be included/represented in the model?

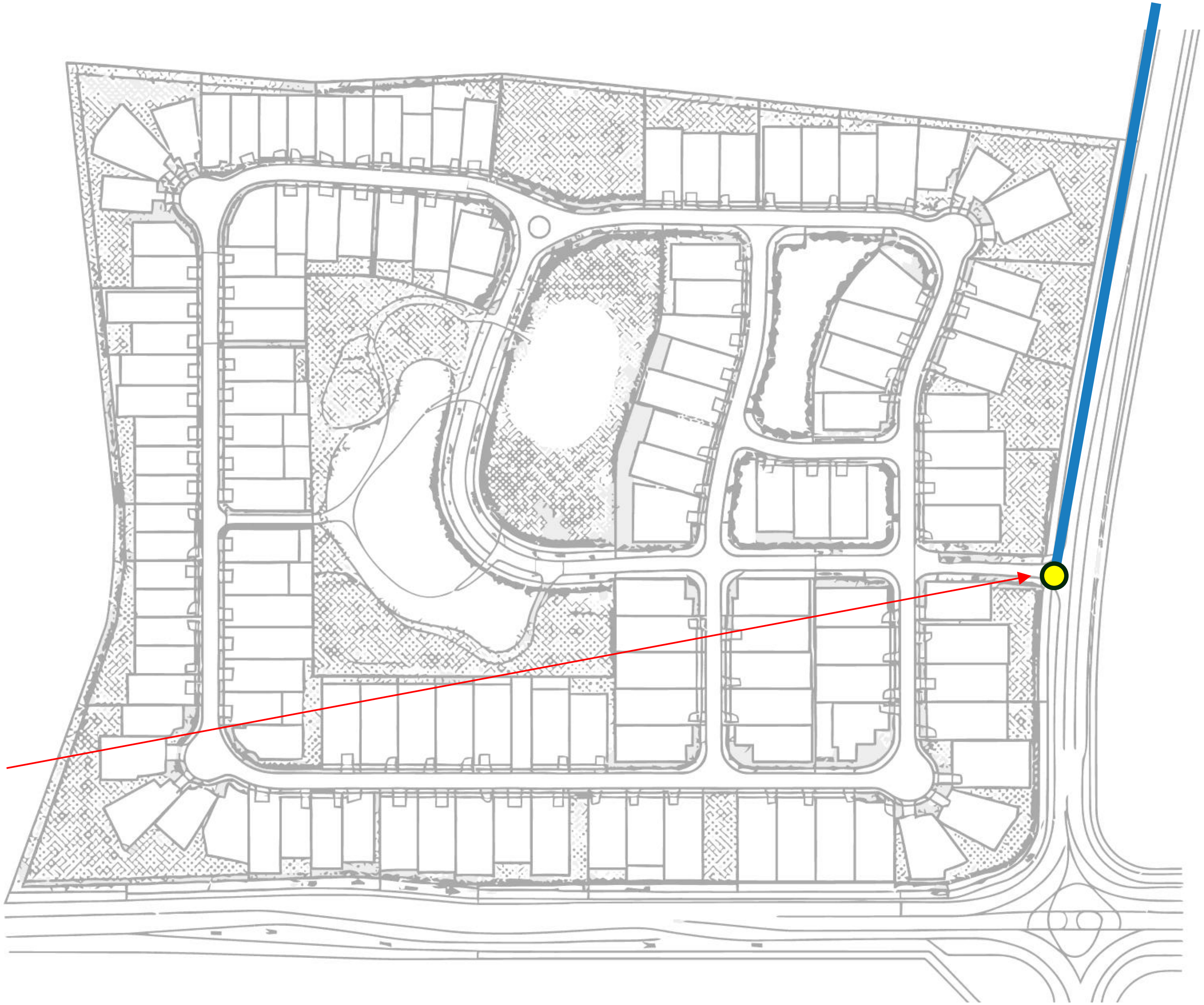
What level of model skeletonization?



2. Determine model scale

What assets will be included/represented in the model?

What level of model skeletonization?



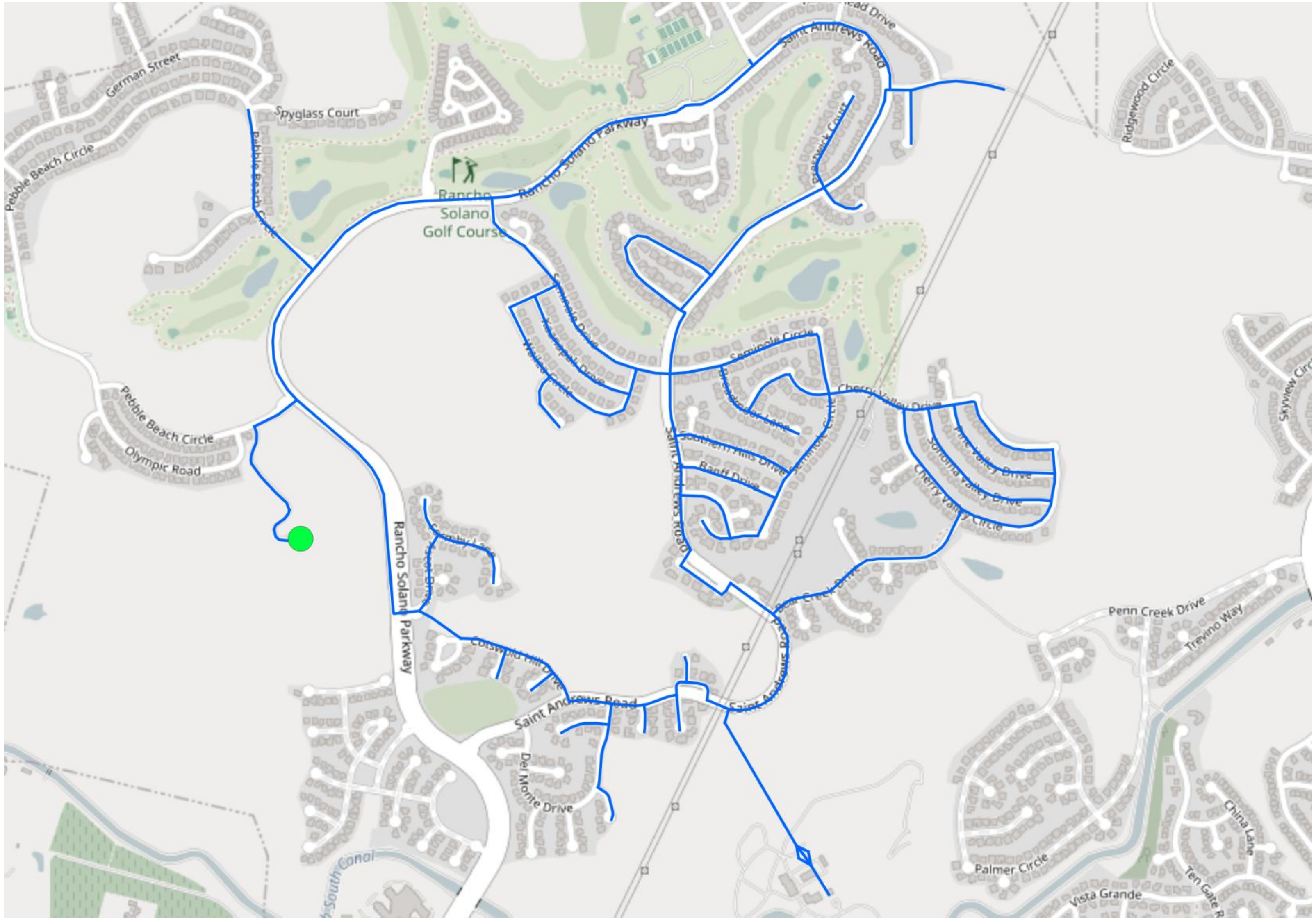
Aggregated demand

Example Dataset

From the University of Kentucky's WDS Research Database

CA1 System

- Rancho Solano Zone III, Fairfield (CA) Water System
- 11.1 miles of pipe
- Pipe diameters range from 6-inch to 16-inch
- Elevation: Min 126 ft; Max 385 ft

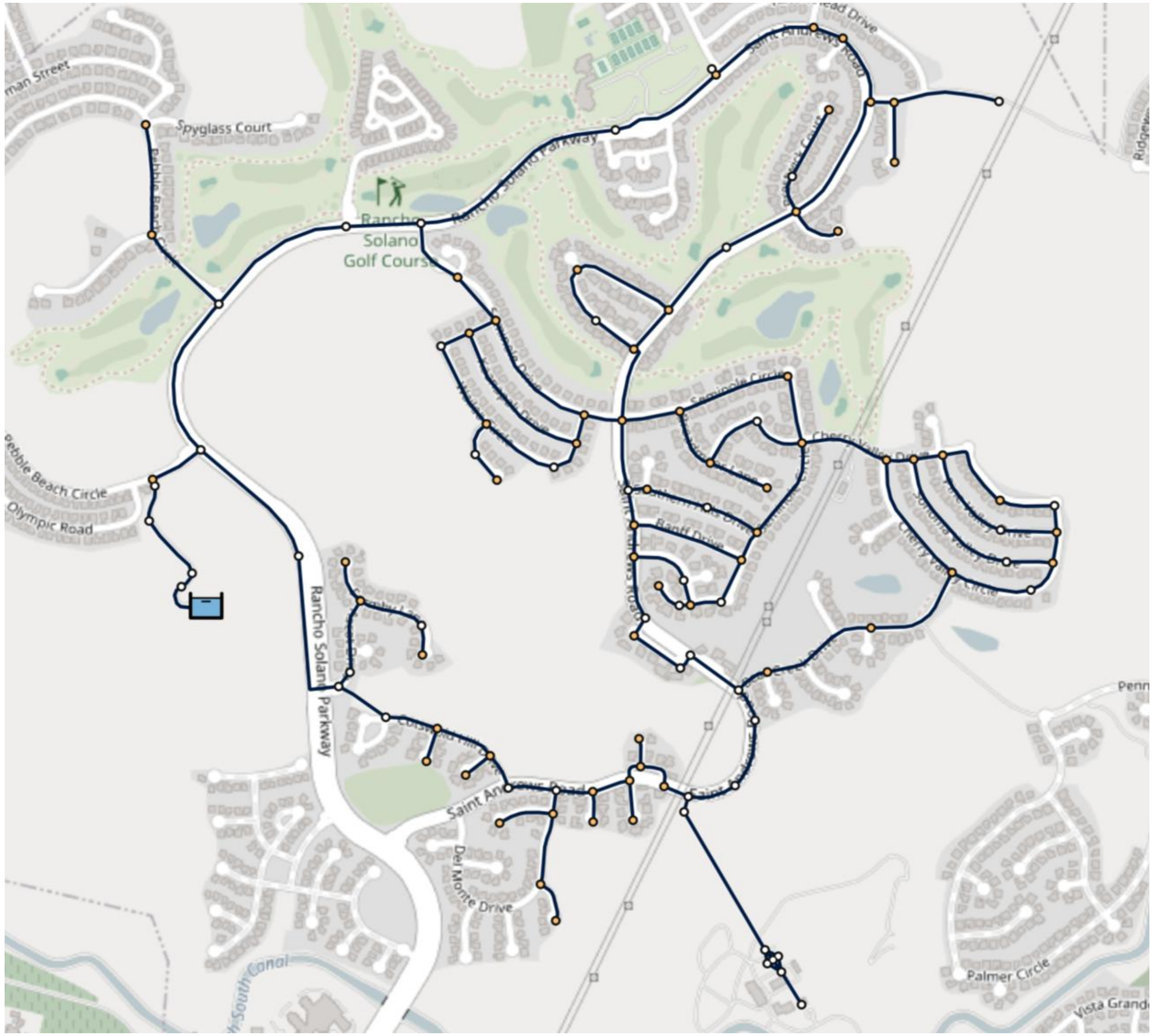


https://doi.org/10.13023/kwrri.wdsrd

3. Create the network

- First, clean up GIS data
  - Snap features together
  - Fill in data gaps (e.g., pipe diameters missing)
  - Match feature types
  - Proper coordinate system

- Data import / network builder
  - Import link (pipes) and node elements (tanks, pumps, etc.)
  - Junction nodes should be automatically created
  - Check connectivity



4. Add node information

Types of nodes[1]:

Junctions

Tanks

Reservoirs

Required Data	Recommended Source(s)
Elevation (ft/m)	Extract approximate ground elevations from publicly available digital elevation models (DEMs); mass offset to account for average bury depth
Base Demand (gpm/cfs/lps)	Convert monthly customer consumption from billing data to average daily demand; assign each customer demand to nearest model junction Note: this process may require multiple steps in GIS

---

[1] *Model-dependent*

4. Add node information

Types of nodes[1]:

- **Junctions**
- **Tanks**
- **Reservoirs**

Required Data	Recommended Source(s)
Elevation[2] (ft/m)	Extract tank ground elevation from design drawings
Minimum Level (ft/m)	Extract tank minimum (empty) elevation from design drawings
Maximum Level (ft/m)	Extract tank maximum (overflow) elevation from design drawings
Initial Level (ft/m)	User-defined initial water level at simulation start
Diameter (ft/m)	Extract tank diameter from design drawings

---

[1] *Model-dependent*

[2] *If tank drawings are not available, extract ground elevation from DEMs*

4. Add node information

Types of nodes[1]:

- **Junctions**
- **Tanks**
- **Reservoirs**

Required Data	Recommended Source(s)
Total Head (ft/m)	User-defined based on water level (if simulating actual reservoir) or average system pressure (if simulating system connection)

---

[1] *Model-dependent*

5. Add link information

Types of links[1]:

- **Pipes**
- **Pumps**
- **Valves**

Required Data	**Recommended Source(s)**
Length (ft/m)	Calculate lengths using GIS before data import / network building; some models offer automatic length calculations
Diameter (in/mm)	User-defined and imported to the model during data import / network building
Roughness (H-W C factor)	Estimated based on pipe material and age; available in any fluid mechanics textbook

---

[1] *Model-dependent*

5. Add link information

Types of links[1]:

- **Pipes**
- **Pumps**
- **Valves**

Required Data	Recommended Source(s)
Pump Curve (Head vs. Discharge)	Pump curves are provided by the pump manufacturer and should be included in the design documents

---

[1] *Model-dependent*

5. Add link information

Types of links[1]:

- **Pipes**
- **Pumps**
- **Valves**

Required Data	Recommended Source(s)
Diameter (in/mm)	Valve diameters are provided by the manufacturer and should be included in the design documents
Type	PRV, PSV, FCV, etc.
Setting (*varies by type*)	User-defined based on operational settings; PRVs and PSVs require a pressure setting; FCVs require a flow setting

---

[1] *Model-dependent*

Next steps

- Select simulation type
  - Additional parameters may be needed
- Confirm simulation settings
- Run model
- **Calibrate!**

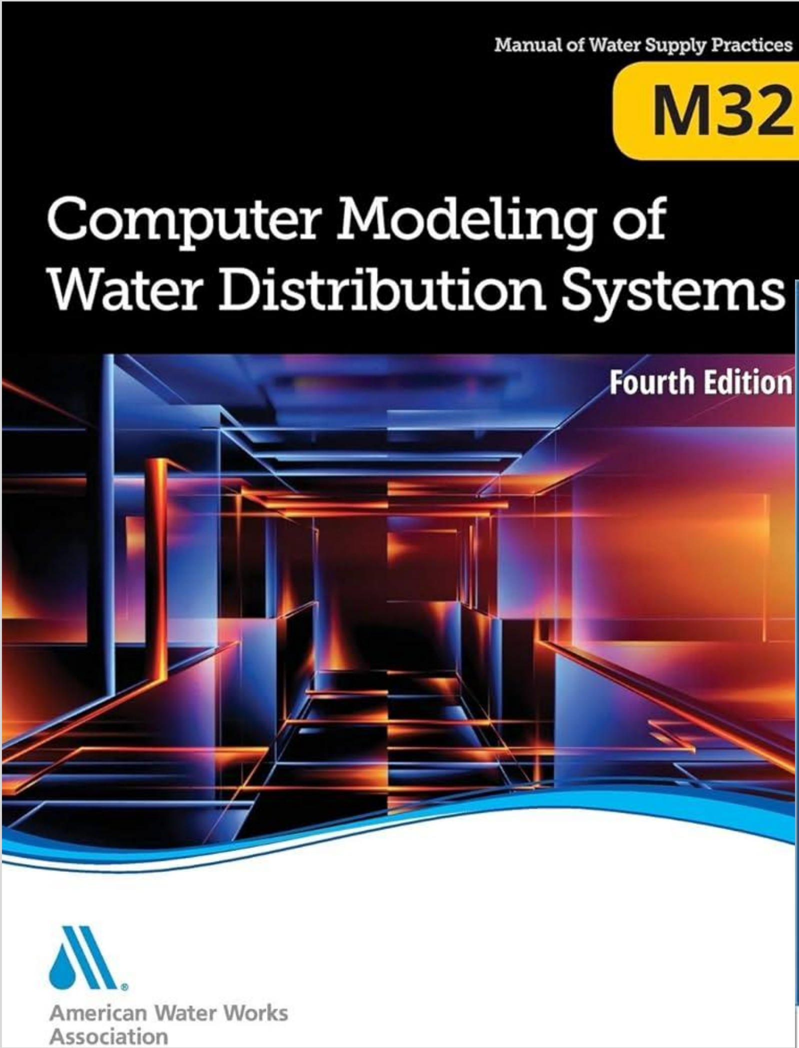
Save the date!

Introduction to WDS Modeling Webinar (Part 2)

May 28, 2026

Registration link coming soon

Recommended Resources



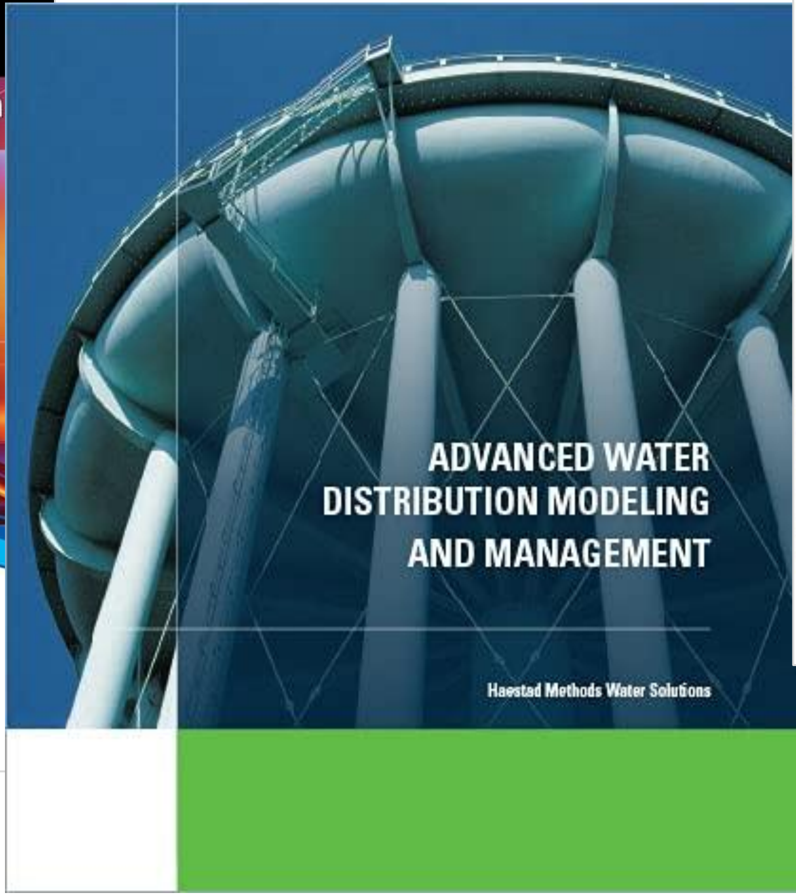
Manual of Water Supply Practices

M32

Computer Modeling of Water Distribution Systems

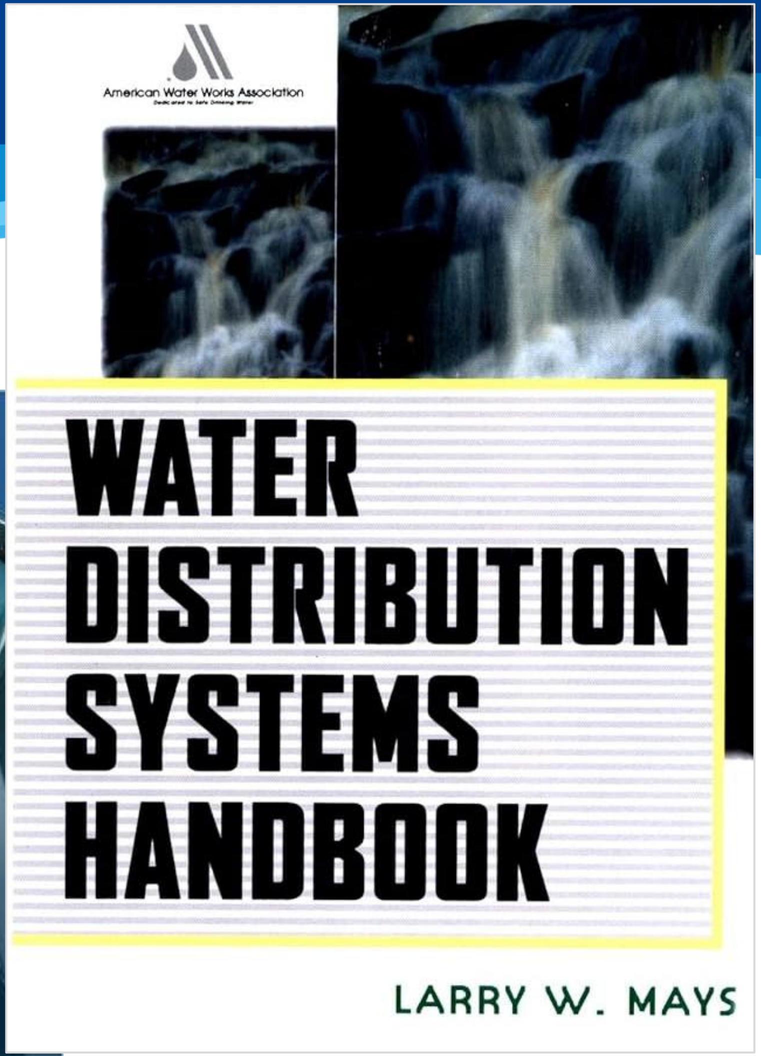
Fourth Edition

American Water Works Association



ADVANCED WATER DISTRIBUTION MODELING AND MANAGEMENT

Haestad Methods Water Solutions



American Water Works Association

WATER DISTRIBUTION SYSTEMS HANDBOOK

LARRY W. MAYS

Tennessee Water Resources Research Center

EFCN

environmental finance center network

Thank you!

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Save the date!

Introduction to WDS Modeling Webinar (Part 2)

May 28, 2026

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Tennessee Water Resources Research Center

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