A SunCam online continuing education course

Water Distribution CIP Management

by

Mark Ludwigson, P.E.

Course Outline:

Water Distribution System Overview
Need for Continual Improvements
Regulations and Standards
Capital Improvement Planning
Long-Term Planning
Project Selection
Budget Planning
Infrastructure Data Management
Hydraulic Modeling
Water Loss Reduction
Condition Assessments
Water Main Rehabilitation
Helpful References
Examination

Water Distribution System Overview

Water distributions systems transfer potable water from a water treatment plant (WTP) or water storage facility to individual consumers/customers. The delivered water needs to be pressurized and safe for drinking.

A water distribution system is comprised of the following main infrastructure, as depicted in Figure 1:

- Storage tanks (reservoirs, ground storage tanks, water towers, standpipes)
- Finished water pumps or booster pumps
- Transmission mains (large pipes, over 14”, conveying water to neighborhoods)
- Distribution mains (large pipes, over 12”, with multiple water main branches)
- Water mains (medium pipes, 6” to 12”, down streets with service branches)
- Service lines (small pipes, ¾” to 6”, serving individual users)
- Flow meters, pressure reducing valves, isolation valves, fire hydrants, etc.
- Backflow preventors and fire service lines

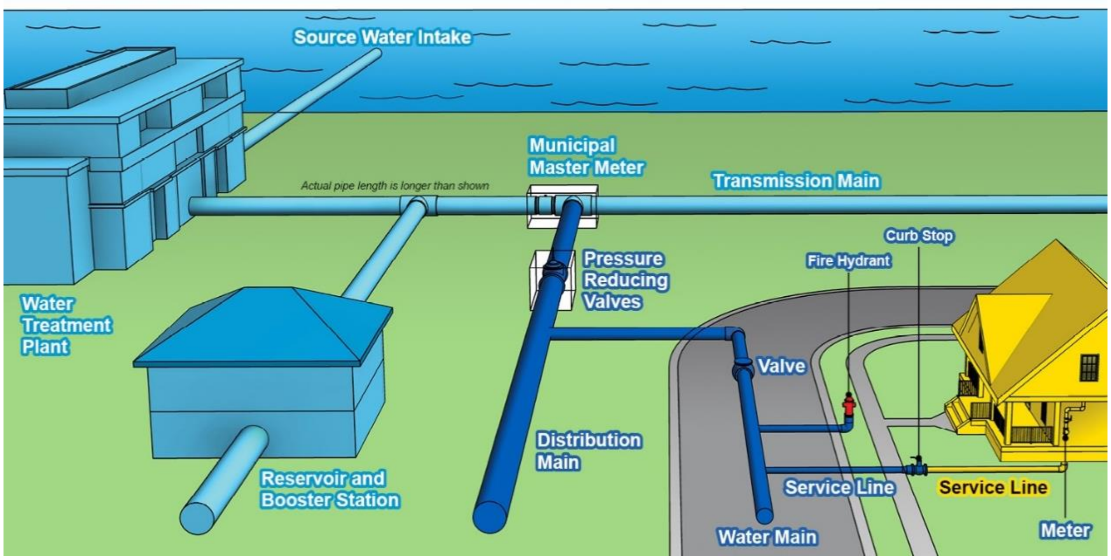


Figure 1: Example distributions system with pipes in shades of blue.
The system starts with the transmission main leaving the WTP and ends at each service line at the property line. The service line in yellow is owned by the customer (in this case a homeowner). The meter is often located at the property line (not at the house).
Source: Great Lakes Water Authority

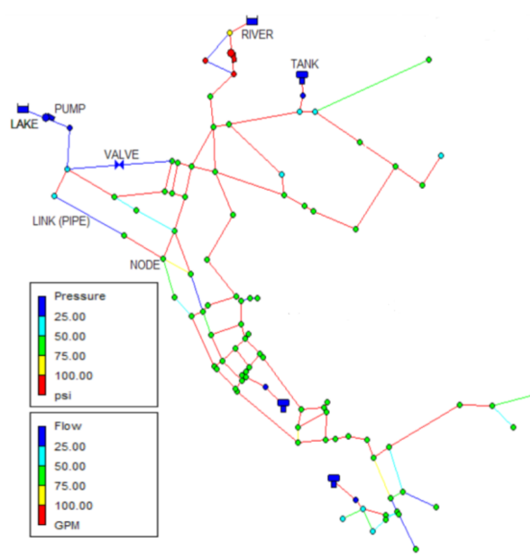
Water distribution systems are found in the following locations:

- Municipalities (cities, towns, villages),
- Counties,
- Utility districts of multiple municipalities and unincorporated areas,
- Large private residential communities,
- Large commercial complexes or business parks,
- Large industrial complexes or industrial parks, and
- Military bases.

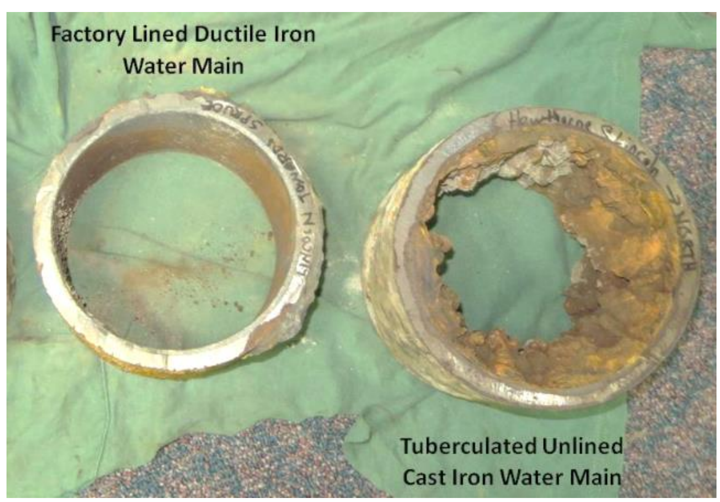
This course focuses on the management of a capital improvement program (CIP), also called a capital improvement plan, for water distribution systems. Organizations often have similar CIPs for treatment facilities and wastewater collection systems.

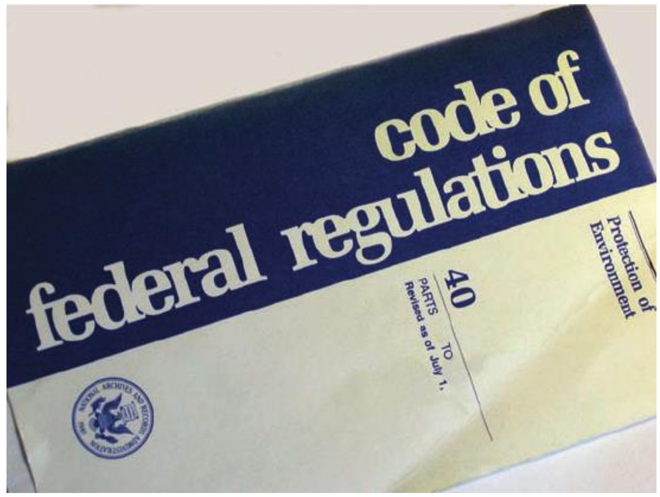
Need for Continual Improvements

Water distribution systems need regular improvements for the reasons listed in Table 1.

Table 1: Reasons for Distribution System Improvements		
Reason	Description	Example
Develop-ment	Accommodate water system expansion for community growth or a new large user. Developers may be responsible for funding or constructing the water and sewer upgrades.	 Source: public domain
Hydraulics	Correct hydraulic restrictions and stagnant branches to reduce pumping energy and improve water quality. Tuberculation of iron water mains leads to hydraulics problems.	 Source: www.epa.gov/water-research/epanet, public domain

Structural Failures	Prevent or repair structural failures such as breaks or collapses of pipes, valves, hydrants, etc. Review historical data to identify water mains with frequent leaks and breaks. Add likelihood of failure (LOF) to consequence of failure (COF) for risk scoring.	 Source: commons.wikimedia.org/wiki/File:Peacock_Street_ water_main_break_986.jpg, Schwede66, CC-BY-SA-4.0
Water Loss	Reduce water loss due to leaks and unapproved connections. Water loss increases over time. Water loss increases water treatment costs, pumping costs, and decreases pipe capacities.	 Source: www.pflugervilletx.gov/city-government/public-works/water-leaks

Age	Replace aged items and older materials to reduce the risk of failures. Typical lifespan of pipes (yrs): Cast iron, 60 Ductile iron, 60 Galv. Steel, 40 HDPE, 80 PCCP, 60 PVC, 70.	 Source: https://commons.wikimedia.org/wiki/File:Belgick%C3%A1_(Praha),_rekonstrukce_(009).jpg, Juandev, CC-BY-SA-3.0
Water Quality	Tuberculation of iron water mains creates a rough surface that can shelter bio-growth and pathogens. Lead-based service lines can result in high lead levels for the associated users.	 Source: www.mwra.com/comsupport/lwsap/images/sample-projects/examples-of-pipe-with-labels-sept-14.jpg

Regulations	Compliance with new federal or state regulations. For example, action may be required to comply with the EPA Lead and Copper Rule, as Revised in 2022.	 Source: public domain
Funding	Utilize available federal or state funding.	 Source: public domain
Road & Sewer Projects	Water improvements done in conjunction with road or sewer improvements (or other projects), thereby saving cost on excavation, traffic control, and pavement restoration.	 Source: https://commons.wikimedia.org/wiki/File:Kitchener_downtown_cycling_grid,_Joseph_and_Gaukel_streets.jpg, Julius177, CC-BY-SA-4.0

Regulations and Standards

Safe Drinking Water Act

The Safe Drinking Water Act (SDWA) gives authority to the Environmental Protection Agency (EPA) to establish and enforce standards that public drinking water systems must follow, including maximum contaminant levels, treatment techniques, monitoring, and reporting requirements. EPA delegates primary enforcement responsibility (also called primacy) for public water systems to states and Indian Tribes.

40 CFR

Title 40 CFR includes regulations for the management of water distribution systems in the following Subchapters:

- 40 CFR 141: National Primary Drinking Water Regulations
- 40 CFR 142: National Primary Drinking Water Regulations Implementation

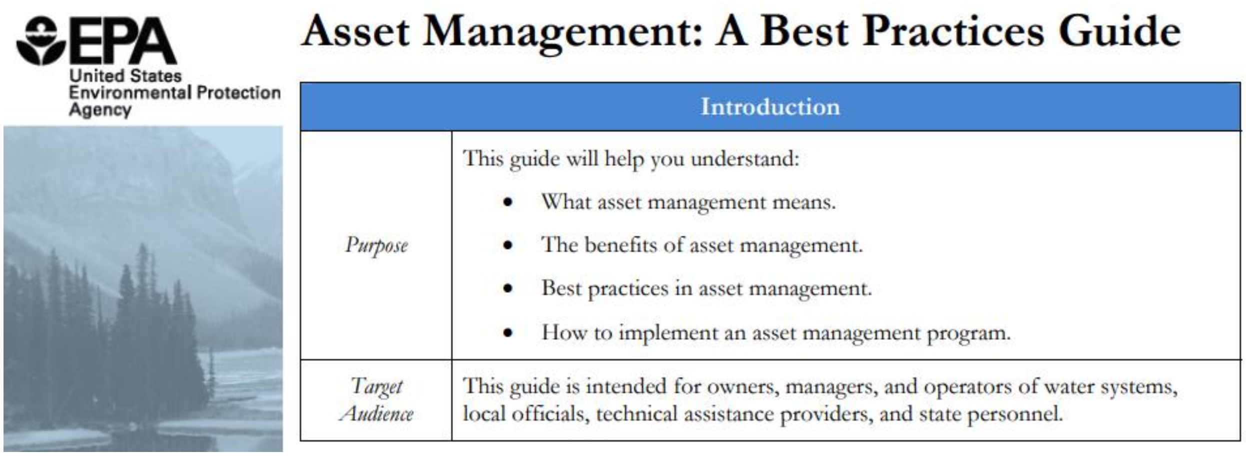
The focus of these regulations is on defining the acceptable contaminant levels in potable water, acceptable treatment methods, protection of water systems from fecal contamination, contaminant monitoring requirements, and reporting requirements. There is some general language about the management of distribution systems, such as the following, 40 CFR 141.63.e:

> *The Administrator, pursuant to section 1412 of the Act, hereby identifies the following as the best technology, treatment techniques, or other means available for achieving compliance with the maximum contaminant level for total coliforms in paragraphs (a) and (b) of this section and for achieving compliance with the maximum contaminant level for E. coli in paragraph (c) of this section:*
>
> 1. *Protection of wells from fecal contamination by appropriate placement and construction;*
> 2. *Maintenance of a disinfectant residual throughout the distribution system;*
> 3. ***Proper maintenance of the distribution system including appropriate pipe replacement and repair procedures**, main flushing programs, proper operation and maintenance of storage tanks and reservoirs, cross connection control, and continual maintenance of positive water pressure in all parts of the distribution system;*

The sentence in bold can be achieved by asset management and CIP management. Showing compliance with the CFR 40 standards is often required when applying for a grant or federal financial assistance.

Compliance Monitoring
The EPA and authorized states have the authority to monitor, inspect and audit the water quality in community water systems for compliance with operating permit conditions and 40 CFR standards.

EPA Asset Management
In 2007, the EPA issued a 4 page paper entitled "Asset Management: A Best Practices Guide", as shown in Figure 2.


EPA United States Environmental Protection Agency

Asset Management: A Best Practices Guide

Introduction	
Purpose	This guide will help you understand: • What asset management means. • The benefits of asset management. • Best practices in asset management. • How to implement an asset management program.
Target Audience	This guide is intended for owners, managers, and operators of water systems, local officials, technical assistance providers, and state personnel.

Figure 2: Cover page title for the Asset Management EPA paper.
Source: Public Domain

In this document, the EPA provides general principles for managing water distribution systems. The term "asset management" is defined as managing infrastructure capital assets to minimize the total cost of owning and operating them, while delivering the service levels that customers desire. See the flow chart in Figure 3 for the five core areas considered essential for asset management. The EPA document provides advice for assessing each of these areas (also called questions).

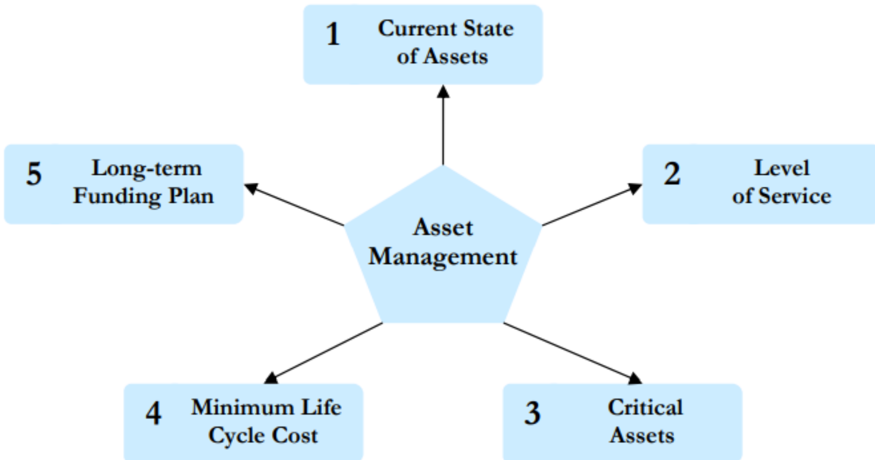


Figure 3: The Five Core Questions (or Areas) of Asset Management Framework.
Source: Public Domain

Asset management should be implemented to achieve continual improvements through a series of "plan, do, check, act" steps. The above framework guides the planning step for asset management. The recommended steps are as follows:

- Plan: Five core questions framework (short-term), revise asset management plan (long-term)
- Do: Implement asset management program
- Check: Evaluate progress, changing factors and new best practices
- Act: Take action based on review results

Distribution System Inventory, Integrity and Water Quality

In 2007, the EPA issued a 28 page paper entitled "Distribution System Inventory, Integrity and Water Quality". A summary of distribution systems around the United States is provided, including total water piping length, age, materials, and break data. The paper addresses the susceptibility of different materials to unexpected contamination, and to various infrastructure degradation processes. Condition assessment approaches are also discussed.

State Requirements

Each state has administrative codes with more detailed requirements, including distribution system design and management policies. These codes vary greatly by state. Many states require risk assessments be performed for critical infrastructure, including water systems. Risk assessments are a part of CIP management.

Ten States Standards

The “Recommended Standards for Water Works”, also known as the Ten States Standards, is adopted by many state administrative codes. The Ten States Standards provides design requirements for distribution system components, including water to sewer line separation and cross-connection prevention techniques.

Capital Improvement Planning

Most owners of distribution systems have a capital improvement program (CIP) as part of the overall asset management. Without asset management, the distribution system would run until major failures occur likely resulting in boil water requirements, public discord, and costly emergency repairs. With asset management, regular work is done on the distribution system and major failures are minimized, as shown in Figure 4.

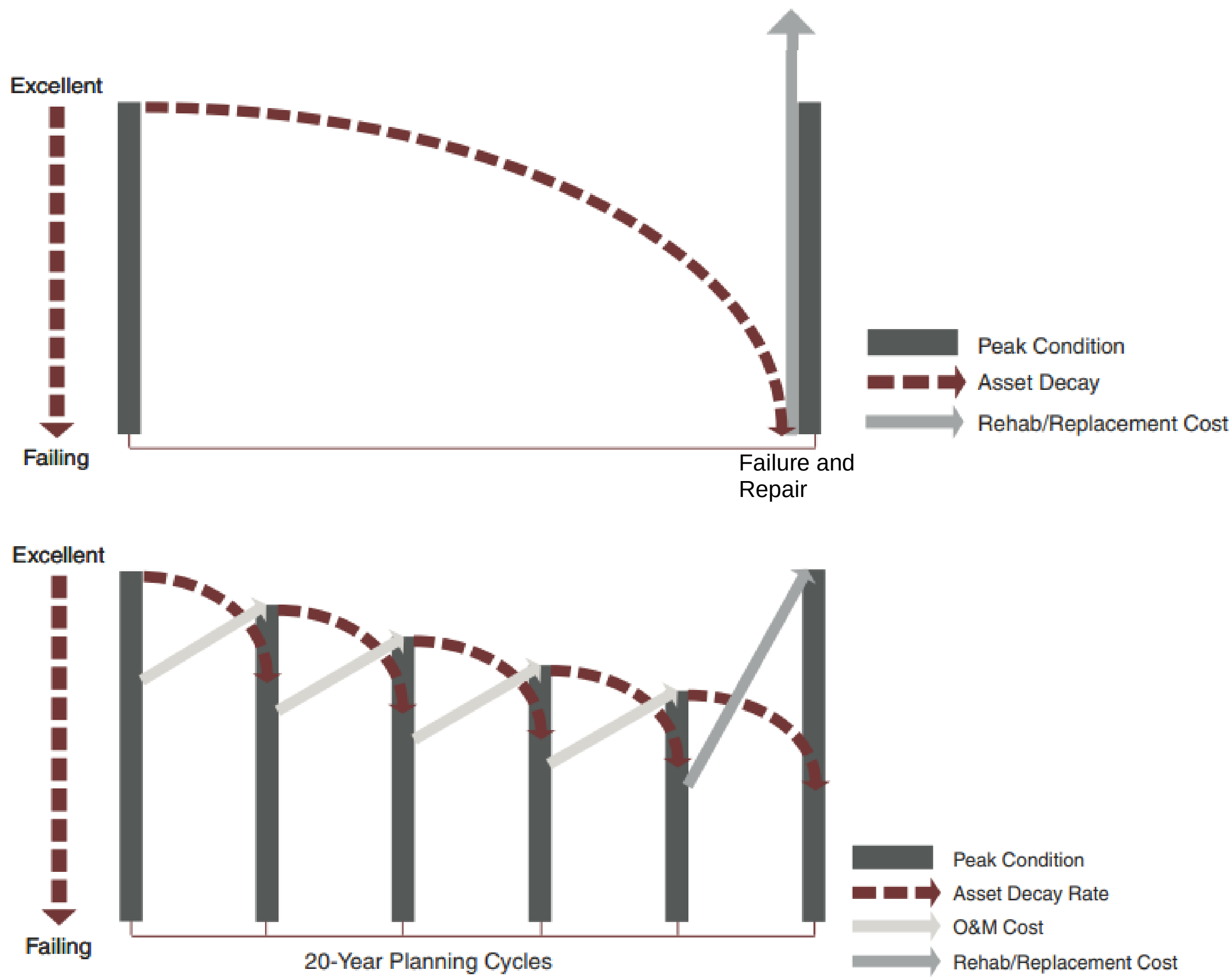


Figure 4: Top: Run-to-Failure Management Model. Once a failure occurs, that part of the system is quickly replaced at a premium cost. Bottom: Asset Management Model. The distribution system is regularly maintained with an annual O&M budget (O&M Cost arrows). The final "Rehab/Replacement Cost" arrow on the right represents the CIP project cost to rehabilitate or replace a prioritized area of the distribution system.

Source: www.epa.gov/sites/default/files/2015-10/documents/assetmanagement.pdf, public domain

Asset management often includes the sewer collection system, wastewater treatment facilities, water distribution system, and water treatment facilities. Finished water storage tanks and high service pump stations are sometimes managed as part of the treatment facilities, especially if located at the water treatment plant.

Key elements of asset management are as followings, with the items in **bold** directly related to CIP management:

- Performance goals
- Information management
- Asset identification and valuation
- **Failure impact evaluation and risk management**
- **Condition assessment**
- **Capacity assessment and hydraulic modeling**
- **Rehabilitation and replacement planning (master planning)**
- Maintenance analysis and planning
- Financial management
- Continuous improvement and auditing

The following are key documents to maintain for CIP management:

- Drinking water ordinances, approved rates, and tariffs,
- Management policies and procedures,
- CIP reports, tables, and schedules
- Financial report with annual CIP budget,
- Past projects database,
- Master Plan for the water distribution system,
- Maps or geographic information system (GIS) of distribution system including pipes, storage tanks, pump stations, valves, flow meters (see Figure 5),
- Hydraulic model (see Figure 6),
- Performance measures for inspections, cleaning, repair, and rehabilitation,
- Flow monitoring records,
- Records of breaks, leaks, and user complaints, and
- As-built plans / record drawings.

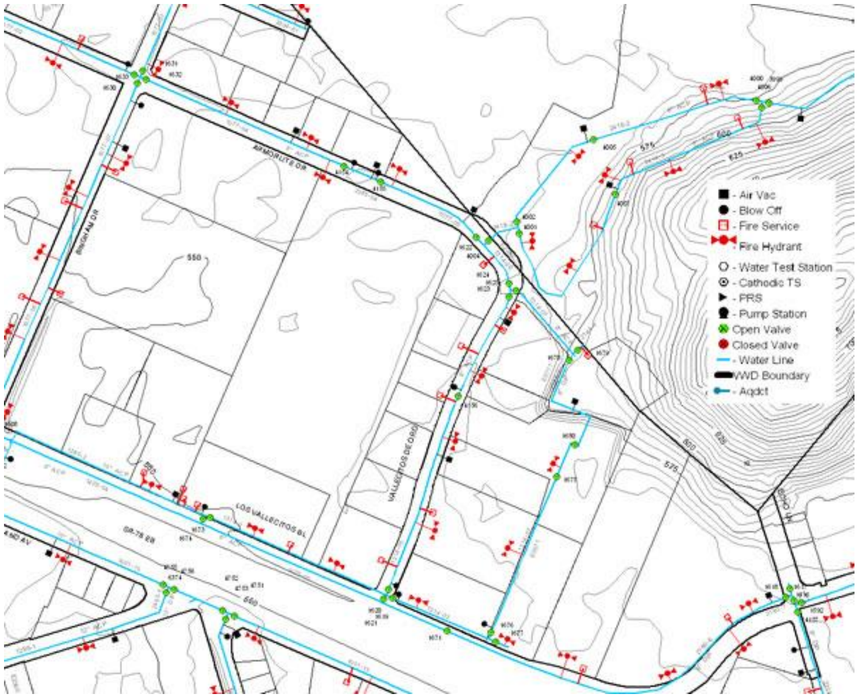


Figure 5: Example of a geographic information system (GIS) with water pipes in blue and fire hydrants in red.
Source: https://www.vwd.org/departments/engineering/gis-mapping, public domain

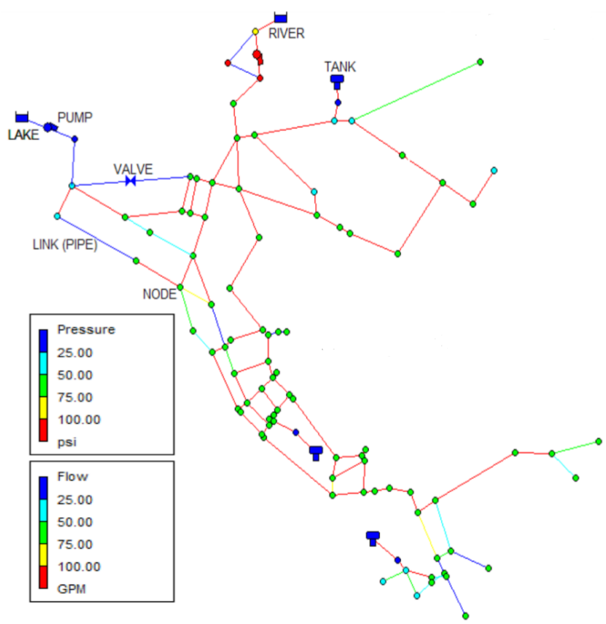


Figure 6: Example of a hydraulic model with the lines (pipes) colored for flow and nodes (branch connections) colored for pressure.
Source: www.epa.gov/water-research/epanet, public domain

There are several different organizational structures for CIP management. Often engineering consultants will be selected and contracted to perform CIP work such as maintaining the hydraulic model, creating a master plan with recommended improvements, and designing CIP projects as engineer-of-record. Sometimes a separate asset management company will operate and maintain the distribution system, including performing the CIP projects with or without consultants.

Long-Term Planning

The goal of infrastructure replacement planning is to schedule CIP projects such that the cost of replacement (or rehabilitation) is balanced against the accelerating cost to maintain the assets, while avoiding unacceptable declines in levels of service. See Figure 7 for a graphical depiction of balancing CIP project costs and maintenance and repair costs.

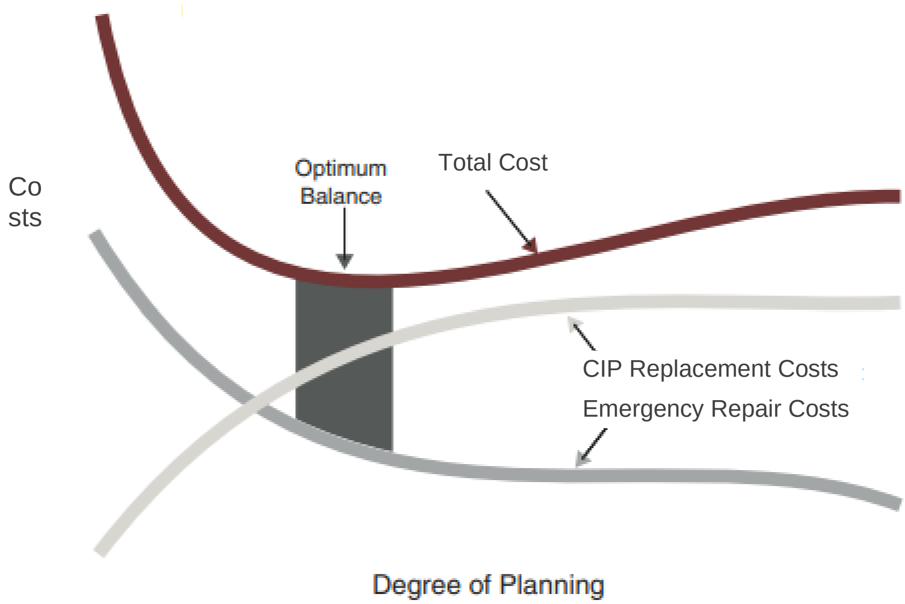


Figure 7: CIP planning chart showing the sum of emergency repair costs and CIP replacement costs based on the degree of planning. There is an optimum balance where just enough planning and CIP projects are done so the total cost is minimized.

Source: www.epa.gov/sites/default/files/2015-10/documents/assetmanagement.pdf, modified, public domain

Estimating the cost of CIP replacement projects is relatively straight forward. However, estimating the emergency repair costs is more difficult as it involves predicting the likelihood of failure of assets in the distribution system such as storage tanks, pump stations, and water mains. To help in this regard, see Figure 8 for a graphical depiction of pipe deterioration over time which suggest replacement at 80 percent of useful life. Although that is a useful rule-of-thumb, it is best to perform regular condition assessments to estimate the useful life remaining, likelihood of failure (LOF), and consequence of failure (COF) of all significant assets in the distribution system. Figure 9 shows the results of a useful life remaining assessment.

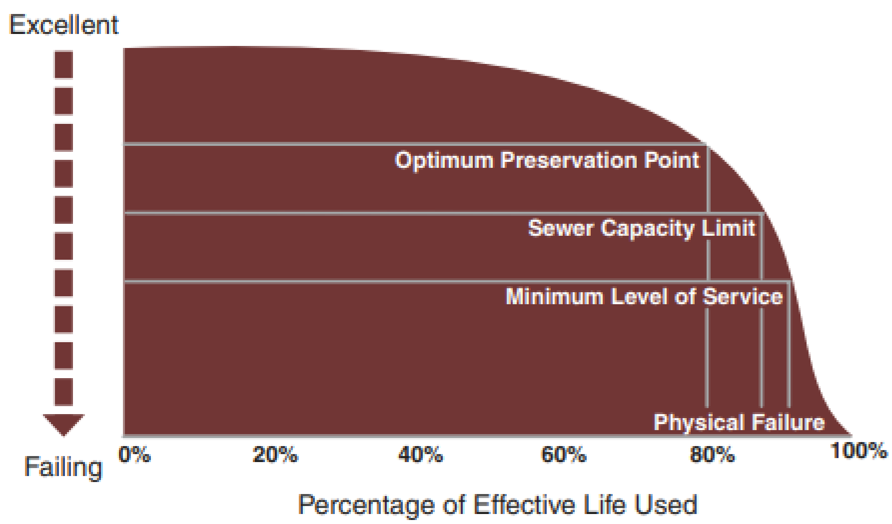


Figure 8: EPA pipe replacement planning chart indicating that CIP projects should aim to replace or rehabilitate pipes at 80 percent of their useful life.

Source: www.epa.gov/sites/default/files/2015-10/documents/assetmanagement.pdf, public domain

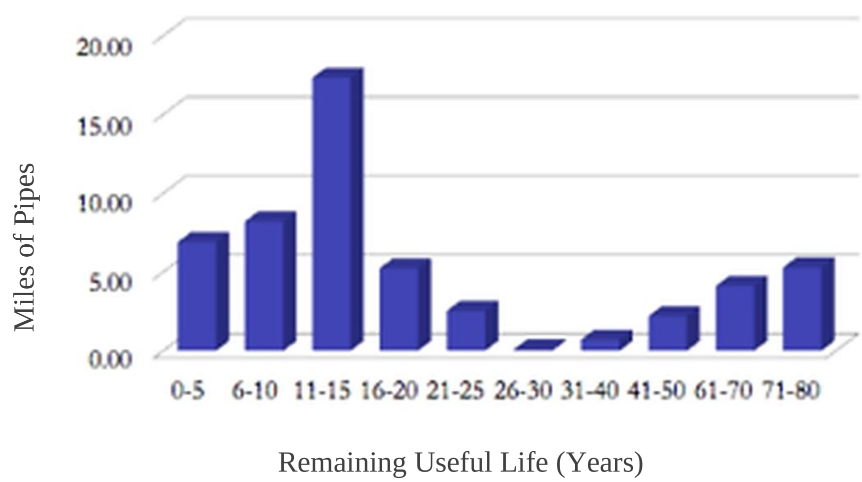


Figure 9: Pipe age chart showing most of the pipes will reach the expected end of useful life within the next 15 years.

Source: www.eastgr.org/221/Public-Works

Based on the age of the system and condition assessment results, it is common to select an annual target for percent rehabilitation or replacement of distribution pipes. For example, a target rehabilitation of **3% per year** would rehabilitate all pipes in approximately 33 years.

Master Planning

A distribution system master plan should be created and updated regularly to help guide the long term planning of CIP projects. The purpose is to identify improvements that will address existing deficiencies and meet projected needs throughout the service area for years to come. A master plan report commonly includes the following topics (see Figure 10 for an example report):

- Distribution System Overview
- Service Area Boundary and Zones
- Growth Projections
- Hydraulic Modeling Results
- Condition Assessment Results
- Water Loss Reduction Recommendations
- Recommended Improvements
- Prioritization of Improvements and Cost Estimates
- Recommended Additional Studies

Executive Summary i
1. Introduction 1
1.1 Authorization 1
1.2 Purpose 1
1.3 Scope of Work 1
1.4 General Information 3
1.5 Meetings with City Staff 10
2. Field Test 11
2.1 Background 11
2.2 HGL Test Results 11
2.3 Model Calibration using New HGL Test 13
3. Evaluate Water Age 14
3.1 Background 14
3.2 Water Age Simulations 14
3.3 Unidirectional Flushing 15
4. Existing Deficiencies 17
4.1 Existing Pressures 17
4.2 Existing Fire Flows 17
4.3 Existing Storage Evaluation 19
4.4 Existing Pump Evaluation 21
5. Water Demand Projections 25
5.1 Overview 25
5.2 Population Projections 25
5.3 Per Capita Use 26
5.4 Nonrevenue Water 26
5.5 New Industrial Demand 27
5.6 Wholesale Allowance 27
5.7 Maximum Day Peaking Factor 27
5.8 Demand Projection Summary 28
6. Evaluate Pump and Tank Capacity 29
7. Recommended Improvements 36
7.1 Background 36
7.2 Model Results with Proposed Improvements 38
7.3 Transmission Main Capacity at the Water Treatment Plant 40
7.4 Improvements by Pressure Zone 42
Main Pressure Zone 42
Fire Flow Improvements 43
Long John Mountain Pressure Zone 48
Town of Laurel Park- Hebron Zone 50
Eastside Pressure Zone 52
Fletcher Pressure Zone 54
Etowah Pressure Zone 56
Southside- Crail Farm Pressure Zone 57
Claremont Pressure Zone 59
Summit Landing Pressure Zone 60
Kenmure Greenleaf Pressure Zone 61
Kenmure Railpengap & Old Distillery Pressure Zone 62
Crab Creek / Evans Road Pressure Zone 63
Champion Hills Pressure Zone 64
Red Top Pressure Zone 65
Cummings Cove Pressure Zone 66
Solomon Jones Pressure Zone 66
Laurel Park Pressure Zone 66
Small Dead-End System Zones 66
Highlander/ Brookside/ Hutch 67
8. Capital Improvement Plan Cost Estimates 68

Figure 10: Example table of contents for a Master Plan report.

Source: www.hendersonvillenc.gov/sites/default/files/uploads/departments/engineering/hville_report_final-with-large-figures-updated-june-2018.pdf, public domain

Project Selection

CIP program management involves the ongoing selection of improvement projects to proceed with design and/or construction. The selection process typically involves the following steps:

1. Gain operations and maintenance ideas and “wish lists”
2. Review latest Master Plan for recommended improvements
3. Review recent condition assessments, nonrevenue water data, hydraulic model results, risk rankings, leak, and break histories, planned road and sewer projects, planned developments, growth projections, and funding opportunities
4. Group potential projects by Service Areas or Zones
5. Estimate the cost for each potential project
6. Create a table of potential projects and motivations (see Table 2 and free software with this course)
7. Sum the total cost and cost for each budget category
8. Compare costs to budgets
9. Sum the number of motivations for each potential project and prioritize
10. Decide on projects to proceed based on priority and budget
11. Schedule out projects based on resources and budgets

Here is an example of an approved annual CIP budget for a distribution system, broken into categories or packages:

- $2M – Zone 1
- $3M – Zone 2
- $3M – Zone 3
- $4M – Zone 4
- $2M – Water Loss Reduction
- $1M – Storage Tank Rehabilitation
- $2M – Pump Station Rehabilitation
- $1M – Multi-Zone and Other Improvements
- **$18M – Total Budget**

Potential projects that cost more than the package budget have the following options:

1. Split into multiple smaller projects and advance only the first project/phase
2. Budget can be passed to the next year and combined with that year’s budget
3. Budget can be used from another package with justification and approval
4. Budget can be increased with justification and approval

Table 2: Example Project Motivation Table														
Zone	Proj. No.	Potential Project Name	Cost Estimate ($M)	New Develop-ment	Hydraulics Correction	High Risk Ranking	Water Loss Reduction	>80% of Useful Life	>100% of Useful Life	Leak & Break History	Qualifies Funding	Road Project	Other	No. of Motivations
1	1a	Saturn Dr Water Main Lining	$1.0			X	X				X			3
	1b	Anderson Ave Road Widening	$2.4									X		1
	1c	Cottage Creek New Water System	$1.5	X								X	City Council Agenda Item	3
2	2a	Highway 18 Redundant Transmission	$6.2		X	X								2
	2b	Cozy Den Development Flow Monitoring Station	$1.1	X			X					X		3
3	3a	Pump Station No. 2 Upgrades	$0.8		X	X		X						3
	3b	Blue Heron Dr Water Main Replacement	$5.2			X		X		X				3
4	4a	Ground Storage Tank Expansion	$5.0	X										1
	4b	Pump Station No. 4 Replacement	$2.6			X		X	X					3
	4c	Kewaunee River HDD Crossing	$3.6		X								Riverbank Restoration	2
	4d	N. 68th St Water Main Lining	$1.5				X	X	X	X	X			5
Multi	M1	Valve Additions	$1.8			X	X						Correct Lack of Isolation	3
	M2	Aerial Crossing Repairs	$4.1			X		X					High Impact of Failure	3
	M3	Fire Hydrant Replacements	$0.6					X		X				2
		Total ($M)	$37.4	$7.6	$10.6	$21.7	$5.4	$14.8	$4.1	$7.3	$2.5	$5.0	$11.0	-

Example Problem 1

Engineer Jeremy helped prepare Table 2 and now needs help to select which project(s) to proceed for Hydraulics Correction, while staying within the budget of $5M for that category. Help Jeremy list options for project selection and provide a recommendation.

Solution

The three Hydraulics Correction projects are as follows:

- $6.2 – 2a, Highway 18 Redundant Transmission, 2 motivations
- $0.8 – 3a, Pump Station No. 2 Upgrades, 3 motivations
- $3.6 – 4c, Kewaunee River HDD Crossing, 2 motivations

All projects cannot be done within the $5M budget. The following are options for proceeding:

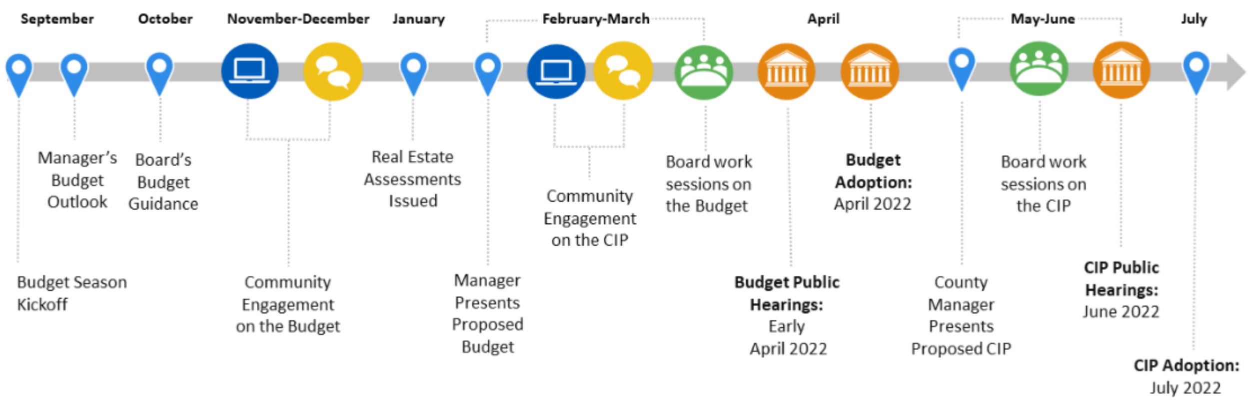
1. Proceed with projects 3a and 4c for a total $4.4M.
2. Proceed with projects 3a and 4c, break up project 2a into a $0.6M project (2a-1) and a $5.6M project (2a-2), and proceed with project 2a-1. A total of $5.0M budget is utilized.
3. Proceed with project 4c, break up project 2a into a $1.4M project (2a-1) and a $4.8M project (2a-2), and proceed with project 2a-1. A total of $5.0M budget is utilized.

Recommendation:

- Proceed with Option 1, projects 3a and 4c, since nearly all of the budget is utilized while avoiding the complexities of only proceeding with a small portion of project 2a.

Budget Planning

Annual CIP budgets are typically approved through a lengthy process like this example:



Projects typically last 1 to 5 years, from design to startup, so the project cost does not occur in a single year. Thus, a long term budget is also required, with projected annual spending over the upcoming 4, 5 or 6 years. This is often called a CIP Program Budget. The CIP Program Budget may require annual approval in addition to an annual CIP Spending Budget. Ideally, the next year's Spending Budget would match the projection in the previous year's CIP Program Budget. To avoid major differences, careful scheduling and detailed budget projections for each project are required.

The following steps can be used to create a basic CIP Program Budget:

1. Create a schedule for each project. Projects are often broken down into the following phases:
    a. Study or Conceptual Design
    b. Final Design
    c. Bidding/Procurement
    d. Construction
2. Develop a construction cost estimate for each project. Assign a cost to each phase. Often the design cost is estimated at 10% of the construction cost.
3. Create a table or schedule of all projects.
4. Enter the project costs for each design phase and divide the costs by year and/or quarter.

See Table 3 for an example of a table style CIP budget and schedule, which is also provided in excel format as free software with this course.

Table 3: Example CIP Budget Schedule

(Phase coloring: study, design, bid, construction) (All costs in $M)

Zone	Proj. No.	Potential Project Name	Cost Estimate ($M)	2023 Q1	2023 Q2	2023 Q3	2023 Q4	2024 Q1	2024 Q2	2024 Q3	2024 Q4	2025 Q1	2025 Q2	2025 Q3	2025 Q4
1	1a	Saturn Dr Water Main Lining	$1.0	-	-	$0.05	$0.05	$0	$0	$0.20	$0.20	$0.30	$0.20	-	-
	1b	Anderson Ave Road Widening	$2.4	$0.10	$0.10	$0.10	$0	$0	$0.30	$0.40	$0.60	$0.60	$0.20	-	-
	1c	Cottage Creek New Water System	$1.5	$0.05	$0.05	$0.10	$0	$0	$0.20	$0.20	$0.40	$0.40	$0.10	-	-
2	2a	Highway 18 Redundant Transmission	$6.2	-	-	$0.20	$0.30	$0.20	$0	$0	$0.80	$1.20	$1.40	$1.60	$0.50
	2b	Cozy Den Development Flow Monitoring Station	$1.1	-	-	$0.05	$0.10	$0.05	$0	$0	$0.20	$0.20	$0.20	$0.20	$0.10
3	3a	Pump Station No. 2 Upgrades	$0.8	-	-	$0.05	$0.05	$0.05	$0	$0	$0.05	$0.20	$0.20	$0.20	-
	3b	Blue Heron Dr Water Main Replacement	$5.2	-	$0.10	$0.20	$0.20	$0	$0	$0.60	$1.00	$1.30	$1.40	$0.40	-
4	4a	Ground Storage Tank Expansion	$5.0	$0.05	$0.10	$0.20	$0.20	$0.20	$0	$0	$0.60	$1.00	$1.40	$1.00	$0.25
	4b	Pump Station No. 4 Replacement	$2.6	-	-	$0.10	$0.20	$0.10	$0	$0	$0.40	$0.60	$0.60	$0.40	$0.20
	4c	Kewaunee River HDD Crossing	$3.6	-	$0.10	$0.10	$0.10	$0.10	$0	$0	$0.50	$0.70	$0.90	$0.90	$0.20
	4d	N. 68th St Water Main Lining	$1.5	$0.05	$0.05	$0.10	$0	$0	$0.20	$0.20	$0.40	$0.40	$0.10	-	-
Multi	M1	Valve Additions	$1.8	$0.10	$0.10	$0	$0	$0.20	$0.40	$0.40	$0.40	$0.20	-	-	-
	M2	Aerial Crossing Repairs	$4.1	$0.10	$0.20	$0.20	$0	$0	$0.60	$0.80	$1.00	$1.00	$0.20	-	-
	M3	Fire Hydrant Replacements	$0.6	-	-	$0.02	$0.02	$0	$0	$0.06	$0.20	$0.20	$0.10	-	-
		Quarter Total	$37.4	$0.45	$0.80	$1.42	$1.27	$0.90	$1.70	$2.86	$6.75	$8.30	$7.00	$4.70	$1.25
		Annual Total		$3.94				$12.21				$21.25			

Example Problem 2

A County Utility Department has created the CIP project budget schedule in Table 3. However, the approved Budget Program does not allow spending of more than $7.5 million in any quarter. Which project schedules be shifted to meet this requirement, assuming all projects must start between Q1 and Q3 of 2023.

Solution

The only quarter with spending in excess of $7.5M is Q1 of 2025 with $8.3M. Although several projects could be shifted to reduce the total, the following is the only project that on its own can reduce the total by $0.8M or more:

- Proj. No. 4a "Ground Storage Tank Expansion": delay to start on Q3 of 2023 instead of Q1 of 2023. The Q1 of 2025 total budget drops by $1.0M to $7.3M.

Infrastructure Data Management

Knowing details of the distribution system is critical for identifying and prioritizing potential projects. This means the data needs to be gathered, saved, organized, and utilized regularly. Figure 11 shows some of the main data structures.

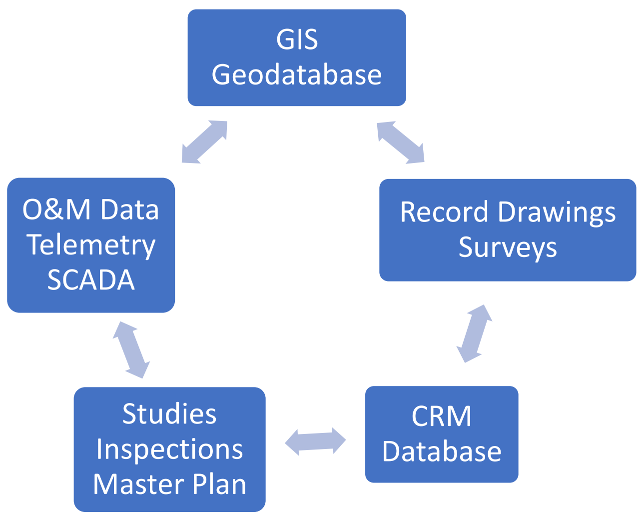


Figure 11: Basic data structures that help in CIP management.
CRM stands for customer relationship management.

Source: Author

GIS

GIS (Geographic Information System) has the power to make information easily accessible. GIS can draw information from all the data structures listed in Figure 11, and more. GIS is a computer software system that analyzes and displays information with geographic references.

For example, distribution system features can be on layers in GIS, including pipes, storage tanks, pump stations, etc., as shown in Figure 12. If you click on a particular pipe there will be information such as length, diameter, and age. There can also be links to relevant documents such as record drawings, photographs, and maintenance data.

GIS can graphically show information such as break history on a map with areas of high breaks shaded, as shown in Figure 13. This approach is commonly called a "hot spot" map. Also, pipe ages can be shown in different colors.

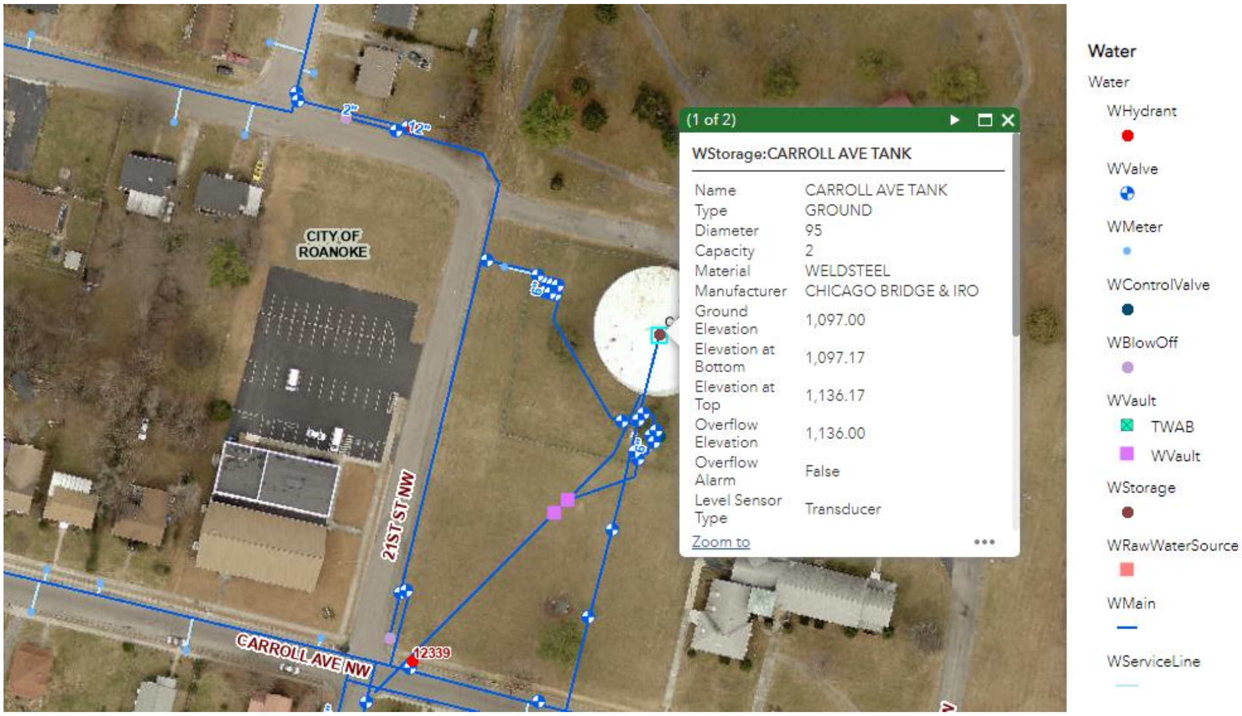


Figure 12: Example of a GIS map with data on a storage tank in the popup window.

Source: www.westernvawater.org/i-am-a-/developer-engineer/authority-gis (public domain)

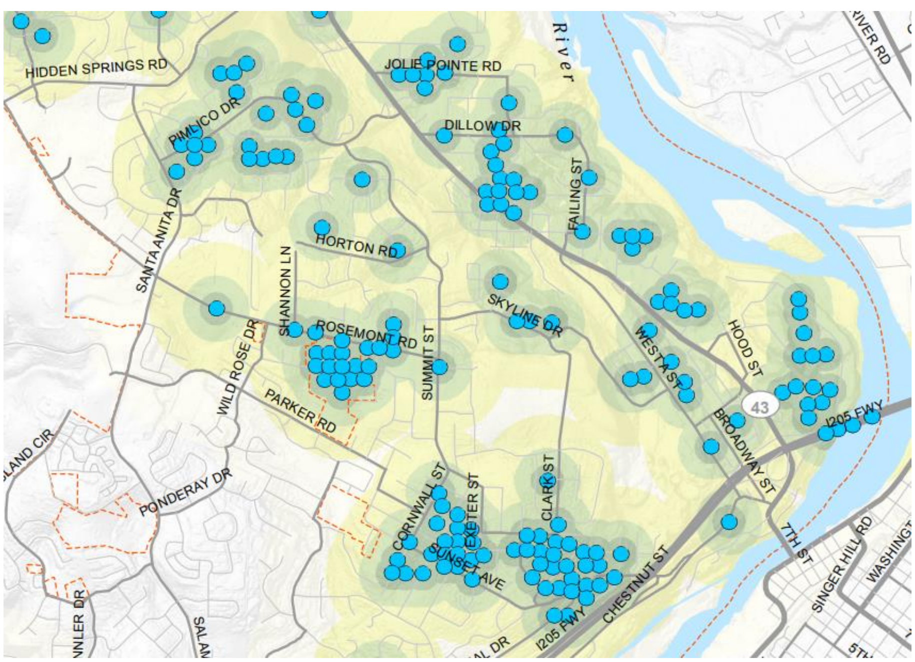


Figure 13: GIS map with main break locations in blue and density of breaks shaded.

Source: westlinnoregon.gov/sites/default/files/gis/water_maps/MainBreakMap01_byLocation.pdf (public domain)

Hydraulic Modeling

A hydraulic model is a useful tool for assessing the hydraulics of a distribution system and thereby identifying CIP improvement projects. Hydraulic models commonly assess the following:

- Capacity remaining for pipes, pump stations, and storage tanks
- Pipes with high water age (see Figure 14)
- Pipes with low or high velocities
- Pipes with low or high pressure
- Points of failure with no redundancy
- Hydraulic restrictions or bottlenecks
- Water loss for district metered areas (DMAs)
- Optimized pipe and pump sizes for proposed improvements
- Ideal locations and capacities for inter-connects to other systems

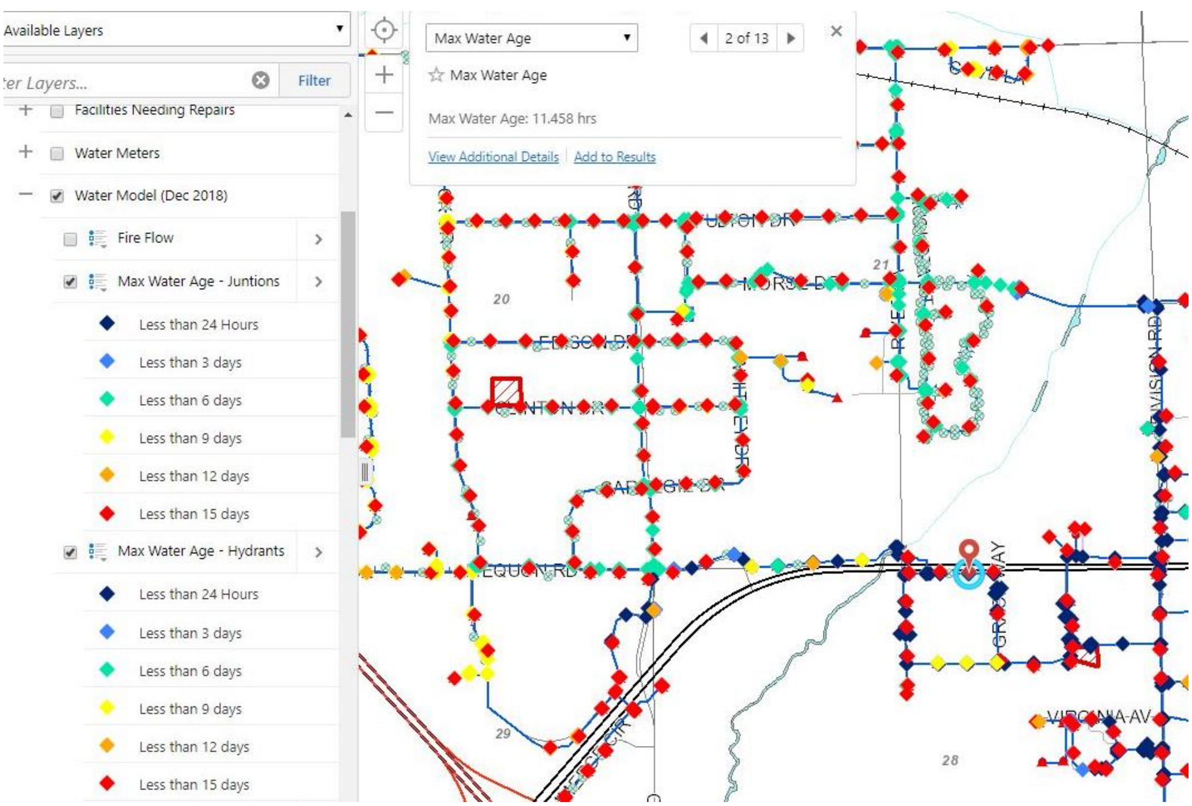


Figure 14: Hydraulic model results showing water age at junctions and hydrants.
Source: www.germantownwi.gov/269/Water-Utility (public domain)

Types of Models

There are three main approaches to running a model simulation:

1. Steady-State Modeling:
    a. Assumes total flow coming in equals total flow going out. There is no accumulation of water in tanks. Steady state means the variables are constant with respect to time.
    b. For example, a model simulation with a constant input that equals the average flow from the WTP and user output flows that add to that input. Water loss (from leaks, breaks, etc.) may also be added as an output divided among nodes or service lines.
    c. Advantages: low cost, simple, easy to calibrate, and reliable for normal flow days.
2. Extended Period Simulation (Dynamic) Modeling:
    a. Allows for water storage tanks to fill or empty in the system when inputs do not equal outputs. An extended period simulation can more accurately calculate the pressure and water age since it includes the typical fill and draw cycles for water storage tanks and the water demand changes throughout the day.
    b. For example, a model simulation over 24 hours with user outputs based on hourly meter readings plus a 20% factor for water loss. Storage tanks fill during low flow periods at night and tanks empty during the high flow periods during the day. Pressures are maintained by pumping, although it is observed that some neighborhoods experience low pressure during the highest flow period of the day.
    c. Advantages: informs storage tank and pump operations, simulates fire flow scenarios, and is more accurate for water age.
3. Real-Time Modeling
    a. Model inputs are drawn directly from current data such as a SCADA system or water meter database. This allows for viewing the current pressures and flows throughout the system. The model can also be calibrated regularly with current or very recent data.
    b. For example, if a fire occurs requiring a large volume of water from nearby hydrants, the model can be opened and run using real time pressure readings and actual storage tank elevations. The model can estimate the water flow rate and duration available for firefighting activities, and the pressure drop to users across the system.

Calibration and Validation

Calibration is the process of modifying the model so that the results more closely align with actual flow readings. Often several iterations are required, as shown in Figure 15. Validation is comparing the final model results to actual field readings and assigning an accuracy grade, such as 5% accuracy. The accuracy grade will be different for different variables such as velocity and pressure. If the model accuracies are deemed too high, the model can be modified such as changing the pipe friction coefficients, and the simulation ran again, which is called calibration.

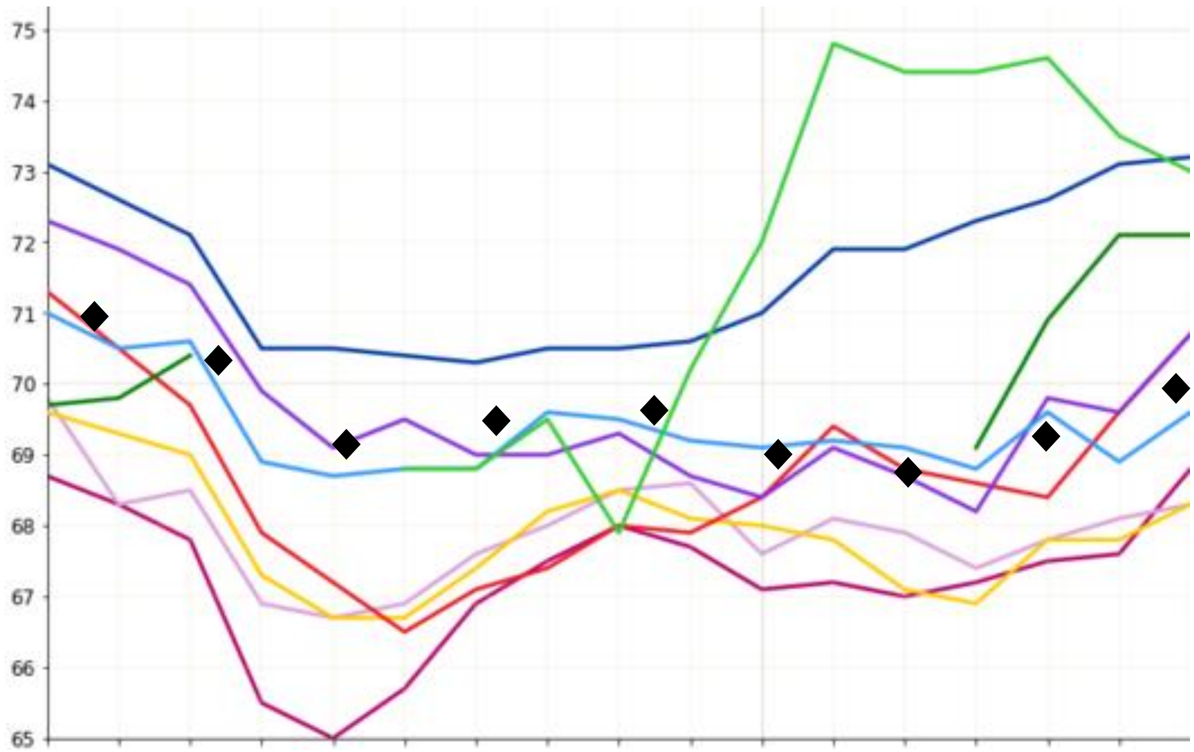


Figure 15: Plot of pressure over a 24 hour period with several calibration iterations. The field results are the block diamonds. The final model results are the light blue line, which has an accuracy grade of 1%.

Source: Author

Water Loss Reduction

Water loss is when some of the potable water supplied does not make it to an authorized user. It costs money to treat and pump water, so losing water is a financial concern. The following are common water loss control approaches:

- Creating a water balance,
- Plotting and reviewing water supply and consumption data,
- Performing a water audit,
- Benchmarking with key performance indicators (KPIs),
- Reviewing and upgrading billing and accounting software,
- Taking measures to better account for unmetered authorized consumption, such as pipe flushing and fire flow,
- Reducing water meter inaccuracies, including meter calibration and replacement,
- Identifying and removing unauthorized connections,
- Streamlining data management,
- Pressure management,
- Creating district metered areas (DMAs) to identify high losses,
- Regular and targeted leak detection efforts, and
- Pipe rehabilitation or replacement based on pipe age, material, leak history, DMA results, etc.

Water loss can be calculated in three ways:

1. Water supplied minus authorized consumption (billed and unbilled).
2. Non-revenue water (supplied but not billed) minus unbilled authorized consumption (flushing, fire flow, sampling, etc.).
3. Sum of real losses (pipe leakage) and apparent losses (unauthorized connections, meter inaccuracies, and data errors).

Water Balance

A water balance is a breakdown of water consumption and water loss for a distribution system. See the water balance in Table 4 to understand the relationship of water loss terms. It is common to create a water balance table with values for each cell to gain an overall understanding of the distribution system and as part of a water audit.

Table 5 shows an example of a water balance with water volumes (per day) in red, in units of million gallons (MG). A water balance can also be done with water volumes, such as million gallons per day (MGD).

Not that *non-revenue water* is slightly different from the term *water loss*. The difference is that water loss does not include unbilled authorized consumption, such as pipe flushing operations, fire flow from fire hydrants, or water sampling.

<table>
<tr><th colspan="10">Table 4: Water Balance Terms for a Distribution System with
Water Loss Categories in Green</th></tr>
<tr><td colspan="10">Water Supplied</td></tr>
<tr><td colspan="4">Authorized Consumption</td><td colspan="6">Water Loss</td></tr>
<tr><td colspan="2">Billed Authorized</td><td colspan="2">Unbilled Authorized</td><td colspan="3">Apparent Losses</td><td colspan="3">Real Losses</td></tr>
<tr><td>Billed Metered</td><td>Billed Unmetered</td><td>Unbilled Metered</td><td>Unbilled Unmetered</td><td>Meter Inaccuracies</td><td>Unauthorized Consumption</td><td>Data Errors</td><td>Leaks & Overflows at Tanks</td><td>Leakage on Mains</td><td>Leakage at Service Lines</td></tr>
<tr><td colspan="2">Revenue Water</td><td colspan="8">Non-Revenue Water</td></tr>
</table>

<table>
<tr><th colspan="10">Table 5: Water Balance for Example Problem 3
with Volumes in Red</th></tr>
<tr><td colspan="10">Water Supplied – 6.32 MG</td></tr>
<tr><td colspan="4">Authorized Consumption
5.20 MG</td><td colspan="6">Water Loss
1.12 MG</td></tr>
<tr><td colspan="2">Billed Authorized
5.00 MG</td><td colspan="2">Unbilled Authorized
0.20 MG</td><td colspan="3">Apparent Losses
0.27 MG</td><td colspan="3">Real Losses
0.85 MG</td></tr>
<tr><td>Billed Metered
4.90 MG</td><td>Billed Unmetered
0.10 MG</td><td>Unbilled Metered
0.10 MG</td><td>Unbilled Unmetered
0.10 MG</td><td>Meter Inaccuracies
0.05 MG</td><td>Unauthorized Consumption
0.15 MG</td><td>Data Errors
0.07 MG</td><td>Leaks & Overflows at Tanks
0.05 MG</td><td>Leakage on Mains
0.40 MG</td><td>Leakage at Service Lines
0.40 MG</td></tr>
<tr><td colspan="2">Revenue Water
5.00 MG</td><td colspan="8">Non-Revenue Water
1.32 MG</td></tr>
</table>

Example Problem 3

Great Utility is operating a distribution system and needs to better understand the water consumption and losses. They have collected the following water data over 24 hours. Create a water balance table, calculate the unauthorized consumption, and determine the percent water loss.

Category	Volume (MG)	Notes
Water Supplied	6.32	WTP Effluent
Billed, metered	4.90	Customers
Billed, unmetered	0.10	Reclaim tank filled each week
Flushing, metered	0.10	Unbilled, metered
Flushing, unmetered	0.05	Estimated by operations staff
Fire flow, unmetered	0.05	Estimated by Fire Dept.
Meter Inaccuracies	Unknown	Assume 1% of billed, metered
Data errors	Unknown	Assume 1% of water supplied
Storage tank losses	0.05	Based on holding and testing
Leakage in pipes	0.80	Assume 50/50 split for water mains versus service lines

Solution:

A water balance is created in Table 5 using the above volumes. Note that the unbilled unmetered volume (0.1 MG) is the sum of the flushing, unmetered (0.05 MG) plus the fire flow, unmetered (0.05 MG).

The unauthorized consumption is calculated as follows:

Unauthorized consumption = Water Supplied – Authorized Consumption – Real Losses – Meter Inaccuracies – Data Errors
= 6.32 – 5.20 – 0.85 – 0.05 – 0.07 = **0.15 MG**

The percent water loss is calculated as follows:

Water Loss = Water Supplied – Authorized Consumption = 6.32 – 5.20 = 1.12 MG

Percent Water Loss = Water Loss / Water Supplied * 100 = 1.12 / 6.32 = **18%**

Pressure Management

The higher the water pressure, the greater the flow through leaks. As a rule of thumb, the percent increase in pressure will produce the same percent increase in leakage. For example, a 10% increase in pressure will result in a 10% increase in the leakage flow rate. Conversely, a 10% drop in pressure will result in a 10% drop in leakage flow.

Distribution systems must maintain a minimum pressure of 35 psi, per the *Ten States Standards* (see Helpful References) and many state standards. A maximum pressure is not specified, although a range of 60 to 80 psi is recommended. Pressures over 100 psi are considered to be excessive due to the potential for water hammer, appliance damage, pipe and joint stresses, and increased leakage. The average pressure for water utilities in North America is 76 psi, per AWWA M36, Table 6-1. In general, utilities should consider dropping the overall distribution system pressure to reduce leakage.

For utilities with great elevation changes, the pressures at the lower elevations can be reduced to decrease water loss. See Figure 16 for an example. The water pressure change due to the elevation change of water pipes is calculated as follows, based on Bernoulli's principle:

$$\Delta p = \frac{\Delta EL * sg}{2.31} = 0.43 * \Delta EL$$

where:

p = water pressure (psi)

ΔEL = elevation change of water pipes (feet)

sg = specific gravity of the fluid (1.0 for water)

Pressure can be reduced by installing a pressure-reducing valve at each branch feeding the low elevation area. These valves can also have flow controllers or timers so that the pressure is only decreased during low flows or the night hours.

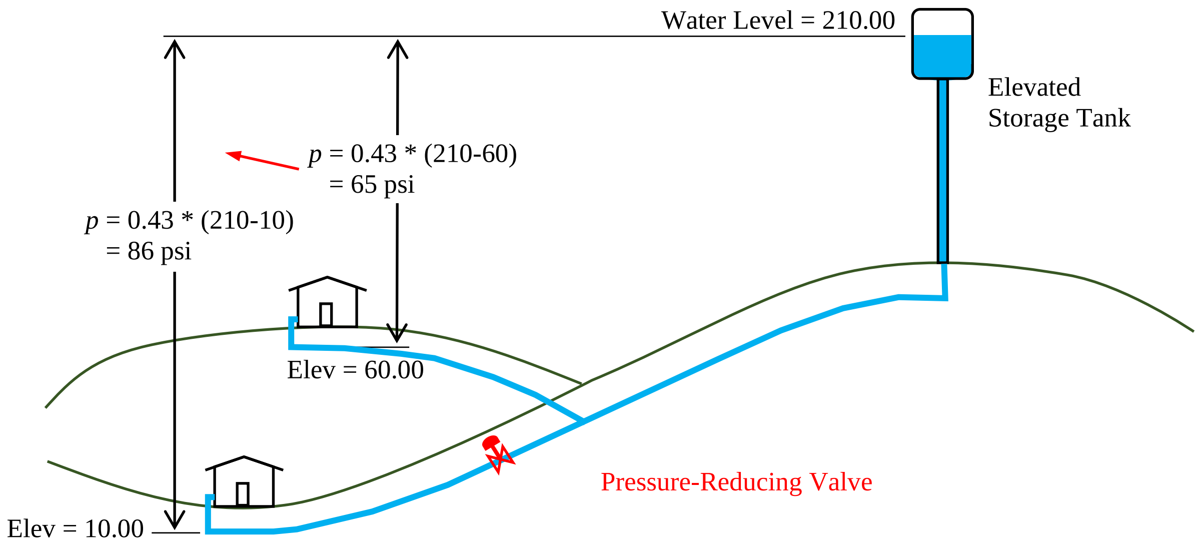


Figure 16: Water pressure (*p*) calculated at the lowest and highest elevations in a community. A pressure-reducing valve (in red) can be added to decrease the pressure from 86 psi to 65 psi, which may correspondingly reduce pipe leakage by 24%.

Leaks can also form or grow from temporary spikes in pressure, also called surges or transients. Surge control techniques include pump speed control (VFD or soft start), cushioned check valves, bladder tanks, pressure relief valves, vacuum valves, and high-pressure discharge or recirculation arrangements.

Tools for pressure management include the following:

- Pressure transmitters located throughout the distribution system. Placing them near sewer lift stations provides a means for remote communications.
- Pressure-reducing, pressure sustaining, or pressure relief valves.
- Altitude valves at storage tanks.
- Transient/surge control techniques.

District Metered Areas

A way to find areas of high leakage is to sectorize the distribution system into logical zones, called district metered areas (DMAs). Creating DMAs requires metering the flow into the zone by installing water meters on all the active water mains at the zone boundary. The formula for calculating the water loss is as follows:

$$\text{Water loss} = \sum \text{zone meters} - \sum \text{billed authorized} - \sum \text{unbilled authorized}$$

Installing meters on buried water mains in the distribution system can be expensive, so typically valves are closed to force all the flow through one or two water mains so fewer meters are required.

For water mains and other large pipes, flow meters are commonly installed in vaults or above ground on concrete pads with isolation valves and a bypass pipe. However, for temporary DMA purposes, there are more economical meter solutions, such as a portable strap-on ultrasonic meter or an insertion meter.

Leak Detection Techniques

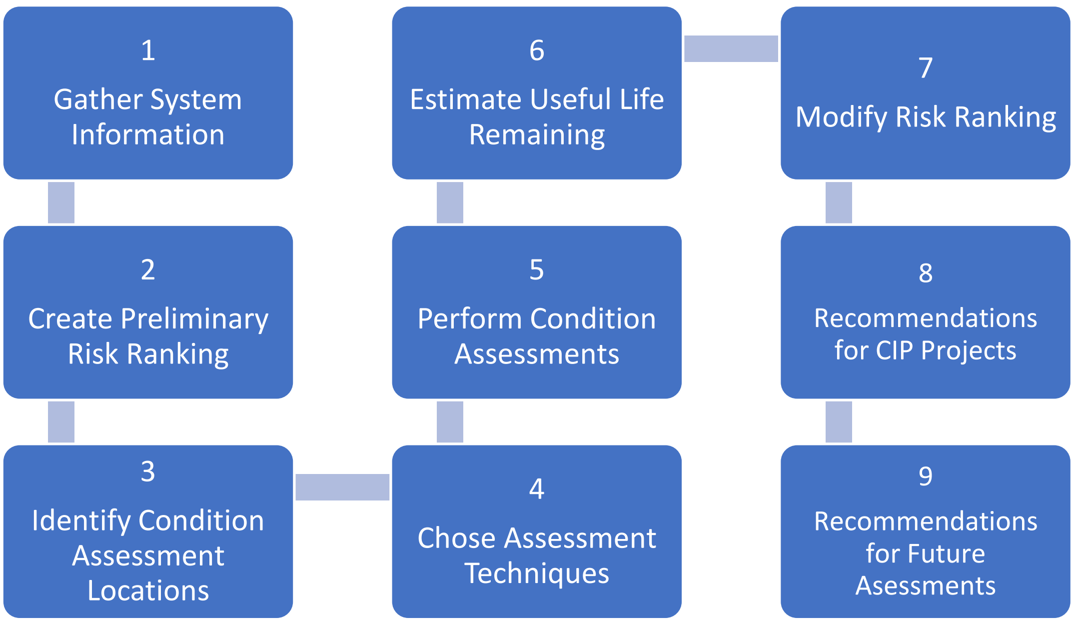
Leak detection is an essential part of water loss control. It is often the most rewarding as you can physically see the water loss being stopped when a leak is found and the pipe is repaired. It can also be frustrating when a pipe break is reported on a pipe that was recently investigated with a leak detection technique with no leaks found. Common techniques to locate leaks are as follows:

- Acoustic leak detection:
    - Ground-microphone method
    - Correlator method
    - Probe method
    - Inline leak detection sensor
    - Automated acoustic devices
- Satellite survey
- Tracer Gas Method
- Ground-penetrating Radar
- Thermography
- Pressure Testing
- Pressure Monitoring

Condition Assessments

Condition assessments help make smart decisions for replacing or rehabilitating aged or failing components in a distribution system. As components ages, the benefit for regular condition assessments increases. The goal is not to inspect every single pipe and valve, but to inspect a sufficient quantity to be representative of the areas of concern and thereby allow smarter decisions for rehabilitation planning.

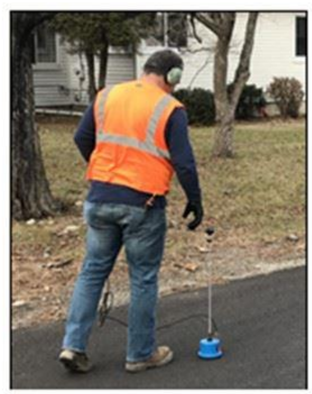
The condition assessment process may involve these steps:



In Step 2, a consequence of failure (COF) value is assigned to each component, including each pipe segment. In Step 7, condition assessment results are used to assign a likelihood of failure (LOF) for each pipe segment.

For Step 4, there are many condition assessment techniques to choose from, as illustrated in Table 6. Many of the techniques are common to sewer collection systems as well. Water mains are often more challenging to internally inspect than sewers for the following reasons:

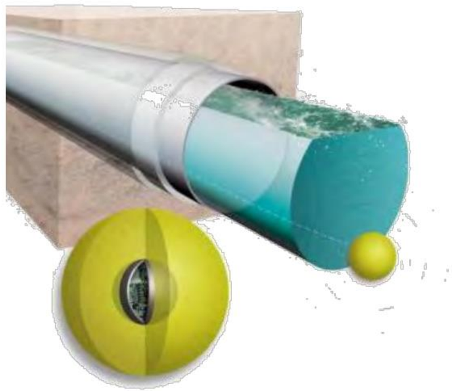
- Taking down a critical water main may result in inadequate water pressure,
- Accessing the inside of a water main requires cutting open the pipe, and
- Disinfection procedures need to be followed to minimize contamination risks.

Table 6: Condition Assessment Techniques	
Component	Common Techniques
Service Lines	○ Exterior inspection, as shown:  ○ Review history of leaks and breaks ○ Leak detection techniques, as shown:   Source: https://concordma.gov/1647/Water-Main-Leak-Detection (public domain)

Water Mains & Transmission Mains (Exterior)	○ Soil corrosion analysis ○ Leak detection techniques ○ Exterior visual Inspection ○ Exterior coupon inspection (for PCCP pipe), as shown:  ○ Exterior acoustic impact echo (for PCCP pipe) ○ Exterior electromagnetic scanning ○ Exterior ultrasonic scanning or spot checking, as shown:  ○ Exterior guided radar scanning ○ Exterior bracelet probe

<table>
<tr>
<td>Water Mains & Transmission Mains (Internal)</td>
<td>

CCTV, as shown:

Source: https://www.northbay.ca/services-payments/water-wastewater/services/camera-inspections/, public domain
Interior acoustic ball, as shown:

Source: https://your.kingcounty.gov/dnrp/library (public domain)
Internal electromagnetic, as shown:

Source: www.denverwater.org/tap/diving-in-to-inspect-pipes-from-the-inside-out (p.d.)
Internal magnetic flux
Internal laser
Internal ultrasonic pig

</td>
</tr>
</table>

Vaults and Pipe Assemblies for Flow Meters, Valves, Backflow Preventors, etc.	○ Visual inspection, as shown:  Source: www.portland.gov/water/backflow-prevention/backflow-assemblies (public domain) ○ Half-cell corrosion mapping ○ Coupon inspection ○ Acoustic impact echo
Storage Tanks	○ Visual Inspection (by tank manufacturer or structural engineer):  Source: stillwater.org/page/home/government/current-projects/water-utilities-engineering-projects/water-projects/water-storage-tank-inspection-evaluation (public domain) ○ Half-cell corrosion mapping ○ Coupon inspection ○ Acoustic impact echo ○ Coating/lining thickness measurement ○ Leak testing

Pump Stations	○ Visual Inspection, as shown:  Source: www.cctexas.com/detail/onswtp-high-services-pump-building-no-3 (public domain) ○ Coating/lining thickness measurement, as shown:  ○ Pump manufacturer inspection and testing ○ Functional testing ○ Pump performance testing

Risk Ranking
For step 7, the assessment results are used to assign a likelihood of failure (LOF) for each pipe segment, often on a scale of 1 to 100. The LOF is added to the COF (consequence of failure) to get a total risk value for each pipe segment. The risk values are sorted by highest risk to help identify CIP project recommendations in Step 8. See Figure 17 for plot of COF versus LOF, also called a risk matrix.

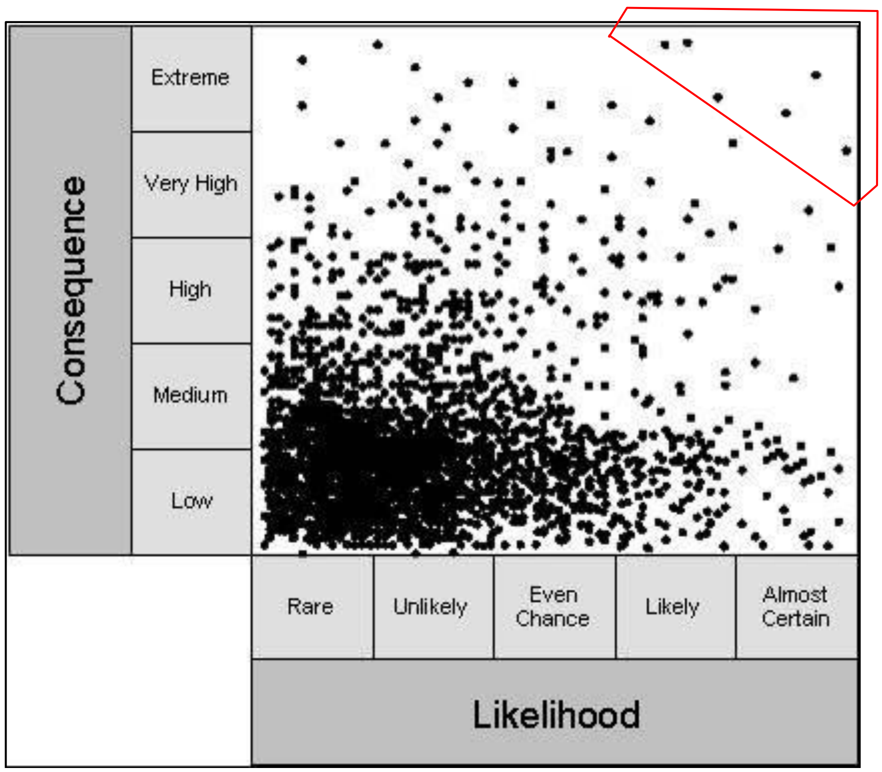


Figure 17: A risk matrix with each dot representing a pipe segment in a system. The dots in the red area in the upper right have the highest total risk.

Source: www.denverwater.org/tap/diving-in-to-inspect-pipes-from-the-inside-out (public domain)

Often the COF is considered of more importance than the LOF. In such cases, an importance factor (IF) is used when calculating the total risk, per this formula:

Total Risk = IF * COF + LOF

For example, an importance factor of 1.5 means the COF is one and a half times as important as the LOF.

Water Main Rehabilitation

An engineering analysis should be done to determine the best method of rehabilitation for existing water mains and transmission mains. The following table provides common pipe rehabilitation techniques. In many cases, special products have been developed that are NSF 61 certified as safe for potable water use.

Table 7: Pipe Rehabilitation Techniques

Technique	Trenchless	Diameter Range	Description & Example
Polymer Coating	Y	> 6”	Spray on interior after pigging and flushing
Cured-in-place Pipe (CIPP)	Y	> 4”	A liner with resin is inflated inside the pipe and heated to cure.
Thermo-formed Pipe	Y	> 4”	“Fold and form” PVC or PE liner is pulled into the pipe and filled with steam.
Grout-in-place Pipe	Y	> 4”	A liner with resin is inflated inside the pipe and heated to cure.
Sliplining	Y	> 4”	Pull a smaller pipe within the larger existing pipe and seal the annular space.
Pipe Bursting	Y	> 4”	A bursting tool and new pipe pulled through the existing pipe.
Spiral Wound Pipe	Y	> 6”	Continuous strips of PVC or HDPE are wound, overlapped and sealed.
Interior Sleeve Repair	Y	> 6”	A stainless sleeve with grout is guided to the damaged area and expanded using air. The grout expands and seals gaps.
Exterior Sleeve Repair	N	All	Expose pipe at damaged area, clean the pipe surface, and install the sleeve.
Partial Replacement	N	All	Isolate the section of pipe, cut, remove, and install new pipe with couplings.

Questions to explore when considering replacement or rehabilitation of a water main:

- When was the asset installed?
- Is there a history of leaks, breaks, or blockages?
- Has there been an inspection or condition assessment?
- Can the anticipated deterioration rate and eventual failure be predicted?
- If so, what is the estimated residual life until rehabilitation or replacement is necessary?
- Could best management practices and maintenance extend the time to failure?
- Can the asset be rehabilitated? How much would this extend the time to failure?
- What is the capital and life-cycle cost of replacement versus rehabilitation?
- Is the asset technically or commercially obsolete, or otherwise not needed?
- Is there an upcoming road project or sewer project where replacement work can be combined?
- Are there planned improvements or developments in the area?
- How does this asset prioritize compared to other assets needing replacement?

Helpful References

AWWA (2021) "Water Audits and Loss Control Programs", AWWA Manual M36, 5th Ed.

AWWA (2012) "Water Distribution System Operation and Maintenance: A Field Study Training Program", 6th Ed.

Cooper, J. P. AWWA (2017) "Computer Modeling of Water Distribution Systems", AWWA Manual M32.

EPA (2002) "Asset Management for Sewer Collection Systems", EPA Fact Sheet 833-F-02-001.

EPA (2016) "Best Practices to Consider When Evaluating Water Conservation and Efficiency as an Alternative for Water Supply Expansion". EPA-810-B-16-005.

EPA (various) "Title 40 of CFR: Protection of Environment".

EPA (2007) "Asset Management: A Best Practices Guide", EPA-816-F-08-014.

EPA (2007) "Distribution System Inventory, Integrity and Water Quality", Office of Water (4601M).

Great Lakes Upper Mississippi River Board of State Public Health & Environmental Managers (2012) "Recommended Standards for Water Works". (Also known as *Ten States Standards)*. Albany, NY: Health Education Services.

Mays, Larry W. (1999) "Water Distribution Systems Handbook". McGraw-Hill.

Strafaci, Adam; et. al. (2007) "Advanced Water Distribution Modeling and Management", Bentley Institute Press.

Wisconsin Department of Natural Resources (WDNR) (2009) "Wisconsin CMOM – Capacity, Management, Operation & Maintenance". PUB-WT-917-2009.

