Hydrodynamics Principles
The General Energy Equation

$$\Delta E = Q - W \quad (\text{first law of thermodynamics})$$

$$\Delta E = \text{The total change in energy in a system}$$
$$= \Delta E_u + \Delta E_k + \Delta E_p$$
$$E_u = \text{Internal energy}$$
$$E_k = \text{kinetic energy} = \frac{1}{2} MV^2$$
$$E_p = \text{potential energy} = \text{(weight)} \times \text{(elevation)}$$

$$Q = \text{The heat transferred to the system in a given time}$$

$$W = \text{The work done by the system on its surroundings in a given time}$$
Energy Equation for a Single Pipe

\[ h_1 - h_2 = h_L - h_p \]

\[ h_1 = \frac{p_1}{\gamma} + z_1 = \text{HGL @ 1} \]

\[ h_2 = \frac{p_2}{\gamma} + z_2 = \text{HGL @ 2} \]
Steady State Network Hydraulics

Conservation of Energy

\[
\begin{align*}
    h_1 - h_2 &= a_{12} \cdot Q_{12}^b \\
    h_2 - h_3 &= a_{23} \cdot Q_{23}^b \\
    h_4 - h_5 &= a_{45} \cdot Q_{45}^b \\
    h_5 - h_6 &= a_{56} \cdot Q_{56}^b \\
    h_1 - h_4 &= a_{14} \cdot Q_{14}^b \\
    h_2 - h_5 &= a_{25} \cdot Q_{25}^b \\
    h_3 - h_6 &= a_{36} \cdot Q_{36}^b
\end{align*}
\]

Conservation of Mass

\[
\begin{align*}
    Q &= Q_{12} + Q_{14} \\
    Q_{12} &= Q_{25} + Q_{23} \\
    Q_{23} &= Q_{36} \\
    Q_{14} &= Q_{45} \\
    Q_{25} &= Q_{45} + Q_{56} \\
    Q_{56} + Q_{36} &= Q
\end{align*}
\]

13 Equations, 13 Unknowns
(6 Unknown heads + 7 Unknown flow rates)
FLOW CONTINUITY

\[ \begin{align*}
Q &= 2.0 \text{ mgd} \\
\text{Flow Out} \\
\hline
Q &= 5.1 \text{ mgd} \\
\text{Flow In} \\
\hline
Q &= 2.3 \text{ mgd} \\
\text{Flow Out} \\
\hline
\text{Demand at Node} &= 0.5 \text{ mgd} \\
\hline
Q &= 0.3 \text{ mgd} \\
\text{Flow Out} 
\end{align*} \]
NETWORK EQUATIONS

1. Geometric (topology) relation (Euler equation)
   \[ NE = NJ + NL + NF - 1 \]
   where
   - **NE** = number of elements (pipes, pumps, valves)
   - **NJ** = number of junction nodes
   - **NL** = number of closed loops
   - **NF** = number of fixed grade nodes

2. Continuity principle (Kirchoff's 1st Law)
   • At any junction node, the algebraic sum of flows must equal zero

3. Energy principal (Kirchoff's 2nd Law)
   • Along each closed loop, the accumulated headloss (or gain) must be zero
Summary

Conservation of Energy in Hydraulic Systems is derived, in its most basic form, from the first law of thermodynamics.

The Energy in a hydraulic system is comprised of potential, kinetic, and internal energy, the sum of which is called the total energy.

The Energy equation for pipe flow relates the total energy difference at two points, to the energy imparted to the fluid by a pump, and to the energy lost in the form of heat.

The Hydraulic Grade Line (HGL) is the sum of the pressure and elevation heads, and represents the height that water would rise in a piezometer.

The Energy Grade Line is the sum of the pressure, elevation, and velocity heads, and represents the height that water would rise in a stagnation tube.

The Energy losses in a pipe can be approximated by at least two methods, the Darcy–Weisbach (theoretical basis) and the Hazen–Williams (empirical basis) formulas.

Network hydraulics are modeled by combining conservation of fluid mass at the pipe junction (continuity) with conservation of energy along each pipe. There are other ways, but every method is based on the same hydrodynamic principles.
THE FLOW METHOD (Q-EQUATIONS)

1. Set headloss around every closed loop to zero (Kirchoff's 2nd Law) where # loops = # pipes - # nodes:

\[ r_{23} (Q_{23})^{1.85} + r_{34} (Q_{34})^{1.85} - r_{24} (Q_{24})^{1.85} = 0 \]
\[ r_{35} (Q_{35})^{1.85} - r_{45} (Q_{45})^{1.85} - r_{34} (Q_{34})^{1.85} = 0 \]

2. Write flow continuity equations at each junction:
\[ Q_{12} - Q_{23} - Q_{24} - D_2 = 0 \]
\[ Q_{23} - Q_{34} - Q_{35} - D_3 = 0 \]
\[ Q_{24} + Q_{34} - Q_{45} - D_4 = 0 \]
\[ Q_{35} + Q_{45} - D_5 = 0 \]

3. Results in (# pipes) equations in unknown flows Q.

4. Find H's by using headloss equation across each pipe, beginning with pipes connected to the reference node.
PROBLEM FORMULATION

1. Given:
   a) a network topology
   b) pipeline characteristics
   c) constant demands at each node, and
   d) fixed hydraulic grade (head) at one or more
      reference nodes (e.g., reservoirs & tanks)

2. Find:
   a) the flow (Q) in each pipe
   b) the head (H) at each junction node
   c) operating status
HYBRID NODE-LOOP METHOD (H-Q EQUATIONS)

1. Begin with pipe headloss and node continuity equations:

\[ H_i - H_j = r_{ij} (Q_{ij})^{1.85} \]
\[ \Sigma Q_{ij} - \Sigma Q_{jk} - D_j = 0 \]

for each pipe (i, j) for each node j

2. Apply gradient operator to these equations resulting in:

\[ A \begin{bmatrix} dQ \\ dH \end{bmatrix} = \begin{bmatrix} dE \\ dq \end{bmatrix} \]

Where \( A \) = coefficient matrix, \( dQ \) = change in flow, \( dH \) = change in head, \( dE \) = imbalance in headloss equation, and \( dq \) = imbalance in continuity equation.

3. After much re-arrangement and manipulation, a coupled set of equations for successively estimating \( H \) and \( Q \) results:

\[ A_0 H_{i+1} = A_1 Q_i + (A_2 Q_i - D) + A_3 \]
\[ Q_{i+1} = A_4 Q_i - A_5 H_{i+1} - A_6 \]

Where \( A_0 \) to \( A_6 \) are matrices containing known constants and \( Q_i \).

4. Solving for \( H_{i+1} \) involves solving a set of (# nodes) linear equations. The \( Q_{i+1} \) can then be solved for one at a time.
SOLUTION TECHNIQUES

1. Hardy Cross Method (Obsolete)

2. Linear Method (Obsolete)

3. Newton-Raphson Method:

   To solve system of nonlinear equations
   \[ F(X) = 0 \]
   solve succession of linear approximations for \( X \):
   \[ (X)_{i+1} = (X)_{i} - (dF/dx)^{-1} (F)_{i} \]
   Where \( (X)_{i} \), \( (F)_{i} \), and \( (dF/dx)_{i} \) are known after iteration \( i \)
## Comparison of Methods

<table>
<thead>
<tr>
<th></th>
<th>Node</th>
<th>Flow</th>
<th>Loop</th>
<th>Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong># Eqns.</strong></td>
<td># nodes</td>
<td># links</td>
<td># links</td>
<td># nodes</td>
</tr>
<tr>
<td><strong>Variable</strong></td>
<td>H</td>
<td>Q</td>
<td>ΔQ</td>
<td>H, Q</td>
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<td><strong>Sparsity</strong></td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td><strong>Symmetric</strong></td>
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<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Convergence</strong></td>
<td>POOR to GOOD</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td><strong>Adaptability</strong></td>
<td>Good</td>
<td>Fair</td>
<td>Fair</td>
<td>Good</td>
</tr>
</tbody>
</table>
Savings in Storage Requirements

Without Sparsity Techniques

With Sparsity Techniques

# Elements to be stored

# Nodes
EXTENDED PERIOD SIMULATION

1. Accommodates temporal variations in water demands, tank levels, and system operation by solving a succession of steady state problems at fixed time intervals.

2. Demands usually assumed constant within each time interval.

3. Tank levels updated through time by solving the following differential equation at the end of each time interval:

   \[ \frac{dH}{dt} = \frac{Q}{A} \]

   where \( H \) = water surface elevation, \( Q \) = flow into tank, \( A \) = cross-sectional area, \( t \) = time.

4. Solution methods include:

   Euler Method \((H_{t+1} = H_t + (Q_t / A) \Delta t)\)

   Predictor - Corrector Method

   Runge - Kutta Method

   where the latter two methods are more accurate but require additional network solutions since they allow \( Q \) to vary between time \( t \) and \( t + 1 \).

5. New network solution found at time \( t + 1 \) using new demands and new tank levels.
Modeling Overview
MODEL DEFINITION \( \leftrightarrow \) SYSTEM MODELS

The essence of systems analysis lies in the construction and use of models. A model is a simplified representation of something real.

Hydraulic Pipe Distribution Systems \( \rightarrow \) Mathematical Models
DISTRIBUTION SYSTEMS: MISSION

Consistent provision of water of ...........

→ acceptable quality
→ sufficient quantity
→ appropriate pressure

..........as economically as possible
MODELING TIMELINE

Time Line of Water Distribution System Modeling

1930's
Hardy Cross Network

1960's
Computer Analysis of Networks

1970's
Widely Available Hydraulic Models for Minis and Micros
Steady State Water Quality Models

1980's
Dynamic Water Quality Modeling
User Friendly Modeling & Display Systems.
Integrated Modeling, Mapping, CAD, GIS, SCADA Systems.
Tank Modeling

1990's
A mathematical model uses mathematical relationships to describe the physical interaction of a physical system. For a given set of data that describes the physical characteristics of the system, the mathematical model is used to determine the response of the system to a given set of boundary and/or loading conditions. Mathematical models are normally constructed and analyzed using computer programs.
MODES OF OPERATION

- Most models operate in the steady-state mode and in the extended period simulation (EPS) mode.

- Steady state: fixed boundary and loading conditions (i.e., all water usage, and operation are constant).

- EPS: time-varying boundary and loading conditions (i.e., tank water level, water usage, and hydraulic component status can vary with time).

- Steady state is easier to use, provides some information and is a good starting point.

- EPS: is necessary to understand the temporal dynamics of a system.
MODEL TYPES

Model Types:

- **Hydraulic Models**
  Compute the pressure distribution and flow through the network under specified operational and demand conditions.

- **Steady State Water Quality & Flow Tracing Models**
  Calculates the travel time and percentage of flow from sources to other points in distribution system and steady state concentrations.

- **Dynamic Water Quality Models**
  Calculates the temporal and spatial concentration of a contaminant throughout the system.

- **Optimization Models**
  Use optimization techniques to determine optimal operating policies or designs, subject to an objective function & constraints.
MODEL APPLICATION

Time Dependent
  - Regular Simulation
  - EPS Simulation

Function Dependent
  - Planning
  - Design
  - Operations
  - Management
STEPS IN MODELING

1. Definition of scope
2. Model selection
3. Model setup
4. Network representation
5. Calibration
6. Validation
7. Problem definition
8. Model application
9. Analysis & display
Model Needs/Uses

- Master planning
- Fire flow assessment
- Operational studies
- New development plan review
- Infrastructure rehabilitation
- Emergency response
- Energy management
- Contact time studies
- Real-time control
- Water quality analysis
- Operator training
Applications

Model

Water Quality

Advanced Applications

Operations

Conservation
Planning

- Calibration
- Capital improvement program
- Emergency planning
- Facility outage planning
- Fire flow analysis
- Load shifting
- System capacity study

- System maintenance program:
  - improvements
  - main rehabilitation

- Water availability studies

- Sizing of facilities:
  - pipelines
  - pump stations
  - reservoirs
  - valves
Operations

- Operator training
- Pressure zone or area studies
- Upcoming summer operations studies
- Analysis of past summer operations

Conservation

- Demand sensitivity
- Alternate source
  - Groundwater, surface water, non-potable, reuse, off peak demands
Water Quality

- Source tracking
- Travel time - water age
- Decay (growth) and propagation
- Tracer studies

Advanced Applications

- Optimization
  - Sizing, cost, pressure trade-offs, options analysis
- Real-time simulation
# Applications and Organization Functions of Network Modeling

<table>
<thead>
<tr>
<th>Application</th>
<th>Planning</th>
<th>Engineering</th>
<th>Operations</th>
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</thead>
<tbody>
<tr>
<td>Capital budgeting</td>
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<td>Conservation studies</td>
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<td>Emergency planning</td>
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<td>Fire flow studies</td>
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<td>Long-range planning</td>
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<td>Main rehabilitation</td>
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<td>Model calibration</td>
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<td>Operations</td>
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<td>Operations efficiency</td>
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<tr>
<td>Operator training</td>
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<tr>
<td>Planned outages</td>
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<tr>
<td>Pump station sizing</td>
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<tr>
<td>Reservoir siting</td>
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<tr>
<td>Reservoir sizing</td>
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<td>Source tracking</td>
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<td>Substance tracking</td>
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<tr>
<td>System improvements</td>
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<td></td>
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<tr>
<td>Valve sizing</td>
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<tr>
<td>Water quality</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
Network Representation
MODEL SELECTION CRITERIA

- Hydraulic analysis and simulation capabilities
- Software architecture
- Graphical capabilities
- Water quality modeling capabilities
- Numerical reliability/stability/convergence
- Model capacity
- Software support
- Hardware requirements
- Ease of use
- Quality of manuals
- Cost
- References
STRATEGY FOR SMALL SYSTEMS

Include

Include most water lines in representation.
Eliminate short, small diameter, ‘dead end’ lines and assign demands to adjacent nodes.

Exception: Include all links that are of importance to your study. For example, potential low pressure areas if you are studying pressure or ‘dead-ends’ if you are studying water quality extremes.
For large systems with many zones and components (valves, pumps, tanks), develop a highly skeletonized representation to study interzone transfers and operations of major components.

Develop separate more detailed representations by zones as needed and, if necessary, merge the detailed representations into the full systems skeleton.
GUIDELINES FOR SKELETONIZATION

- Include points of major concern or interest
  - Large water users
  - Sampling points or points of known pressure
  - Points where you want to know what’s happening
  - Facilities of interest
- Include all major and secondary feeder mains and selected smaller pipes that are of a particular importance (minimum diameter + important smaller pipes)
- Use engineering judgement to complete loops
- If needed, experiment with adding questionable links
- Topography
OPPOSING VIEWS

“All systems should be represented by 300 links or fewer.”

“It is always best to include as many pipes as possible. If you include all pipes, then data entry can be performed by less skilled personnel since they do not need to make as many judgements.”
SKELETONIZATION

- Representation of only selected pipes within a network (eliminate unimportant pipes)

- Controversial topic

- Should include all pipes/features of major concern. Use engineering judgement in skeletonization

- The more pipes you include the greater the data handling needs, the larger the model you require, and increased ‘run’ times
## Network Components

Components in a network are represented as nodes or links (may vary in different models).

<table>
<thead>
<tr>
<th>Nodes</th>
<th>Links</th>
</tr>
</thead>
<tbody>
<tr>
<td>Junctions</td>
<td>Pipes</td>
</tr>
<tr>
<td>Demands</td>
<td>Pumps</td>
</tr>
<tr>
<td>Tanks</td>
<td>Valves</td>
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<tr>
<td>Reservoirs</td>
<td></td>
</tr>
<tr>
<td>Sources</td>
<td></td>
</tr>
</tbody>
</table>
Network Representation

Distribution systems are represented in a network model by a series of nodes and links. Each node and link is uniquely numbered or identified.
Water System Components
Schematic of a Surface Water System

- Lake, River, Reservoir
- Treatment Plant
- Reservoir (Clearwell)
- Distribution System

Raw Water -> Treatment Plant -> Treated Water
Network Representation

A model is always an approximation of the real world. An important consideration in distribution system modeling is which components will be represented and what approximations are made in representing the components.

The level of representation may be limited by model constraints, cost, time, information availability, or personal preference.

With the increasing power of computers and availability of more powerful simulation models, the general trend is towards more detailed representation.
Network Creation
MODEL DEVELOPMENT

Data Gathering
- Physical Data
- Operating Data

Map Development
- As-Built Maps
- System Map
- Skeleton Map
- Working Map

Data Coding
- Transfer Data To Map
- Transfer Data to Computer file
Physical Data

- Geometric Data
- Network Data
- Hydraulic Parameters
Geometric Data

Each link is simulated as a linear line segment located between two nodes.

Each link and each node must be assigned a number. All demands are assigned at junction nodes.

Each tank (or reservoir) or junction node at which the hydraulic grade is known is called a fixed grade node.
**NETWORK DATA**

Components in a network are represented as nodes or links (may vary in different models).

<table>
<thead>
<tr>
<th>NODES</th>
<th>LINKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Junctions</td>
<td>Pipes</td>
</tr>
<tr>
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<tr>
<td>Reservoirs</td>
<td></td>
</tr>
<tr>
<td>Sources</td>
<td></td>
</tr>
</tbody>
</table>
HYDRAULIC PARAMETERS

- Pipe Roughness
- Nodal Demands

Although pipe roughness and nodal demands can sometimes be estimated from available data these parameters should always be fine tuned through the process of model calibration.
NETWORK COMPONENTS

- PIPES: length, diameter, C-value, minor loss
- RESERVOIRS: HWL, top, bottom, ground
- PUMPS: lift, horsepower, rpm, curve
- PRVs: downstream setting
- CONTROL VALVES: diameter, setting
- ALTITUDE VALVES: diameter, change in head required
- CHECK VALVES: diameter, flow direction
PIPEDS

• TYPES
  Mains, Pumps, CVs, Ck, etc.

• BASE DATA
  Dia, Length, C, Fr-To Nodes

• SUPPLEMENTAL DATA
  Description, Installation Date, Material, etc.
NODERS

- **TYPES**
  - Source (fixed grade)
  - Demand (fixed flow)

- **BASE DATA**
  - Elevation
  - Demand or HGL

- **SUPPLEMENTAL DATA**
  - Description
  - Zone Designation
NODE PLACEMENT

At pipe junctions

Where pipe characteristics change
  Diameter, C-value, material

At locations of known pressure

At locations where pressure is desired
INPUT TO STEADY STATE MODELS

Input requirements for most models are very similar:

- Connectivity: nodes at end of pipes
- Pipe related information: length, diameter, roughness
- Node related information: elevation, water usage
- Pumps: pump curves (head vs, flow)
- Dynamic Valves: critical pressures/flows.
- Tanks/Reservoirs: water level
Consumption
EXAMINE YOUR OUTPUT

- Look for unreasonably high or low pressures
- Read the warning messages issued by the model (e.g., pump out of range)
- Try to understand the movement of water (i.e., does it make sense for the flow to be going in a particular direction?)
- Are pumps cycling on and off in a reasonable manner?
- **MOST IMPORTANT: IS THE SYSTEM RESPONDING IN A WAY THAT YOU WOULD EXPECT OR IS IT DOING FUNNY THINGS?** If it is acting strangely, then there may be a problem with the representation of the system or maybe even with the model
STEPS TO DEVELOP A HYDRAULIC MODEL

DEFINE OBJECTIVES
- Master Plan
- Water Quality Study
- Water System Evaluation
- Energy-Saving Study
- Site New System Facilities
- Interconnecting Adjacent Systems
- Water System Development
- Upgrading Existing Facilities

ANALYZE DEMANDS
- Compile demand data
- Develop peaking factors
- Develop water use factors

DEFINE LAND USE AND SERVICE AREAS
- Identify and locate land use types
- Identify service areas
- Identify boundary valves between pressure zones

SELECT MODEL
Consider needs for:
- Hydraulic analyses
- Water quality modeling
- Simulation characteristics
- On-screen graphics
- Hardware requirements
- Convergence
- Ease of use
- Cost

COLLECT DATA
- Previous water system reports
- System maps
- Pipe data (length, diam., material, age)
- Pump station and reservoir plans
- Pump curves
- Recent pump tests
- Production records
- Consumption records
- Large user consumption

DEVELOP MODEL
- Prepare maps with numbering scheme
- Allocate system demands
- Prepare input file
- Debug

COLLECT CALIBRATION DATA
CALIBRATE MODEL AND VERIFY

USE MODEL TO SATISFY OBJECTIVE

ESTABLISH SYSTEM CRITERIA
- Min. & max. pressure
- Max. pipe velocity
- Fire flow requirements
- Storage requirements
INPUT TO EPS MODELS

- Same information required by steady state model

+ Temporal water use patterns based on demand type (e.g., single family residential, industrial, commercial)

- Tank water level limits and cross sections

- Pump and valve controls
CALIBRATION GUIDELINES

- Calibration is part art and part science. There are many more knobs to turn than sample data available
- Collect field data
- Adjust parameters which have greatest level of uncertainty, e.g.
  - C-values
  - Demand (average and temporal pattern)
  - Skeletonization
- Keep parameters within reasonable bounds
WATER USAGE

A key input to all distribution system models is information on water usage. This is also referred to as demands or consumption. For detailed modeling over time, spatial and temporal water usage patterns are required.
WATER USAGE - STEADY STATE

- Usage assigned to nodes in most models
- Estimate usage by land use
- Count structures of different types & use representative gpd per structure
- Use meter readings and assign each meter to a node
- Include universal adjustment factor so total usage in model corresponds to total sendout
- Equally divide water usage among nodes in each meter route
ASSIGN METERS TO NODES

- Manually assign meters to nodes
  OR
- Digitize locations of connections and automatically aggregate demands at nodes
- Calculate average water usage by directly accessing data from water billing systems
Usage by Meter Routes

Meter route A:
9 nodes  Total usage = 180 gpm  Usage per node = 20 gpm

Meter route B:
15 nodes  Total usage = 150 gpm  Usage per node = 10 gpm
A = 6 houses
B = 6 houses + 2 apt. bldgs.
C = 5 houses
D = 9 houses

house = 300 gpd
apt. bldg. = 750 gpd
WATER USAGE BY LAND USE

A
High Density Residential
= 1600 gal/acre

B
Low Density Residential
= 800 gal/acre

C

D
Commercial
= 500 gal/ac

<table>
<thead>
<tr>
<th>Acres</th>
<th>Low Density</th>
<th>High Density</th>
<th>Comm.</th>
<th>Tot. Usage gpd</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>6400</td>
</tr>
<tr>
<td>B</td>
<td>5</td>
<td>1</td>
<td>0</td>
<td>5600</td>
</tr>
<tr>
<td>C</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>2400</td>
</tr>
<tr>
<td>D</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>3000</td>
</tr>
</tbody>
</table>
WATER USAGE FOR EPS MODE

- EPS mode requires information on temporal variations in water usage over the period being modeled.
- Most models permit temporal patterns to be defined for groups of nodes
- Where good information on temporal patterns can be estimated (some industrial users have continuous meters, schools, etc.) use these patterns
- Literature values can sometimes be used for a first guess at residential patterns
- Analysis of information from SCADA system can be used to estimate systemwide temporal pattern
ADJUSTING PARAMETERS

- Use continuous pumping records and tank water level elevation records to establish systemwide temporal usage pattern

- Slope of the tank water level curve defines the usage rate
  e.g. (feet/hr) x (cross-sectional tank area) = usage rate
- Calculations can be made easily in a spreadsheet
### Calculating Temporal Use

Sample spreadsheet for estimating temporal water use in system

<table>
<thead>
<tr>
<th>Time</th>
<th>Q Into System (gpm)</th>
<th>Tank level (feet)</th>
<th>Tank flow (gpm; out)</th>
<th>System use (gpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 AM</td>
<td>980</td>
<td>48.7</td>
<td>460</td>
<td>1440</td>
</tr>
<tr>
<td>8 AM</td>
<td>960</td>
<td>46.1</td>
<td>230</td>
<td>1190</td>
</tr>
<tr>
<td>9 AM</td>
<td></td>
<td>44.8</td>
<td></td>
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</tr>
</tbody>
</table>
EXAMPLE DAILY PATTERN

Average: 479 MG
EXAMPLE SEASONAL PATTERN

MAX WEEK

MGD

Month

January
February
March
April
May
June
July
August
September
October
November
December

Days

1 8 15 22 29 5 12 19 26 13 20 27 3 10 17 24 31
Model Calibration
MODEL CALIBRATION

Model calibration is the process of adjusting model input data (or, in some cases, model structure) so that the predicted hydraulic and water quality output sufficiently match observed field data.
HYDRODYNAMICS REVIEW

• Outline
  The General Energy Equation
  Simplified Forms
  Energy Losses in Pipes
  Network Hydraulics
  Summary

• Objectives
  To Review and Understand ...
    The forms of energy in hydrodynamic systems
    The concepts of hydraulic and energy grade line
    The methods of quantifying energy losses in pipes
    The procedure for applying the energy equation to single pipes and pipe networks
“Acceptable degree of accuracy” depends upon the purpose and intended use of the model.

Intended use:
Planning
   conceptual
   large pipes, simplified network
   medium degree of accuracy
Operations
   most pipes
   much detail
   high degree of accuracy needed
Training
   any network
   variable degree of accuracy
Water Quality
   “all pipes”
   much detail and additional data
   can be very difficult
MINIMIZING CALIBRATION NEEDS

Calibration can be a difficult, costly and time consuming process. The extent and difficulty of calibration is minimized by development of an accurate representation of the network and its components. Calibration under time-varying (EPS) conditions is strongly encouraged.
CALIBRATION METHODS

Traditional methods:
- Fire flow pressure measurements
- Pressure/flow data logging

New method:
- Use of water quality tracers

All methods can be a part of an effective calibration scheme
FIRE FLOW TESTS

Field measurement of pressures and flows in isolated pipe sections. Adjustment of C factors to reflect field data.


PRESSURE-FLOW DATA LOGGING

- Collection of flow and pressure traces at a large number of locations in a network, over a range of conditions.
- Adjustment of C factors to reflect field data
- Requires considerable initial investment in transducers and data loggers
- Used quite extensively in Europe
WATER QUALITY TRACERS

Naturally occurring or added chemical tracers may be measured in the field and the results used to calibrate hydraulic and water quality models. Most common tracer is fluoride. It is relatively conservative, safe and can usually be added (or normal feed can be curtailed) and the movement can be traced in the system using hand held analyzers. For conservative tracers, adjustments may be made primarily in the hydraulic model to adequately match the predicted and observed concentrations.
EXAMPLE SAMPLING STUDY

1) Define the goals of the study (calibrate a network model, study behavior of tank and study the decay of chlorine)

2) Define general methodologies to be employed (use fluoride as a tracer and sample at selected stations for fluoride and chlorine residual)

3) Use model to simulate expected behavior during sampling study

4) Prepare detailed plan (schedule, equipment, methods) for sampling study

5) Perform sampling study
   - Shut off fluoride
   - Collect data on system operation (tank levels, pumps, etc.)
   - Monitor fluoride at pump, tank (in & out) & selected nodes
   - Take grab samples and some continuous monitoring
   - Turn fluoride on and repeat sampling

6) Analyze results

7) Calibrate model
USING FIELD DATA TO CALIBRATE

Information on a network is only an approximation of the actual real world situation. There is uncertainty associated with all data. In calibration, field data is used to adjust network parameters, within a reasonable range, so that observed and modeled data are within reasonable agreement.

Parameters include:
- C-values
- Average point demands (including losses)
- Temporal demand patterns
- Pipe diameters (changes due to encrustation)
- Valve settings, pump curves
- Pipes included in network representation
ADJUSTING PARAMETERS

Field studies may yield a large amount of data. Use of this data to systematically adjust the many potential calibration parameters may be very difficult.

Method of Adjusting Model Parameters:

- Ad hoc logical adjustments
- Heuristic algorithm
- Optimization techniques

Issue: What is the best measure of fit between field data and model results?
Water Quality Modeling
WATER QUALITY MODEL

Inputs:
- Network topology (node-link representation)
- Flows (velocities) in all pipes
- Reaction rates
- Source concentrations
- Initial concentrations at all nodes

Outputs:
- Concentrations at all nodes at each time step
- Average concentrations for all pipes at each time step
DISTRIBUTION SYSTEMS

- constitute a complex network of uncontrolled chemical/biological reactors
- produce significant variations in tap water quality in both space and time
- are normally designed and operated with little regard for water quality
- storage facilities may significantly affect distribution water quality
WATER DISTRIBUTION PIPE

**INPUTS**
- TREATED DRINKING WATER
- SOLUBLE COMPOUNDS
- PARTICULATE MATTER
- CROSS CONNECTIONS

**OUTPUTS**
- CHLORINE VIABLE/NON-VIABLE CELLS ORGANICS
- TRANSFORMATION AT/NEAR INTERFACE
- TAP WATER
WHY MODEL WATER QUALITY?

- SDWA regulations require compliance at the tap; not just at the treatment plant
- Movement and fate of substances in a distribution system are complex and non-intuitive
- Water quality sampling provides only a limited picture of the water quality in a distribution system and is time consuming and expensive
- Modifying the physical system or operations of the system is expensive and time consuming; modeling provides a cost effective way of testing potential changes
EXAMPLE USES

- Study the movement and fate of constituents in a distribution system such as chlorine residual, THM, hardness, etc.
- Determine the best way to operate a system with multiple sources of water with differing quality characteristics
- Determine the likely impacts of a contaminant that is introduced into a distribution system
- Assist in the design of a cost-effective sampling plan and flushing program
- Useful in legal actions concerning water quality in distribution systems
- Assist in calibrating a hydraulic model
- Estimate the travel times and age of water in a distribution system
- Test alternative design and operational policies prior to implementation
MODEL INTERACTION

- Water quality models are generally piggy backed on hydraulic models.

![Diagram showing interaction between hydraulic and water quality models]

HYDRAULIC MODEL

Flows and velocities

WATER QUALITY MODEL

Water quality results
WATER QUALITY MODEL

Inputs:
- Network topology (node-link representation)
- Flows (velocities) in all pipes
- Reaction rates
- Source concentrations
- Initial concentrations at all nodes

Outputs:
- Concentrations at all nodes at each time step
- Average concentrations for all pipes at each time step
DYNAMIC WQ MODEL

TYPES OF MODELS

- EULERIAN
  - DISCRETE VOLUME METHOD
  - FINITE DIFFERENCE

- LAGRANGIAN
  - TIME DRIVEN METHOD
  - EVENT DRIVEN METHOD
STEADY-STATE v. DYNAMIC MODELS

- Steady-State Models:
  - are easier to run and interpret
  - almost impossible to verify
  - provide less (and possibly misleading) information

- Dynamic Models:
  - require more information to setup and run
  - need post-processors for meaningful interpretation
  - provide the most accurate picture of system behavior
Water Quality Models (Dynamic)

- Eulerian Finite-Difference Method (FDM)
- Eulerian Discrete Volume Method (DVM)
- Lagrangian Time-Driven Method (TDM)
- Lagrangian Event-Driven Method (EDM)


THE BASIC PROBLEM

Given:
- Network topology
- Flows in all pipes
- Reaction rates
- Source concentrations
- Initial nodal concentrations (dynamic case only)

Determine:
- Concentration at all nodes (over all time periods)
STEADY-STATE EXAMPLE

Original Network

Topologically Sorted Network
(All nodes that can be reached from node K have higher number)
CONSERVATION OF MASS-PIPE JUNCTION

Total Mass Out = Total Mass In

\[ C_{\text{out}} = \frac{\sum C_{\text{in}} Q_{\text{in}}}{\sum Q_{\text{in}}_{\text{out}}} \]

Diagram:
- \(Q_1\) and \(C_1\) entering on one side
- \(Q_2\) and \(C_2\) entering on another side
- \(C_{\text{out}}\) exiting on both sides
Sorted Network

Node 1: \( C = 100 \text{ mg/L} \)

Node 2: \( C = 0 \text{ mg/L} \)

Node 3: \( C = \frac{(14 \times 100 + 10 \times 0)}{(14 + 10)} = 58.3 \text{ mg/L} \)

Node 4: \( C = \frac{(19 \times 100 + 4 \times 58.3 + 17 \times 0)}{(19 + 4 + 17)} = 53.3 \text{ mg/L} \)
CONSERVATION OF MASS:
SINGLE PIPE SECTION

\[ \Delta \text{mass} = \text{mass in} - \text{mass in} - \text{mass out} - \text{mass reacted} \]

\[ \Delta X \]

Mass In
\( (Q_C \text{in} \Delta t) \)

Mass Reacted
\( (\Theta (C) \Delta t) \)

Mass Out
\( (Q_C \Delta t) \)
DYNAMIC MODELING WITH THE DISCRETE VOLUME ELEMENT METHOD

1. Flows are known & stay constant over current hydraulic time period.
2. Choose a water quality time step $\Delta t$
3. Divide each pipe into $N$ segments where
   \[
   N = \frac{\text{Pipe Volume}}{\text{Flow rate} \times \Delta t}
   \]
4. Re-allocate mass from previous segmentation into new segmentation
5. Repeat for each time interval $\Delta t$ until the next change in hydraulic conditions occurs:
   a. react mass within each segment
   b. for all pipes, shift mass from one segment to the next, accumulating mass & flow at junctions
   c. compute new junction concentrations
   d. shift new junction concentration into first segment of each pipe leaving the junction
Discrete Volume Element Method

Original Mass

After Reaction

Transport Into Node

Transport Along Link

Transport Out of Node
REACTION RATES

- Zero-Order Growth (Age):
  \[ \Delta C = K \Delta t \]
  \[ C = C_0 + Kt \]

- First-Order Decay:
  \[ \Delta C = -KC_0 \Delta t \]
  \[ C = C_0 \exp(-Kt) \]
1st Order Bulk + Wall Decay

\[ K = k_b + \frac{2k_f k_w}{r (k_f + k_w)} \]

where

- \( k_b \) = bulk decay coeff.
- \( k_w \) = wall decay coeff.
- \( k_f \) = mass transfer coeff.

Diagram:
- Bulk Decay \((k_b)\)
- Axial Transport
- Radial Transport
- Wall Decay \((k_w)\)
- Boundary Layer
- Pipe Wall
MODEL CALIBRATION

Model calibration is the process of adjusting model input data (or, in some cases, model structure) so that the predicted hydraulic and water quality output sufficiently match observed field data.

- Assuming an adequately calibrated hydraulic model, conservative water quality models should require no additional calibration
- Rate coefficients can be adjusted in non-conservative models
- Water quality models offer an alternative (and better?) method for calibrating hydraulic models
- Calibration is minimized by developing accurate representation of network & components
EXAMPLE SAMPLING STUDY

1) Define the goals of the study (calibrate a network model, study behavior of tank and study the decay of chlorine)

2) Define general methodologies to be employed (use fluoride as a tracer and sample at selected stations for fluoride and chlorine residual)

3) Use model to simulate expected behavior during sampling study

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5) Perform sampling study
   • Shut off fluoride
   • Collect data on system operation (tank levels, pumps, etc.)
   • Monitor fluoride at pump, tank (in & out) & selected nodes
   • Take grab samples and some continuous monitoring
   • Turn fluoride on and repeat sampling

6) Analyze results

7) Calibrate model
STORAGE FACILITIES

Storage facilities (tanks, standpipes, reservoirs) may have a significant impact on water quality.

- Most models represent tanks as completely mixed
- Recent research shows that there is frequently short-circuiting and incomplete mixing
- The age of the water leaving a tank may be much older (1 to 10 days) than incoming water resulting in low chlorine and/or increased bacteria levels
- Design, siting and operations of tank can significantly affect its impact on water quality
- Experimental ‘jet’ models and systems models have been developed to represent tanks
TANKS HAVE DEAD SPOTS

Storage tanks may have dead zones where reduced flow interchange with the bulk of the tank results in older water of diminished quality due to long residence lines.

Dead spots primarily occur in regions of the tank that are either extremely removed from the inlet/outlet or other mixing device, e.g. the surface of the tank if flow enters the bottom, or transport limited such as confined areas in corners. The location and extent of dead zones generally depend on the tank geometry, inlet/outlet configuration, temperature gradients within the tank, and the total wet volume of the tank.
STEPS TO DEVELOP A WATER QUALITY MODEL

DEFINE OBJECTIVES
- Predict Water Quality Degradation Problems
- Predict Water Quality Changes in Storage Facilities
- Analyze Blended Water Properties
- Optimize Disinfection Regime
- Predict Disinfection-By Product Growth
- Site Rechlorination Facilities

Develop, Calibrate, and Validate Hydraulic Model

MODEL SAMPLING STUDY
- Use model to predict system performance during study

PREPARE SAMPLING PLAN
- Sampling/manpower schedule
- Equipment needs
- Sampling/analytical methods

SELECT & PREPARE SAMPLING SITES
- Based on initial modeling results
- Consider readily-available sites such as hydrants and dedicated sampling stations

PERFORM SAMPLING STUDY

COLLECT WATER QUALITY SAMPLES
- Feed conservative or non-conservative substance
- Sample sites at predetermined intervals
- Analyze samples on-site or ship to laboratory

COLLECT HYDRAULIC DATA
- Continuous changes in tank elevations
- Pump on/off times
- Production data
- Pump flows and discharge heads

CALIBRATE WATER QUALITY MODEL
- Input hydraulic data
- Input water quality data
- Refine model until results are acceptable

ANALYZE DATA

USE MODEL TO SATISFY OBJECTIVE
WATER QUALITY MODELING APPLICATIONS

- Source Blending (North Marin, CA)
- Chlorine Decay (New Haven, CT)
- Disease Outbreak (Gideon, MO)
Chlorine is removed due to bulk fluid reaction and also because of pipe wall.

**CHLORINE REACTIONS WITHIN A PIPE**

![Diagram showing chlorine reactions within a pipe](image)

- NOM (natural organic matter) reactions with hypochlorous acid (HOCl) and hypochlorite (HOCl^-) result in production of THM (haloacetic acids).
- Iron (Fe^2+) reacts with HOCl to form iron (III) chloride (FeCl_3).

Handwritten notes:
- “Corrosion product formation from the pipe to give FeCl_3 another source of chlorine corrosion.”
PIPE CHLORINE DECAY MODEL

$\Delta C = -KC \Delta t$  
First Order Decay

$K = k_{\text{bulk}} + \frac{k_{\text{wall}} k_f}{R_h (k_{\text{wall}} + k_f)}$  
Bulk + Wall Demand

$k_f = f(Re, Sc)$  
Mass Transfer Coeff.
DETERMINATION OF CHLORINE BULK DECAY COEFF.

NOTE: Use 8-10 bottles & run test until > 50% loss

\[ \ln(C_{Cl2}) \]

Time, days
BRUSHY PLAINS - BULK CHLORINE DECAY ONLY

Chlorine for Node 19, mg/L

0.00 0.20 0.40 0.60 0.80 1.00 1.20

0.  10.  20.  30.  40.  50.  60.

Time, hrs

Tank

Chlorine for Node 34, mg/L

0.00 0.20 0.40 0.60 0.80 1.00 1.20

0.  10.  20.  30.  40.  50.  60.

Time, hrs

Chlorine for Node 6, mg/L

0.00 0.20 0.40 0.60 0.80 1.00 1.20

0.  10.  20.  30.  40.  50.  60.

Time, hrs

Pump Station
CHLORINE LOSS RATE IN BRUSHY PLAINS

Free Chlorine Loss (kg/hour)

Tank
Bulk
Wall

Hours from 10 am 8/13/91
SAMPLING SITES FOR THE AWWARF STUDY ON CHLORINE DECAY KINETICS
## AWWARF CHLORINE DECAY STUDY - RESULTS

<table>
<thead>
<tr>
<th>SITE</th>
<th>BULK DECAY 1/2-LIFE, DAYS</th>
<th>WALL DECAY MG/FT²/DAY</th>
<th>ROUGHNESS CONSTANT</th>
</tr>
</thead>
<tbody>
<tr>
<td>BELLINGHAM</td>
<td>0.84</td>
<td>20</td>
<td>1600</td>
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<tr>
<td>FAIRFIELD</td>
<td>0.60</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HARRISBURG</td>
<td>3.0</td>
<td>8.5</td>
<td>650</td>
</tr>
<tr>
<td>LANSDALE</td>
<td>8.5 (IMP)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LANSDALE</td>
<td>0.91 (SW)</td>
<td>5.0</td>
<td>500</td>
</tr>
<tr>
<td>LANSDALE</td>
<td>2.0 (GW)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NORTH MARIN</td>
<td>0.53</td>
<td>20</td>
<td>2600</td>
</tr>
</tbody>
</table>
WATERBORNE DISEASE OUTBREAK IN GIDEON

- Salmonella outbreak during Nov-Dec 1993 affected 44% of town's residents with 31 confirmed cases of salmonellosis resulting in 7 deaths

- First cases reported 2 days after entire system was flushed in response to taste & odor complaints

- Suspected cause was bird infestation of storage tank in disrepair completely drained during flushing

- Water quality modeling confirmed that locations with first reported cases were receiving significant amounts of water from the suspect tank
GIDEON DISTRIBUTION SYSTEM

1 - Well No. 5
2 - 50,000 Gallon Tank
3 - 100,000 Gallon Tank
4 - Cotton Compress Tank
5 - Nursing Home
6 - Schools

AREA RECEIVING > 20% OF WATER FROM TANK 3 AFTER 6 HRS.
WQ Sampling Studies
WATER QUALITY SAMPLING STUDIES

General guidelines for planning and performing a water quality sampling study in support of a water quality model

OVERVIEW

1) Define the goals of the study
2) Define general methodologies to be employed
3) Use model to simulate expected behavior during sampling study
4) Prepare detailed plan for sampling study
5) Perform sampling study
6) Laboratory analyses
7) Data Report
8) Analyze and assess sampling results
9) Use study results
SAMPLING LOCATIONS

- Accessibility of sampling locations
- Safety of sampling sites
- Representativeness of sampling locations
- Dedicated sampling taps or hydrants are generally the best options. Residences or businesses are usually the worst options.
- Sampling sites should be prepared and tested prior to sampling

SAMPLING PARAMETERS

- Water quality constituent being studied (e.g. chlorine)
- Supporting parameters (e.g., temperature)
- More complete one-time characterization of water (pH, ammonia, TOC, iron, etc.)
- Tracer (e.g., fluoride)
**PURPOSE OF WQ SAMPLING**

- Develop a better understanding of the water quality behavior of the system
- Calibrate a hydraulic and/or water quality model of a distribution system
- Investigate a particular water quality phenomena in the distribution system such as chlorine decay

**SAMPLING PLAN**

- Sampling locations
- Sampling parameters
- Sampling schedule
- System operation
- Sample collection procedures
- Logistical arrangements
- Safety issues
- Data recording
- Equipment
- Training
- Contingencies
SAMPLE COLLECTION PROCEDURES

- When, where, how and by who samples are to be collected

- Details include:
  - flushing time
  - methods for filling sample containers
  - methods for marking sample containers
  - reagents to be added to samples
  - storage of samples
  - data logging procedures
  - etc.

LOGISTICAL ARRANGEMENTS

- Crew schedules
- Communications/transportation
- Lodging/meals
- Laboratory schedules
- Interaction with Utility operations
- etc.
**SAMPLING SCHEDULE**

- Sampling may be automated or manual
- With automated sampling, need to define the start and stop time and frequency of sampling
- For manual sampling, generally a 'circuit' of sampling stations visited by a sampling team is defined
- Schedule of sampling may vary during study due to operations, time of day, etc.
- Following a water quality 'front' requires intensive coordination and immediate feedback on location of front

**SYSTEM OPERATION**

- System operation may significantly impact water quality behavior
- Options: accept whatever occurs in system operation or be proactive and try to define desired operational strategy. Latter is better.
- Try to minimize unusual system. Try to simplify system behavior.
- It may be easier to influence system operation based on time of year or day of the week. For example, operations are less flexible during high peak usage and drought conditions.
EXAMPLE SAMPLING FORM

STUDY AREA: ____________________  SHEET NUMBER:__________________

<table>
<thead>
<tr>
<th>DATE</th>
<th>STATION</th>
<th>TIME</th>
<th>INITIALS</th>
<th>TEMPERATURE</th>
<th>COLLECTED</th>
<th>SAMPLE</th>
<th>FL</th>
<th>COMMENTS</th>
</tr>
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</table>

EQUIPMENT

- Select and test all equipment
- Have backup equipment where possible
- Be familiar with all equipment (manual and automated)
- Don't forget pens, pliers, flashlights, rain gear, etc.
SAFETY ISSUES

- Notification of local police and governmental agencies
- All samplers should have safety equipment (orange vests, flashlights, etc.)
- Samplers should have Utility ID and preferably wear clothing with Utility name. Provide each sampler with a letter describing purpose of sampling study.
- Use marked vehicles with safety lights
- Work in pairs whenever feasible

DATA RECORDING

- Prepare data recording sheets
- Fill in sheets neatly, completely and in ink
- Number each sheet so that you can tell if one is missing
- Avoid keeping completed sheets in the field. Bring them to a central location and copy them as backup.
CONDUCTING THE STUDY

- Follow your plan
- Maintain good communications during the sampling study
- Establish a central control point where data is brought and decisions are made
- Examine results during the study and make adjustments in your plan as needed
- Document all aspects of the sampling work during the study

POST SAMPLING ANALYSIS

- Laboratory analysis
- Data report
- Database management system
- Data analysis
TRAINING

- Study participants should be trained in using the equipment, recording information, etc. before the start of the study.
- Sampling personnel should be shown sampling locations.
- Don't assume that sampling personnel know the correct way to use the equipment even if they have used it before.
- A 'dry run' should be conducted so that all the bugs are worked out.

CONTINGENCIES

Adages that apply to sampling:

"If anything can go wrong when sampling, it will"

"No matter how much planning you do, something unexpected will always occur when sampling"

In the sampling plan, try to anticipate and plan for problems.
DATA REPORT

- Prepare the data report as soon after the study as possible
- Data report should include all information and results
- Circulate report to participants for corrections
- A well written data report serves as a complete & permanent record of the study
- If it is well written, then a stranger should be able to take the report and fully understand what was done.
Modeling Tanks & Reservoirs
Modeling Tanks & Reservoirs

PHENOMENON OF CONCERN IN MODELING WATER QUALITY BEHAVIOR IN TANKS AND RESERVOIRS

- MIXING
- REACTIONS
- OPERATIONAL CONTROL

Mixing Regimes

- Complete Mix
- Plug Flow
- Short Circuiting
- Stagnant Zones
- Thermal Stratification
**Completely Mixed**

CONTINUOUSLY STIRRED TANK REACTOR (CSTR)

If the concentration of fluoride in the tank is 1 mg/l and the fluoride entering the tank is then changed to 0 at time = 0, the resulting concentration leaving the tank is shown below. The inflow water continually mixes with the tank water during the fill cycle and during each subsequent emptying cycle the concentrations decrease.

**Plug Flow**

FIRST IN - FIRST OUT (FIFO)

If the concentration of fluoride in the tank is 1 mg/l and the fluoride entering the tank is then changed to 0 at time = 0, the resulting concentration leaving the tank is shown below. In plug flow, the non-fluoridated water must move entirely through the tank before it shows up in the outflow.
Thermal Stratification

Field Determination of Mixing

CONSTITUENTS TO BE MONITORED
- Tracer Tests (Fluoride, Chloride)
- Naturally Occurring or Normal Additives
  (Temperature, Chlorine)

SAMPLING LOCATIONS
- Inlet - Outlet Sampling
- Invasive Sampling of Tank

SAMPLING METHODS
- Manual Grab Samples
- Mechanically Aided Grab Samples
- Continuous Samplers

ANALYSIS METHODS
- Automated Analysis
- Field Kits
- Lab Analysis
Short Circuiting

LAST IN - FIRST OUT (LIFO)

If the concentration of fluoride in the tank is 1 mg/l and the fluoride entering the tank is then changed to 0 at time = 0, the resulting concentration leaving the tank is shown below. With short circuiting, the last water entering the tank is the first to leave, and old water can be trapped in the tank.

Concentration in inlet-outlet

Stagnant Zones

Another phenomena that occurs in tanks or reservoirs are 'dead spots' or 'stagnant zones'. These are areas where there is reduced interchange of flow with the remainder of the tank. This can result in locations in the tank where the age of the water can be very old.

Examples of potential stagnant zones include corners, the bottom of the tank or the top of the tank. Locations and extent of stagnant zones can depend on the shape of the tank, the inlet-outlet configuration and the relative temperature of the water in the tank and the influent water.
Mixing Models

TANK MODELS

PHYSICAL MODELS (Scale Models)
- Hydrodynamic Based
  - Jet theory
  - Navier Stokes

MATHEMATICAL MODELS
- System Models
  - CSTR
  - Plug flow
  - Short Circuit
  - Compartment

System Models

- Emphasizes the inputs and outputs of a system
- System viewed as a black box
- May reflect some physical processes
- Can rely on statistical relationships
- Requires extensive data base of input-output data
- Sampling data restricts the range of applicability
3-Compartment Model

A conceptual systems model that represents the various phenomena occurring in a tank. Currently, the model parameters (size of compartment A and C, and interchange rate between compartment C and B) can only be estimated by trial and error using field data.

Jet Mixing Models

Predicts vertical concentration profile after filling:
1. Jet volume increases and exchanges momentum & mass with ambient fluid
2. Net downward flux of ambient fluid to replace fluid entrained in jet
3. Surface level increase as filling proceeds
Operational Trade-Offs

HYDRAULIC RELIABILITY OBJECTIVES
• Provide Emergency Storage
• Pumping Equalization Storage
• Equalize Pressure in System

WATER QUALITY OBJECTIVES
• Minimize Water Age
• Maximize Disinfectant Residual
• Minimize Biological Activity

Sample Uses for Models
• In conjunction with network models to study impacts of tanks on distribution system water quality
• Determine best design for a new tank
• Study alternative operating strategies
• Test alternative retrofitting strategies to improve water quality
Navier Stokes Models

1) 2-D or 3-D representation of concentration vs. time within tank
2) Based on differential equations that express conservation laws (mass, momentum & heat energy) for fluid and its chemical constituents
3) Requires computer-based solutions using finite difference or finite element techniques
4) Can model complex inlet-outlet configurations, internal baffling systems or irregular tank shapes
5) Computational Fluid Dynamics (CFD) Models are commercially available

Reactions Within Tanks

- CHLORINE DECAY
- DBP FORMATION
- NITRIFICATION
- MICROBIAL REGROWTH (Algae, Klebsiella)
- THM
- RADON DE-GASSING
Conceptual schematic representation of Completely Stirred Tank Reactor.
Conceptual schematic representation of Linear Compartment Model.
Figure: Comparison of Completely Stirred Tank Reactor data to field measured data for concentrations of: (a) chlorine and (b) fluoride.
VENT

308 93.9
HATCH

302 92.0

287 81.4

232 70.7

FEET METERS
Elevation (msl)

VOLUME = 1 million gallons (3.785 million liters)
DIAMETER = 51 feet (15.55 meters)
INLET & OUTLET PIPE DIAMETER = 12 inches (0.305 meters)

Brushy Plains tank schematic.
Figure  Comparison of Linear Compartment Model data to field measured data for concentrations of: (a) chlorine and (b) fluoride.
Figure 1: Schematic plan view of a clearwell
Figure 3: Depth-averaged particle paths (no diffusion walls)
Figure 2: Velocity vectors at mid-depth in the clearwell with no diffusion walls
Figure 5: Depth-averaged particle paths (with diffusion walls)
Figure 4: Velocity vectors at mid-depth in the clearwell with diffusion walls
Figure 6: Velocity vectors near 180 degree turn (no diffusion walls)
Figure 7: Velocity vectors near 180 degree turn (with diffusion walls)
Interfaces to Network Models:

Computer-Based System Integration Technology
DEFINITIONS

CAD/GIS (Geographic Information System):  
Computer-based system that stores and retrieves utility maps and associated descriptive facility information.

RDBMS (Relational Database Management System):  
Computer-based system that comprises a collection of interrelated data items.

SCADA (Supervisory Control and Data Acquisition):  
Computer-based system that monitors and controls remote/hydraulic facility sites.

CIS (Customer Information System):  
Computer-based system that contains data on the physical characteristics of service to the customer, as well as customer billing and consumption data.
LINKING WITH INFORMATION SYSTEMS

- Minimize Cost
- Improve Data Entry, Efficiency and Accuracy
- Avoid Maintenance of Multiple Database with Duplicate Data
- Boost Productivity
GIS INTEGRATION: Small Scale

GIS

Database

Hydraulic Model

INTELLIGENT GRAPHICAL MODEL
GIS INTEGRATION: Large Scale

- **WCIS**: Water Consumption Information System
- **GIS**: Geographic Information System
- **EMS**: Energy Management System
- **HWRM**: Hydraulic and water Quality Model
- **OP/NET**: Operations Network
- **SCADA**: Supervisory Control & Data Acquisition
- **CIS**: Customer Information System
- **LIMS**: Laboratory Information Management System
- **MMS**: Maintenance Management System

**Database RDBMS**
System Integration Architecture

- Graphical User Interface
- Data Exchange Programs
- CAD
- Modeling and Facility Management
- RDBMS
- Water Quality Model
- Hydraulic Model

Windows Operating System
Central Asset Database
STEPS FOR GIS DEVELOPMENT

1. Needs assessment
2. Review existing data and systems designs
3. Database schema definition
4. Map processing utilities
5. User interface
6. Systems integration
7. Reporting and querying functionality
8. User manual and training
SYSTEMS INTEGRATION:
HYDRAULIC MODEL/SCADA

Update hydraulic model operating parameters with SCADA information in Quasi-Real time mode.

A. Hydraulic Model:
   • System data or physical properties (geometry, pipe, pump, valve, tank and node characteristics)

B. Input from SCADA:
   • Boundary conditions (tank water levels and pump and valve status)
   • Loading conditions (total system (or zone demands): peaking factors apply to junction node types)
Complete GIS/Database Querying Functionalities

Quickly and easily display, query and highlight any water system information (Combination)

- All unlined cast iron pipes 16” and larger that were installed before 1940 with velocities greater than 6 ft/sec and chlorine concentrations less than 0.2 mg/l
- All pipes recommended for rehabilitation based on hydraulic modeling results
- All hydrants scheduled for flushing
- All pipelines with more than three leaks in the past six years
Energy Management Model

- Develop operating policies
- Evaluate storage/pumping trade-offs
- Evaluate rate schedules
- Monitor cost of operations
ENERGY MANAGEMENT MODEL

Input:
• Pump efficiency curve
• Rate schedule (pattern)
• Pump operating schedule

Output:
• Percent of time use
• Average energy use over the simulation period
• Cost of use
• Total cost for all pumps
FIRE FLOW MODEL

Given:
Fire Demand based on user type

Find:
Residual Pressures
Available Flows at 20 psi
Design Flows to Maintain 20 psi System (or Zone) Wide
Advanced Applications

- Automatic fire flow modeling
- System head curves
- Facilities and demand scenarios management
- Complete GIS (map/database) import/export
- Interface with information systems
- Automatic skeletonization
- Complete database management
- Customized modeling database
- Polygon processing
- Manual EPS simulation (operator training)
- Real-time simulation