CHAPTER

# 6

# Pressure Piping Systems and Water Quality Analysis

## 6.1 Pressure Systems

Pressure piping network analysis has many applications, including well pumping systems and heating and cooling systems. This chapter deals primarily with the topic of pressure piping as it relates to potable water distribution systems.

The main purpose of a water distribution system is to meet demands for potable water. People use water for drinking, cleaning, gardening, and any number of other uses, and this water needs to be delivered in some fashion. A secondary purpose of many distribution systems is to provide water for fire protection.

If designed correctly, the network of interconnected pipes, storage tanks, pumps, and regulating valves provides adequate pressure, adequate supply, and good water quality throughout the system. If incorrectly designed, some areas may have low pressures, poor fire protection, and even present health risks.

### *Water Demands*

Just as storm sewer analysis is driven by the watershed runoff flow rate, water distribution system analysis is driven by customer demand. Water usage rates and patterns vary greatly from system to system and are highly dependent on climate, culture, and local industry. Every system is different, so the best source of information for estimating demands is directly recorded system data.

**Metered Demand**

Metered demands are often a modeler's best tool, and can be used to calculate average demands, minimum demands, peak demands, and so forth. This data can also be compiled into daily, weekly, monthly, and annual reports that show how the demands are influenced by weather, special events, and other factors.

Unfortunately, many systems still do not have complete system metering. For these systems, the modeler is often forced to use other estimation tools (including good engineering judgment) to obtain realistic demands.

### Demand Patterns

A ***pattern*** is a function relating water use to time of day. Patterns allow the user to apply automatic time-variable changes within the system. Different categories of users, such as residential or industrial customers, will typically be assigned different patterns to accurately reflect their particular demand variations. A ***diurnal curve*** is a type of pattern that describes changes in demand over the course of a daily cycle, reflecting times when people are using more or less water than average. Most patterns are based on a multiplication factor versus time relationship, whereby a multiplication factor of 1.0 represents the base value (often the average value). In equation form, this relationship is written as:

$$Q_t = A_t \times Q_{base}$$

where $Q_t$ = demand at time $t$
$A_t$ = multiplier for time $t$
$Q_{base}$ = baseline demand

Using a representative diurnal curve for a residence (Figure 6-1), we see that there is a peak in the diurnal curve in the morning as people take showers and prepare breakfast, another slight peak around noon, and a third peak in the evening as people arrive home from work and prepare dinner. Throughout the night, the pattern reflects the relative inactivity of the system, with very low flows compared to the average. (Note that this curve is conceptual and should not be construed as representative of any particular network.)

There are two basic forms for representing a pattern: stepwise and continuous. A ***stepwise pattern*** is one that assumes a constant level of usage over a period of time, and then jumps instantaneously to another level where it again remains steady until the next jump. A ***continuous pattern*** is one for which several points in the pattern are known and sections in between are transitional, resulting in a smoother pattern. Notice that, for the continuous pattern in Figure 6-1, the magnitude and slope of the pattern at the start and end times are the same — a continuity that is recommended for patterns that repeat.

Because of the finite time steps used in the calculations, most computer programs convert continuous patterns into stepwise patterns for use by the algorithms, with the duration of each step equal to the time step of the analysis.

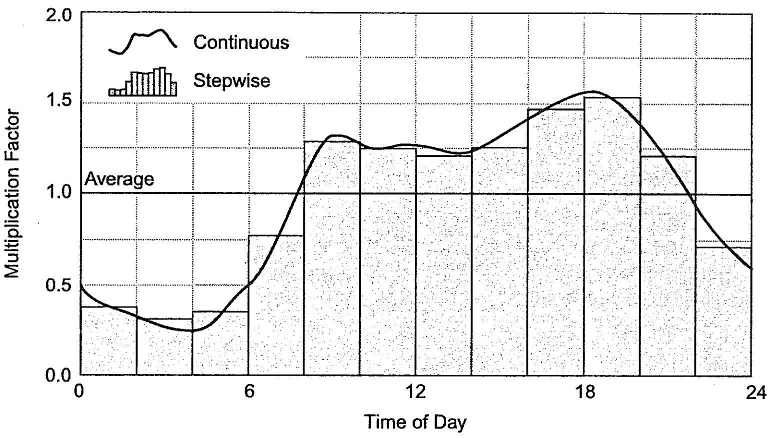


*Figure 6-1: Typical Diurnal Curve*

## 6.2 Energy Losses

### *Friction Losses*

The hydraulic theory behind friction losses is the same for pressure piping as it is for open channel hydraulics. The most commonly used methods for determining head losses in pressure piping systems are the Hazen-Williams equation and the Darcy-Weisbach equation, both discussed in Chapter 1. Many of the general friction loss equations can be simplified and revised because of the following assumptions that can be made for a pressure pipe system:

- Pressure piping is almost always circular, so the flow area, wetted perimeter, and hydraulic radius can be directly related to diameter.
- Pressure systems flow full (by definition) throughout the length of a given pipe, so the friction slope is constant for a given flow rate. This means that the energy grade and hydraulic grade drop linearly in the direction of flow.
- Because the flow rate and cross-sectional area are constant, the velocity must also be constant. By definition, then, the energy grade line and hydraulic grade line are parallel, separated by the constant velocity head.

These simplifications allow for pressure pipe networks to be analyzed much more quickly than systems of open channels or partially full gravity piping. Several hydraulic components that are unique to pressure piping systems, such as regulating valves and pumps, add complexity to the analysis.

## Minor Losses

Localized areas of increased turbulence cause energy losses within a pipe, creating a drop in the energy and hydraulic grades at that point in the system. These disruptions are often caused by valves, meters, or fittings (such as the pipe entrance in Figure 6-2), and are generally called ***minor losses***. These minor losses are often negligible relative to friction losses and may be ignored during analysis.

Although the term "minor" is a reasonable generalization for most large-scale water distribution models, these losses may not always be as minor as the name implies. In piping systems that contain numerous fittings relative to the total length of pipe, such as heating or cooling systems, the minor losses may actually have a significant impact on the energy loss.

The equation most commonly used for determining the loss in a fitting, valve, meter, or other localized component is:

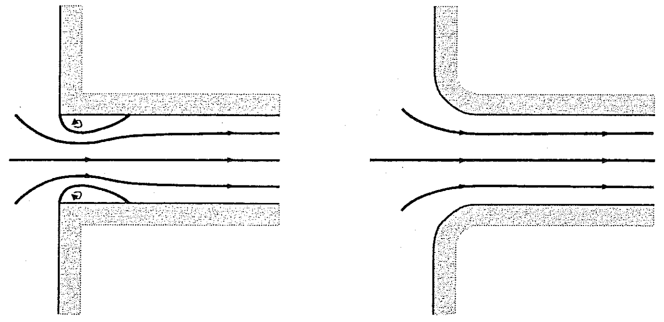
$$H_m = K\frac{V^2}{2g}$$

where $H_m$ = minor loss (m, ft)
$K$ = minor loss coefficient for the specific fitting
$V$ = velocity (m/s, ft/s)
$g$ = gravitational acceleration (m/s$^2$, ft/s$^2$)

Typical values for the fitting loss coefficient are included in Table 6-1. As can be seen with similar fitting types, the *K*-value is highly dependent on bend radius, contraction ratios, and so forth. Gradual transitions create smoother flow lines and smaller head losses than sharp transitions because of the increased turbulence and eddies that form near a sharp change in the flow pattern. Figure 6-2 shows flow lines for a pipe entrance with and without rounding.

*Table 6-1: Typical Fitting K Coefficients*

| Fitting | *K*-value |
|---|---|
| Pipe Entrance | |
| Bellmouth | 0.03 - 0.05 |
| Rounded | 0.12 - 0.25 |
| Sharp Edged | 0.50 |
| Projecting | 0.80 |
| Contraction – Sudden | |
| $D_2/D_1 = 0.80$ | 0.18 |
| $D_2/D_1 = 0.50$ | 0.37 |
| $D_2/D_1 = 0.20$ | 0.49 |
| Contraction – Conical | |
| $D_2/D_1 = 0.80$ | 0.05 |
| $D_2/D_1 = 0.50$ | 0.07 |
| $D_2/D_1 = 0.20$ | 0.08 |
| Expansion – Sudden | |
| $D_2/D_1 = 0.80$ | 0.16 |
| $D_2/D_1 = 0.50$ | 0.57 |
| $D_2/D_1 = 0.20$ | 0.92 |
| Expansion – Conical | |
| $D_2/D_1 = 0.80$ | 0.03 |
| $D_2/D_1 = 0.50$ | 0.08 |
| $D_2/D_1 = 0.20$ | 0.13 |
| 90° Smooth Bend | |
| Bend radius / $D = 4$ | 0.16 - 0.18 |
| Bend radius / $D = 2$ | 0.19 - 0.25 |
| Bend radius / $D = 1$ | 0.35 - 0.40 |
| Mitered Bend | |
| $\theta = 15°$ | 0.05 |
| $\theta = 30°$ | 0.10 |
| $\theta = 45°$ | 0.20 |
| $\theta = 60°$ | 0.35 |
| $\theta = 90°$ | 0.80 |
| Tee | |
| Line Flow | 0.30 - 0.40 |
| Branch Flow | 0.75 - 1.80 |
| Cross | |
| Line Flow | 0.50 |
| Branch Flow | 0.75 |
| 45° Wye | |
| Line Flow | 0.30 |
| Branch Flow | 0.50 |



Sharp Entrance: K=0.50

Rounded Entrance: K=0.03

*Figure 6-2: Flow Lines in Minor Losses*

## 6.3 Energy Gains — Pumps

Pumps are an integral part of many pressure systems and are an important part of modeling head change in a network. Pumps add energy (head gains) to the flow to counteract head losses and hydraulic grade differentials within the system. There are several types of pumps that are used for various purposes; pressurized water systems typically have centrifugal pumps.

A centrifugal pump is defined by its ***characteristic curve***, which relates the pump head (head added to the system) to the flow rate. To model the behavior of the pump system, additional information is needed to ascertain the actual point at which the pump will be operating.

The ***system operating point*** is the point at which the pump curve crosses the ***system curve*** – the curve representing the static lift ($H_s$) and head losses ($H_L$) due to friction and minor losses. When these curves are superimposed (as in Figure 6-3), the operating point is easily located.

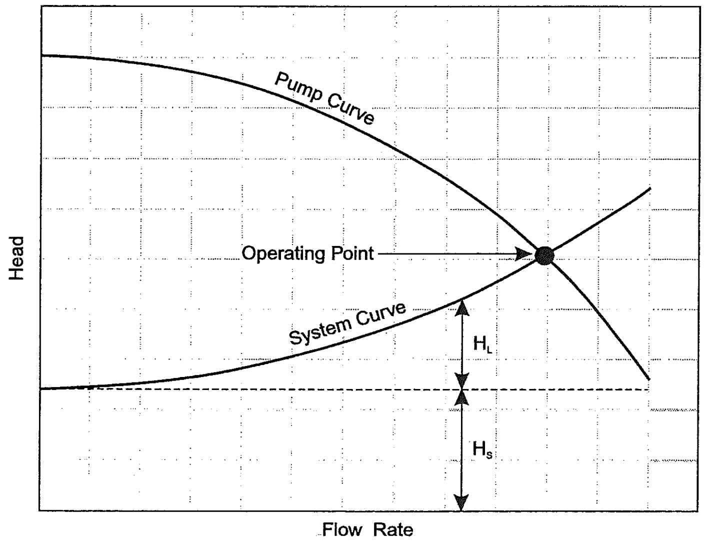


*Figure 6-3: System Operating Point*

As water surface elevations and demands throughout the system change, the static head ($H_S$) and head losses ($H_L$) vary. These changes cause the system curve to move around, whereas the pump characteristic curve remains constant. These shifts in the system curve result in a shifting operating point over time.

### *Variable-Speed Pumps*

A centrifugal pump's characteristic curve is fixed for a given motor speed and impeller diameter, but can be determined for any speed and any diameter by applying the affinity laws. For variable-speed pumps, these affinity laws are presented as:

$$\frac{Q_1}{Q_2}=\frac{n_1}{n_2} \quad \text{and} \quad \frac{H_1}{H_2}=\left(\frac{n_1}{n_2}\right)^2$$

where $Q$ = pump flow rate (m$^3$/s, ft$^3$/s)
$H$ = pump head (m, ft)
$n$ = pump speed (rpm)

Thus, pump discharge rate is proportional to pump speed, and the pump discharge head is proportional to the square of the speed. Using this relationship, once the pump curve is known, the curve at another speed can be predicted. Figure 6-4 illustrates the affinity laws applied to a variable-speed pump. The line labeled "Best Efficiency Point" indicates how the best efficiency point changes at various speeds.

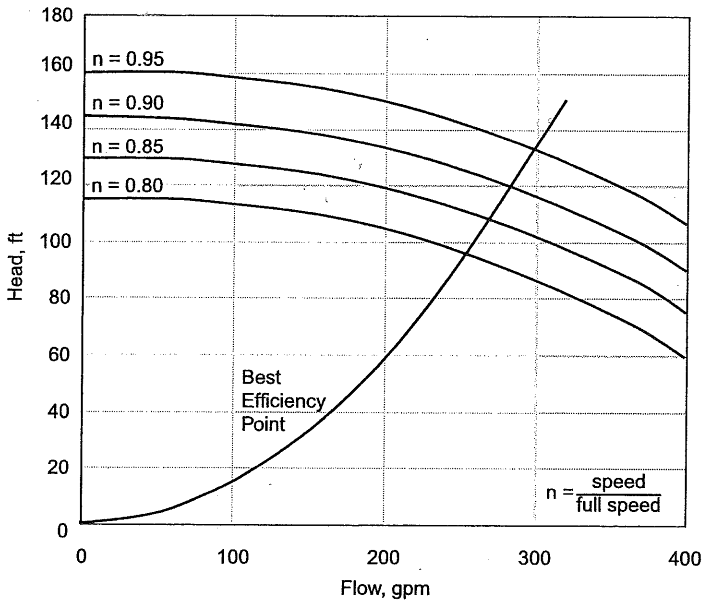


*Figure 6-4: Relative speed factors for variable-speed pumps*

### *Constant Horsepower Pumps*

During preliminary studies, the exact characteristics of the pump may not be known. In these cases, the assumption is often made that the pump is adding energy to the water at a constant rate. Horsepower is input as the actual power added to the system, and not the rated horsepower of the motor (because there is a loss of efficiency in the motor, and motors usually run at less than their rated capacity). Specifying a pump as a constant horsepower pump means that the pump will add the same power to the water at any flow rate. Although this assumption is useful for some applications, a constant horsepower pump should only be used for preliminary studies.

## 6.4 Control Valves

There are several types of valves that may be present in a typical pressurized pipe system. These valves have different behaviors and different applications, but all valves are used to automatically control parts of the system, opening, closing, or throttling to achieve the desired result.

### *Check Valves (CVs)*

***Check valves*** are used to maintain flow in one direction only by closing when the flow begins to reverse. When the flow is in the same direction as the specified direction of the check valve, the valve is considered to be fully open.

### *Flow Control Valves (FCVs)*

A ***flow control valve*** limits the flow rate through the valve to a specified value in a specified direction. A flow rate is used to control the operation of a flow control valve. These valves are commonly found in areas where a water district has contracted with another district or a private developer to limit the maximum demand to a value that will not adversely affect the provider's system.

### *Pressure Reducing Valves (PRVs)*

***Pressure reducing valves*** are often used to separate pressure zones in water distribution networks. These valves prevent the pressure downstream from exceeding a specified level, in order to avoid pressures and flows that could otherwise have undesirable effects on the system. A pressure or a hydraulic grade is used to control the operation of a PRV.

### *Pressure Sustaining Valves (PSVs)*

***Pressure sustaining valves*** maintain a specified pressure upstream of the valve. Similar to the other regulating valves, PSVs are often used to ensure that pressures in the system (upstream, in this case) will not drop to unacceptable levels. A pressure or a hydraulic grade is used to control the operation of a pressure sustaining valve.

### *Pressure Breaker Valves (PBVs)*

***Pressure breaker valves*** create a specified head loss across the valve and are often used to model components that cannot be easily modeled using standard minor loss elements.

### *Throttle Control Valves (TCVs)*

***Throttle control valves*** simulate minor loss elements whose head loss characteristics change over time. With a throttle control valve, the minor loss $K$ is adjusted based on some other system flow or head.

## 6.5 Pipe Networks

In practice, pipe networks consist not only of pipes, but also of miscellaneous fittings, services, storage tanks, reservoirs, meters, regulating valves, pumps, and electronic and mechanical controls. For modeling purposes, these system elements can be organized into four fundamental categories:

- ***Junction nodes***: Junctions are specific points (nodes) in the system where an event of interest is occurring. Junctions include points where pipes intersect, points where major demands on the system (such as a large industry, a cluster of houses, or a fire hydrant) are located, or critical points in the system where pressures are important for analysis purposes.
- ***Boundary nodes***: Boundaries are nodes in the system where the hydraulic grade is known, and they define the initial hydraulic grades for any computational cycle. They set the hydraulic grade line used to determine the condition of all other nodes during system operation. Boundary nodes are elements such as tanks, reservoirs, and pressure sources. A model must contain at least one boundary node for the hydraulic grade lines and pressures to be calculated.
- ***Links***: Links are system components such as pipes that connect to junctions or boundaries and control the flow rates and energy losses (or gains) between nodes.
- ***Pumps and valves:*** Pumps and valves are similar to nodes in that they occupy a single point in space, but they also have link properties because head changes occur across them.

An event or condition at one point in the system can affect all other locations in the system. Although this fact complicates the approach that the engineer must take to find a solution, there are some governing principles that drive the behavior of the network, such as the Conservation of Mass and the Conservation of Energy.

### *Conservation of Mass — Flows and Demands*

This principle is a simple one. At any node in the system under incompressible flow conditions, the total volumetric or mass flow entering must equal the mass flow leaving (plus the change in storage).

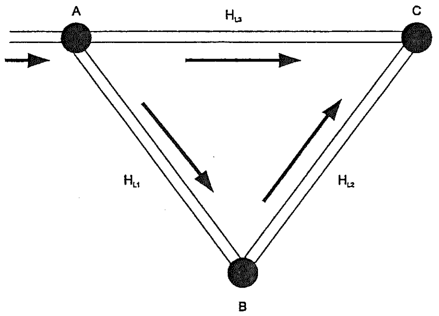
Separating the total volumetric flow into flows from connecting pipes, demands, and storage, we obtain the following equation:

$$\sum Q_{in}\Delta t = \sum Q_{out}\Delta t + \Delta\forall_S$$

where $\Sigma Q_{in}$ = total flow into the node
$\Sigma Q_{out}$ = total flow out of the node
$\Delta\forall_S$ = change in storage volume
$\Delta t$ = change in time

### Conservation of Energy

Chapter 1 introduced the application of the energy equation to hydraulic analysis. The principle of conservation of energy dictates that the head losses through the system must balance at each point (Figure 6-5). For pressure networks, this means that the total head loss between any two nodes in the system must be the same regardless of the path taken between the two points. The head loss must be "sign consistent" with the assumed flow direction (that is, head loss occurs in the direction of flow, and head gain occurs in the direction opposite that of the flow).



Path from A to C

$$H_{L3} = H_{L1} + H_{L2}$$

Path from A to B

$$H_{L1} = H_{L3} - H_{L2}$$

Loop from A to A

$$0 = H_{L1} + H_{L2} - H_{L3}$$

*Figure 6-5: Conservation of Energy*

Although the equality can become more complicated with minor losses and controlling valves, the same basic principle can be applied to any path between two points. As shown in Figure 6-5, the combined head loss around a loop must equal zero in order to compute the same hydraulic grade for a given point.

## 6.6 Network Analysis

### Steady-State Network Hydraulics

Steady-state analysis is used to determine the operating behavior of a system at a specific point in time, or under steady-state conditions. This type of analysis can be useful in discovering the short-term effect of fire flows or average demand conditions on the system.

For this type of analysis, the network equations are determined and solved with tanks being treated as fixed-grade boundaries. The results that are obtained from this type of analysis are instantaneous values, and may not be representative of the values of the system a few hours — or even a few minutes — later in time.

### Extended-Period Simulation

An extended-period simulation is used to determine the behavior of the system over time. This type of analysis allows the user to model tanks filling and draining, regulating valves opening and closing, and pressures and flow rates changing throughout the system in response to varying demand conditions and automatic control strategies formulated by the modeler.

Whereas a steady-state model may tell the user whether the system has the capability to meet a specific demand, an extended-period simulation indicates whether the system has the ability to provide acceptable levels of service over a period of minutes, hours, or days. Extended-period simulations can also be used for energy consumption and cost studies, as well as for water quality modeling.

Data requirements for an extended-period simulation go beyond what is needed for a steady-state analysis. The user must determine water usage patterns, provide more detailed tank information, and enter operational rules for pumps and valves.

## 6.7 Water Quality Analysis

In the past, water distribution systems were designed and operated with little consideration of water quality, due in part to the difficulty and expense of analyzing a dynamic system. The cost of extensive sampling and the complex interaction between fluids and constituents makes numeric modeling the ideal method for predicting water quality.

To predict water quality parameters, an assumption is made that there is complete mixing across finite distances, such as at a junction node or in a short segment of pipe. Complete mixing is essentially a mass balance given by:

$$C_a = \frac{\Sigma Q_i C_i}{\Sigma Q_i}$$

where $C_a$ = average (mixed) constituent concentration
$Q_i$ = inflow rates
$C_i$ = constituent concentrations of the inflows

## *Age*

Water age provides a general indication of the overall water quality at any given point in the system. Age is typically measured from the time that the water enters the system from a tank or reservoir until it reaches a junction.

Along a given link, water age is computed as:

$$A_j = A_{j-1} + \frac{x}{V}$$

where $A_j$ = age of water at $j$-th node
$x$ = distance from node $j$-1 to node $j$
$V$ = velocity from node $j$-1 to node $j$

If there are several paths for water to travel to the $j$-th node, the water age is computed as a weighted average using the equation:

$$AA_j = \frac{\sum Q_i \left[ AA_i + \left( \frac{x}{V} \right)_i \right]}{\sum Q_i}$$

where $AA_j$ = average age at the node immediately upstream of node $j$
$Q_i$ = flow rate to the j-th node from the $i$-th node

## *Trace*

Identifying the origin of flow at a point in the system is referred to as ***flow tracking*** or ***trace modeling***. In systems that receive water from more than one source, trace studies can be used to determine the percentage of flow from each source at each point in the system. These studies can be very useful in delineating the area influenced by an individual source, observing the degree of mixing of water from several sources, and viewing changes in origins over time.

## *Constituents*

Reactions can occur within pipes that cause the concentration of substances to change as the water travels through the system. Based on conservation of mass for a substance within a link (for extended-period simulations only):

$$\frac{\partial c}{\partial t} = V \frac{\partial c}{\partial x} + \theta(c)$$

where $c$ = substance concentration as a function of distance and time
$t$ = time increment
$V$ = velocity
$x$ = distance along the link
$\theta(c)$ = substance rate of reaction within the link

In some applications, there is an additional term for dispersion, but this term is usually negligible (plug flow is assumed through the system).

Assuming that complete and instantaneous mixing occurs at all junction nodes, additional equations can be written for each junction node with the following conservation of mass equation:

$$C_k\big|_{x=0} = \frac{\sum Q_j C_j\big|_{x=L} + Q_e C_e}{\sum Q_j + Q_e}$$

where $C_k$ = concentration at node $k$
$j$ = pipe flowing into node $k$
$L$ = length of pipe $j$
$Q_j$ = flow in pipe $j$
$C_j$ = concentration in pipe $j$
$Q_e$ = external source flow into node $k$
$C_e$ = external source concentration into node $k$

Once the hydraulic model has solved the network, the velocities and the mixing at the nodes are known. Using this information, the water quality behavior can be derived using a numerical method.

## *Initial Conditions*

Just as a hydraulic simulation starts with some amount of water in each storage tank, initial conditions must be set for a water age, trace, or constituent concentration analysis. These initial water quality conditions are usually unknown, so the modeler must estimate these values from field data, a previous water quality model, or some other source of information.

To overcome the problem of unknown initial conditions at the vast majority of locations within the water distribution model, the duration of the analysis must be long enough for the system to reach equilibrium conditions. Note that a constant value does not have to be reached for equilibrium to be achieved; rather, equilibrium conditions are reached when a repeating pattern in age, trace, or constituent concentration is established.

Pipes usually reach equilibrium conditions in a short time, but storage tanks are much slower to show a repeating pattern. For this reason, extra care must be taken when setting a tank's initial conditions, in order to ensure the model's accuracy.

### *Numerical Methods*

There are several theoretical approaches available for solving water quality models. These methods can generally be grouped as either Eulerian or Lagrangian in nature, depending on the volumetric control approach that is taken. Eulerian models divide the system into fixed pipe segments, and then track the changes that occur as water flows through these segments. Lagrangian models also break the system into control volumes, but then track these water volumes as they travel through the system. This chapter presents two alternative approaches for performing water quality constituent analyses.

### *Discrete Volume Method*

The Discrete Volume Method (DVM) is an Eulerian approach that divides each pipe into equal segments with completely mixed volumes (Figure 6-6). Reactions are calculated within each segment, and the constituents are then transferred to the adjacent downstream segment. At nodes, mass and flow entering from all connecting pipes are combined (assuming total mixing). The resulting concentration is then transported to all adjacent downstream pipe segments. This process is repeated for each water quality time step until a different hydraulic condition is encountered. When this occurs, the pipes are divided again under the new hydraulic conditions, and the process continues.

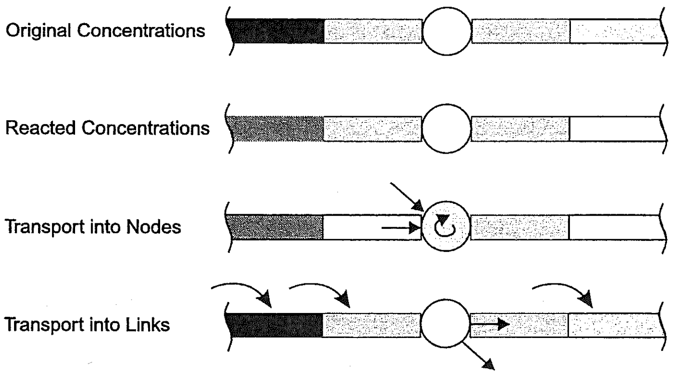


*Figure 6-6: Eulerian DVM*

### *Time-Driven Method*

The Time-Driven Method (TDM) is an example of a Lagrangian approach (Figure 6-7). This method also breaks the system into segments, but rather than using fixed control volumes as in Eulerian methods, the concentration and size of water parcels are tracked as they travel through the pipes. With each time step, the farthest upstream parcel of each pipe elongates as water travels into the pipe, and the farthest downstream parcel shortens as water exits the pipe.

Similar to the Discrete Volume Method, the reactions of a constituent within each parcel are calculated, and the mass and flow entering each node are summed to determine the resulting concentration. If the resulting nodal concentration is significantly different from the concentration of a downstream parcel, a new parcel will be created rather than elongating the existing one. These calculations are repeated for each water quality time step until the next hydraulic change is encountered and the procedure begins again.

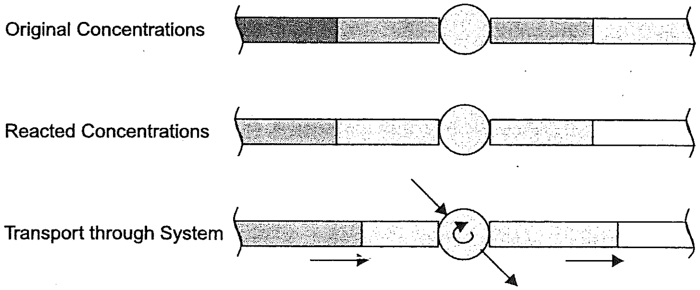


*Figure 6-7: Lagrangian TDM*

## 6.8 Automated Optimization

WaterGEMS has the capability to optimize a model based on field data or design criteria. Many times, water utility managers will use a model to make design decisions or gather field data to calibrate a model. This process is typically a trial-and-error approach where the modeler will modify a few parameters in a model to either compare design solutions based on cost or benefit, or have the model better predict the real conditions. Because this can be very time consuming, WaterGEMS has the capability to create many potential solutions and provide a measure of which solution is the "better" solution based on specific boundary conditions and input criteria.

WaterGEMS employs a genetic algorithm search method to find "better" solutions based on the principles of natural selection and biological reproduction. This genetic algorithm program first creates a population of trial solutions based on modeled parameters. The hydraulic solver then simulates each trial solution to predict the hydraulic grade line (HGL) and flow rates within the network and compares them to any input criteria. Based on this comparison, a goodness-to-fit value is assigned. This information is now used to create a new population of trial solutions which again are used to find new solutions. The program compares these solutions to the specific boundary conditions and input criteria until the goodness-to-fit value is optimized. In other words no better solution can be generated.

### *Model Calibration*

Model calibration is the process of modifying parameters or values in a model so it better matches what is happening in the real system. The calibration of water distribution models is very complicated. There are many unknown values and parameters that are needed at any one time to reduce the discrepancy between the model and real system. Many times the pipe roughness value is adjusted to have the model results match the measured or expected values in the real system. However, there are many other parameters that could influence the modeled results. The water demand at junctions and the status of pipes and valves in the system could also be adjusted when calibrating a model.

Calibrating a model relies on accurate field measurement data. Field measurements of pressures in the system, pipe flow rates, water levels in tanks, valve status, and pump operating status and speed are all used to calibrate models. Critical to all these measurements is the time for which the measurements are made. The time of these measurements must all be synchronized to the timeframe of the model. In addition, because the conditions within a real system changes throughout the day or year, field data should be collected for many different conditions and times. The calibration process is used to adjust the model to simulate multiple demand loading and operational boundary conditions. Only then can the modeler be confident that the model is valid for many different conditions.

WaterGEMS uses Darwin Calibrator to assist in optimizing the model to match field measurement data. The Darwin Calibrator allows the modeler to input field data then request the software to determine the optimal solution of pipe roughness values, junction demands, or status (on/off). Pipes that have the same hydraulic characteristics where one roughness values is assigned to all pipes can be grouped together. Junctions can also be grouped based on the demand pattern and location. Caution should be used grouping pipes and junctions since this could greatly affect the model calibration accuracy.

### *System Design*

The goal of water distribution system design is to maximize the benefits of the system while minimizing the cost. The optimal solution is a design that meets all the needs of the system at minimal cost. Some planning is needed to account for additional future needs of the system including potential growth of the system in terms of demand and its location. The modeler must work with the system owner and planning groups to account for both the current and future needs.

WaterGEMS uses Darwin Designer to assist engineers to plan and design water distribution networks. The Darwin Designer can be used to size new pipe and/or rehabilitate old pipes to minimize cost, maximize benefit, or create a scenario to trade-off cost and benefit. The least cost optimization is used to determine the pipe material and size to satisfy the needed design requirements. The maximum benefit optimization is used to determine the most beneficial solution based on a known budget. The Darwin Designer will generate a number of solutions that meet the design requirements at minimal cost or maximum benefit. In either case, the best solution of new pipe or rehabilitation of old pipe will be based upon the following input hydraulic criteria.

- Minimum and maximum allowable pressures
- Minimum and maximum allowable pipe flow velocity
- Additional demand requirements
- Pipe, pump, tank, valve, etc. status change requirements

Critical to creating an accurate designed system is time and peak demand requirements. The peak demand and fire flow conditions are used to size pipes since the pipe network must work for all conditions. Using average demand values to size pipe without accurately accounting for peaking factors can create networks that are either undersized and will not deliver the required water needs, or oversized and much more expensive than need be. The daily and seasonal variations can also greatly affect the final design. Demand variations need to be synchronized in the model to accurately reflect what could happen in the real system.

## 6.9 WaterGEMS

### *What Does WaterGEMS Do?*

WaterGEMS is a powerful, easy-to-use program that helps civil engineers design and analyze water distribution systems. It is also used by water utility managers to as a tool for the efficient operation of distribution systems. WaterGEMS provides intuitive access to the tools you need to model complex hydraulic situations. WaterGEMS's sophisticated modeling capabilities can:

- Perform steady-state, extended-period, and water quality simulations
- Analyze multiple time-variable demands at any junction node
- Model flow control valves, pressure reducing valves, pressure sustaining valves, pressure breaking valves, and throttle control valves
- Model cylindrical and non-cylindrical tanks and constant hydraulic grade source nodes
- Track conservative and non-conservative chemical constituents
- Determine water source and age at any element in the system
- Estimate construction costs
- Simulate the operating cycles of constant or variable speed pumps

- Estimate the cost of pumping over any time period
- Use field measurement data to calibrate a model
- Provide design solutions to maximize benefits at minimal cost

WaterGEMS can be used as a stand-alone program, integrated with AutoCAD, or linked to a Geographical Information System (GIS) via the GEMS component. The theory and background used in WaterGEMS are presented in this chapter and in the WaterGEMS online help system. Additional information on features contained in the professional version and available options are presented in Appendix A.

### *How Can You Use WaterGEMS?*

WaterGEMS can analyze complex distribution systems under a variety of conditions. For a typical WaterGEMS project, you may be interested in determining system pressures and flow rates under average loading, peak loading, or fire flow conditions. Extended-period analysis tools also allow you to model the system's response to varying supply and demand schedules over a period of time; you can even track chlorine residuals or determine the source of the water at any point in the distribution system.

In summary, you can use WaterGEMS for:

- Pipe sizing
- Pump sizing
- Master planning
- Operational studies
- Rehabilitation studies
- Vulnerability studies
- Water quality studies

WaterGEMS is a state-of-the-art software tool primarily for use in the modeling and analysis of water distribution systems. Although the emphasis is on water distribution systems, the methodology is applicable to any fluid system with the following characteristics:

- Steady or slowly changing turbulent flow
- Incompressible, Newtonian, single phase fluid
- Full, closed conduits (pressure system)

Examples of systems with these characteristics include potable water systems, sewage force mains, fire protection systems, well pumps, and raw water pumping.

## 6.10 Tutorial Example

The following tutorial gives step-by-step instructions on how to solve an example problem using WaterGEMS (included on the CD that accompanies this textbook).

### *Tutorial 1 – Three Pumps in Parallel*

**Problem Statement**

A pump station is designed to supply water to a small linen factory. The factory, at an elevation of 58.0 m, draws from a circular, constant-area tank at a base elevation of 90.0 m with a minimum water elevation of 99.0 m, an initial water elevation of 105.5 m, a maximum water elevation of 106.0 m, and a diameter of 10.0 m.

Three main parallel pumps draw water from a source with a water surface elevation of 58.0 m. Two pumps are set aside for everyday usage, and the third is set aside for emergencies. Each pump has a set of controls that ensure it will run only when the water level in the tank reaches a certain level. Use the Hazen-Williams equation to determine friction losses in the system. The network layout is given in Figure 6-8; the pump and pipe data are given in the tables below.

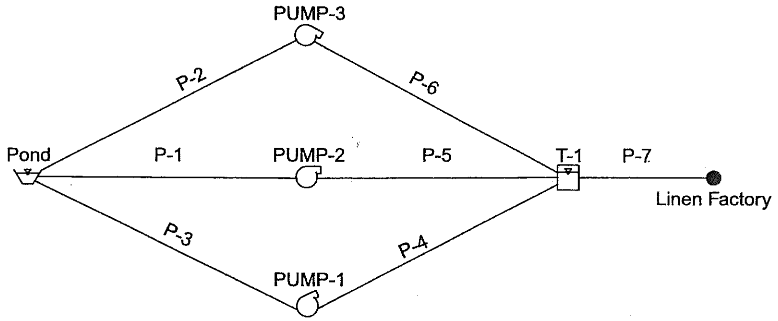


*Figure 6-8: Schematic of Example Problem*

a) Can the pumping station support the factory's 20 l/s demand for a 24-hour period?

b) If there were a fire at the factory that required an additional 108 l/s of water for hours 0 through 6, would the system with the pump controls given in the problem statement be adequate? Supply the Extended Period Simulation report describing the system at each time step.

c) How might the system be operated so that the fire flow requirement in part (b) is met?

*Pipe Information for Tutorial Problem*

| Pipe | Length (m) | Diameter (mm) | Material | Roughness |
|---|---|---|---|---|
| P-1 | 6 | 150 | Cast Iron | 90 |
| P-2 | 6 | 150 | Cast Iron | 90 |
| P-3 | 6 | 150 | Cast Iron | 90 |
| P-4 | 71 | 150 | Cast Iron | 90 |
| P-5 | 72 | 150 | Cast Iron | 90 |
| P-6 | 73 | 150 | Cast Iron | 90 |
| P-7 | 18 | 200 | Cast Iron | 90 |

*Pump Information for Tutorial Problem*

| Pump | Elevation (m) | Pump Curve | | Controls |
|---|---|---|---|---|
| | | Flow (l/s) | Head (m) | |
| PUMP-1 | 58.0 | 0<br>32<br>63 | 78.0<br>58.5<br>0 | On when T-1 is below 105.5 meters<br>Off when T-1 is above 106.0 meters |
| PUMP-2 | 58.0 | 0<br>32<br>63 | 78.0<br>58.5<br>0 | On when T-1 is below 105.2 meters<br>Off when T-1 is above 106.0 meters |
| PUMP-3 | 58.0 | 0<br>32<br>63 | 67.0<br>50.3<br>0 | On when T-1 is below 99.25 meters<br>Off when T-1 is above 103.00 meters |

***PART (a):*** *Can the pumping station support the factory's 20 l/s demand for a 24-hour period?*

**Solution**

*Setting up the Project*

- When you start WaterGEMS, you should be prompted with the **Welcome to WaterGEMS** dialog. From this dialog, you can access the tutorials, open existing projects, and create new ones. Select **Create New Project**.
- If the **Welcome to WaterGEMS** dialog does not appear, WaterGEMS is set to **Hide Welcome Page on startup**. To start a new project, select **New** from the **File** menu. You can change from **Hide Welcome Page** mode to **Show Welcome Page** mode in the **Global Options** dialog, which is accessible by selecting **Options** from the **Tools** menu.

- As always when starting a new project, the file should be save frequently to avoid loosing data or simulations. To save a new project, select **Save As** under the **File** menu. Enter your project title **Tutorial 1** and at any time you can save your project by clicking the **Save** button .
- A more descriptive project title and other general information can be entered into the **Project Properties** found under the **File** menu.
- Before starting, you should setup the general default settings for the project. You can find the default settings in **Options** under the **Tools** menu. In the **Drawing** tab select **Schematic** from the **Drawing Mode** field. This option will allow you to define the pipe lengths and node locations without having to worry about scale and spatial placement on the x-y plane.
- To define the default units go to the **Units** tab found under **Options** from the **Tools** menu. Select **System International** from the list box in the **Results Default** field if it is not already selected. You can define any of the default label units by clicking the unit field and selecting the desired unit from the list. For example, to change the **Angle** units from radians to degrees, click on **Radians** in the unit field, then select **Degrees** by locating it on the dropdown list of available units.

*Laying Out the System*

- Begin with the pipeline running horizontally through the center of the system. Because you selected **Schematic** in the **Drawing Mode** field, you do not have to layout the system exactly as shown in the problem statement. You can roughly sketch the schematic by following the instructions here. You will likely have to rename many of the elements to match the names shown in Figure 6-8. The steps below will describe how to do this.
- Click the **Pipe Layout** button on the vertical toolbar on the left side of the layout screen.
- Move the cursor to the layout screen and right-click the mouse. Select **Reservoir**. To place the reservoir, simply click the left mouse button.
- Move your mouse horizontally to the right to place a pump. Right-click and select **Pump** from the pop-up menu then left-click to place the pump.
- Repeat the process for the tank by selecting **Tank** from the pop-up menu.
- Now, place the junction node "Linen Factory." After placing the junction, right-click and select **Done**.
- Continue by entering the remaining two pumps and four pipes in the same way as described previously. To connect a pipe to an object on the layout screen, click the object while in the pipe layout mode. The object should turn red when it is selected.
- Except for the scale, your schematic should look roughly like the one given in the problem statement.

- To exit the pipe layout mode, click the arrow button on the vertical toolbar on the left side of the layout screen.

*Entering the Data*

- Double-click the reservoir node to open its dialog editor. Change the name to "Pond" in the **Label** field. Enter 58 m in the **Elevation** field. Close the dialog editor.
- Double-click the tank. Enter the given diameter for the circular section and the appropriate elevations from the problem statement. Disregard the inactive volume field. Be sure that **Elevation** is selected in the **Operating Range Type** field. Close the dialog editor.
- Double-click the bottom pump. Change the name to "PUMP-1" in the **Label** field. Enter the appropriate elevation from the pump data table in the problem statement into the **Elevation** field. Click the **Pump Definition** field and select **Edit Pump Definitions** to open the Pump Definitions dialog. Add a new pump definition and label it "Pumps 1 and 2". In the **Head** tab select **Standard (3 Point).** Enter the pump curve data given for PUMP-1. If you need to change the units, right-click on the Flow or Head table headings and open the "Units and Formatting" dialog. Click **Close** to close **Pump Definition** dialog. Now select "Pumps 1 and 2" in the **Pump Definitions** field. Close the dialog editor.
- Repeat the above process for the other pumps. When entering the data for PUMP-3, you will have to create a new pump definition titled "Pump 3" for the **Pump Definitions** field.
- Next, enter the pump controls given in the problem statement. Click **Controls** in the **Components** menu.
- Select the **Conditions** tab to enter the five Tank conditions as described from the problem statement information. Enter each condition as **New** and **Simple**. The **Condition Type** is **Element**; select the Tank from the layout screen by clicking the ellipse button ; select **Hydraulic Grade** as the **Tank Attribute**; the **Operator** and **Hydraulic Grade** is entered based on the problem statement information.
- Select the **Actions** tab to enter whether the pump is on or off. The default setting is generally with the pumps on. Enter the six actions (each pump either on or off) as **New** and **Simple**. For example, to turn off PUMP-1, the **Element** is entered by clicking the ellipse button and selecting PUMP-1 from the layout screen; the **Pump Attribute** would be Pump Status; the **Operator** would be the default "="; then select Off for the **Pump Status**.
- Select the **Controls** tab to enter the six controls. The controls are all Simple and entered as If Then statements. For example, click **New** then the **Evaluate as Simple Control** box; in the IF Condition field, select {"Tank" level > 106.00 m}; in the THEN Action field, select {"PUMP-1" pump status = off}. Close the **Controls** dialog.

- Double-click the junction node. Change the name to "Linen Factory". Enter 58 m in the **Elevation** field. Click the **Demand Collection** field to enter a fixed demand of 20 l/s after clicking the ellipse button. Close both dialog editors.
- For the pipes, you can edit the data as you have been by clicking each element individually, and then entering in the appropriate data. However, this method can be time consuming, especially as the number of pipe elements increase. It is often easier to edit the data in a tabular format.
- Click the **Flex Tables** button in the toolbar at the top of the screen. Select **Pipe Table** from the available tables.
- The fields highlighted in the **Pipe Table** are output fields. The fields in white are input fields and can be edited as you would edit data in a spreadsheet.

  **Warning:** The pipes may not be listed in the table in numerical order. You may want to sort the pipe labels in ascending order. To do this, move the cursor to the top of the table and place it on the **Label** column. Right-click, select **Sort,** and then select **Sort Ascending.** The pipes should then be listed in numerical order.
- Enter the correct pipe lengths into the **Length (User Defined)** column found on the Pipe Table. Also enter the pipe diameters and Hazen-Williams C value. Close the Pipe Table.
- **Note:** You can customize which columns appear in the **Pipe Table** by clicking the **Edit** button in the toolbar at the top of the table. Table columns can be added or removed as desired.

*Running the Model*

- To run the model, first click the **Compute** button on the main toolbar. Arrows should appear on your layout screen indicating the flow direction in each pipe. If you click on any of the objects, you will see the results in the dialog. You could look at the results for all similar objects by opening the **Flex Tables** button. For example, if you want to look at flows in all the pipes, select the **Pipe Table**. To examine the flow through the system over a 24-hour period, select the **Calculation Options** under the **Analysis** menu. Double-click the **Base Calculation Options,** then in the **Time Analysis Field** select **EPS**. Set the start time to 12:00:00 a.m. and the duration to 24 hours. The **Hydraulic Time Step** of 1 hour will provide sufficient output for the purpose of this tutorial. Click the **Compute** button.
- There are a couple of ways to determine whether your model meets the target demand:

  Scroll through the Calculation Summary and check to see if there are any disconnected node warnings. When the level in Tank T-1 drops to the minimum tank elevation of 99 m (tank level of 9 m), the tank closes off, preventing any more water from leaving. This closure will cause the linen factory to be disconnected from the rest of the system (that is, it will not get the required 20 l/s).

-OR-

Close the Calculation Summary window and select the Linen Factory junction. To create a graph of the pressure at this node click the Graphs button in the main toolbar. Create a **Line-Series Graph** from the **New** button in the Graphs dialog. Select the **Pressure** box in the **Graph Series Options** window then close the options window. You should see the calculated pressure at the Linen Factory and notice that it never reached zero (no water pressure).

**Answer**

As you will see for this problem, all the pressures at the linen factory hover around 465 kPa, and no disconnected nodes are detected. Therefore, the pumping station can support the factory's 20 l/s demand for a 24-hour period.

***PART (b):*** *If there were a fire at the factory that required an additional flow of 108 l/s for hours 0 through 6, would the system with the pump controls given in the problem statement be adequate?*

**Solution**

- Add another demand to the Linen Factory node. To do this, double-click the Linen Factory junction and enter into the **Demand Collection** field a second fixed demand of 108 l/s in the row below the 20 l/s demand after clicking the **Ellipse** button. Close the dialog editor.
- Select the **Calculation Options** under the **Analysis** menu, then double-click the **Base Calculation Options.** You only need to run this model for six hours, so change 24 to 6 in the **Duration** field. Click **Compute** to run the model.
- As you scroll through the results, you will see warning messages (yellow or red indicators instead of green) indicating a disconnected node at the linen factory after 3 hours. Close the **User Notifications** window. Select the tank and create a Line-Series Graph of the water level in the tank by selecting **Level (Calculated)** in the Graph Series Options window. The graph indicates that the water level in the tank reaches the minimum level of 9 m at 3:37:30 and cannot supply water to the linen factory.

**Answer**

If there were a fire at the factory, the existing system would NOT be adequate.

***PART (c):*** *How might the system be operated so that the fire flow requirement in Part (b) is met?*

**Answer**

PUMP-3 could be manually switched on at the beginning of the fire to supply the flow necessary to fight the fire at the linen factory. To do this delete the pump controls for PUMP-3. Then PUMP-3 will be always on during the model simulation.

## *Tutorial 2 – Water Quality*

This tutorial example demonstrates the use of WaterGEMS to simulate water quality in a water distribution system. The Scenario Manager is used to facilitate different types of analysis on the same network (within the same project file).

**Problem Statement**

A local water company is concerned with the water quality in its distribution network. The company wishes to determine the age and chlorine concentration of the water as it exits the system at different junctions. The water surface at the reservoir is 70 m.

Chlorine is injected into the system at the source of flow, R-1, at a concentration of 1 mg/l. It has been determined through a series of bottle tests that the average bulk reaction rate of the chlorine in the system (including all pipes and tanks) is approximately –0.5/day.

The network model may be entered in WaterGEMS using the layout in Figure 6-9 and the data that follows.

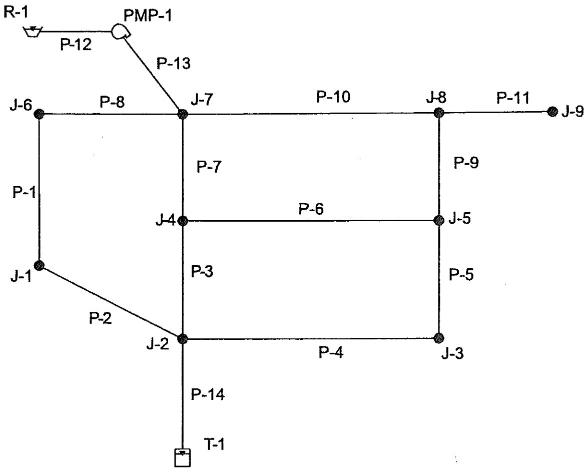


*Figure 6-9: Schematic for Water Quality Tutorial*

The tank is circular with a diameter of 15.0 m. The minimum elevation is 99.0 m. The maximum elevation is 104.0 m, and the initial elevation is 103.4 m. The base elevation is 98.0 m, and the inactive volume is 10.0 m$^3$. The elevation of the pump is 70.0 m and initially on.

***Pump Information for Water Quality Tutorial***

| Flow (l/min) | Head (m) | Controls |
|---|---|---|
| 0 | 40 | Off if node T-1 above 103.5 m |
| 3,000 | 35 | On if node T-1 below 99.5 m |
| 6,000 | 24 | |

***Continuous Demand Pattern Data for Water Quality Tutorial***

| Time from Start (hr) | Multiplier |
|---|---|
| Start | 0.80 |
| 1 | 0.60 |
| 2 | 0.50 |
| 3 | 0.50 |
| 4 | 0.55 |
| 5 | 0.60 |
| 6 | 0.80 |
| 7 | 1.10 |
| 8 | 1.50 |
| 9 | 1.40 |
| 10 | 1.30 |
| 11 | 1.40 |
| 12 | 1.40 |
| 13 | 1.30 |
| 14 | 1.40 |
| 15 | 1.50 |
| 16 | 1.60 |
| 17 | 1.80 |
| 18 | 1.80 |
| 19 | 1.40 |
| 20 | 1.20 |
| 21 | 1.00 |
| 22 | 0.90 |
| 23 | 0.80 |
| 24 | 0.80 |

***Junction Data for Water Quality Tutorial***

| Junction | Elevation (m) | Demand (l/min) |
|---|---|---|
| J-1 | 73 | 151 |
| J-2 | 67 | 227 |
| J-3 | 85 | 229 |
| J-4 | 61 | 212 |
| J-5 | 82 | 208 |
| J-6 | 56 | 219 |
| J-7 | 67 | 215 |
| J-8 | 73 | 219 |
| J-9 | 55 | 215 |

***Pipe Data for Water Quality Tutorial***

| Pipe | Length (m) | Diameter (mm) | Roughness |
|---|---|---|---|
| P-1 | 300 | 200 | 130 |
| P-2 | 305 | 200 | 130 |
| P-3 | 225 | 200 | 130 |
| P-4 | 301 | 200 | 130 |
| P-5 | 225 | 200 | 130 |
| P-6 | 301 | 200 | 130 |
| P-7 | 225 | 200 | 130 |
| P-8 | 301 | 200 | 130 |
| P-9 | 200 | 200 | 130 |
| P-10 | 301 | 200 | 130 |
| P-11 | 300 | 200 | 130 |
| P-12 | 1 | 250 | 130 |
| P-13 | 3,000 | 300 | 130 |
| P-14 | 300 | 300 | 130 |

a) Perform an age analysis on the system using a duration of seven days and a time step of one hour. Determine the youngest and oldest water in the distribution system and the storage tank. Explain why water age varies.

b) Perform a constituent analysis using the same duration and time step as in part (a). Determine the range of concentrations in the system and the storage tank. Explain the behavior of the system with regard to chlorine.

c) Are the simulation results consistent with the known behavior of chlorine?

d) Why is it necessary to run the model for such a long period of time? Do you feel seven days is too long or too short a time period to test the model? Why?

**Solution**

- Use the same steps as in Tutorial 1 to setup the project, layout the system, and enter the data. Be sure to set units to **System International** and the drawing mode to **Schematic.** Again, you will likely have to rename many of the elements after you draw the general layout to make sure data is correctly entered for each element.
- The demand pattern data can be entered by selecting **Patterns** under the **Components** menu. Right-click **Hydraulic** to select **New**. The Start Time is **12:00:00 AM**, the Starting Multiplier is **0.80**, and the Pattern Format is **Continuous**. Enter the data from the problem statement table under the **Hourly** tab.
- The demand pattern can be assigned to a selected junction by clicking a junction and entering **Hydraulic Pattern – 1** into the **Demand Collection** field, or the pattern can be assigned to all junctions as a Global Edit. In this case, assign the demand pattern to all junctions by selecting **Demand Control Center** under the **Tools** menu. Click **Yes** to continue. On the **Junctions** tab, right-click the **Pattern (Demand)** table heading to select **Global Edit**. Select **Hydraulic Pattern – 1** in the **Value:** field. Click **OK** and close the Demand Control Center dialog.

*Base Scenario*

- Run the model for a 24-hour period by selecting the **Calculation Options** under the **Analysis** menu. Double-click the **Base Calculation Options** then in the **Time Analysis Type** select **EPS.** The **Duration (hours)** is 24 hours and the **Hydraulic Time Step (hours)** is 1.0 hour. Close the Base Calculation Options dialog.
- At the bottom of the Calculation Options window are more tabs. Click on the **Scenarios** tab. Notice that the Compute button is in the Scenario window toolbar. Click the **Compute** button. WaterGEMS calculates the system parameters for a 24-hour simulation period. Details of the calculation can be viewed on the **Calculation Summary** window. Close the Calculation Summary and Scenarios windows.
- Click on the tank then the Graphs button in the main toolbar. Create a **Line-Series Graph** from the **New** button in the Graphs dialog. Select the **Percent Full** box under "Results" under the **Fields** field in the **Graph Series Options** window. Close the Graph Series Options window. Size the graph window to fit on the layout screen such that you can see most of the layout and the toolbar in the Graph window to click the **Play** button. Play the 24-hour simulation by clicking the **Play** button in the Graph window. The flow in the pipes is indicated by the arrows. Note that that there is no flow in pipes P-12 and P-13 when the pump is not operating. The flow direction reverses in pipes P-1, P-2, P-3, P-4, P-5, P-7, P-8, P-9, and P-14 over the 24-hour period. The volume of the water in tank T-1 is indicated by the **Percent Full (%)** on the y-axis of the graph.

*Age Analysis*

- The analysis of the age of water within the network may be performed by defining and running an age analysis scenario. From the **Analysis** menu, select **Scenarios**.
- Create a new **Base Scenario** by clicking the **New** button. Enter "Age Analysis" as the name of the scenario.
- Click on the **Calculation Options** tab at the bottom of the window. Create a new Calculation Option by clicking the **New** button and enter "Age Analysis Calculation Options" as the name. Double-click the calculation options you just created and select **Age** in the **Calculation Type** field. The **Duration** is 168 hours (7 days), and the **Hydraulic Time Step** is 1.00 hr.
- Go back to the **Scenarios** tab, right-click the Age Analysis scenario, and select **Make Current**. The red check should now be on the Age Analysis scenario. Double-click on the Age Analysis scenario and select the Age Analysis Calculation Options in the **Calculation Options** field.
- Go back to the Scenarios tab and click the **Compute** button.
- Close the Calculation Summary window and Scenarios dialog to view the layout screen.

**Results:** The oldest water in the network will be found in tank T-1. Click on the tank then the **Graphs** button in the main toolbar. Create a **Line-Series Graph** from the **New** button in the Graphs dialog. Select the **Age Analysis** box in the **Scenarios** field and **Age (Calculated)** found under "Results (Water Quality)" in the **Fields** field in the **Graph Series Options** window. You should also unclick any other selected lines in the **Field** field. Close the options window. The resulting graph is shown below.

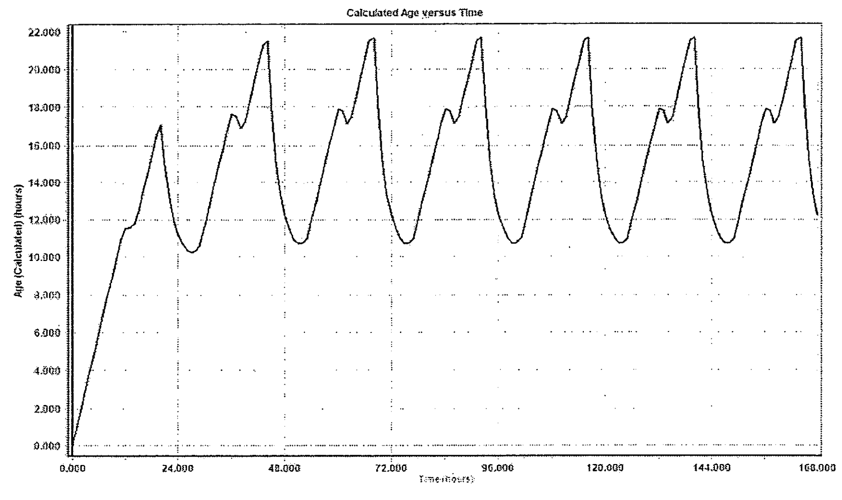


*Figure 6-10: Age of water in Tank T-1*

Note that the water distribution network reaches dynamic equilibrium after two days of the simulation. After 48 hrs, the maximum age at T-1 is approximately 21.5 hours, and the minimum age is approximately 10.5 hours.

To view the variation in age in the network, click on the tank, J-2, J-3, J-7, and J-9 while holding the shift on the keyboard to select each object. Then click the **Graphs** button in the main toolbar. Create a **Line-Series Graph** from the **New** button in the Graphs dialog. Select the **Age Analysis** box in the **Scenarios** field and **Calculated Age**, both under Tank and Junction in the **Fields** field in the **Graph Series Options** window. Close the options window to look at the graph. Notice that the water age in the junctions is much less (2 to 4 hours) than the water in the tank while the pump is on and feeding fresh water into the system. Then the water age in the junctions greatly increases when the system is fed by the tank water after the pump turns off.

### *Water Quality Analysis*

In order to analyze the behavior of chlorine in the network, the properties of chlorine must be defined in the engineering library.

- From the **Components** menu, select **Engineering Libraries**. Double-click the Constituent Libraries. Then right-click on the ConstituentLibrary.xlm to select **Add Item**.

- Rename the new constituent by right-clicking it and selecting **Rename**. Change the label to "Chlorine." Click on the Chlorine dialog. Enter the **Diffusivity** (1.122e-010 $m^2/s$). Enter the **Bulk Reaction Order** as 1 and the **Bulk Reaction Rate** as $-0.5\ (mg/l)^{1-n}/day$. Because $n = 1$, the units of the rate constant are $day^{-1}$. Close the Engineering Libraries.
- From the **Analysis** menu, select **Scenarios**. Create a new base scenario named "Chlorine Analysis".
- Click on the **Calculation Options** tab at the bottom of the window. Create a new Calculation Option by clicking the **New** button and enter "Chlorine Analysis Calculation Options" as the name. Double-click the calculation options you just created and select **Constituent** in the **Calculation Type** field. The **Duration** is 168 hours (7 days), and the **Hydraulic Time Step** is 1.00 hr.
- Go back to the **Scenarios** tab and right-click the Chlorine Analysis scenario and select **Make Current**. The red check should now be on the Chlorine Analysis scenario. Double-click on the Chlorine Analysis scenario and select the Chlorine Analysis Calculation Options in the **Calculation Options** field.
- Go to the **Alternatives** tab. Double-click on the **Constituent**; right-click on **Base Constituent Alternative** to select **Open**. Select the **Constituent System Data** tab then click the ellipse button. Click the **Synchronization Options** button to select **Import from Library**. Select **Chlorine** from the **Constituent Libraries** list. Close the Constituents dialog. Select **Chlorine** in the **Constituent** field on the **Constituents: Base Constituents Alternative** window. Close the Constituent Alternative window.
- Double-click the reservoir to define the loading of chlorine. Select **True** in the **Is Constituent Source?** field. The **Constituent Source Type** is Concentration and the baseline concentration is 1.0 mg/L. The constituent source pattern is fixed.
- The bulk reaction rate in the pipes can be adjusted using the **Tables** tool. Click the **Flex Table** button, then select the **Pipe Table**. Add the **Bulk Reaction Rate (Local)** and **Specify Local Bulk Reaction Rate?** to the table by clicking the **Edit** button in the toolbar at the top of the table. Scroll to the **Specify Local Bulk Reaction Rate?** column to click the box for the pipe you want to adjust. Now you can enter a reaction value for the pipe in the Bulk Reaction Rate (local) column. In this case we will not change any of the default values so close the Pipe Table.
- Double-click the tank. Set the initial chlorine concentration to 0.000 mg/l, select **True** in the **Specify Local Bulk Rate?** field, then enter the bulk reaction rate of –0.5 /day. Close the editor dialog.
- From the **Analysis** menu, select **Scenarios**. Make sure Chlorine Analysis is the current scenario then run the scenario by clicking the **Compute** button in the top row.

- Open the EPS Results Browser window by clicking the icon button. To create a contour map of the chlorine concentration, click the **Contour** button. After clicking the **New** button, contour by **Concentration (Calculated)**; select all elements; set the **Minimum** to 0.0, **Maximum** to 1.0, **Increment** to 0.025, and **Index** to 0.1 mg/L. Click the Play button on the Animation Control window. The chlorine concentrations for each time step can be viewed through time as shown in Figure 6-11.
- Save your simulation as "Tutorial 2" since this network will be used in the following tutorials.

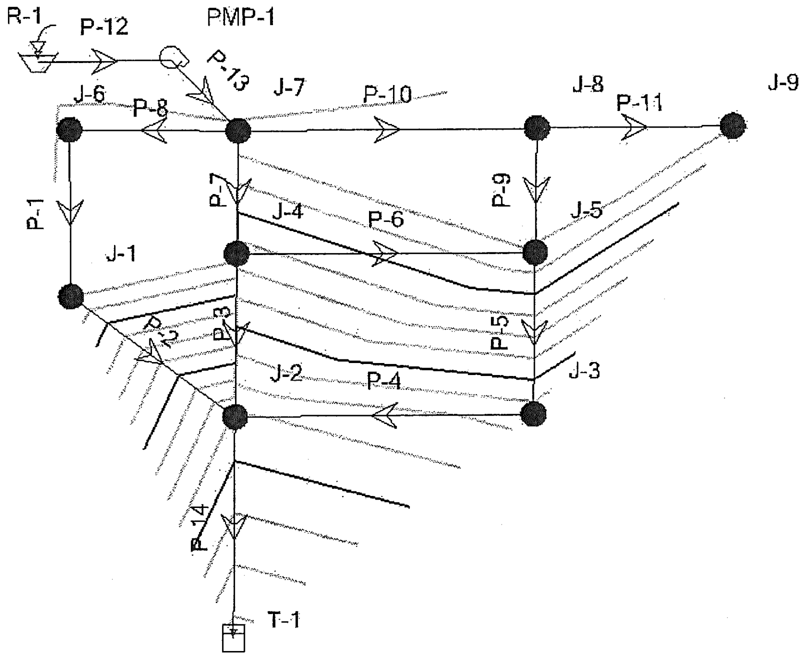


*Figure 6-11: Contours of Chlorine Concentration at 42 Hours*

## Answer

To view the variation of the chlorine concentration in the network, click on the tank, J-2, J-3, J-7, and J-9 while holding the shift on the keyboard to select each object. Then click the **Graphs** button in the main toolbar. Create a **Line-Series Graph** from the **New** button in the Graphs dialog. Select the **Chlorine Analysis** box in the **Scenarios** field, and **Concentration (Calculated)** found under "Results (Water Quality)" for both the Tank and Junction in the **Fields** field in the **Graph Series Options** window. Close the options window to look at the graph which should like Figure 6-12. The lowest chlorine concentration is found in tank T-1. Junctions J-2 and J-3 each have similar chlorine concentration values. In addition, the water distribution network reaches dynamic equilibrium during the second day of the simulation. After dynamic equilibrium in achieved, the maximum chlorine concentration at tank T-1 is 0.799 mg/l, and the minimum concentration is 0.687 mg/l.

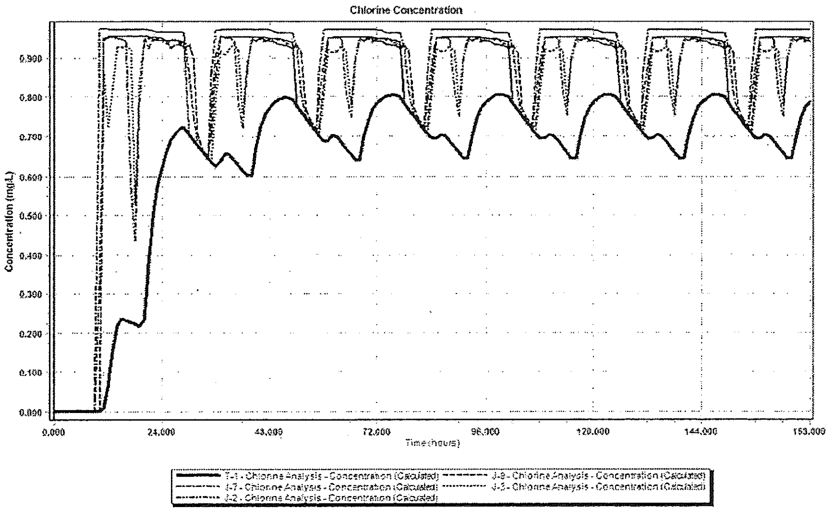


*Figure 6-12: Chlorine Concentration in Tank T-1 and selection junctions*

To compare age against chlorine concentration at a selected junction, open the graph that plotted the **Calculated Age** for the tank and junctions. The graphs of age versus time and chlorine concentration should now be open on the desktop. Move the graphs so that both are visible and the axes are aligned. Comparison of the two graphs suggests an inverse correlation between age and chlorine concentration.

## Answers

a) The oldest water is found in the storage tank. It is far from the source, and incoming water is mixed with the tank's contents. In the distribution system, the oldest water is found at J-9. The newest water is found at J-7 when pump PMP-1 is running.

b) The lowest chlorine concentration is in Tank T-1 when it is nearly empty. In the distribution system, the lowest chlorine concentration is found at J-3 when T-1 is emptying. The highest concentration is at J-7 when pump PMP-1 is running.

c) These results are consistent with the fact that chlorine concentration declines over time. For example, during the third day of operation, the minimum chlorine concentration at Junction J-3 is coincident with the maximum age, and the maximum chlorine concentration is coincident with the minimum age.

d) Inspection of the graph of chlorine concentration in tank T-1 suggests that the system stabilizes into a daily pattern on the second day. However, if the initial tank level or the demands are changed, stabilization may take longer. It appears that the seven-day simulation period is adequate for this network.

## *Tutorial 3 – Pumping Costs*

This tutorial demonstrates the use of WaterGEMS to calculate the energy costs associated with pumping.

### Problem Statement

Calculate the daily electrical costs for the network in Tutorial 2 using the following data:

| | |
|---|---|
| Energy price | $0.10/kWh |
| Motor efficiency | 90% |
| Pump efficiency | 50% at 2,000 l/m<br>60% at 2,500 l/m<br>55% at 3,000 l/m |

### Solution

- Open Tutorial 2.
- The first step is to add the pump and motor efficiency data to PMP-1. On the layout view, double-click **PMP-1.** In the **Pump Definition** field, select **Edit Pump Definitions**. The pump definition dialog for PMP-1 appears.
- On the **Efficiency** tab, select the **Multiple Efficiency Points** option for the pump efficiency. In the **Efficiency Points** table, add the efficiency data from the problem statement.
- In the **Motor** section, enter 90% for the motor efficiency.
- Close the Pump Definition tool and the pump dialog.
- The Energy Cost tool is used to calculate energy costs. From the **Analysis** drop down menu, select **Energy Costs** or click the icon button in the toolbar.
- Click the icon button to open the **Energy Pricing** field dialog.

- Create a **New** label "Energy Pricing-1" to enter the electricity cost. Enter one line in the cost table. The Time from Start is 0.000, and the Energy Price is $0.10/kWh. Close the Energy Pricing dialog to return to the Energy Cost window.
- Set the scenario to **Chlorine Analysis** then select "Energy Pricing-1" in the **Energy Pricing** field located on the "Pumps" tab, then click the **Compute** button.

### Answer

On the left panel of the Energy Cost window, highlight the Chlorine Analysis line. On the right panel, select the **Summary** tab. For the seven-day simulation, the following data were calculated:

| | |
|---|---|
| Pump energy used | 4,030 kWh |
| Volume pumped | 21,220 $m^3$ |
| Pump cost | $403.00 |
| Daily cost | $58.60 |

## *Tutorial 4 – Pipe Sizing using Darwin Designer*

WaterGEMS can help size pipes and prepare project cost estimates. In this exercise, the Darwin Designer with the Minimum Cost function will be demonstrated.

### Problem Statement

Prepare a minimal cost estimate for pipe materials and installation portion of the project in Tutorial 2. The system pipes should be sized using a demand multiplier of 3.4 (peak flow factor) with a calculated pressure for each junction between 170 and 550 kPa. In addition, the system should supply to an industry located at junction 9 an additional 1,500 l/min with a minimum pressure of 275 kPa. Use the following cost data:

*Pipe Material and Cost*

| Material | Diameter (mm) | Cost ($/m) |
|---|---|---|
| Ductile Iron | 75 | 40.32 |
| Ductile Iron | 150 | 56.64 |
| Ductile Iron | 200 | 79.36 |
| Ductile Iron | 250 | 114.72 |
| Ductile Iron | 300 | 156.16 |
| Ductile Iron | 350 | 201.92 |

Do not consider the cost of the reservoir, tank, pump, or pipes P-12 and P-13.

## Solution

- Open Tutorial 2.
- From the **Analysis** menu, select **Scenarios**. Create a new base scenario named "Designer Analysis".
- Click on the **Calculation Options** tab at the bottom of the window. Create a new Calculation Option by clicking the **New** button and enter "Designer Calculation Options" as the name. Double-click the calculation options you just created. The **Time Analysis Type** is **Steady State**.
- Go back to the **Scenarios** tab, right-click the Designer Analysis scenario, and select **Make Current**. The red check should now be on the Designer Analysis scenario. Double-click on the Designer Analysis scenario and select the Designer Calculation Options in the **Calculation Options** field. Click the **Compute** button.
- Click the **Darwin Designer** button or find it under the **Analysis** menu to create a scenario to determine the minimum design cost. Click the **New** button to select **New Designer Study**. Check to make sure the Scenario window has Designer Analysis selected.
- Enter the design criteria on the **Design Events** tab in the dialog by clicking the **New** button. The top window is used to enter the general design criteria; the bottom window is for entering specific design criteria for any elements (i.e. pipe, junction, tank, etc.). It is typical that pipe networks are designed for high flow conditions. Scroll across to set the **Demand Multiplier** to 3.4. Criteria are set to maintain a working network to avoid low flow or pressure conditions. The **Minimum Pressure (Global)** to 170 kPa, and **Maximum Pressure (Global)** to 550 kPa. The flow velocity criteria will be the default settings (0 to 2.44 m/s).
- Enter the design criteria for the industry at junction 9 using the bottom window. In the **Demand Adjustment** tab, use the button to select junction 9 from the drawing by clicking on the J-9 junction, then the green check in the **Select** dialog. Enter 1,500 l/min into the **Additional Demand** window. In the **Pressure Constraints** tab, again select J-9 from the drawing then click the box in the **Override Defaults?** window, then enter 275 kPa and 550 kPa for the minimum and maximum pressures.
- Now the software is told which pipes are to be designed. Pipes with similar properties can be grouped together and will be designed the same, or the software can analyze each pipe separately. In this case, the software will analyze each pipe separately. From the problem statement, all pipes will be considered except P-12 and P-13, which are the pipes from the reservoir and pump. On the **Design Groups** tab, click the button to select all the pipes. A table with all the pipes should appear, but if not highlight "<All Available>" in the **Selection Set** window, then click **OK**. In the table, delete pipes P-12 and P-13 to remove them from the analysis.

- The pipe material, properties, and costs to be used in this design scenario are entered in the **Cost/Properties** tab. Open the new pipe table by highlighting **New Pipe** in the window, then select **Design Option Groups** under the New button. Rename "New Pipe-1" to "New Ductile Iron Pipe". Enter the pipe type, diameter, and cost per linear meter from the table in the problem statement. The Hazen-Williams C is 130 for ductile iron pipe. To change the units for the pipe cost, right-click the column heading **Unit Cost**, then select **Units and Formatting**. In the **Unit** field, select **$/m**, then click **OK.**
- The objective of this scenario is to size the pipes to deliver the required flow while maintaining reasonable pressures throughout the network at the minimal design cost. To do this, select the **Minimize Cost** criteria in the **Objective Type** window located in the **Design Type** tab.
- After the design criteria is entered, you can start the simulation by right-clicking on the New Design Study-1 in the left window to select **New Optimized Design Run**. Now you could perform many different types of design runs by selecting different design events or design groups to be analyzed. Since we have only one design run in this demonstration, you will not have to compare different potential design solutions. In many cases, different solutions will need to be compared to evaluate which would be best for a specific case. The left window helps organize these different solutions.
- On the **Design Events** tab, you can select the design criteria to be evaluated. In this case there is only one choice.
- On the **Design Groups** tab, select the ductile iron properties and cost that were entered. The data in entered in the **Design Option Group** column. Since all designed pipe will come from the same ductile iron table, you can enter the data as a global edit. Right-click the **Design Option Group** field and select **Global Edit**. Select the "New Ductile Iron Pipe" in the **Value** window. Click **OK** then all the Design Option Group fields should automatically fill in.
- The **Options** tab allows the Darwin Designer parameters to be adjusted. In this case the default values will be used.
- To start the run, click the **Compute** button in the Darwin Design toolbar. When the run is completed, close the **Designing...** window. The top three solutions will be listed under the "New Optimized Design Run" in the left window.

## Answer

A summary table of the three solutions is shown by clicking the **Solutions** folder and beneath this are tables that have the determined pipe diameters for each solution. In this example, the minimal pipe cost is $217,382. A summary of each solution cost and the design pipe diameters for Solution 1 are shown in the tables below. The pipe diameters range from 75 to 300 mm and the cost for each pipe is determined based on the expected pipe length. Opening **Solution 1** and selecting the **Simulated Results** tab, the calculated pressure at the industry (J-9) is 275.48 kPa, just within the required range.

It also should be noted that there are a number of 75 mm (3 in) pipes in this solution, and the pipe connecting the network to the tank (P-14) is only a 200 mm (8 in) pipe. If this solution was evaluated for fire flow conditions, it is likely that these pipes would not deliver the required fire flow. Further simulations should be conducted on this solution to ensure that this design can deliver the required flow during a fire event.

*Darwin Designer Solutions*

| Solution | Total Cost ($) |
|---|---|
| Solution 1 | 217,382 |
| Solution 2 | 218,687 |
| Solution 3 | 220,548 |

*Pipe Diameters and Costs for Solution 1*

| Pipe | Diameter (mm) | Cost ($) |
|---|---|---|
| P-3 | 250 | 25,812 |
| P-10 | 200 | 23,887 |
| P-6 | 200 | 23,887 |
| P-14 | 200 | 23,808 |
| P-11 | 200 | 23,808 |
| P-8 | 150 | 17,049 |
| P-4 | 150 | 17,049 |
| P-9 | 200 | 15,872 |
| P-7 | 150 | 12,744 |
| P-2 | 75 | 12,298 |
| P-1 | 75 | 12,096 |
| P-5 | 75 | 9,072 |

## *Tutorial 5 – Model Calibration using Darwin Calibrator*

WaterGEMS has the ability to use measured field data to calibrate the model. In many cases, data that are entered into the model are an approximation or guess. When the model results do not match field data, then parameters in the model are adjusted. Also, the Darwin Calibrator with field data can be used to locate potential differences between the real network and the model which could be caused by problems in the system (blockages, closed valves, etc.).

### Problem Statement

Adjust the Hazen-Williams C factor (roughness factor) for pipes P-2, P-1, and P-8 for the pipe network from Tutorial 2. During the field measurements, the tank level was 3.93 meters, the pump was off, and a hydrant with a measured flow of 3,400 l/min at junction 7 (J-7) was opened to increase the head loss in the pipe network. The measured field data is shown in the table below.

*Field Data with Hydrant open*

| Junction | Pressure (kPa) |
|---|---|
| J-7 | 296.0 |
| J-6 | 406.5 |
| J-1 | 263.5 |
| J-2 | 327.0 |

### Solution

- Open Tutorial 2.
- From the **Analysis** menu, select **Scenarios**. Create a new base scenario named "Calibrator Analysis".
- Click on the **Calculation Options** tab at the bottom of the window. Create a new Calculation Option by clicking the **New** button and enter "Calibrator Calculation Options" as the name. Double-click the calculation options you just created. The **Time Analysis Type** is **Steady State.**
- Go back to the **Scenarios** tab and right-click the Calibrator Analysis scenario and select **Make Current**. The red check should now be on the Calibrator Analysis scenario. Double-click on the Calibrator Analysis scenario and select the Calibrator Calculation Options in the **Calculation Options** field. Click the **Compute** button.
- Click the **Darwin Calibrator** button to create a calibration study to determine the pipe roughness factors. Click the **New** button to select **New Calibration Study**. Check to make sure the **Representative Scenario** window has Calibrator Analysis selected.
- Enter the field data in the **Field Data Snapshots** tab. Click the **New** button to enter new data. Enter the measured pressures on the **Observed Target** tab. Select the junctions from the drawing by clicking the select button then clicking junctions J-7, J-6, J-1, and J-2 from the drawing. Click the green check ✓ in the **Select** dialog. Select Pressure (kPa) for each junction in the **Attribute** field. Enter the measured pressure for each junction in the **Value** field.
- Enter the tank level in the **Boundary Overrides** tab. Select the tank from the drawing by clicking the select button then clicking the tank. Click the green check ✓ in

the **Select** dialog. Select **Tank Level (m)** in the **Attribute** field, then enter 3.93 m in the **Value** field.

- To make sure the pump is off, click the **New** button in the **Boundary Overrides** tab. Select the pump by clicking the select button, then clicking the pump. Click the green check in the **Select** dialog. Select **Pump Status** in the **Attribute** field, then select **Off** in the **Value** field.
- Enter the additional demand at junction 7 in the **Demand Adjustments** tab. Select this junction from the drawing by clicking the select button, then clicking J-7. Click the green check in the **Select** dialog. Enter 3,400 l/min in the **Value** field.
- Select the pipes where the roughness values are to be determined in the **Roughness Groups** tab. Pipes with similar roughness can be grouped together, or the software can analyze each pipe separately. In this case, the software will determine the pipe roughness values for P-2, P-1, and P-8 separately, and pipes P-3 and P-7 will be grouped since we assume they are both 200 mm (8 in) ductile iron pipe, and we do not have any field measurements isolating these pipes. Click the **New** button, then the **Ellipse** button in the **Elements** field. Click the select button, and then pipe P-2 from the drawing. Click the green check in the **Select** dialog. Click **OK** to enter this pipe into the table. Repeat these steps to add pipes P-1 and P-8 to the table. You should have three defined roughness groups in the table on the **Roughness Groups** tab.
- Add the grouped pipes by clicking the **New** button, then the **Ellipse** button in the **Elements** field. Click the select button, then pipes P-3 and P-7 from the drawing. Click the green check in the **Select** dialog. Click **OK** to enter these pipes into the table as a group. There should now be four roughness groups in the table on the **Roughness Groups** tab.
- The calibration method settings are found on the **Calibration Criteria** tab. In this case, these setting will be left as the default settings.
- To use this data to determine the pipe roughness values, create a new run by clicking the **New** button above the left window then select **New Optimized Run**.
- The pipe roughness values are assumed to have a range between 5 and 140 for each pipe. This is wide range and any chokes (blockages, partially closed valves, etc.) in a pipe could greatly reduce the pipe roughness value. It is not expected that any roughness value above 140 would not be observed for ductile iron pipe. On the **Roughness** tab in the **Operation** field, **Set** should be selected; the expected minimum and maximum roughness values are entered in the **Minimum Value** and **Maximum Value** fields. Enter the increment for the software to analyze the roughness values by entering 5 into the **Increment** field. Other increments could be used.

- For this simulation, the top 5 solutions will be displayed. To do this, click the **Options** tab and enter 5 into the **Solutions to Keep** field.
- To start the run, click the **Compute** button in the Darwin Calibrator toolbar. When the run is completed, close the **Calibration...** window. The top five solutions will be listed under the "New Optimized Run" in the left window.

**Answer**

The fitness values of the five solutions are shown by clicking the **Solutions** folder. In this example, the fitness values ranged from 0.280 to 0.303 where a lower fitness value indicates a "better" solution. A summary of each solution with the determined roughness values are shown in the table below. To view the determined roughness values for the "best" solution, click the **Solution 1** summary and highlight **Roughness** in the **Adjustments Results** window under the **Solutions** tab. To view the observed and simulated Hydraulic Grade Line (HGL), click the **Simulated Results** tab.

*Darwin Calibrator Solutions*

| Solution | Roughness Value | | | |
|---|---|---|---|---|
| | P-2 | P-1 | P-8 | P-3 and P-7 |
| Solution 1 | 115 | 55 | 140 | 100 |
| Solution 2 | 120 | 55 | 140 | 100 |
| Solution 3 | 100 | 45 | 140 | 110 |
| Solution 4 | 115 | 55 | 125 | 100 |
| Solution 5 | 125 | 55 | 140 | 100 |

These results indicate that pipes P-2, P-8, and the grouped pipes P-3 and P-7 have a roughness value that is about what would be expected for the installed ductile iron pipe. However, the results for pipe P-1 show that the roughness value is much lower. This could indicate a partially closed valve, the pipe is blocked, or that the pipe diameter may be smaller than expected. In this case, pipe P-1 should be investigated to determine the cause of this low roughness value. If there is a problem and that problem was fixed, new field measurements should be taken.

These roughness values can be entered into the model and further simulations can be conducted. With enough field data, a model that closely simulates the actual system can be created. Keep in mind that many times the person doing the modeling must decide what values to put into the model. The software can only calculate values based on what is entered. The person doing the modeling must judge how accurate the model is and whether the model can be used to make decisions.

## 6.11 Problems

Solve the following problems using the WaterGEMS computer program.

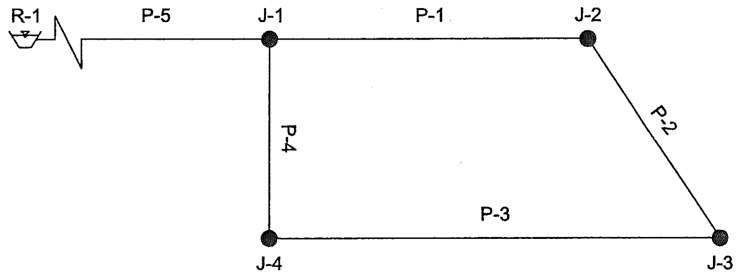
1. The ductile iron pipe network shown below carries water at 20°C. Assume that the junctions all have an elevation of 0 m and the reservoir is at 30 m. Use the Hazen-Williams formula ($C = 130$) and the pipe and demand data below to perform a steady-state analysis and answer the following questions:

   a) Which pipe has the lowest discharge? What is the discharge (in l/min)?

   b) Which pipe has the highest velocity? What is the velocity (in m/s)?

   c) Calculate the problem using the Darcy-Weisbach equation ($k = 0.26$ mm) and compare the results.

   d) What effect would raising the reservoir by 20 m have on the pipe flow rates? What effect would it have on the hydraulic grade lines at the junctions?



*Schematic for Problem 1*

*Pipe and Junction Information for Problem 1*

| Pipe | Diameter (mm) | Length (m) |
|---|---|---|
| P-1 | 150 | 50 |
| P-2 | 100 | 25 |
| P-3 | 100 | 60 |
| P-4 | 100 | 20 |
| P-5 | 250 | 760 |

| Junction | Demand (l/min) |
|---|---|
| J-1 | 570 |
| J-2 | 660 |
| J-3 | 550 |
| J-4 | 550 |

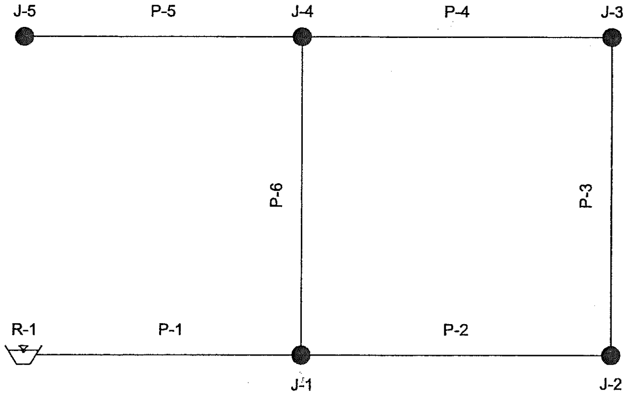
---

2. A pressure gage reading of 288 kPa was taken at J-5 in the pipe network shown below. Assuming a reservoir elevation of 100 m, find the appropriate Darcy-Weisbach roughness height (to the hundredths place) to bring the model into agreement with these field records. Use the same roughness value for all pipes. The pipe and junction data are shown below.

   a) What roughness factor yields the best results?

   b) What is the calculated pressure at J-5 using this factor?

   c) Other than the pipe roughnesses, what other factors could cause the model to disagree with field-recorded values for flow and pressure?



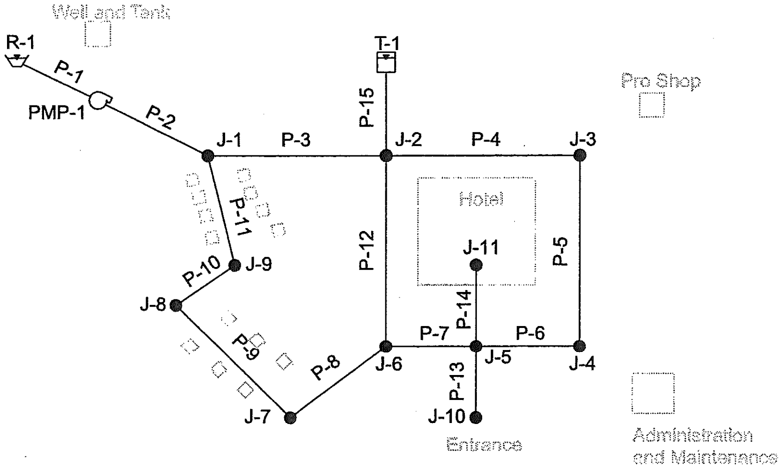
*Schematic for Problem 2*

*Pipe and Junction Information for Problem 2*

| Pipe | Diameter (mm) | Length (m) |
|---|---|---|
| P-1 | 250 | 1,525 |
| P-2 | 150 | 300 |
| P-3 | 150 | 240 |
| P-4 | 150 | 275 |
| P-5 | 150 | 245 |
| P-6 | 200 | 230 |

| Junction | Elevation (m) | Demand (l/min) |
|---|---|---|
| J-1 | 55 | 950 |
| J-2 | 49 | 1,060 |
| J-3 | 58 | 1,440 |
| J-4 | 46 | 1,175 |
| J-5 | 44 | 980 |

3. A distribution system is needed to supply water to a resort development for normal usage and emergency purposes (such as fighting a fire). The proposed system layout is shown in the following figure:



*Proposed Network for Problem 3*

The source of water for the system is a pumped well. The water is treated and placed in a ground-level tank (shown above as a reservoir because of its plentiful supply), which is maintained at a water surface elevation of 210 ft. The water is then pumped from this tank into the rest of the system.

The well system alone cannot efficiently provide the amount of water needed for fire protection, so an elevated storage tank is also needed. The bottom of the tank is at 376 ft (high enough to produce 35 psi at the highest node), and the top is approximately 20 ft higher. To avoid the cost of an elevated tank, this 80-ft diameter tank is located on a hillside, 2,000 ft away from the main system. Assume that the tank starts with a water surface elevation of 380 ft.

The pump was originally sized to deliver 300 gpm with enough head to pump against the tank when it is full. Three defining points on the pump curve are as follows: 0 gpm at 200 ft of head; 300 gpm at 180 ft of head; and 600 gpm at 150 ft of head. The pump elevation is assumed to be the same as the elevation at J-1, although the precise pump elevation is not crucial to the analysis.

The system is to be analyzed under several demand conditions with minimum and maximum pressure constraints. During normal operations, the junction pressures should be between 35 psi and 80 psi. Under fire flow conditions, however, the minimum pressure is allowed to drop to 20 psi. Fire protection is being considered both with and without a sprinkler system.

**Demand Alternatives:** WaterGEMS enables you to store multiple demand alternatives corresponding to various conditions (such as average day, peak hour, etc.). This feature allows you run different scenarios that incorporate various demand conditions within a single project file without losing any input data. For an introduction and more information about scenarios and alternatives, see WaterGEMS's online help system and Appendices A and B.

***Junction Information for Problem 3***

| Junction | Elevation (ft) | Average Day (gpm) | Peak Hour (gpm) | Minimum Hour (gpm) | Fire with Sprinkler (gpm) | Fire without Sprinkler (gpm) |
|---|---|---|---|---|---|---|
| J-1 | 250 | 0 | 0 | 0 | 0 | 0 |
| J-2 | 260 | 0 | 0 | 0 | 0 | 0 |
| J-3 | 262 | 20 | 50 | 2 | 520 | 800 |
| J-4 | 262 | 20 | 50 | 2 | 520 | 800 |
| J-5 | 270 | 0 | 0 | 0 | 0 | 800 |
| J-6 | 280 | 0 | 0 | 0 | 0 | 800 |
| J-7 | 295 | 40 | 100 | 2 | 40 | 40 |
| J-8 | 290 | 40 | 100 | 2 | 40 | 40 |
| J-9 | 285 | 0 | 0 | 0 | 0 | 0 |
| J-10 | 280 | 0 | 0 | 0 | 360 | 160 |
| J-11 | 270 | 160 | 400 | 30 | 160 | 160 |

**Pipe Network:** The pipe network consists of the pipes listed in the following tables. The diameters shown are based on the preliminary design, and may not be adequate for the final design. For all pipes, use ductile iron as the material and a Hazen-Williams $C$-factor of 130.

***Pipe Information for Problem 3***

| Pipe | Diameter (in) | Length (ft) |
|---|---|---|
| P-1 | 8 | 20 |
| P-2 | 8 | 300 |
| P-3 | 8 | 600 |
| P-4 | 6 | 450 |
| P-5 | 6 | 500 |
| P-6 | 6 | 300 |
| P-7 | 8 | 250 |
| P-8 | 6 | 400 |

| Pipe | Diameter (in) | Length (ft) |
|---|---|---|
| P-9 | 6 | 400 |
| P-10 | 6 | 200 |
| P-11 | 6 | 500 |
| P-12 | 8 | 500 |
| P-13 | 6 | 400 |
| P-14 | 6 | 200 |
| P-15 | 10 | 2000 |

To help keep track of important system characteristics (like maximum velocity, lowest pressure, etc.), you may find it helpful to keep a table such as the following:

***Results Summary for Problem 3***

| Variable | Average Day | Peak Hour | Minimum Hour | Fire with Sprinkler | Fire without Sprinkler |
|---|---|---|---|---|---|
| Node w/ low pressure<br>Low pressure (psi) | | | | | |
| Node w/ high pressure<br>High pressure (psi) | | | | | |
| Pipe w/ max. velocity<br>Max. velocity (ft/s) | | | | | |
| Tank in/out flow (gpm) | | | | | |
| Pump discharge (gpm) | | | | | |

Another way to quickly determine the performance of the system is to color-code the pipes according to some indicator. In hydraulic design, a good performance indicator is often the velocity in the pipes. Pipes consistently flowing below 0.5 ft/s may be oversized. Pipes with velocities over 5 ft/s are fairly heavily stressed, and those with velocities above 8 ft/s are usually bottlenecks in the system under that flow pattern. Color-code the system using the ranges in the table below. After you define the color-coding, place a legend in the drawing.

***Color-Coding Range for Problem 3***

| Max. Velocity (ft/s) | Color |
|---|---|
| 0.5 | Magenta |
| 2.5 | Blue |
| 5.0 | Green |
| 8.0 | Yellow |
| 20.0 | Red |

a) Fill in or reproduce the Results Summary table after each run to get a feel for some of the key indicators during various scenarios.

b) For the average day run, what is the pump discharge?

c) If the pump has a best efficiency point at 300 gpm, what can you say about its performance on an average day?

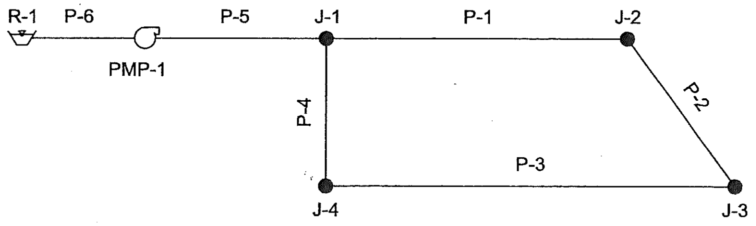
d) For the peak hour run, the velocities are fairly low. Does this mean you have oversized the pipes? Explain.

e) For the minimum hour run, what was the highest pressure in the system? Why would you expect the highest pressure to occur during the minimum hour demand?

f) Was the system (as currently designed) acceptable for the fire flow case with the sprinkled building? On what did you base this decision?

g) Was the system (as currently designed) acceptable for the fire flow case with all the flow provided by hose streams (no sprinklers)? If not, how would you modify the system so that it will work?

4. A ductile iron pipe network ($C = 130$) is shown below. Use the Hazen-Williams equation to calculate friction losses in the system. The junctions and pump are at an elevation of 5 ft and all pipes are 6 in. in diameter. (Note: Use a standard, 3-point pump curve. The data for the pump, junctions, and pipes are in the tables below.) The water surface of the reservoir is at an elevation of 30 ft.



*Schematic for Problem 4*

***Pump Information for Problem 4***

| Head (ft) | Flow (gpm) |
|---|---|
| 200 | 0 |
| 175 | 1,000 |
| 100 | 2,000 |

*Junction Information for Problem 4*

| Junction Label | Demand (gpm) |
|---|---|
| J-1 | 400 |
| J-2 | 550 |
| J-3 | 550 |
| J-4 | 350 |

*Pipe Information for Problem 4*

| Pipe Label | Length (ft) |
|---|---|
| P-1 | 78 |
| P-2 | 40 |
| P-3 | 90 |
| P-4 | 39 |
| P-5 | 10 |
| P-6 | 10 |

a) What are the resulting flows and velocities in the pipes?

b) What are the resulting pressures at the junction nodes?

c) Place a check valve on pipe P-3 such that the valve only allows flow from J-3 to J-4. What happens to the flow in pipe P-3? Why does this occur?

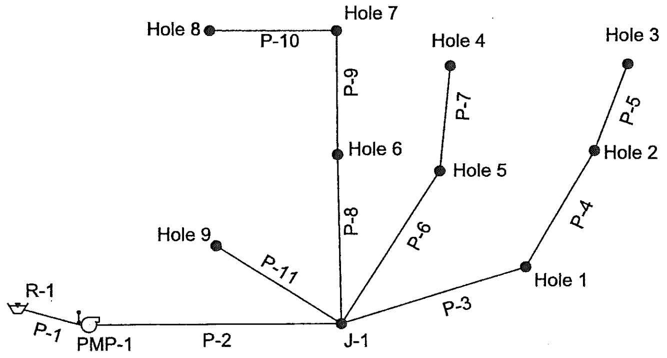
d) When the check valve is placed on pipe P-3, what happens to the pressures throughout the system?

e) Remove the check valve on pipe P-3. Place a 6-in flow control valve node at an elevation of 5 ft on pipe P-3. The FCV should be set so that it only allows a flow of 100 gpm from J-4 to J-3 (Hint: a check valve is a pipe property). What is the resulting difference in flows in the network? How are the pressures affected?

f) Why doesn't the pressure at J-1 change when the FCV is added?

g) What happens if you increase the FCV's allowable flow to 2,000 gpm? What happens if you reduce the allowable flow to zero?

5. A local country club has hired you to design a sprinkler system that will water the greens of their nine-hole golf course. The system must be able to water all nine holes at once. The water supply has a water surface elevation of 10 ft. All pipes are PVC ($C = 150$, use the Hazen-Williams equation to determine friction losses). Use a standard, three-point pump curve for the pump, which is at an elevation of 5 ft. The flow at the sprinkler is modeled using an emitter coefficient. The data for the junctions, pipes, and pump curve are given in the tables that follow. The initial network layout is shown below.



*Schematic for Problem 5*

*Junction and Pipe Information for Problem 5*

| Junction Label | Emitter Coefficient ($gpm/psi^{0.5}$) | Elevation (ft) |
|---|---|---|
| J-1 | - | 10 |
| Hole 1 | 8 | 7 |
| Hole 2 | 10 | 7 |
| Hole 3 | 15 | 40 |
| Hole 4 | 12 | 5 |
| Hole 5 | 8 | 5 |
| Hole 6 | 8 | 15 |
| Hole 7 | 10 | 20 |
| Hole 8 | 15 | 10 |
| Hole 9 | 8 | 12 |

| Pipe Label | Diameter (in) | Length (ft) |
|---|---|---|
| P-1 | 4 | 10 |
| P-2 | 4 | 1,000 |
| P-3 | 4 | 800 |
| P-4 | 3 | 750 |
| P-5 | 3 | 500 |
| P-6 | 3 | 700 |
| P-7 | 2 | 400 |
| P-8 | 4 | 800 |
| P-9 | 3 | 500 |
| P-10 | 2 | 400 |
| P-11 | 2 | 500 |

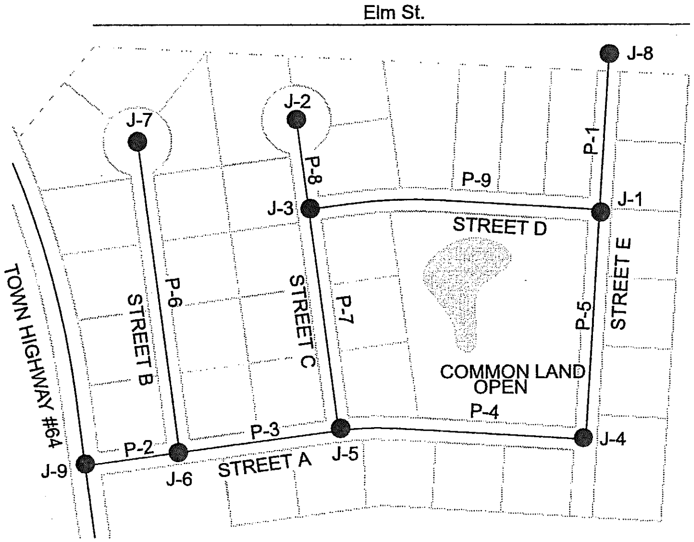
***Pump Information for Problem 5***

| Head (ft) | Flow (gpm) |
|---|---|
| 170 | 0 |
| 135 | 300 |
| 100 | 450 |

a) Determine the discharge at each hole.

b) What is the operating point of the pump?

6. A subdivision of 36 homes is being constructed in a new area of town. Each home will require 1.7 l/s during peak periods. All junction nodes are 192 m in elevation. All pipes are ductile iron ($C = 130$, use the Hazen-Williams Equation to determine the friction losses in the pipe). The current lot and network layout is shown below.



***Schematic for Problem 6***

***Junction and Pipe Information for Problem 6***

| Junction Label | Number of Lots Serviced |
|---|---|
| J-1 | 5 |
| J-2 | 4 |
| J-3 | 4 |
| J-4 | 5 |
| J-5 | 6 |
| J-6 | 6 |
| J-7 | 6 |

| Pipe Label | Length (m) | Diameter (mm) |
|---|---|---|
| P-1 | 60.0 | 150 |
| P-2 | 60.0 | 150 |
| P-3 | 110.5 | 150 |
| P-4 | 164.0 | 150 |
| P-5 | 152.5 | 150 |
| P-6 | 204.0 | 100 |
| P-7 | 148.0 | 150 |
| P-8 | 61.0 | 100 |
| P-9 | 194.0 | 150 |

Currently, a model of the entire water system does not exist. However, hydrant tests were conducted using hydrants located on two water mains, one in Town Highway #64 and the other in Elm Street. The following data were obtained:

Town Highway #64 Hydrant Test
Static Pressure 310.3 kPa
Residual Pressure 98.5 kPa at 32 l/s
Elevation of Pressure Gauge 190 m

Elm Street Hydrant Test
Static Pressure 413.7 kPa
Residual Pressure 319.3 kPa at 40 l/s
Elevation of Pressure Gauge 191.5 m

The subdivision will connect to existing system mains in these streets at nodes J-8 and J-9. (Hint: Model the Connection to an Existing water Main with a reservoir and a pump.)

a) What are the demands at each of the junction nodes? What is the total demand?

b) Does the present water distribution system have enough capacity to supply the new subdivision?

c) Which connection to the existing main is supplying more water to the subdivision? Why?

d) Are the proposed pipe sizes adequate to maintain velocities between 0.15 m/s and 2.44 m/s, and pressures of at least 140 kPa?

e) Would the subdivision have enough water if only one connection were used? If so, which one?

f) What do you think are some possible pitfalls of modeling two connections to existing mains within the same system, as opposed to modeling back to the water source?

7. Use the pipe sizes given in the table below for the subdivision in Problem 6.

*Pipe Information for Problem 7*

| Pipe Label | Diameter (mm) |
|---|---|
| P-1 | 200 |
| P-2 | 150 |
| P-3 | 150 |
| P-4 | 150 |
| P-5 | 150 |
| P-6 | 150 |
| P-7 | 150 |
| P-8 | 150 |
| P-9 | 150 |

City ordinances require the following:

The pressure at the fire flow discharge and at other points in the distribution system cannot fall below 125 kPa during a fire flow of 34 l/s. (Hint: The total flow at the fire flow node does not need to include the baseline demand.)

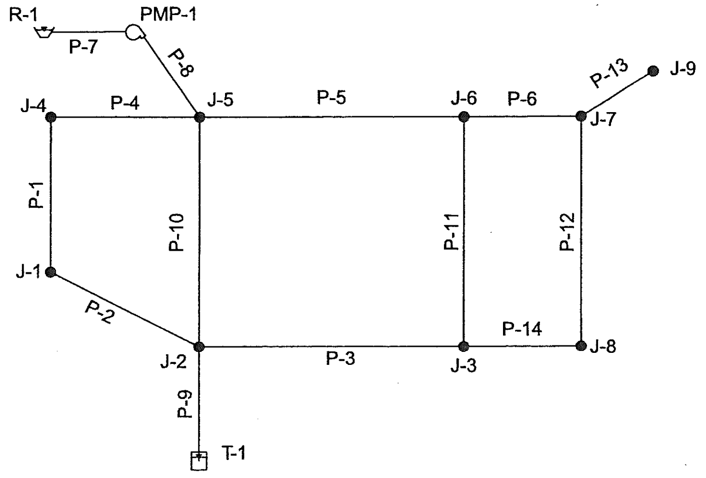
a) If a residential fire occurs at J-7, would the current system be able to meet the fire flow requirements set by the city?

b) If not, what can be done to increase the available flow to provide adequate fire flow to that hydrant?

c) If a fire flow is placed at J-4, does the system meet the requirements with the proposed improvements? Without the proposed improvements?

8. A local water company is concerned with the water quality within its water distribution network. They want to determine the age and the chlorine concentration of the water as it exits the system at different junctions. The water surface at the reservoir is 70 m.

Chlorine is injected into the system at the source of flow, R-1, at a concentration of 1 mg/l. It has been determined through a series of bottle tests that the average bulk reaction rate of the chlorine in the system (including all pipes and tanks) is approximately –0.5 /day.



*Schematic for Problem 8*

The cylindrical tank has a diameter of 15 m. The base and minimum elevations are 99 m. The maximum elevation is 104 m, and the initial elevation is 103.4 m.

*Pump Information for Problem 8*

| Head (m) | Discharge (l/min) | Controls |
|---|---|---|
| 40 | 0 | Off if node T-1 above 103.5 m<br>On if node T-1 below 100.5 m |
| 35 | 3,000 | |
| 24 | 6,000 | |

*Stepwise Demand Pattern Data for Problem 8*

| Time from Start (hr) | Multiplier | Time from Start (hr) | Multiplier |
|---|---|---|---|
| 0 | 0.80 | 13 | 1.30 |
| 1 | 0.60 | 14 | 1.40 |
| 2 | 0.50 | 15 | 1.50 |
| 3 | 0.50 | 16 | 1.60 |
| 4 | 0.55 | 17 | 1.80 |
| 5 | 0.60 | 18 | 1.80 |
| 6 | 0.80 | 19 | 1.40 |
| 7 | 1.10 | 20 | 1.20 |
| 8 | 1.50 | 21 | 1.00 |
| 9 | 1.40 | 22 | 0.90 |
| 10 | 1.30 | 23 | 0.80 |
| 11 | 1.40 | 24 | 0.80 |
| 12 | 1.40 | | |

*Junction Data for Problem 8*

| Junction | Elevation (m) | Demand (l/min) |
|---|---|---|
| J-1 | 73 | 151 |
| J-2 | 67 | 227 |
| J-3 | 81 | 229 |
| J-4 | 56 | 219 |
| J-5 | 67 | 215 |
| J-6 | 73 | 219 |
| J-7 | 55 | 215 |
| J-8 | 84 | 180 |
| J-9 | 88 | 151 |

*Pipe Data for Problem 8*

| Pipe | Length (m) | Diameter (mm) | Roughness |
|---|---|---|---|
| P-1 | 300 | 200 | 130 |
| P-2 | 305 | 200 | 130 |
| P-3 | 300 | 200 | 130 |
| P-4 | 200 | 200 | 130 |
| P-5 | 300 | 300 | 130 |
| P-6 | 200 | 200 | 130 |
| P-7 | 1 | 300 | 130 |
| P-8 | 5,000 | 300 | 130 |
| P-9 | 300 | 300 | 130 |
| P-10 | 500 | 200 | 130 |
| P-11 | 500 | 200 | 130 |
| P-12 | 500 | 200 | 130 |
| P-13 | 150 | 150 | 130 |
| P-14 | 200 | 200 | 130 |

a) Perform an age analysis on the system using a duration of 300 hrs and a time step of 2 hrs. Fill in the results table, indicating the maximum water age at each junction and tank after the system reaches equilibrium (a pattern of average water age vs. time becomes evident). What point in the system generally has the oldest water? Explain why the water is oldest at this location.

b) Perform a constituent analysis using the same duration and time step as in part (a). Fill in the results table, indicating the minimum chlorine concentration for each junction and tank after the system has reached equilibrium (a pattern of concentration versus time becomes evident). What point in the system has the lowest chlorine concentration? Explain why the chlorine residual is lowest at this location.

***Results Table for Problem 8***

| **Junction** | **J-1** | **J-2** | **J-3** | **J-4** | **J-5** | **J-6** | **J-7** | **J-8** | **J-9** | **T-1** |
|---|---|---|---|---|---|---|---|---|---|---|
| Age (hours) | | | | | | | | | | |
| Chlorine Concentration (mg/l) | | | | | | | | | | |

c) From the above table and graphs of demand, age, and concentration versus time generated within WaterGEMS, determine the following correlations:

1) Age and chlorine concentration

2) Demand and chlorine concentration at a junction

3) Demand and water age at a junction

d) Why is it necessary to run the model for such a long time? Do you feel that 300 hours is too long or too short a time period for testing the model? Why?

9. A planning commission has indicated a new industry may be connected to the water system described in Problem 8. You are to determine the pipe diameters in the network to minimize the installation cost assuming all the pipes are ductile iron. Use the Darwin Designer to determine the total cost and size each pipe for each of the following conditions. Use the pipe cost information from Tutorial 4 for the ductile iron pipe.

a) Size the pipes using a demand multiplier (peaking factor) of 3.2. The pressure must remain between 170 and 550 kPa during peak demand. Exclude pipes P-7 and P-8 in your analysis when determining the pipe sizes. Hint: you will need to specify an additional demand of zero (0 l/min) with the default pressure constraints at the junctions or a fatal error will occur.

b) It is expected that a new industry with an expected additional demand of 2,000 l/min with a required minimum pressure of 260 kPa will be added to the system. It could be tapped into the network at either junction 6, 7, or 8. Size the pipes for the conditions in part a above along with the industry added to all proposed junctions. You will need to analyze the network three times, once for the industry at J-6, again with the industry at J-7, then finally with the industry at J-8.

a. Indicate which option(s) would work.

b. Which junction should the industry be tapped into to be the least costly and what is the expected cost?

c. What is the size of each pipe for the best solution for the least costly option with the industry added?

d. What is the calculated minimum pressure at the industry for the best solution?