U.S. Fire Administration

Water Supply Systems and Evaluation Methods

Volume II: Water Supply Evaluation Methods

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Water Supply Systems and Evaluation Methods

Volume II: Water Supply Evaluation Methods

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Acknowledgement

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About the Author

Dr. Harry E. Hickey's career in fire protection spans more than 50 years. He taught Fire Protection Engineering at the University of Maryland for 26 years. He also has extensive experience in the fire service as a firefighter, fire officer, and emergency coordinator. His combination of municipal fire administration and fire protection engineering experience gives him unique insight into the challenges of design and operation of municipal water supplies.

He received his Ph.D in Public Administration from American University in Washington, DC. He has authored many book and articles including *Public Fire Safety, A Systems Approach*; *Fire Protection Hydraulics*; and two editions of *The Fire Suppression Rating Schedule Handbook*.

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Chapter 1: Evaluating Municipal Water Distribution Systems

Primary Considerations

This topic has two primary objectives: The first is to understand the evaluation of an installed municipal water supply delivery system by identifying all the physical components of any specific water distribution system. The same basic concepts and principles apply to small community water systems and large city water systems. For a basic understanding of these concepts, two illustrations are provided that include a relatively small water distribution system and a medium size water distribution system. These concepts will cover 92 percent of all the water supply systems in the United States. While there are similarities to all water systems, it should be recognized that the likelihood of two water systems being exactly alike in physical features is remote because the raw water sources in relation to the water delivery demands can hardly be the same.

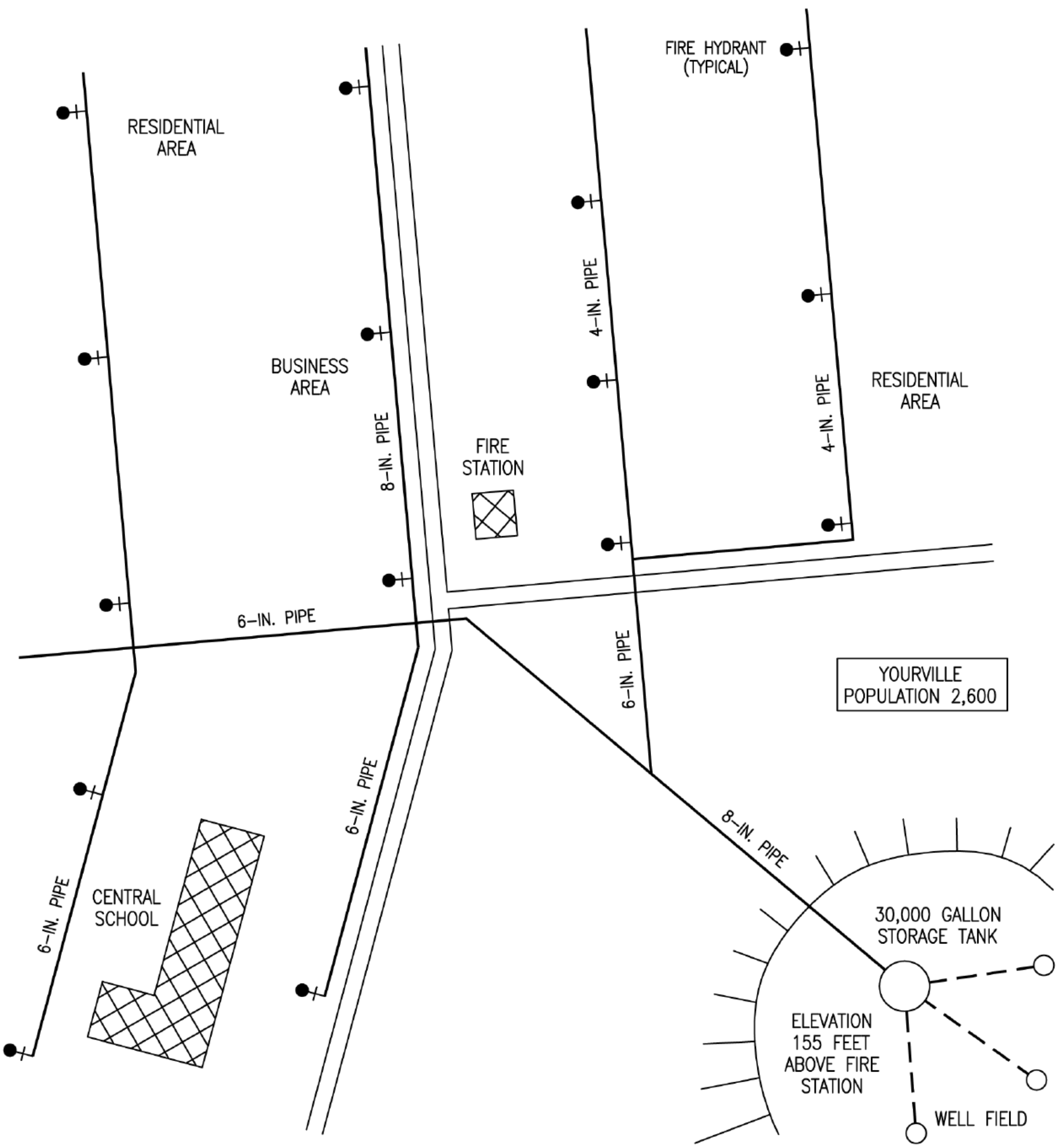
The second objective is to provide recognized practices for conducting water supply tests at prescribed intervals to measure the water system delivery capability and ensure that the system is meeting the water supply demand. An important part of this second objective is to use the results of water supply tests to monitor the performance of the water delivery system in relation to the existing water supply and the constant changes in demand on the water system. The following material will illustrate the broad features of water supply systems in order to understand how this can be accomplished. Chapter 2 presents a basic understanding of hydraulic fundamentals needed to accomplish water supply testing and evaluation accurately, and Chapter 3 presents water supply system evaluation methods for determining existing water supplies for consumer consumption and especially for fire protection

Functional Components of a Water Utility System

A water utility system can be relatively simple for a community of 3,000 to 5,000. At this level of population, communities often are served by wells. The well water is treated typically by chlorination and then either pumped directly into water distribution mains to supply customers or pumped into ground-level or elevated storage tanks where the water flows by gravity on demand to each customer on the water system. Some fire hydrants **may be** located on the distribution system to provide a minimum fire flow capability in the range of 250 gallons per minute (gpm) to 500 gpm. **Figure 1-1** illustrates an actual example of a community that has these characteristics.

Figure 1-1

Features of a Small Community Water Distribution System



As the population served in the illustration of a small community increases, so does the complexity of the water delivery system. **Figure 1-2** depicts the functional components expected to be in place in communities with populations ranging from 25,000 to 50,000. (Reference #1, pg. 12) This is fairly typical of what one needs to understand in evaluating water supply systems to assure that rates of water can be delivered through the distribution system to simultaneously meet consumer consumption demands and meet Needed Fire Flow (NFF) criteria for structural fire suppression. Therefore, before specifically examining and tracing the water system component diagramed in **Figure 1-2**, it is essential that each component be evaluated in relationship to the capability of the water delivery system, plus the function of selected components of the water system to meet the needed domestic and fire protection demands on the system. This needs to be assessed for each and every water system as a function of **rates of water usage**. Three historical or predicted water demand rates are involved in the discussion of consumer demand and fire protection: (Reference #2, pg. 12)

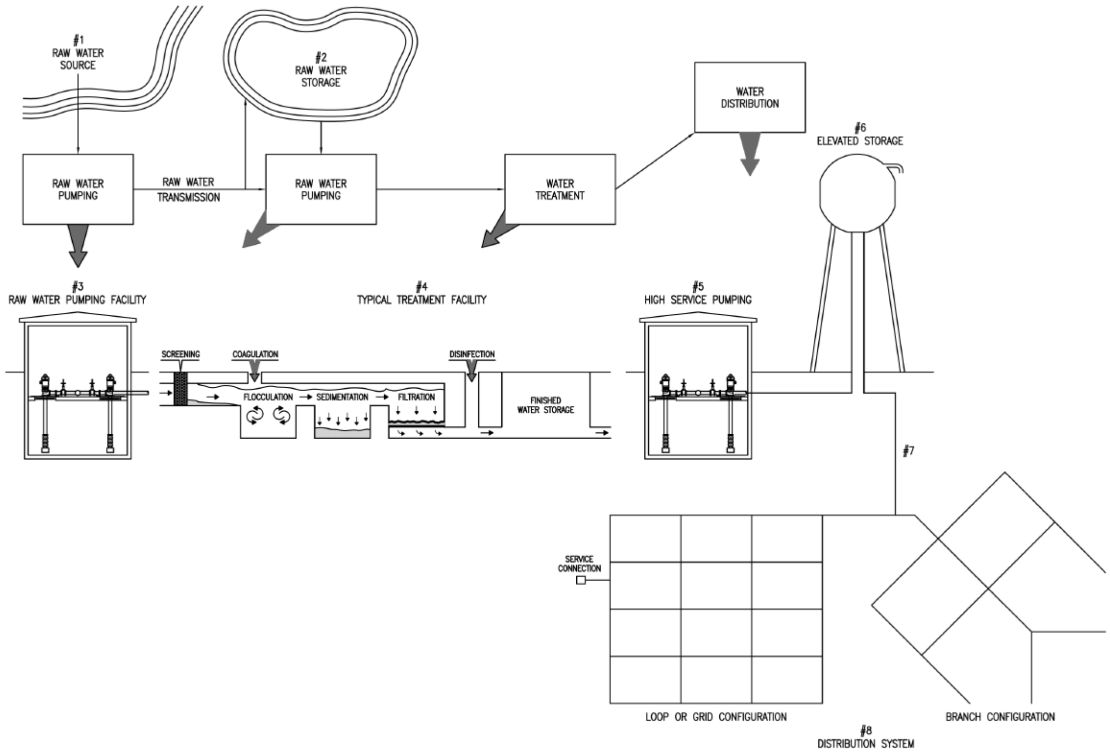
- **Average daily demand**–the average of the total amount of water used each day during a 1-year (designed) period.

- **Maximum daily demand**–the maximum total amount of water used during any 24-hour period. The Insurance Services Office. Inc. (ISO) bases this calculation on the highest demand during the previous 3 years from the years of an ISO *Grading Schedule* evaluation. Note: This number should consider and exclude any unusual and excessive uses of water that would affect the calculation i.e., a broken water main.

- **Maximum hourly demand**–the maximum amount of water used in any single hour of any day in a 3-year period. It normally is expressed in gallons per day by multiplying the actual peak hour by 24.

Figure 1-2

Features of a Minimum Size Community Water Distribution System



When specific data on past consumption levels are not available, a good rule of thumb is that maximum daily demand may vary from 1.5 to 3.0 times the average daily demand, while the peak hourly rate may vary from 2 to 8 times the average daily rate. In small water systems, peaking factors may vary significantly higher.

Design flow and analysis should be based on the maximum hourly demand or the maximum daily demand plus the fire flow requirement, whichever is greater. This distribution system should be designed to maintain a minimum pressure of 20 pounds per square inch (psi) at **all** water taps including fire hydrant locations under all conditions of design flow.

[This is a recommended practice of the American Water Works Association (AWWA) *Manual of Water Supplies Practices*–M-31 and M-17 along with criteria published by the ISO in accordance with Grading Schedule evaluations.]

In order to account for system demands, chart recorders should be in place at every separate location where **purified water** enters the distribution system, including finished water holding basins, direct pumping facilities, finished water standpipe tanks, and finished water gravity tanks. This is the only reasonably accurate way to monitor water system demand on an hourly, or less frequent, time period, 24 hours a day, 365 days a year. This is a key consideration in matching water system demand to water system availability.

Tracing the Components of an Urban Water Distribution System

The following information is presented in the context of **Figure 1-2.** (Reference #1, pg. 12)

1. Raw water source shown in the upper left of the drawing marked #1.

   The water source may be a lake, a river, a reservoir, a well field, or, more recently, salt water sources which can be purified through new techniques in water filtration and reverse osmosis. The Tampa, Florida, municipal water system now has the capability of producing 60 percent of the city's water demand using salt water. The AWWA recommended guideline on raw water capability is that the supply source(s) have a sufficient capacity at all time to meet maximum daily demand for a continuous period of 5 days. (Reference #1, pg. 12) This is demonstrated on the drawing by a raw water storage pond marked #2.

   Water Department action needed: A depth gauge is needed on each raw water source. A hydrologist or geologist needs to asses the gallons of water in storage at gauge level. There typically is not an equal drop or increase as water is drawn off or is supplemented by rain and runoff, due to the slope of the container sides and the slope of the bottom of the holding basin. This monitoring needs to be done daily if a diminishing supply is observed, to predict long-term supply conditions.

2. Typical raw water pumping facility marked #3.

   In the case of the illustrated water system, the pumping facility has a dual purpose. First it can pump the raw water, which is filtered by trash racks (coarse screws) and other finer screening, if necessary, to the treatment facility where the water is processed to meet Environment Protection Agency (EPA) criteria and even more rigid requirements for water treatment in several States through State health departments. Second, there needs to be the capability to transfer water to and from the raw water storage facility. This builds reliability into the water system. Constant-recording flow meters are needed on each of the pumps in this facility to assess how and when water is being transported through facility and the rate of water in gpm.

   Water Department action needed: The secondary raw water storage facility is important for retaining a reserve supply of water in case of a major pipe failure on the distribution piping, or if the main source of water become depleted due to drought conditions or contamination of the primary supply.

3. The treatment facility marked #4.

   Chapter 6 covers the basic of water supply treatment and the sampling of water required to meet EPA criteria. There is a need to know the maximum water processing rate and the length of time that water can be processed at this rate, because this could limit water delivery to the distribution piping system. Process flow rates need to be monitored on a continuous timeline, which also will account for the downtime in the treatment plant to flush and clean equipment.

   Note in the illustration that a **finished water** facility is provided on the delivery side of the treatment plant; this is commonly called a clear well. In gravity feed systems, water flows from the clear well(s) into the distribution piping, or it is pumped where the land surface is relatively level. Water levels in the clear well(s) needed to be monitored closely on a daily basis with data recorded hourly.

4. A high service pumping station marked #5.

   Note that this pumping station is located on the water distribution delivery side of the water treatment plant. High-level service pumps may be needed to:

   a. Pump water up to service areas that have higher elevations than other areas of a community.

   b. Fill gravity tanks that float on the water supply distribution system.

   c. When service pumping stations are used to distribute water, and no water storage is provided, the pumps force water directly into the water mains. From a water system evaluation perspective, there is no outlet for the water except as it furnishes consumer consumption for actual fire flows. Variable speed pumps or multiple pumps may be required to provide adequate water delivery service because of fluctuating demands. The efficiency and expense of this pumping equipment needs to be considered carefully. For example, it is a disadvantage that the peak power demand of the water plant is likely to occur during periods of high electrical consumption, and thus increase power costs. Furthermore, systems with little or no storage should be provided with standby electrical generating capability or pumps driven directly by internal combustion engines. These standby generators and engines needs to be tested routinely (e.g., several hours per week).

5. A gravity storage facility marked #6.

   An extremely important element in a water distribution system is water storage. (Reference #3, pg. 12) System storage facilities have a far-reaching effect on a system's ability to provide adequate consumer consumption during periods of high demand while meeting fire protection requirements. The two common storage methods are ground-level storage and elevated storage. The finished water storage at number 4 on **Figure 1-2** is an example of ground-level storage; this type of storage also may be contained in covered tanks. Emphasis is put on elevated storage as a stand-alone in Chapter 7 of this Manual.

6. Water entering the distribution system marked #7.

   There are two basic types of pipe layout for delivering water to consumer taps and to supply water to individual fire hydrants. The preferred method is to loop the entire service area with a primary feeder main; the size is determined by hydraulic analysis. Interior to the ring main are cross-connected secondary feeders provided along the major streets in the community. Interior water mains that essentially provide water to residential areas are cross-connected to the secondary feeders. The advantages of this type of pipe system layout are two fold: 1) the water to every service location or demand point is supplied from two directions, which is considered to be the most efficient hydraulic design to minimize pipe sizes; and 2) in the event that a pipe section is out of service for cleaning, breakage from an accident, tapping for service extension, or whatever reason, water can be supplied to any demand point from a different travel path. In older community water systems a single primary feeder supplies secondary feeders and distributor pipes along block fronts in a branched layout configuration where at any demand point water is supplied from one direction only. This arrangement decreases the reliability of a water system significantly and has a tendency to decrease fire flow capability for larger scale fires. The capability of water main systems for meeting fire flow criteria can be determined only by semiannual fire flow tests as presented below.

Specific Considerations

Figure 1-2, discussed above, provides a conceptual layout of a typical water distribution system and highlights the features of this system that require evaluation on a frequency ranging from hourly to annually. A number of water system features need to be examined more specifically in relation to providing adequate and reliable water supplies for fire protection. The following topics need to be considered carefully in the evaluation of any given water supply system, not only for consumer consumption but especially for meeting model building code required water supplies and/or the ISO's NFF for public-sector fire protection.

Distribution System Storage: An extremely important element in a water distribution system is water storage. System storage facilities have a far-reaching effect on a water system's ability to provide adequate and reliable water supplies for domestic needs and especially for fire protection. Storage within a distribution system enables the system to process water at times when treatment facilities otherwise would be idle. It then is possible to distribute and store water at one or more locations in the service area which are closer to the end user, and provide the needed volume of water at a minimum of 20 psi residual pressure on fire hydrants to meet fire flow demands. The considerations presented below need to be evaluated carefully for any given municipal water delivery system.

1. Advantages: The principal advantages of distribution storage include the fact that storage equalizes demands on supply sources, production works, plus transmission and distribution mains. As a result, the sizes or capacities of these elements need not be so large. Additional system flows and pressures are improved and stabilized to better serve the customers throughout the service area. Finally, reserve supplies are provided in the distribution system for emergencies, such as fire suppression and power outages.

2. Meeting system demands and required/NFF: In the evaluation of both existing and needed water supply storage, it is essential to consider the location, capacity, and elevation (if elevated) of distribution storage in relation to system demands and the variation of demands that occur throughout the day in different parts of the system. System demands can be determined only after a careful analysis of an entire distribution system. However, some general rules may serve as a guide to such an analysis. **Table 4-1** in Chapter 4 lists daily and hourly variations for a typical city and the resultant storage depletion. (Reference #4, pg. 12) Such data are of great assistance in determining the adequacy of storage capacities. This type of analysis needs to be performed for each water system because each has its own requirements. Studies show that it is more advantageous to provide several smaller storage units in different parts of the water system than to provide an equivalent capacity at a central location. Smaller pipelines are required to serve decentralized storage and, other things being equal, a lower flow-line elevation and pumping head or pressure results.

3. Comparing and contrasting ground storage and elevated storage: Storage within the distribution system network normally is provided in one of two ways: ground-level storage with high-service pumping, and elevated storage. It is noted by the AWWA that elevated storage provides the best, most reliable, and most useful form of storage, **particularly** for fire protection. (Reference #5, pg. 12)

a. Ground-level storage: Since water kept in ground-level storage is not under pressure, it must be delivered to the point of use by pumping equipment. This arrangement limits water system effectiveness for fire protection in three ways: 1) There must be sufficient excess pumping capacity to deliver the peak demand for normal uses as well as any fire demands; 2) Standby power sources and standby pumping units must be maintained at all times because the system cannot function without the pumps; and 3) The distribution lines at all points in the system must be significantly oversized to handle peak delivery use plus fire flow, no matter where a fire might occur.

b. Elevated storage: Properly sized elevated water tanks provide dedicated fire storage and are used to maintain constant system pressure. Where elevated tanks are used, ground storage tanks **may** still be required to provide water to the water treatment plant based on the type of system design. However, the size of the ground storage tank(s) can be reduced to the minimum required to treat the water adequately, usually in the 300,000- to 500,000-gallon range. The elevated storage tanks are used to store treated water to provide water directly to the water distribution system. What needs to be evaluated with elevated storage is that the water supply is fed to the distribution system from the top 10 to 15 feet of water in the elevated tank(s). The high-service pumps are constant-speed pump units, which can operate at their highest efficiency point virtually all the time. The remaining water in the tanks (70 to 75 percent) normally is held in reserve as dedicated fire storage. When domestic consumption is at a minimum during a 24-hour period, water in the gravity tank is recycled with fresh treated water to eliminate aging of the water in the holding tank. (Reference #6, pg. 12)

4. Pumping for distribution storage: The two types of distribution storage (i.e., ground level and elevated) have, in turn, two types of pumping systems that need to be evaluated on a performance basis. One is a direct pumping system, in which the instantaneous system demand is met by pumping with no elevation storage provided. The second type is an indirect system in which the pumping station lifts water to a reservoir or elevated storage tank, which floats on the water system and provides system pressure by gravity. Some comments on each pumping system are in order:

   a. Direct pumping: The direct pumping system is being phased out for municipal water delivery systems primarily because of operating costs. However, many older systems, especially for smaller communities, still exist. Variable-speed pumping units operated off direct system pressure are also in use in some communities. Hydropneumatic tanks at the pumping station provide some storage. These tanks permit the pumping-station pumps to start and stop, based on a variable-system pressure preset by controls operating off of the tank.

   b. Indirect pumping: In an indirect system, the pumping station is not associated with the demands of the major load center. It is operated from the water level difference in the reservoir or elevated storage tank, enabling the prescribed water level in the tank to be maintained. The majority of systems have an elevated storage tank or reservoir on high ground floating on the system. This arrangement permits the pumping station to operate at a uniform rate, with the storage either making up or absorbing the difference between station discharge and system demand.

Evaluating Distribution System Appurtenances

1. Piping and valve arrangement.

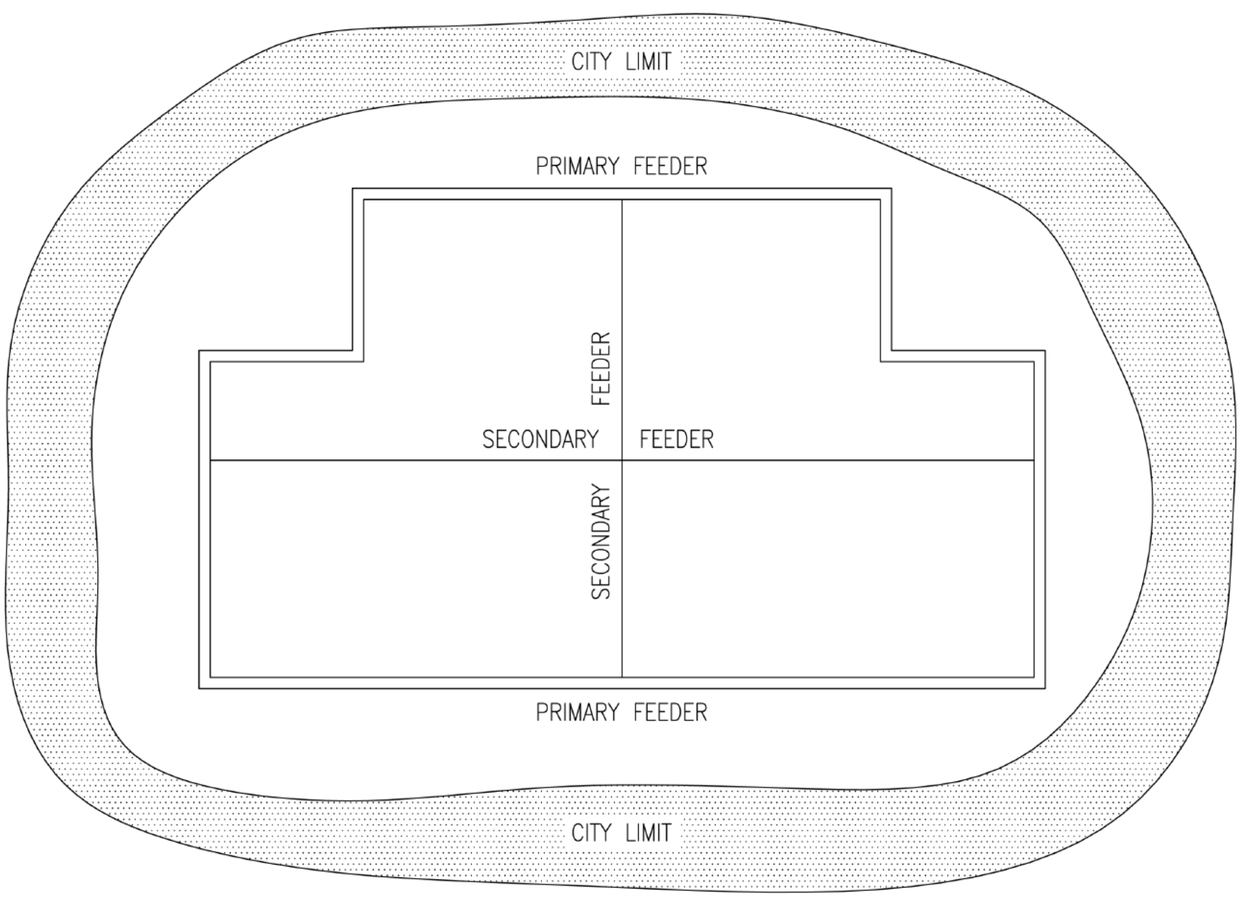
   A piping system serving the consumers in a small community is illustrated in **Figure 1-3**. The primary feeders, sometimes called arterial mains, form the skeleton of the distribution system. They are located so that large quantities of water can be carried from the pumping plant to and from the storage tanks and the distribution system. (Reference #7, pg. 12)

   Primary feeders should be arranged in several interlocking loops, with the mains not more than 3,000 feet apart. Looping allows continuous service as previously identified through the rest of the primary mains, even when one portion is shut down temporarily for repairs. Under normal conditions, looping also allows supply from two directions for large fire flows. Large feeders and long feeders should be equipped with **blow-off valves** at low points and **air relief valves** at high points. Valves should be placed so that a pipe break will affect water service **only** in the immediat area of the break.

Figure 1-3

Typical Small City Distribution System

(Reference #7, pg. 12)



The secondary feeders carry large quantities of water from the primary feeders to points in the system in order to provide for normal domestic consumption supply and fire suppression. They form smaller loops within the loops of the primary mains by running from one primary feeder to another. Secondary feeders should be spaced only about three blocks apart, or a maximum of 1,500 feet. This spacing allows concentration of large amounts of water for firefighting without excessive head loss and resulting low pressure.

Small distribution mains (i.e., distributors) are to form a grid over the area to be served. They supply water to residential taps and fire hydrants along residential block fronts throughout areas with this occupancy classification. In no case should the pipe size be less than 6 inches in diameter. Larger size pipes may be needed in residential areas for multiple occupancy buildings. In this case, pipe sizing is based on the sum of the peak day water use plus fire-flow requirements. Where there are multiple-occupancy buildings of more than one floor, required pipe sizing is almost always controlled by the fire-flow requirement.

Water distribution piping should be sized and spaced to meet design flow. The minimum size water main for providing fire protection and serving fire hydrants is 6 inches in diameter. Typical values for distribution system piping are summarized in **Table 1-2**. (Reference #8, pg. 12)

Table 1-2

Values Commonly Used in Distribution Piping

Appurtenance	Minimum Standard
Lines	
Smallest pipes in network	6 inch
Smallest branching pipes (dead ends)	8 inch
Largest spacing of 6” grid (8” pipe used beyond this value)	600 ft.
Smallest pipes in high-value district	8 inch
Smallest pipes on principal streets in central district	12 inch
Largest spacing of supply mains or feeders	3,000 ft.
Valves	
Spacing in single and dual main systems:	
Largest spacing on long branches	800 ft.
Largest spacing in high-value district	500 ft.

2. Fire hydrant locations.

All areas served by a water distribution system should have fire hydrants installed in locations and with spacing for fire department use. The following method of locating fire hydrants should be observed in the United States. This method is outlined in Section 614 of the the ISO *Fire Suppression Rating Schedule*–2003 edition. (Reference #9, pg. 12) [Sidebar: Canada uses an area method.]

Briefly summarized, the procedure examines a representative fire-risk location and a computed NFF at that location. The first determination is that a recognized fire hydrant be within 1,000 feet of the fire risk, as fire hose is laid from the fire hydrant to the fire risk. A recognized fire hydrant on a municipal water system must flow a minimum of 250 gpm at 20 psi residual pressure for 2 hours.

The actual flow capability from each fire hydrant in the vicinity of the fire risk is limited by the distance to the fire risk as follows: (Reference #9, pg. 12)

Credit is awarded up to 1,000 gpm from each hydrant within 300 feet of the fire-risk building; 670 gpm from hydrants within 301 to 600 feet of the fire-risk building; and 250 gpm from hydrants within 601 to 1,000 feet of the fire-risk building.

Furthermore, the water utility should review hydrant spacing or representative fire risks in the community with the responsible first-due fire company because the supply hose capacity on fire apparatus may limit the credit assigned by ISO to this item in the *Fire Suppression Rating Schedule*.

The pipe connecting the fire hydrant to the water main is call the **hydrant branch** or **lateral**. Every lateral needs to have an installed valve to enable the water utility to isolate the fire hydrant for repair or general maintenance.

In addition, fire department use typically requires a maximum lineal distance between fire hydrants along street fronts in commercial and congested built-up areas of 300 feet, and 600 feet for light single-family residential areas. Good practice calls for fire hydrants at intersections, in the middle of a block where the NFF equals or exceeds 1,200 gpm, and at the end of dead-end streets.

Summary Statement on Water Supply Distribution

Water supply distribution systems are rather straightforward to evaluate in small communities with a population range up 5,000. The proper evaluation of water supplies and distribution for larger communities, up to cities over 100,000 population, is no simple thing. Water system maps that are kept current and electronic graph records for all of the water supply that enters the distribution system are **essential** to establish an understanding of actual supply versus consumption on an hourly basis, daily basis, monthly basis, and yearly basis. If this information is not in place, the first step to the evaluation of a water system is to put in place a records management system, and then to pay close attention to this system. The water utility has the responsibility to keep public officials, especially fire officials, apprised of the current conditions of the water system. This topic paints the **big picture** for developing and maintaining a comprehensive evaluation of a water system.

References:

1. Mays, Larry W. *Water Distribution Systems Handbook*. New York: McGraw-Hill, 1999, pg. 18.
2. American Water Works Association. *Distribution System Requirements for Fire Protection*, AWWA–M-31. Denver: Author, 1999, pg. 16.
3. *ibid*., pg. 25.
4. *ibid*., pg. 24.
5. *ibid*., pg. 25.
6. *ibid*., pg. 24.
7. *ibid*., pg. 19.
8. *ibid*., pg. 20.
9. Insurance Services Office. *Fire Suppression Rating Schedule*. Jersey City: Author, 2003.

Chapter 2: Fundamental Concepts of Hydraulics Applied to Municipal Water Supply Systems

Overview

The design and evaluation of municipal water supply systems is based on both theoretical and applied hydraulics. Hydraulics is the branch of science that defines the mathematical laws of liquids at rest and in motion. This text material is confined to fundamental principles and what is generally referred to as **applied hydraulics**. These fundamentals are essential for understanding many of the considerations involved in the design of a municipal water supply system, the periodic testing of water systems, and the proper evaluation of water systems to assess a given community's water supply with respect to providing adequate water supplies.

A municipal water supply system has the objective of providing an adequate and reliable water supply to meet the following demands:

- residential occupancy water consumption;
- commercial occupancy water consumption;
- industrial occupancy consumption;
- municipal and educational building use;
- Needed Fire Flows (NFFs) that are available from a planned location of fire hydrants throughout the municipality; and
- water for special community needs that include parks and recreation, street cleaning, decorative water fountains, sale of water to contractors through metered water from fire hydrants, etc.

The primary objective of the following material is to present the fundamental concept of hydraulics applied to municipal water systems, in order for municipal officials and fire officials to better understand the design and evaluation of public-sector water delivery systems. Some fundamental hydraulic problems are provided to establish principles used to meet the above objective. A number of tables and charts are provided for future reference by the user of this material in actually working with a specific water supply system.

A supporting objective is to stimulate a more accurate and clearer perception of field practices in evaluating water systems. These practices and procedures need to be based on a fundamental understanding of basic hydraulics. Finally, there are a number of computer-based programs available for the design and evaluation of water pipe systems. One has to understand the fundamentals of water flow in pipe networks to assess whether the computer output is providing reasonably accurate results and to use the computer output to identify significant problems with a water system.

Accomplishment of these objectives requires that operational definitions, concepts, and procedures associated with the science of fluid mechanics and hydraulic theory be related carefully to the subject area of water supply hydraulics. The topics presented below are not unduly difficult, and only a basic understand of algebra is needed to feel comfortable with the level of mathematics presented. Interpretations of the fundamental laws of fluid mechanics are placed in the context of familiar water supply applications so that the reader can quickly establish the relevance of the topics to practical water delivery system concerns.

OPERATIONAL DEFINITIONS

The following definitions provide meaning to terms used throughout the entire text. Other special terms applicable to specific topics will be defined in the subsequent subject matter.

1. Fluid mechanics is the term that defines the physical behavior of fluid systems and the physical laws that describe this behavior. (Reference #1, pg. 46)

   It has broad application in water system design and analysis, and encompasses the behavior of compressible and incompressible fluids, with the primary attention given to water as the fluid under consideration. Such fluids include plain water, water mixed with one or more additives to produce low-expansion foam for both Class A and Class B fires, high-expansion foam, aqueous-film-forming foam (AFFF), carbon dioxide, Halon® and clean-agent extinguishing fluids, and an array of synthetic agents. However, this text material concentrates on municipal water systems and therefore **water** is the only fluid medium discussed in this text.

2. Liquids are fluids that have a definite volume independent of the shape of the container. (Reference #2, pg. 46)

   In conditions of constant temperature and pressure, a liquid will assume the shape of its container and fill a portion equal to the liquid in volume. In most conditions, liquids are considered noncompressible; that is, their volume does not change appreciably under pressure, or with change in temperature. A liquid exposed to atmospheric pressure has a free-standing surface, which means that it seeks its surface level, providing a constant surface datum plane or reference line for calculation. This applies to water storage in a gravity tank, standpipe tank, or other water-holding container. For practical reasons, when the liquid is water, calculations are performed using the **assumption** of a temperature of 70 °F (21 °C) unless there is a sound engineering reason to use a higher or lower temperature because of local climatic conditions.

3. Atmospheric pressure is created by the weight of the atmosphere on the earth. (Reference #3, pg. 46)

   Municipal water systems definitely are affected by atmospheric pressure in relationship to the elevation above sea level. Water contained in pressure tanks on some water systems is an exception. At sea level, atmospheric pressure is 14.7 psi, or 29.9 inches of mercury (Hg), commonly referred to as **one** atmosphere. Atmospheric pressure diminishes with elevation above sea level in accordance with the values depicted in **Table 2-1.**

Table 2-1

Atmospheric Pressure and Elevation

Elevation Above Sea Level	Atmospheric Pressure	
Feet	Psi	Hg (in.)
0	14.7	29.9
1,000	14.2	29.9
2,000	13.7	28.9
3,000	13.2	27.9
4,000	12.7	25.8
5,000	12.2	24.8
6,000	11.8	24.0
7,000	11.3	23.0
8,000	10.9	22.2
9,000	10.5	21.4
10,000	10.1	20.6

4. Hydraulics: The science of hydraulics defines the differential in water head (feet) or the mechanical principles that contribute to placing water at rest or water in motion. (Reference #4, pg. 46)

5. Hydrostatics is the science of water at rest. (Reference #5, pg. 46)

   The scientific laws of hydrostatics defines the principles of water at rest. An excellent example of a hydrostatic condition on a water supply system is where a water storage tank is connected to a water supply pipe using a control valve to be opened on demand. The weight of the water in the storage tank causes pressure on the control valve. The calculation of the pressure on the tank side of the control valve is a hydrostatic problem.

6. Hydrokinetics is the science of water in motion. (Reference #6, pg. 46)

   When a fire hydrant is opened with a cap removed from a discharge spout, the flowing water is a hydrodynamics problem. Hydrodynamics is a general term associated with the science of forces exerted on the pipe wall when water is flowing through a pipe, or the flowing pressure when a quantity of water is discharging from an open pipe or from an orifice device connected to the pipe, such as a fire hydrant opening. The potential energy (i.e., static pressure) becomes kinetic energy (i.e., residual pressure). The weight of the water based on the elevation head supply at the fire hydrant causes the water to move through the piping system and out of the fire hydrant discharge opening. Calculating the water supply and the pipe to supply fire hydrants is also a problem of hydrokinetics.

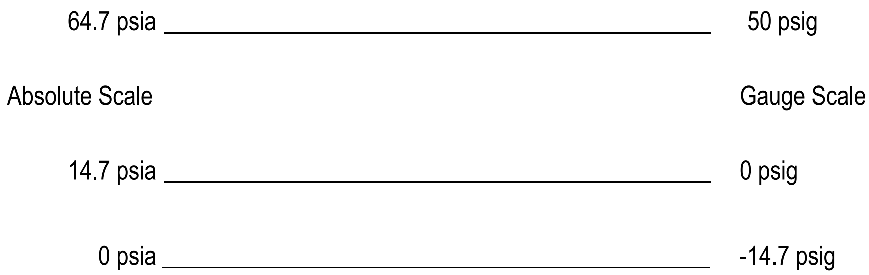
7. Hydrodynamics is a general term associated with the science of forces exerted by water in motion. (Reference #7, pg. 46) The term generally is applied to hydraulic considerations of fire pumps, but also connotes problems involving the relation of flow, pressure head, and velocity head for closed systems.

8. Absolute pressure (pounds per square inch absolute (psia)): Absolute pressure is the sum of atmospheric pressure (14.7 pounds per square inch (psi)) and the pressure recorded on a gauge (psig). (Reference #8, pg. 46)

   In other words, atmospheric pressure plus gauge pressure equals absolute pressure. Absolute pressure must be evaluated when a liquid is confined by a pressure vessel, and positive or negative pressure forces are exerted on the surface of the liquid. The most common example of this condition is the use of water storage tanks that are under pressure to supply water to pipe lines without a pump interface. Absolute pressure also can be examined from another perspective. Since atmospheric pressure at sea level is 14.7 psi, it is obvious that a gauge pressure reading of minus 14.7 psi represents no pressure. This condition is called absolute zero or 0 psia: 14.7-14.7=0, and provides a reference from which pressure can be measured.

   The relationship of atmospheric and absolute pressures is presented in **Figure 2-1**.

Figure 2-1



It is impossible to make a pressure measurement on the earth's surface unless it is made relative to atmospheric pressure. Therefore, a reference can be established at the atmospheric pressure level, as indicated in **Figure 2-1**. If the pressure one wishes to measure is at the same level, there will be zero pressure relative to atmospheric pressure. Pressure gauges, piezometers, and other pressure-flow measuring devices indicate **gauge** pressure.

Atmospheric pressure is equal to zero pressure on a gauge, often abbreviated as psig on gauges calibrated to register pounds per square inch. Gauge pressures are positive if greater than atmospheric, and negative if less than atmospheric, or measured down from the atmospheric reference. Negative pressure also is called a vacuum.

Vacuum

A perfect vacuum is a space entirely devoid of gas, liquids, and solids. (Reference #9, pg. 46) The literature on this subject indicates that only the National Aeronautics and Space Administration (NASA) in space has ever succeeded in exhausting all the air from a closed vessel. This applies to suction pipes on stationary fire pumps. Therefore, the word **vacuum** actually means **practical vacuum**, and is measured by the amount of this pressure below the prevailing atmospheric pressure. Vacuum is measured by **gauges** graduated in inches of mercury (Hg).

Physical Characteristics of Water

Water is the only fluid considered in this text material. Therefore, it is important to define its physical characteristics and properties that affect hydraulic calculations involving both public and private water supply systems. The following characteristics should be considered for all calculations involving water supply systems.

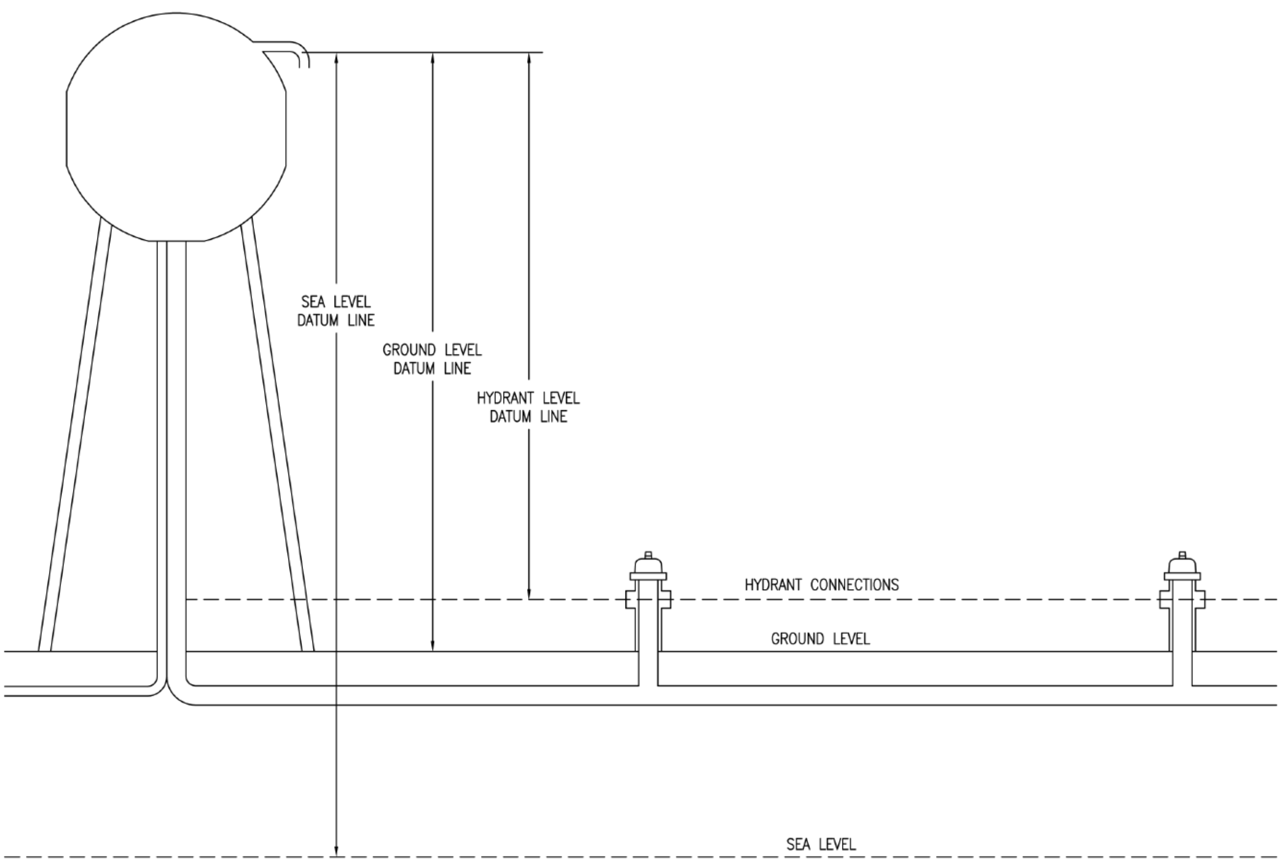
Datum Line

A datum line is a line designating the potential energy of water; also a line that serves as the basis for mathematical computations. (Reference #10, pg. 46)

Water is a colorless liquid that takes the shape of the container in which it is placed. The top surface of the water seeks its own level and, therefore, is flat for practical considerations. The top level of the water in a container is often referred to as the **surface datum line**. The measurement is given in feet above sea level, or some other reference point. This concept is illustrated in **Figure 2-2**. Note that the underground pipe reference line may change with time if water is being used from the holding tank. In hydrokinetic problems, the water surface datum line is often referenced as the potential energy line.

Figure 2-2

Water Service Datum Line



Water has weight, normally expressed in pounds per cubic foot, (lb/ft^3) or kilograms per liter, (kg/L). A commonly used value for fresh water is 62.4 lb/ft^3. This constant is based on the weight of a cubic foot of water when the water temperature is 50 °F (10 °C), the pressure is atmospheric, and the water has been treated for human consumption. Therefore, it should be recognized that the water varies with temperature, pressure, and impurities or additives.

Figure 2-3

Variation of Weight With Temperature

Temperature (Degrees F)	Weight (lb/ft^3)	Temperature (Degrees F)	Weight (lb/ft^3)
32	62.416	75	62.261
40	62.423	80	62.217
45	62.419	85	62.169
50	62.408	90	62.118
55	62.390	95	62.061
60	62.198	100	61.998
65	62.000	150	61.203
70	62.000	200	60.135

Variation With Weight and Pressure

Pressure (psi)	Weight (lb/ft^3)	Pressure (psi)	Weight (lb/ft^3)
0	62.40	20,000	62.82
1,000	62.421	30,000	63.02
10,000	62.81	65,000	68.60

Note: These figures are approximate, as compressibility also varies with pressure.

Variation of Weight With Impurities

Source	Weight (lb/ft^3)
Garonne River, France	62.409
Thames River, England	62.419
Mississippi River, U.S. (filtered)	62.415
Springs, West Virginia	62.419 to 62.77
Pacific Ocean	64.05
Dead Sea	73.17

Note: Weight of water variations around the globe.

Figure 2-3 illustrates the effect of these three variables on the weight of a **cubic foot** of water. With the exception of variations due to impurities, the magnitude of variations is negligible. For practical hydraulic calculation of water supply problems, the weight of water is considered to be 62.5 lb/ft^3. However, for more precise calculations, this average condition value must be replaced by the actual measured value when experimental work is being conducted.

Fundamental Characteristics of Water as a Fluid Medium

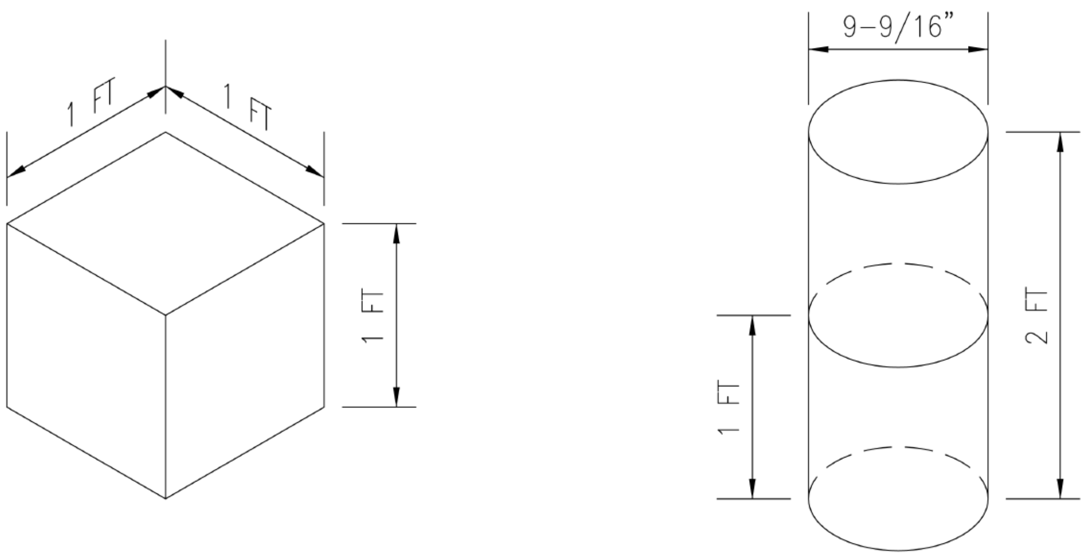
The preceding material has established that liquids in general have a definite volume but no definite shape. It is important to consider the volume of water in different shaped containers that have equal volumes.

EQUAL VOLUMES

Figure 2-4 shows a tank with a volume of 1 cubic foot (ft^3) that measures 1 linear foot on each surface edge. When the container is filled, it will hold 1 ft^3 of water. In contrast, the cylinder shown has a diameter of 13-9/16 inches, giving a computed cross-sectional area of one square foot (ft^2). Now consider that the liquid is poured from the cube into the cylinder.

Figure 2-4

Cubical and Cylindrical Tank Volume Comparison



How high will the liquid rise in the cylindrical container? This can be determined from Formula 1:

Formula 1 Volume=Base Area x Height

Height=Volume/Base Area=1 ft^3/1ft^2=1 ft

Therefore, when the base areas are equal, equal volumes of liquid will rise to the same height, even though the containers have dissimilar shapes.

References:

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3. Wood, Clyde M., CE. *Automatic Sprinkler Hydraulic Data*. Cleveland: Automatic Sprinkler Corporation of America, pg. 3-1.
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25. *ibid.*, pg. 567.
26. Rusk, *op. cit.*, pg. 168.
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28. King, Horace, and Ernest Brater. *Handbook on Hydraulics for the Solution of Hydrostatic and Fluid Flow Problems*. New York: McGraw-Hill Book Company, Inc., pg. 6.

29. *ibid*., pg. 4.

30. *ibid*., pg 31.

31. Wood, *op. cit*., pg. 3-11.

32. *ibid*.

Chapter 3: Evaluating Existing Water Supplies for Fire Protection Delivery Capability

A Water Supply Effectiveness Issue

Fire marshal's offices and insurance adjuster's offices are filled with reports that read like the following:

The LOSS REPORT: Fire was discovered on the second floor of the Hamilton Elevator Company at 10:45 p.m. The second floor served as the product finishing area and painting area before the elevator cage components were assembled. Fire was showing through an outside window on the street side when the first Engine Company arrived at the fire site. A 2-1/2 inch line was stretched to the fire floor for the initial fire attack. However, the lack of water from the fire hydrant supply resulted in a weak and ineffective fire steam. Due to the lack of an effective water supply the interior of the building was a total loss. The loss to the building is estimated to be $960,000.00 and the estimated content loss was set at $780.000.00 by the Insurance Adjuster. (American Mutual Insurance Alliance) (Note: The company name has been changed to prevent specific identification in accordance with privacy legislation.)

Without adequate and reliable water supplies at fire hydrants to protect fire risks, the best-trained firefighters with the best of equipment have only a very limited opportunity of protecting lives in a building fire and confining, controlling to the area of origin, and extinguishing a hostile fire. Therefore, it is essential that community officials, from the highest ranking administrator/manager, to the water department superintendent or an equal authority, and the ranking fire chief, provide means and opportunity to monitor the community water system's performance capability constantly. (Reference #1, pg. 65)

Determining Existing Community Water Supply Adequacy and Reliability

A community water supply system is one of the most important factors in both public and private fire protection. Fire departments and fire protection engineers, as well as those responsible for the design, operation, and maintenance of water systems, are concerned with two aspects of the total water supply system: its adequacy and its reliability.

Adequacy, in the case of a water system supplying water for normal consumer consumption and for fire protection, means having the capability of simultaneously supplying water for maximum consumption demands plus water that may be needed to combat and extinguish a major fire within the area served by the water system. Adequacy concerns itself with sufficient flow and pressure on all installed fire hydrants on the water system; the minimum residual pressure on each fire hydrant under flow conditions is to be 20 pounds per square inch (psi) residual pressure. (References #2 and 3, pg. 65)

Reliability of a community water system is having the capability of supplying the maximum daily consumption plus a required fire-flow demand, even in the event of a malfunction or the outage of important system components, such as a pipeline break, valve failure, power outage, or stationary pump outage. Reliability is a more subjective evaluation and requires both a **what-if** look at the water system and a determination of what to do about the **what-if** happening. (Reference #4, pg. 65)

Today, the reliability of community water systems has to be extended to the consideration that the water supply sources maybe contaminated through terrorist operations or depleted through overt operations.

This topic examines the objectives of water supply testing, using fire hydrants to determine water supply capability throughout a given water distribution system, some applications of fundamental hydraulics (introduced in Chapter 2), flow test procedures, and graphical solutions to test for water flow problems. The results of this type of analysis are essential to understanding a given water system's capability to provide both consumer consumption and needed fires flows at representative locations throughout the built areas of the community.

FLOW TEST OBJECTIVES

Fire hydrant flow tests conducted on public water supply systems are done for several reasons: 1) to determine the rate at which water is available at specific locations within a given distribution system; 2) to use flow-test data between two fire hydrants on the same water main to determine a pipe coefficient or to determine if control valves are completely open; 3) to determine water availability at the end of an existing pipeline for the determination of pipeline extensions; 4) for determining the need for booster pump applications; 5) to verify or calibrate the accuracy of water distribution system models; and 6) to determine a water flow and pressure profile where the water system supplies an automatic sprinkler system. The flow-test data may be used for the evaluation of new developments that would be supplied by the water system and for evaluating tradeoffs for providing water supplies for public fire protection and/or private fire protection in the form of automatic sprinkler systems.

Of particular interest to fire departments and insurance companies is the rate and quantity at which water is available to concentrated high-value areas, such as shopping centers, industrial parks, highrise hightech buildings, institutional buildings, and residential areas. (Reference #5, pg. 65) Also see National Fire Protection Association (NFPA) 25, *Standard for Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems*, which outlines testing requirements for private fire hydrants. (Reference #5, pg. 65)

Fire hydrant flow tests should not be attempted until all the operational characteristics of a water system are known. Results may differ substantially, depending on the operation of pumping equipment, water levels in the system's storage facilities, rates of consumption, and points of demand on the water system. Even though it is possible to conduct accurate tests within acceptable tolerances, often the results obtained will vary from day to day, and even at different periods during the same day, because of the many variables involved.

Basic Hydraulic Concepts

Persons involved in water supply testing and flow testing from fire hydrants need to understand some of the fundamentals of water as a fluid flowing through pipe and flowing out of orifices such as an outlet on a fire hydrant. The Hazen-Williams Formula for evaluating water flow though pipes is the most practical and usable formula for analyzing water supply systems in relation to providing effective water supplies for fire protection. (Reference #6, pg. 65) Many standards published by the NFPA, including those on sprinklers, water spray systems, and suburban and rural water supplies, make direct reference to the Hazen-Williams Formula for pipe configuration calculations. It is the formula of choice for water system operators and field engineers to measure pressure loss in pipe sections and to verify the "c" value or the coefficient of roughness on the interior of pipe walls which signals a reduction in the actual pipe diameter. These concepts will be discussed further below. (Reference #7, pg. 65)

The **Hazen-Williams Formula** is used widely for pipe flow problems involving municipal water supply system evaluations and sprinkler system piping design layout and evaluation. This is an empirical formula that evolved for water test work over a period of 30 years and is considered to be valid today for water distribution system analysis. The formula is presented as follows: (Reference #8, pg. 65)

$$P=4.52xQ^{1.85}/c^{1.85}xd^{4.87}$$

Where:

P=pressure loss in psi per foot of pipe, often refereed to as friction loss.

Q=flow of water in U.S. gallons of water per minute expressed as gpm.

c=roughness coefficient to be used with this formula; see further explanation below.

d=the actual internal diameter of the pipe; for practical hydraulics the published diameter of the pipe is used, not the actual manufacturers' diameter. (A given brand of 6-inch pipe has an actual internal diameter of 5.871, which is indistinguishable from field hydraulic problems.)

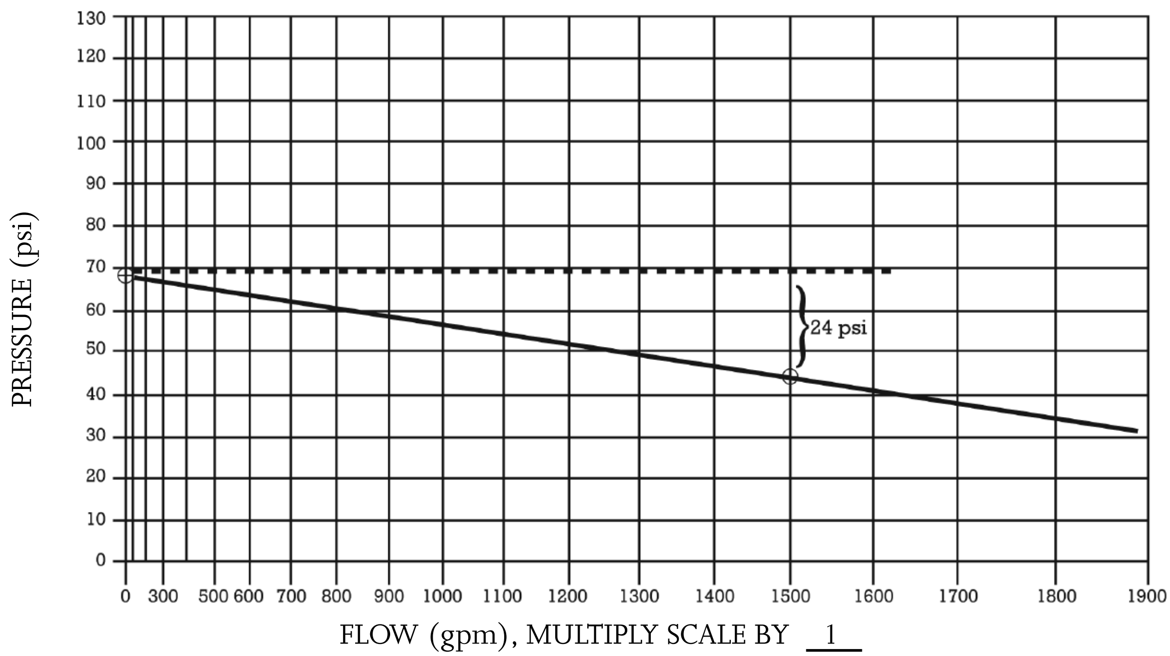
NOTE: on a special understanding the correct use of this formula: If the constant for the pipe which is now an acceptable constant for all pipe from the perspective of practical hydraulics is canceled out, and the coefficient of roughness (c) is canceled out, and the diameter of the pipe being tested remains constant (i.e., all 8-inch pipe), it too can be canceled out. The remaining equation now reads

psi loss varies as $Q^{1.85}$

This concept is very important because it permit preparing Log graphs that are based on this equation. This is useful for plotting flow data to show the relationship between flow and pressure loss through pipelines without doing a lot of mathematical calculations. **Figure 3-1** illustrates this type of graph labeled as a Water Flow Test Summary Sheet. This type of sheet will be used in sample problems.

Figure 3-1

Water Flow Test Summary Sheet



The calculation of friction loss in a pipe section depends on the quantity of flow in gpm, the roughness coefficient and the internal diameter of the pipe. Several methods can be used for solving the formula: 1) straight mathematical computation; 2) the use of power tables; or 3) the use of nomograph (e.g., hydraulic slide rules). With the use of scientific calculators and computer hydraulic calculation software calculations are easier.

The basic Hazen-Williams Formula above can be transposed as given below to solve for the "c" pipe condition or roughness factor. Actually, friction loss in a pipe section cannot be determined until the pipe coefficient is known or estimated. To improve the accuracy of computations, it is often desirable to conduct flow studies to determine the actual "c" value for a given pipe section, a representative "c" value for the pipe system. The friction loss is determined from a field study with a know quantity of water flowing in a given diameter of pipe. The empirical field value then can be used to solve for "c" as follows:

$$c=2.26Q/(d^{2.63}xp^{0.54})$$

A number of laboratory and field studies were conducted in the in the 1970s by Factory Mutual (FM) Systems to determine representative "c" values for different pipe conditions flowing water. (Reference #9, pg. 65) **Table 3-1** depicts a number of "c" values that can be used for hydraulic calculations or to conduct comparative "c" values between existing conditions and the table values.

Table 3-1

Hazen-Williams Pipe Coefficients*

Kind of Pipe	Value of C		
	1	2	3
Cast iron, unlined, public mains or fire-protection mains with mill-use draft			
10 years old	105	90	75
15 years old	100	75	60
20 years old	95	65	55
30 years old	87	55	45
50 years old	75	50	40
Cast iron, unlined, new	120		
Cast iron, cement-lined	130		
Cast iron, bitumastic-enamel lined ...	140		
Cement-asbestos	140		
Average new steel	140		
Sprinkler piping, black or galvanized:			
Over 2 in	120		
2 in or less	100		
1. Water mildly corrosive. Use same values for fire-protection mains having no mill-use or domestic draft.			
2. Water moderately corrosive.			
3. Water severely corrosive, including well water.			

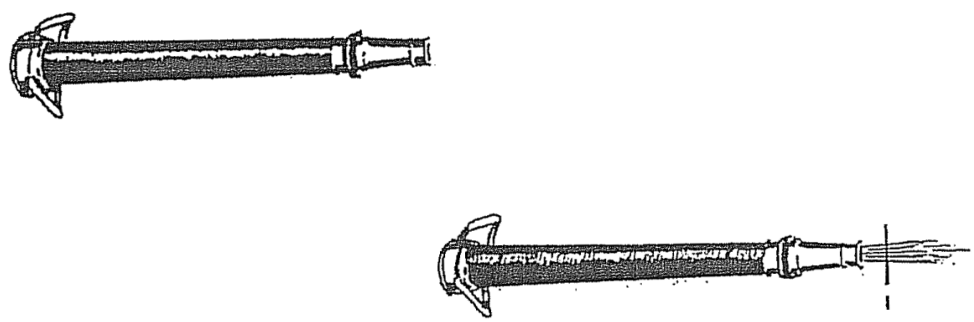
*Factory Mutual Systems, *Handbook of Industrial Loss Prevention*, New York: McGraw Hill Book Company, 1967, p. 21-9.

Measuring Water Flow From Smooth-Bore Orifices

The original experimentation on flow from smooth-bore orifices was conducted by the National Board of Fire Underwriters in 1912. (Reference #10, pg. 65) This work led to the creation of the standard playpipe, or the Underwriters playpipe, as illustrated in **Figure 3-2**.

Figure 3-2

Underwriters Playpipe



Playpipe nozzle and measurement of orifice pressure

John R. Freeman adapted a Pitot tube device to be used in measuring flow from the Underwriters playpipe. The follow formula is known both in hydraulic textbooks and in fire service publications as the Freeman Flow Formula or the Underwriters Flow Formula for measuring flow in gpm from smooth-bore fire-service nozzles and fire hydrant outlets. The final version of the discharge formula is as follows: (Reference #10, pg. 65)

$gpm = 29.83\ Cdxd^2(Po)^2$

Where:

Cd=a coefficient for the nozzle or fire hydrant outlet type being used.

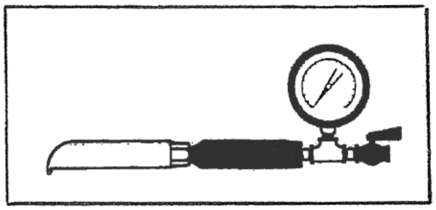
d=the measured diameter of the orifice where the water is discharged.

Po=orifice pressure measured by a Pitot tube placed in the flowing steam at a distance one-half the diameter of the orifice; technically called the vena contracta point to achieve the most accurate flow reading.

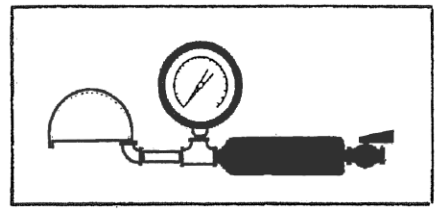
Figure 3-3 provides illustrations of typical Pitot tubes and the proper position of the Pitot tube in the waterway; this is considered to be one-half the distance of the orifice opening.

Figure 3-3

Illustrations of Typical Pitot Tubes



Air Chamber Type



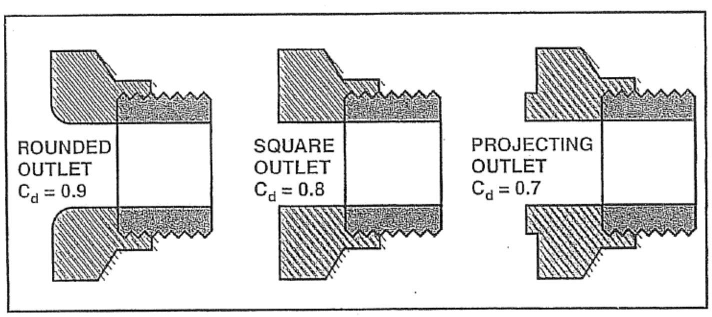
Pressure Snubber Type

Therefore for the 2-1/2-inch standard opening on a fire hydrant, the opening on the blade to the Pitot tube should be approximately 1-1/4 inches from the hydrant opening.

Also of importance is the coefficient of discharge from different hydrant outlets. **Figure 3-4** illustrates how the discharge nipple on hydrants may be installed. In hydrants produced over the past 50 years, three types of nipple insertions have been used by different hydrant manufacturers. Each has a different coefficient of discharge that needs to be used in the Underwriters Flow Formula (also known as the Freeman Flow Formula). This is illustrated in the following example of computing the available flow from a hydrant outlet.

Figure 3-4

Typical Fire Hydrant Outlet Coefficients



Example 1: Determine the discharge flow in gpm from a hydrant with a flowing 2-1/2-inch outlet that has a coefficient of discharge that is 0.90 and the flowing Pilot pressure is $16^{1/2}$ psi.

- Step 1: The formula is $gpm=29.83xCdxd^2x(Po)^{1/2}$

- Step 2: Insert the given values for *Example 1* in the formula: $gpm=29.83x0.90x(2.5)^2x16^{1/2}$

- Step 3: gpm=29.83x0.90x6.26x4

- Step 4: Or, 29.83x0.90x25.04

- Step 5: Answer: 672.25, or 672 gpm

The American Water Works Association (AWWA) has developed tables that can be used to read flows directly based on the above formula and all of the variables.

The Underwriters Flow Formula may be used to calculate the discharge from other fire protection equipment and pipe by using a typical discharge coefficient for solid-stream nozzles and devices. The **key words** here are **solid stream**. It is essential that the entire perimeter of the discharge orifice be **wetted**. In other words, water must be flowing full through the orifice, which requires a good stream of water. Partial flows can not be calculated accurately using the above formula because there is a cavitation in the stream diameter flow. A full-flowing outlet is essential when the hydrant is initially opened; then close the fire hydrant and attach a smooth-bore nozzle. Try tip sizes until the pressure reading is between 30 and 80 psi; the ideal pressure range is 40 to 60 psi.

Table 3-5 presents discharge coefficients for different types of outlets.

Table 3-5

Typical Discharge Coefficients of Solid-Stream Nozzles*

Outlet	Discharge Coefficient
Standard sprinkler, average (nominal 1/2-inch diameter)	0.75
Standard orifice (sharp edge)	0.62
Smooth-bore nozzles, general	0.96 – 0.98
Underwriters playpipes or equal	0.97
Deluge or monitor nozzles	0.997
Open pipe, smooth, well-rounded	0.90
Open pipe, burred opening	0.80
Hydrant butt, smooth, on well-rounded outlet, flowing full	0.90
Hydrant butt, square and sharp at hydrant barrel	0.80
Hydrant butt, outlet square, projecting into barrel	0.70

*U.S. Army Engineering School. *Hydraulics II*. Fort Belvoir: Author, Sub-course No. 433, March 1969, p. 3-5.

CONDUCTING FIRE-FLOW TESTS

1. General considerations.

   Fire-flow tests are conducted to determine pressure and flow-producing capabilities at any location within the distribution system. The primary function of fire-flow tests is to determine how much water is available for fighting fires, but the tests also serve as a means of determining the general condition of the distribution system piping network. For example, heavily tuberculated water mains, or those with heavy wall deposits can reduce the flow-carrying capacities of pipe; this reduced capacity can be detected by means of flow tests. Flow tests also can help detect closed valves in the system. The results of flow tests are used extensively by insurance underwriters as a factor in setting property insurance rate premiums; they also are used by designers of automatic sprinkler systems. (Reference #11, pg. 65)

   It is good practice to conduct flow tests on all parts of the distribution system annually and at representative fire risks semiannually to identify the service areas that might be affected by any significant change in the distribution system piping and accessories such as control valves. All problem conditions should be investigated immediately and the proper corrections made in a timely manner.

   An accurate flow graph as discussed below should be kept on file at the water department office for each flow test conducted. Each graph line should be dated. A copy of each flow graph with the updates should be provided to the fire chief for distribution to the first-responding companies in specific areas of the community.

2. Operational definitions of terms used in water flow testing. (Reference #12, pg. 65)

   a. **Flow Hydrant**: The hydrant or hydrants where flow is actually measured.

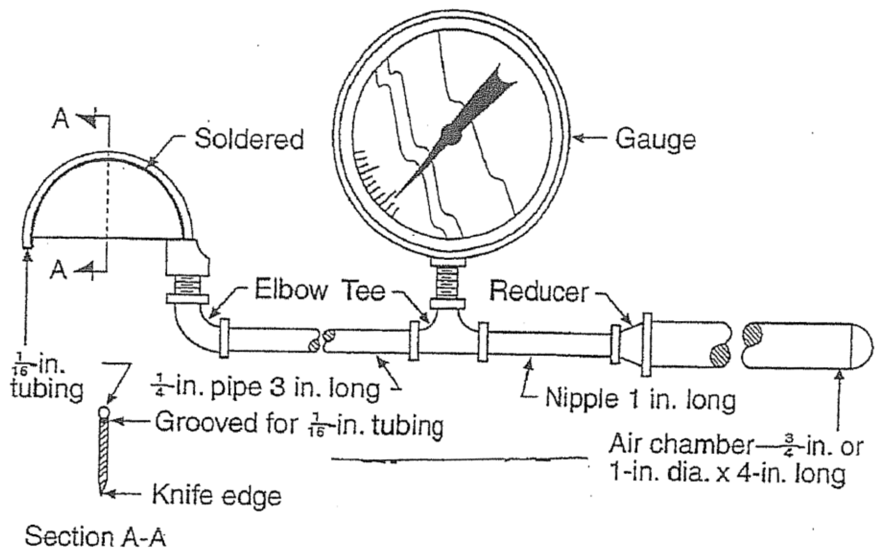
   b. **Pitot Pressure**: The pressure reading obtained on the Pitot gauge during a flow test.

   c. **Pitot Tube**: An instrument, as discussed above, that is used to measure the flow of water discharged from a fire hydrant outlet (orifice) by measuring and converting velocity head into a pressure head reading on a gauge in psi. See **Figure 3-6**.

   d. **Residual Pressure**: The pressure in the distribution system piping, measured at the residual pressure fire hydrant, at the time the flow readings are taken at the flow hydrant(s).

   e. **Static Pressure**: The pressure that exists at a given point under normal distribution-system flow conditions.

Figure 3-6



3. Personnel and equipment for flow tests. (Reference #13, pg. 65)

The following list includes the required personnel and equipment needed to conduct a flow test. Equipment should be in good working order and be available at the time of the test.

a. For each designated flow hydrant, one Pitot tube with a calibrated pressure gauge capable of reading 0 to 60 psi.

b. One outlet-nozzle cap that will fit the outlet nozzle of the residual fire hydrant; often referred to as a cap gauge. (Refer to **Figures 3-6** and **3-7**.) The outlet nozzle is equipped with a pressure gauge capable of reading from 0 psi to 25 psi greater than the pressure expected at the residual fire hydrant.

c. A ruler, graduated to at least 1/16 of an inch, to measure the inside diameter of the outlet nozzle of each flow hydrant.

d. One hydrant wrench to operate the residual fire hydrant and one to operate each of the fire hydrants at which the flow will be measured.

e. One discharge diffuser to absorb the energy from the hydrant flow so that it is contained, where necessary, to avoid property damage or to minimize the effect on traffic.

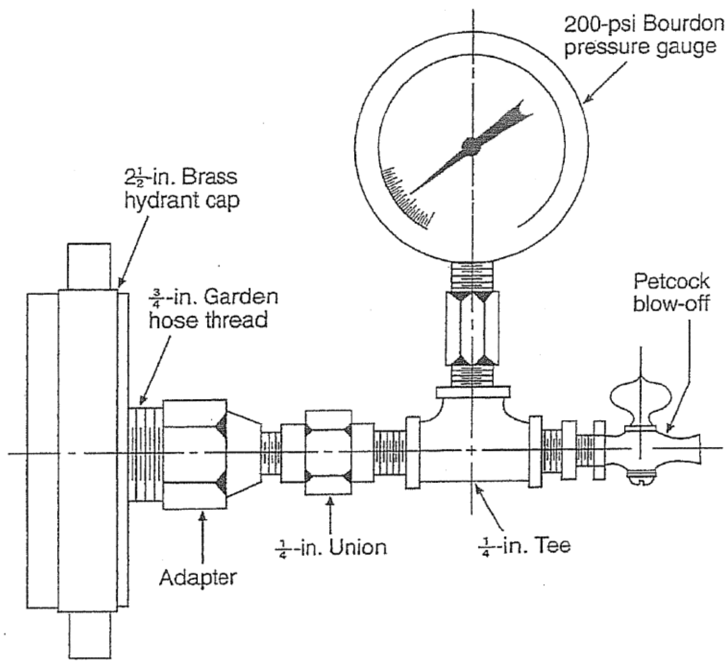
f. One person to read the gauge on the residual hydrant and one person to read the gauge on the Pitot tube for each of the flow hydrants.

g. Clipboards and sheets for recording data at each fire hydrant.

h. For wet-barrel hydrants found in the Sun Belt regions, it may be necessary to install a specially designed nozzle to minimize turbulence caused by the discharge valve.

Special Note: The Pitot tube and the pressure gauges are relatively delicate instruments and must be treated accordingly. Gauges should be checked for accuracy at reasonable intervals to ensure that the flow tests will be as accurate as possible.

Figure 3-7

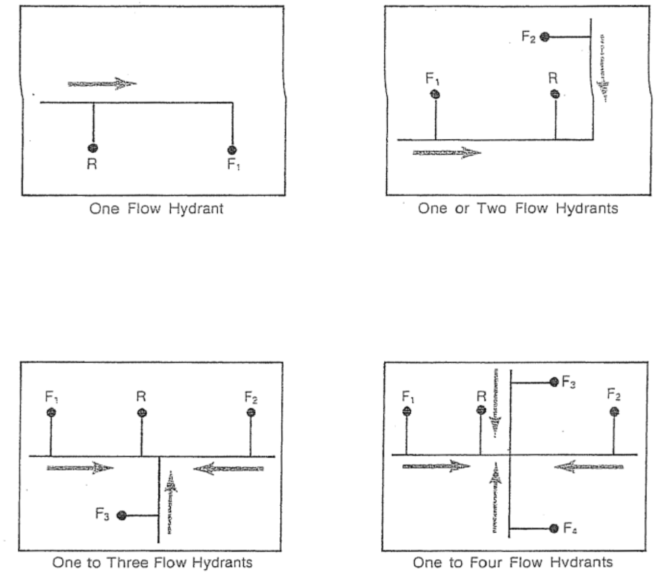


4. Preplanning prior to conducting field tests.

   a. Review **up-to-date** water system distribution maps and determine which hydrants will be used to measure flow and which will be used to measure the static and residual pressures according to the **suggested flow-test locations** depicted in **Figure 3-8**. All fire hydrants should be at approximately the same elevation. Otherwise test results may need to be corrected for elevation differences.

Figure 3-8

Suggested Flow-Test Locations



Note that the arrows indicate direction of flow: R–residual fire hydrant; F–flowing fire hydrant.

b. Review previous tests to estimate the flow and pressures that can be expected.

c. Select a day for testing when system consumer consumption will be normal and weather predictions indicate that conditions will be reasonable. The operating division should be notified as to the time and location of the tests so necessary adjustments to the system can be made. Investigate traffic patterns, as the tests may affect traffic flow. It may be necessary to notify the traffic division of the police department to reroute traffic for the short period that fire-flow tests are being conducted.

5. Field procedures for flow tests.

a. Make provisions for minimizing interruption to traffic to the extent possible and for adequate discharged drainage of water to avoid property damage.

- Locate the residual fire hydrant and do the following:
  - -- Flush the residual fire hydrant to eliminate sediment that may damage the gauge.
  - -- Install the outlet-nozzle cap equipped with the pressure gauge on a hydrant nozzle; preferably on the side where the reader can observe the flowing fire hydrant.
  - -- Open the main valve **slowly** until all the air is vented. Close the vent and open the main valve fully.

-- Read the gauge; when the needle has stabilized, record the reference static pressure.

- Locate the flow hydrant(s) and do the following:

  -- Measure and record the inside diameter (ID) of the outlet nozzle from which the flow is to be measured.

  -- Determine the outlet nozzle coefficient in accordance with **Figure 3-4**. The coefficient allows for differences in hydraulic entrance losses. The first illustration is the most common assembly and represents a rounded shoulder at the entrance. If the configuration of the hydrant to be tested differs significantly from the configuration shown in **Figure 3-4**, contact the hydrant manufacturer for the coefficient.

b. Conduct the flow test as follows:

- Station one observer at the residual hydrant and one observer at each flow hydrant.

- Open each flow hydrant slowly until it is fully open. Open one fire hydrant at a time to avoid a pressure surge.

- When the pressure at the residual fire hydrant has stabilized, the observer signals the persons stationed at the flow hydrants to take the readings. The readings for residual pressure and the Pitot-tube readings for each flow hydrant must be taken simultaneously. The air should be exhausted from the flow hydrant before the reading is taken. For an accurate reading, hold the Pitot tube in the center of the nozzle, with the axis of the Pitot tube opening parallel to the direction of flow. The Pitot tube should be held away from the end of the nozzle at a distance of about half the nozzle diameter.

- Record the residual reading and the Pitot-gauge reading at each flow hydrant. Then close the flow hydrants one at a time.

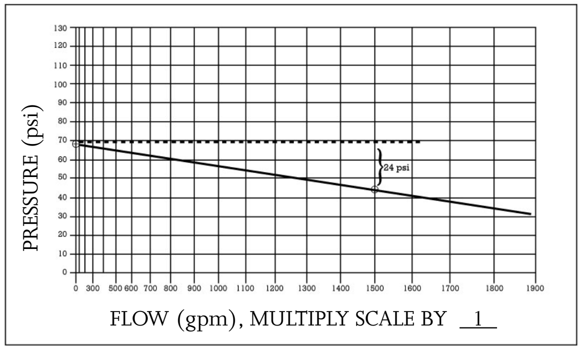
For reasonably accurate test results, the pressure drop between the static and the residual pressures should be at least 10 psi; a 50-percent drop is considered to be the most accurate test, since at this drop on any given system the mean velocity of the underground main should be reached. Additional flow hydrants, if possible, should be added to achieve this condition.

It is best for observers to calculate the flow in the field so that, if the results appear in error, the test can be repeated immediately.

1. Flow Analysis Problem #1 with associated flow test **Diagram 3-1**.

Diagram 3-1

Water Flow Test Summary Sheet



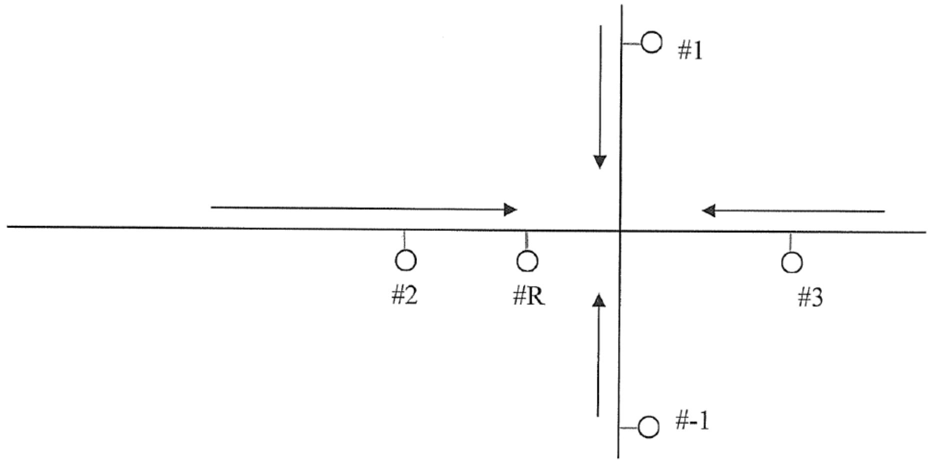
One Flow Hydrant

The diagram illustrates a typical flow-test arrangement for a dead-end water main. In other words, the water main flow does not extend beyond flow hydrant 1. The residual pressure is measured at hydrant R. The following provides the collected field information:

- Location R: static pressure = 65 psi.
- Residual pressure = 30 psi.
- Location F1: Flow from a 2-1/2-inch open butt on the fire hydrant indicates a flow of 498 or 500 gpm as measured by a Pitot and the flow determined from charts by or orifice calculation (see example).
- Using the left psi pressure line, the static pressure of 65 psi is recorded.
- Again, moving down the left psi pressure line find a residual pressure of 30 psi; move right along this line until the flow in the underground pipe of 500 gpm vertical point is reached; plot this point.
- Next, connect the dots between 65 psi static pressure and 500 gpm at 30 psi residual pressure and extend the line down to the baseline that has the marked flow values.
- Go to the 20 psi pressure line; indexed left. Read right until this line intercepts the diagonal flow line. Read a flow of 565 gpm at 20 psi residual pressure. Understand that this is the calculated potential flow from the **R** hydrant in **Diagram 3-1**. The flow hydrant downstream of the residual pressure/ flow hydrant is used to calculate the water system flow at this location to avoid turbulence in the water main for the best accuracy possible under field conditions. For comparative purposes in the future, the bottom line indicates that there is essentially no water system pressure when the flow is calculated to be 600 gpm.

2. Flow Analysis Problem #2 with Associated **Diagram 3-2**.

Diagram 3-2



Four Flow Hydrants

In high-value commercial districts of a community, water may feed to an intersection to provide fire protection along the street fronts in each direction from the intersection. In this case it is useful to conduct what is called an area fire-flow test. This test will indicate the potential amount of water flow from four fire hydrants that provide water for four mobile pumps in case of a serious fire that has the potential for spreading between buildings.

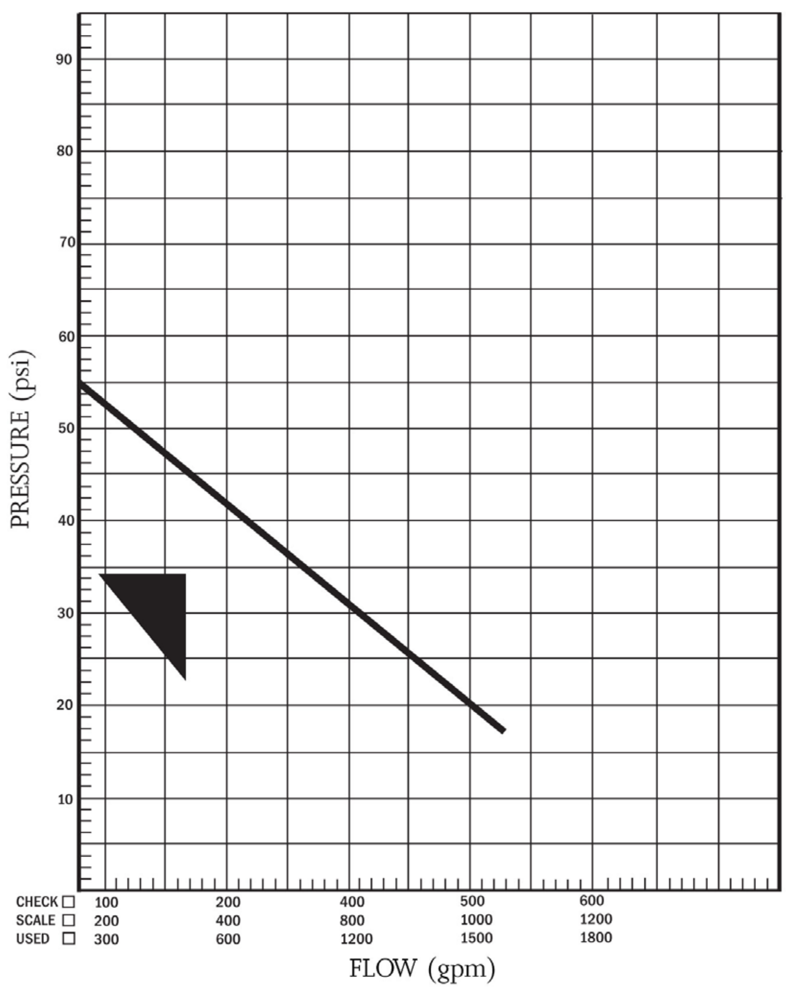
Problem # 2 follows the same logical analysis as Problem #1 above. Therefore the following points summarize the calculations at 20 psi residual pressure:

- Hydrant F1 = 650 gpm.
- Hydrant F2 = 875 gpm.
- Hydrant F3 = 950 gpm.
- Hydrant F4 = 1,150 gpm.
- The pressure is dropped on the water system around the intersection of pipe as illustrated in **Diagram 3-2** to **no less** than 20 psi residual pressure on any one flow fire hydrant. When the **residual** gauge reading becomes stable, flow readings are taken with a Pitot tube on all four flowing hydrants. These readings are converted into gpm flow. Finally, the 20 psi should be maintained on a fire hydrant that is supplying a mobile pump to avoid cavitation in the underground pipe network.

Problem #2 summary: The total available fire flow around the subject intersection is 3,625 gpm at 20 psi residual pressure.

Problem #3 is concerned with water supply to a structural property that is protected by an automatic sprinkler system. It is essential that sprinkler pressure at the alarm valve or dry pipe valve be maintained during a fire. There also may be the need to supplemental hose streams to complete extinguishment of the fire while the sprinklers are operating.

Figure 3-11



In this problem, a commercial fire risk at 140 Adams Street in Yourville has an installed sprinkler system. The calculated sprinkler system demand is 170 gpm at 34 psi at the street connection. The water system static pressure at this location is 55 psi. A flow test near this location indicates a flow of 500 gpm at 20 psi. This information is shown as **Figure 3-11**. The flow diagram depicts the amount of water and the sustained pressure for the sprinkler system in the shaded area to the left. Reading down the curve, it is determined that only approximately 100 gpm can be used for a supplemental hose stream. An excessive amount of water will cause a diminishing pressure on the sprinkler system.

Summary

This topic is about conducting evaluations of municipal water systems by conducting water supply tests at regular intervals; semiannually is recommended. Most important is the concept of preparing a *Water Flow Test Summary Sheet* for each test location, along with the information discussed above. These sheets are very important for monitoring the municipal water system at specific locations over time. When flow curves at the same location over succeeding tests do not match, there is a need to know why they do not match and identified problems need immediate attention.

Responding fire companies to specific fire risks need to have current information about water supplies. Therefore, all first-due fire companies should have a set of flow test sheets to make informed decisions on fire suppression tactics. This type of evaluation should be part of any cost reduction program.

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2. Cote, Arthur E., Ed., *Fire Protection Handbook*. 19th Ed., Quincy: NFPA, 2005, pg. 10-97.
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8. *ibid*., pg. 95.
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10. Shepperd, Fred. *Fire Service Hydraulics*. Case-Shepperd-Mann Publishing Corporation, 1941, pg. 35.
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Chapter 4: Evaluating Municipal Water System Storage

Fundamental Considerations

Municipal water supply systems are concerned with two classifications of water storage.

1. Raw water storage: Water supplies that are used to feed water to a filtration and treatment plant for purification in order to produce **finished water** that is used for domestic purposes including drinking water is classified as **raw water**. Raw water sources from streams, rivers, ponds, lakes, and even reservoirs are **not suitable** for any domestic purposes including water for cooking, bathing, and especially drinking. The one exception is individual well water that has been chlorinated and disinfected for individual household use in accordance with individual State Public Health regulations.

   Extreme caution: Raw water or any water supply that has not been treated to Environmental Protection Agency (EPA) standards **is not** to be pumped into fire hydrants attached to a municipal water system. During the summer drought conditions of 2005 in the Middle Atlantic States, there were reports where community fire departments were pumping water from creeks and ponds into small water systems because there was no water in the reservoirs to supply the water piping system. This is considered a very dangerous situation, and such practices present serious health risks to persons using these water supplies. Furthermore, all components of the water system are required by either State or Federal regulations to be completely disinfected along with biological testing before the water system can be placed back in service to provide treated water for human consumption.

   A more positive approach to raw water supplies is to use raw water holding basins, ponds, or reservoirs as an alternative water supply source to meet unusual demand on the water system, including a major fire, situations when the main water supply is low, or any other emergency situation requiring large volumes of water such as a primary or secondary water main break. These raw water sources should be arranged so that the water flows by gravity, if possible, to the water treatment plant. If the terrain in the area of the treatment plant does not permit this height differential, then arrangements need to be made for stationary pumps, or even fire department pumpers to pump water from the raw water source to the water treatment plant.

2. Finished water storage: The most common type of water storage on a municipal water system is the use of clear wells on the outboard side of water treatment plants, ground-level water-storage tanks and elevated water-storage tanks to store **finished water** that is suitable for domestic consumption. Therefore, an extremely important element in a water distribution system is **finished water storage**. Water system **storage facilities** have far-reaching effects on a given system's ability to provide adequate consumer consumption plus adequate water supplies for meeting fire-flow demand in addition to consumer consumption. The two common finished water storage methods 1) ground-level storage, and 2) elevated storage, are presented below. Emphasis is placed on the relative merits of both methods.

Functions of Distribution Storage

Storage within a distribution system enables the system to process water at times when treatment facilities otherwise would be idle. It is then possible to distribute and store water at one or more locations in the service area that are closer to the user.

1. Advantages.

   The principal advantages of distribution storage include the fact that storage equalizes demands on supply sources, production works, and transmission and distribution mains. As a result, the sizes or capacities of these elements need not be so large. Additionally, system flows and pressures are improved and stabilized to better serve the customers throughout the service area. Finally, reserve supplies are provided in the distribution system for emergencies, such as firefighting and power outages.

2. Meeting system demands and required fire flow.

   The location, capacity, and elevation (if in fact elevated) of distribution storage are closely associated with system demands and the variations in demand that occur throughout the day in different parts of the distribution system. System demands can be determined only after a careful analysis of an entire distribution system. However, some general rules may serve as a guide to such analysis. **Table 4-1** lists daily and hourly variations for a typical city and the resultant storage depletion. Such data are of great assistance in determining required storage capacities. However, it should be recognized that each municipal water distribution system has its own specific requirements.

Table 4-1

Water Use and Storage Depletion of Maximum Day in a Typical Municipality

Hour	Ratio of Hourly Demand Rate To Maximum Day Demand Rate	Hourly Variation in Distribution Storage Reserve *mil gal*	Cumulative Storage Depletion *mil gal*
7-8 a.m.	1.00	-0.00	0.00
8-9	1.10	-0.10	0.10
9-10	1.25	-0.25	0.35
10-11	1.28	-0.28	0.63
11-12	1.20	-0.20	0.83
12-1 p.m.	1.18	-0.18	1.01
1-2	1.16	-0.16	1.17
2-3	1.10	-0.10	1.27
3-4	1.00	-0.00	1.27
4-5	1.08	-0.08	1.35
5-6	1.15	-0.15	1.50
6-7	1.30	-0.30	1.80
7-8	1.60	-0.60	2.40
8-9	1.40	-0.40	2.80
9-10	1.25	-0.25	3.05**
10-11	0.90	+0.10	2.95
11-12	0.85	+0.15	2.80
12-1 a.m.	0.70	+0.30	2.50
1-2	0.60	+0.40	2.10
2-3	0.50	+0.50	1.60
3-4	0.50	+0.50	1.10
4-5	0.50	+0.50	0.60
5-6	0.60	+0.40	0.40
6-7	0.80	+0.20	0.20

*Average day, 16 mil gal; maximum day, 25 mil gal; constant hourly supply rate (at maximum day demand rate), 24 mgd or 1 mil gal/h.
**Maximum storage depletion.

Rarely can distribution storage be justified economically in an amount greater than will take care of normal daily variations and provide the needed reserve for fire protection and **minor** emergencies. In systems of moderate size, the amount of water storage available for equalizing water production is 30 to

40 percent of the total storage available for water-pressure equalization purposes and emergency water supply reserves. In normal water system operations, some water from storage should be used each day, not only to maintain uniformity in production and pumping, but also to ensure circulation of the stored water, to prevent ageing of the water which affects water quality. Storage in the distribution system normally is brought to full capacity each night and is increased during low-demand periods of the day.

Normally, it is more advantageous to provide several storage units in different parts of the water distribution system than it is to provide an equivalent capacity at a central location.

Smaller pipelines are required to serve decentralized storage and, other things being equal, a lower flow-line elevation and pumping head result.

ELEVATED AND GROUND-LEVEL STORAGE

Storage within the distribution system normally is provided in one of two ways: elevated storage or ground storage with high-service pumping. It should be noted that elevated storage provides the best, most reliable, and most useful form of storage, particularly for structural fire suppression.

Elevated Storage

Properly sized elevated water tanks provide dedicated fire storage and are used to maintain constant pressure on the water supply distribution system.

Domestic water supplies are regularly fed to the system from the top 10 to 15 feet of water in the elevated tanks. As the water level in the tank drops, the tank controls call for additional high-service pumps to start in order to satisfy the system demand and refill the tanks. The high-service pumps are constant-speed units, which can operate at their highest efficiency point virtually all the time. The remaining water in the tanks (70 to 75 percent) normally is held in reserve as dedicated fire storage. This reserve will feed into the system automatically as the fire-flow demand and the domestic use at a specific time exceed the capacity of the system's high-service pumps.

Ground Storage

Since water kept in ground storage is not under any significant pressure, it must be delivered to the point of use by pumping equipment. This arrangement limits the water distribution system's effectiveness for fire suppression in three ways:

1. There must be sufficient excess pumping capacity to deliver the peak demand for normal uses as well as any fire demand, which requires a generally unused investment in pumping capacity. The pumps are activated periodically to redistribute the water in the holding tank to avoid stagnation of the water.

2. Standby power sources and standby pumping systems must be maintained at all times because the system cannot function without the pumps.

3. The distribution lines to all points in the water distribution system must be significantly oversized to handle peak delivery use plus fire flow, no matter where the fire might occur near one or more fire hydrants on the piping system.

However, in hilly areas it is frequently possible to install ground reservoirs at sufficient elevation so that the water would "float" on the distribution system. This eliminates the need for pumps at the ground-storage facility. If the desired overflow elevation can be achieved on a hill, a considerably larger storage capacity can be installed when compared to an elevated tank. This may result in placement of the storage facility on a hill in a less desirable location. Such a placement would provide larger storage capacity than could be achieved by an elevated storage tank(s), or it should provide the equivalent storage more economically.

When ground-level storage is used in areas of high fire risks, the energy that would be needed to deliver the water is lost on the initial delivery of water to the tank. The water supply must be repumped and repressurized with the consequent addition of more standby generators and more standby pumps. In addition, the system's high-service pumps must be either variable speed or controlled by discharge valves to maintain constant system pressures. This equipment is expensive, uses additional electrical power, and requires extensive operation and maintenance. Frequently, the additional capital costs for pumps, generators, and backup systems, and the long-term energy costs, significantly increase the costs of a ground-storage system.

Pumping For Distribution Storage

There are two types of water supply distribution storage as defined above:

1. Ground-level storage.
2. Elevated storage.

There also are two types of pumping supply systems. Both of the concepts are expanded upon below. One is a direct pumping system, in which the instantaneous system demand is met by pumping with no elevated storage provided. The second type is an indirect system in which the pumping station lifts water to a reservoir or elevated storage tank, which **floats** on the water system, based on demand, and provides system pressure by the gravity method.

1. Direct pumping.

   The direct pumping system is considered obsolete today, although there are some systems of this type still in existence. Variable-speed pumping units operated off of direct system pressure are also in use in some communities. Hydropneumatic tanks at the pumping station provide some storage capability.