## C·H·A·P·T·E·R·9

# PUMP SERVICES

# SECTION 9.1

# WATER SUPPLY

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## SOURCES OF WATER

***Surface Water*** Surface water supplies are obtained from streams, rivers, lakes, and reservoirs. The quantity of water available from a surface supply can be determined with reasonable accuracy from yield studies that take into account the local effects of rainfall, runoff, evaporation and sedimentation rates, and other hydrological factors. Development of a surface supply usually requires pumps to transport raw water from the source to a treatment plant and to provide the head necessary for proper hydraulic operation of the treating facilities. Pumps utilized for this purpose are classified as low-lift pumps because relatively low discharge heads are required.

Selection of a specific type of pump for low-lift service is dependent on intake conditions. Because surface water supplies vary significantly in temperature, bacteria count, and turbidity at varying depths and because the water level may fluctuate considerably, it is necessary to provide some type of intake structure that will permit withdrawal of water at several elevations. Multiple intake ports equipped with trash racks and water screens provide this capability and provide protection from fish and debris. The design and location of the intake structure influence the selection of either a horizontal or vertical pump for low-lift service.

***Groundwater*** In many areas of the United States where rainfall and runoff are sparse, significant supplies of water are available from underground sources. The groundwater table is formed when rainfall percolates through the soil and reaches a zone of saturation, the depth of which is governed by soil characteristics and subsurface conditions.

Groundwater can be developed as a source of supply through utilization of wells or springs. Shallow wells generally utilize the water table as a source, whereas deep wells

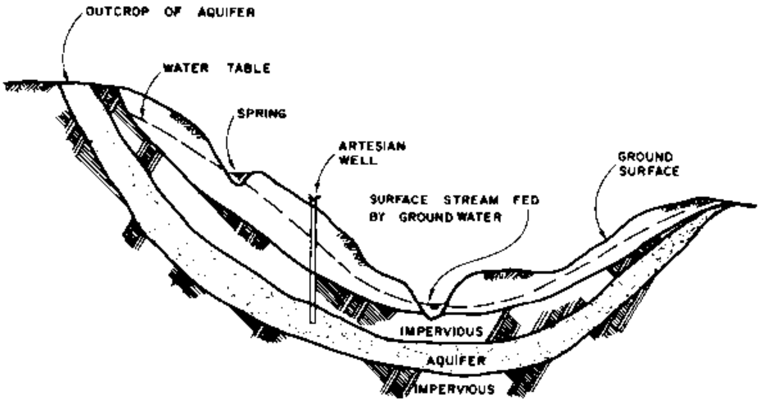

**FIGURE 1** Subsurface conditions for development of groundwater supplies

utilize water held in a pervious subsurface stratum (aquifer). Deep wells generally provide more constant and more prolific supplies than do shallow wells.

Artesian wells may be developed when an aquifer outcrops at a surface elevation significantly higher than the ground elevation at the well site. The aquifer is thus pressurized, and water flows from the well without pumpage. A natural artesian well may occur if a fault extends from the aquifer to the ground surface.

Springs occur where the groundwater table outcrops at the surface of the earth. However, the supply available from springs is seldom great enough to serve more than one or two homesteads and is thus usually insignificant in terms of supplying communities. Surface streams may also be fed from the groundwater table, and vice versa. Figure 1 depicts these various conditions.

Well water is usually pumped to a treatment site or into a distribution system by either vertical turbine line shaft pumps or submersible pumps. Economics dictates the selection of one type over the other. In general, at depths greater than 500 ft (150 m) submersible pumps become economically competitive with line shaft pumps. For shallower depths, line shaft pumps are used almost exclusively.

***Effects of Source on Water Quality*** Although the quality of water obtained from both groundwater and surface supplies varies greatly according to local climatological, hydrological, and geological conditions, some general comparisons can be made between groundwater and surface supplies. Surface supplies generally contain more bacteria, algae, and suspended solids than do groundwater sources and thus require specific treatment to eliminate the resulting turbidity, colors, odors, and tastes.

Groundwater supplies generally contain few bacteria and in some instances are pure enough for domestic use without chemical treatment. Frequently, however, groundwater supplies contain significant amounts of dissolved minerals. Depending upon the mineral type, the resulting supply may exhibit such characteristics as extreme hardness, toxicity, or undesirable color, odor, or taste. Special treatment such as aeration, lime softening, and disinfection may be required to remove such objectionable characteristics.

## USES OF WATER

***Classifications*** History has shown that significant concentrations of population have always occurred where a water supply was readily available. Accordingly, technology has been developed to make full use of the available supply, not only for domestic use but also for public, commercial, industrial, and agricultural consumption.

*Domestic usage* consists of water used for household purposes. The amounts used for such purposes vary with the standard of living of the consumers, the quality of the water, whether metering devices are used, and other factors. Consumption for domestic purposes is generally in the range of 50 to 60 gal per capita per day (gpcd) [190 to 230 liters (lpcd)], which is defined as the total quantity of water used in one calendar year divided by (365 × average number of persons supplied).

*Public usage* includes the water used for such purposes as street cleaning, water for public parks, and supply to public buildings. Such consumption generally amounts to about 10 to 15 gpcd (38 to 57 lpcd).

*Commercial usage* varies according to the number and size of shops and stores in the area served. Attempts have been made to assign commercial consumption on the basis of gallons per day per square foot of floor space. However, the nature of business conducted in commercial installations varies widely, and accurate allocation of specific demands for commercial use must be based on a thorough investigation of the individual establishments.

*Industrial usage* can play a major role in the design of water supply, treatment, and distribution systems. In heavily industrialized areas, industrial usage can account for 30% or more of the total water consumption.

*Agricultural usage* includes the water used for irrigation and for watering livestock. In most localities, irrigation water will not be a factor in system design. However, in semiarid locations where crops rely heavily on irrigation water, consideration must be given to such needs, and a thorough analysis must be made.

***Water Consumption*** A necessary element in the design and selection of pumping equipment for water supply projects is the determination of the amount of water required. Population forecasts and estimates of future usage serve as a basis for the design of municipal and urban systems.

The rate of consumption is usually expressed as the average annual usage in gallons per capita per day. Actual average use varies throughout the country, generally from 120 to 200 gpcd (450 to 760 lpcd). In metropolitan areas, an average value of 175 gpcd (660 lpcd) is often used for design purposes.

***Demand and Daily Fluctuations*** Water supply systems are subject to wide fluctuations in demand. The rate of consumption varies seasonally, monthly, daily, and hourly. For design purposes, it is essential that a reasonably dependable relationship between certain water use rates be determined from past experience records. The usage and demand rates are as follows:

1. *Average daily demand* may be expressed as gallons (liters) per capita per day or million gallons (liters) per day (the total year's usage divided by 365). The average daily demand rate is generally used as the yardstick by which all other demand rates are measured.
2. *Maximum monthly demand* is the average daily use during the month of greatest consumption. It is determined by dividing that month's total usage by the number of days in the month.
3. *Maximum daily demand* is the total amount of water used during the day of heaviest consumption in the year. Experience shows this demand rate occurs on from three to five consecutive days during the year.
4. *Maximum hourly demand* is the rate of use during the hour of peak demand on the day of maximum demand. This demand rate normally establishes the highest rate of design for distribution systems and "peaking pumpage."

Recording the hourly variations in water consumption over a 24-hour period is no simple undertaking. It involves taking synchronized hourly readings of all pump discharge rates and storage levels and, from these, computing the hourly rate of consumption. Such recordings of hourly consumption rates made for Dallas are shown in Figure 2 and can be used to establish system design parameters.

**Water Consumption Rates as a Basis of Design** The variations in demand, expressed as a ratio of the average daily demand, must be considered in basic designs of water supply systems.

Figure 3 illustrates graphically the relationship that is characteristic of many water supply demand rates. It also serves to establish percentage ratios for design purposes as follows:

Maximum monthly rate = 155% × average daily rate
Maximum daily rate = 186% × average daily rate
Maximum hourly rate = 343% × average daily rate

Alternately, the design demand rates may be expressed in terms of per capita consumption:

Average daily demand = 175 gpcd (662 lpcd)
Maximum monthly demand = 270 gpcd (1022 lpcd)
Maximum daily demand = 325 gpcd (1230 lpcd)
Maximum hourly demand = 600 gpcd (2270 lpcd)

These demand rates are indicative of water requirements in the southwestern United States and will vary in other regions. Nevertheless, the values shown are reasonable and will assist designers in establishing local criteria. Above all, such values depict the broad range of pumping rates for which equipment must be chosen.

**Variations for Pumping-Time Evaluations** The pumps of most water supply systems must operate continuously throughout the year. Studies are often required to determine operating costs and evaluate equipment. Thus, pumping time in days, which can also be expressed as a percentage of average daily demands, is a useful piece of information in various pumping design problems. Based upon studies made of municipally owned waterworks of various sizes in the southwestern United States, the total pumpage for the year will vary approximately as shown in Table 1.

## PUMPING STATIONS

**Pumping Capacity** Determination of the capacity required at a particular pumping station must be based on a thorough analysis of the proposed system. Such factors as the projected average and maximum daily demands, the safe yield of the available supply, and the function of the pumping station in the total system must be considered.

Accurate forecasts of future demands will often establish the design criteria for a pumping station, which should be capable of supplying demands for the area served for many years. Common practice involves sizing the station for anticipated demands for 25 years or more, with initial installation of only enough pumping capacity for 5 to 10 years. Additional capacity can then be added, as directed by future demands, simply by installation of additional pumping units.

Limitations on pumping capacity may be imposed by the yield of the raw water supply. It is sometimes desirable to size pumps to deliver only the safe yield of the source. More often, however, it is practical to impose severe overdrafts on the supply source for short periods of time and to allow the source to refill during sustained periods of low demand. In such cases, pumping capacity may exceed the safe yield of 200% or more, depending on the magnitude of anticipated peak demands and the length of time for which such demands must be satisfied.

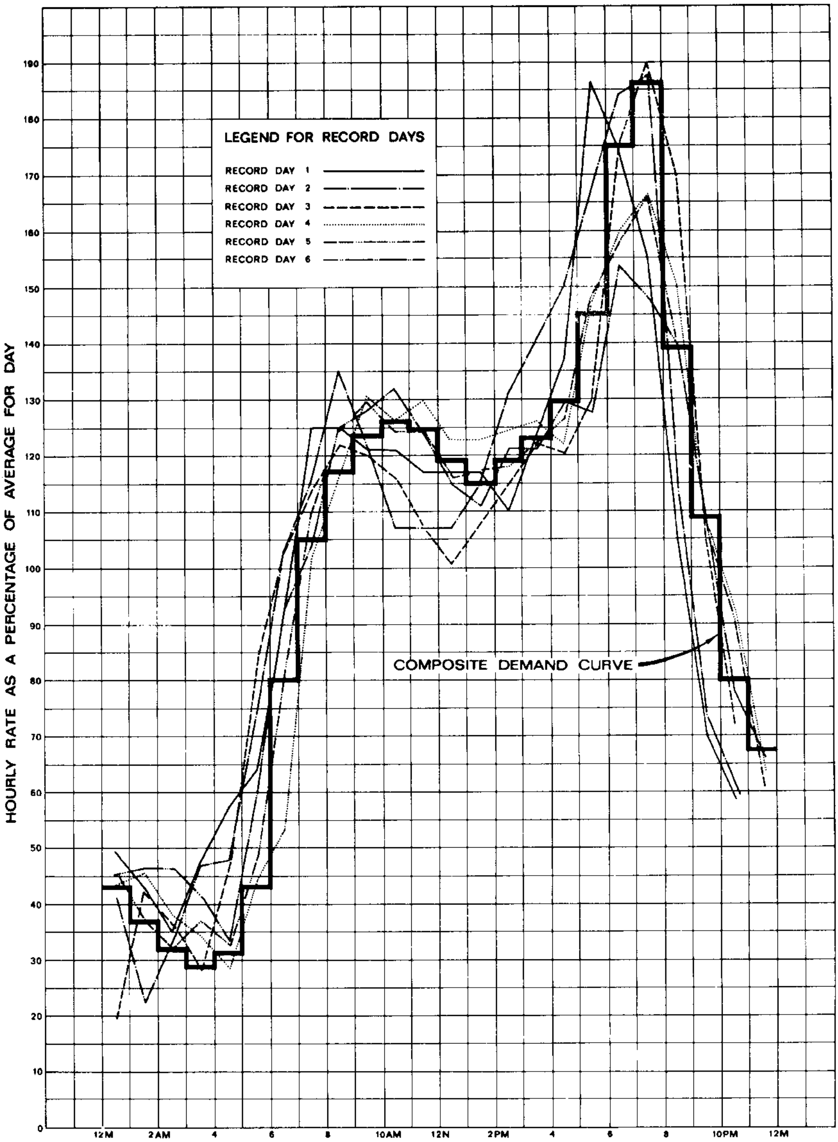

**FIGURE 2** Percentage rate of hourly water consumption for Dallas, showing variations on the days of recorded maximum demand and composite demand curve. This information can be used as a basis of system design (URS/Forrest and Cotton).

The function of the pumping station in overall system operation can also affect the determination of required pumping capacities. It is sometimes practical to provide constant-rate pumpage from the source by constructing a balancing reservoir near the treatment site. The balancing reservoir must have ample capacity to permit withdrawal at

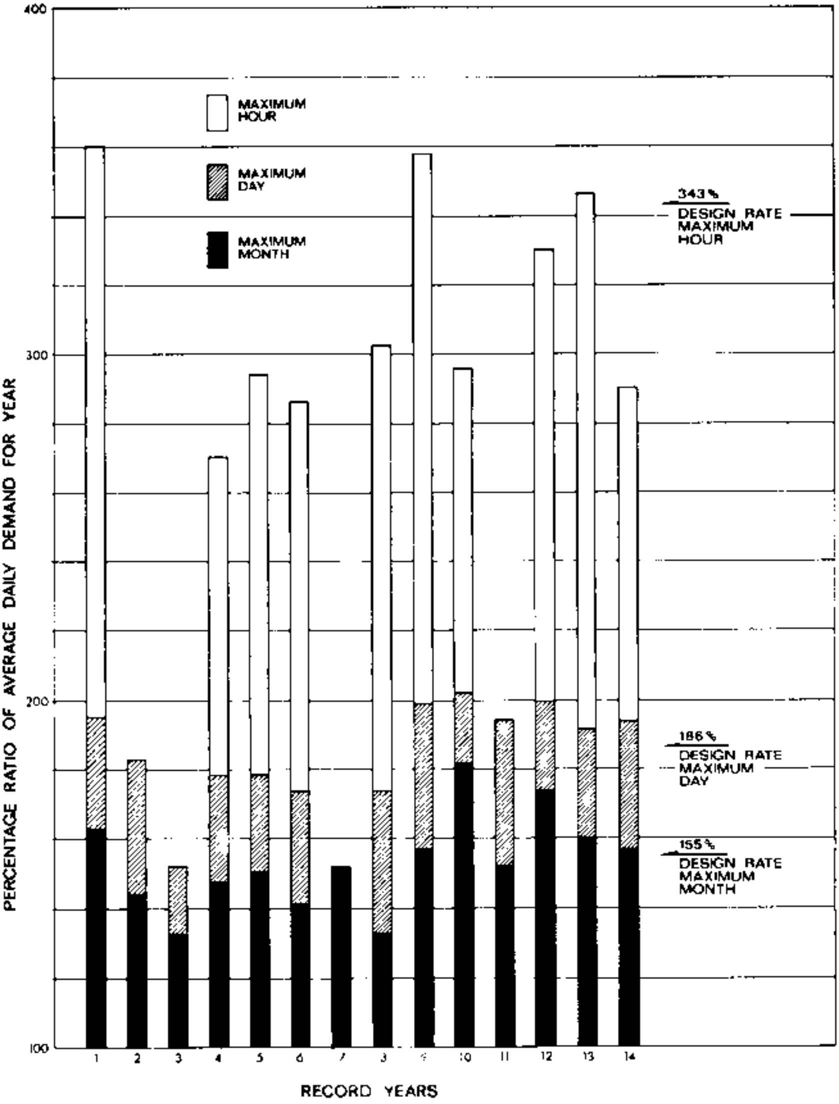

**FIGURE 3** Comparison of maximum monthly, daily, and hourly demand rates, expressed as percentage of average daily rate for the year (URS/Forrest and Cotton)

varying rates (in accordance with treated water demands) without overflowing or draining. Since the balancing reservoir is sized for a constant input, the transmission line from the source requires no peaking capacity and the size of the transmission line is thus minimized. This type of operation is thus economically feasible when the savings realized from the reduced size of the transmission line are greater than the cost of constructing a balancing reservoir and variable-rate pumping and transmission facilities for the short distance from the balancing reservoir to the treatment facilities. Accordingly, this operational

**TABLE 1** Number of days of pumpage in year expressed as ratio of average daily demand rate

| Demand, % of average daily rate | Days of pumpage per year |
|---|---|
| 190 | 11 |
| 185 | 14 |
| 180 | 12 |
| 165 | 11 |
| 155 | 13 |
| 145 | 17 |
| 135 | 12 |
| 115 | 27 |
| 85 | 95 |
| 75 | 64 |
| 65 | 89 |
|  | 365 |

scheme becomes desirable when the source of supply is located a great distance from the treatment site.

***Selection of Pump Type*** The location and configuration of the pumping station and intake structure and the anticipated heads and capacities are the major factors influencing the selection of a specific type of pump. If the pumping station and intake structure are to be located within a surface reservoir, vertical turbine pumps with columns extending down into a suction well are a logical choice.

In many cases, however, the pumping station is located downstream from the dam, with connecting suction piping from the intake structure. In such instances, a horizontal centrifugal pump represents a more logical selection. Horizontal centrifugal pumps of split-case design are commonly used in waterworks because the rotating element can be removed without disturbing suction and discharge piping. Selection of a bottom suction pump (in lieu of side suction) should be considered when possible because the former requires less space on the station floor.

***Effect of Source on Selection of Pump Materials*** Although many service conditions are involved in the selection of pump materials, the primary factors that can be related to source of supply are alkalinity and abrasiveness. The alkalinity (or acidity) of a raw water source is reflected by the raw water pH. In general, a pH above 8.5 or below 6.0 precludes the use of a standard bronze-fitted pump (cast iron casing, steel shaft, bronze impeller, wearing rings, and shaft sleeve). The high pH values often associated with groundwater sources then dictate the use of all-iron or stainless steel-fitted pumps.

Abrasiveness, which may result from sand and other suspended matter in a surface water supply, may dictate the selection of stainless steel or nickel-cast iron casing; cast iron, nickel-cast iron, or chrome steel impellers; and stainless steel, phosphor bronze, or Monel wearing rings, shafts, sleeves, and packing glands.

***Suction and Discharge Piping*** In order to minimize head loss and turbulence, the use of long-radius bends in both suction and discharge piping is strongly recommended. American Water Works Association (AWWA) approved double-disk gate valves with outside screw and yoke or AWWA-approved butterfly valves of the proper classification are recommended for use as isolation valves in the pump suction and discharge piping. Additionally, a check valve should be provided on the discharge side of the pump to prevent backflow through the pump upon shutdown or power failure. Many types of check valves have been used satisfactorily in such applications. However, the regulated opening and closing times afforded by cone valves, combined with excellent throttling characteristics,

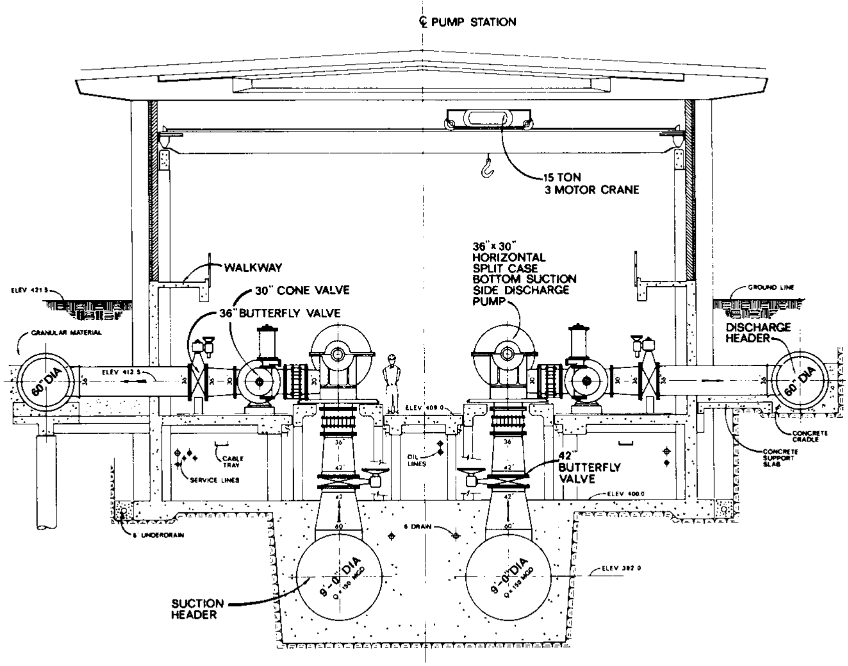

**FIGURE 4** Typical section of the Forney raw water pumping station in Dallas, showing pump suction and discharge piping (1 in = 2.54 cm; 1 ft = 0.3048 m) (URS/Forrest and Cotton)

have proved effective in minimizing surges and should be considered for pump check service if economically feasible.

Manifolding of suction and discharge headers is common practice in the design of pumping stations because parallel operation can be readily achieved with such an arrangement. Suction headers may be located directly below the pumps (Figure 4) or along the outside wall of the pump station (Figure 5), depending on the location of the intake structure and the configuration of the suction piping. Interconnection of discharge headers (Figure 6) provides additional system flexibility and added protection in the event of line breakage.

***Pump Drivers*** The waterworks industry has evolved to the point of almost exclusive use of electric motors as pump drivers. Diesel or gasoline engines may be used as emergency drivers or as the primary drivers where reliable electric power is not available. However, the high costs of continuous operation and the limitations of rotative speed preclude the use of diesel or gasoline drivers in most installations.

Although some dc motors are used in the waterworks industry, the great majority of electric motors used as pump drivers are ac motors of the squirrel-cage-induction, wound-rotor, or synchronous type. Hydraulic or magnetic variable-speed devices can be used in conjunction with the pump driver to vary pumping rates in accordance with demand.

***System-Head Curves*** The capacity of a pumping installation cannot be determined without an accurate determination of the head requirements of the system. Consequently, a system-head curve must be derived, depicting calculated losses through the system for various pumping rates. The construction of a system-head curve must be based upon a logical sequence of determinations of the various components of system losses.

A preliminary sketch or schematic should be derived, showing the configuration and size of suction and discharge piping, including all pipe, valves, and fittings.

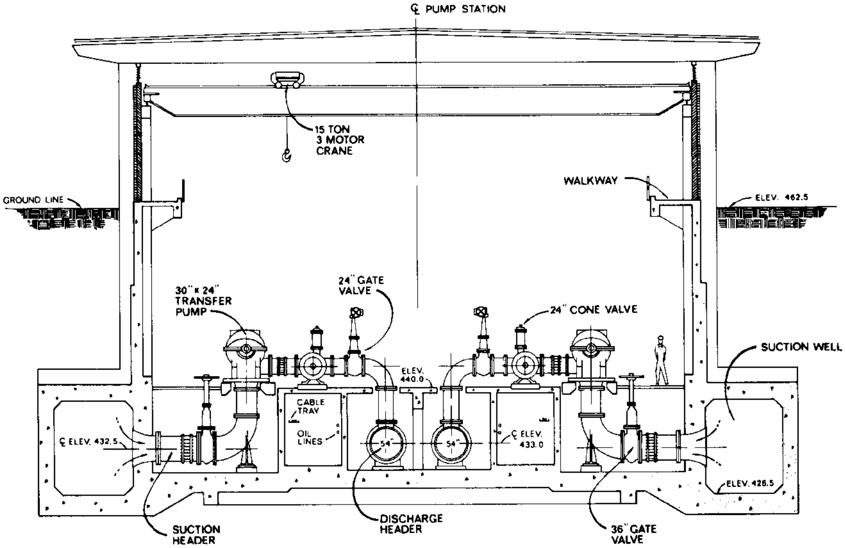

**FIGURE 5** Typical section of the high-service pumping station of the East Side water treatment plant in Dallas (1 in = 2.54 cm; ft = 0.3048 m) (URS/Forrest and Cotton)

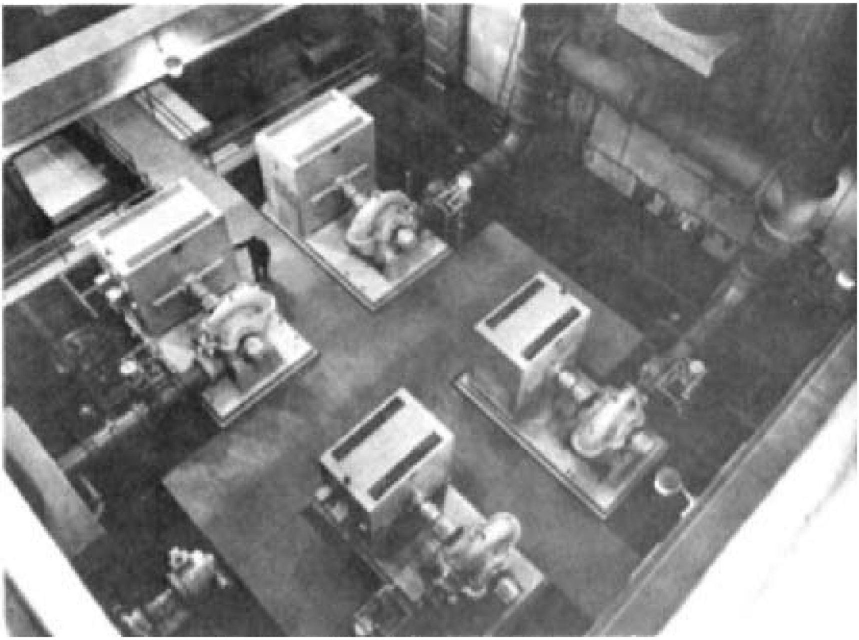

**FIGURE 6** Dallas Iron Bridge 100-mgd ($3.78 \times 105$ m$^3$/day) raw water pumping station, showing layout with bottom-suction, side-discharge pumping units (URS/Forrest and Cotton)

FRICTIONAL LOSSES Frictional loss in the discharge piping can be determined for various pumping rates from the formula:

In US units $$h_f = KQ^{1.85} \tag{1a}$$

In SI units $$hf = 2.618 \times 10^{-5} KQ^{1.85} \tag{1b}$$

where $h_f$ = head loss, ft (m)

$K$ = a constant depending on pipe size and friction factor $C$

$Q$ = flow, mgd ($m^3$/h)

Equation 1 is a modification of the basic Hazen-Williams formula for the special case of circular pipes flowing full. Values of $10^5K$ for various pipe sizes and friction factors are listed in Table 2. Common practice has been to design systems on the basis of $C = 100$. However, investigations for the Dallas Water Utilities have indicated that a regulated cleaning program for pipelines can result in sustained values of $C$ as high as 135 or 140. Accordingly, consideration should be given to providing for periodic cleaning of pipelines so the initial design capacity of the pumping units can be sustained.

To demonstrate the use of Eq. 1, assume that it is desired to compute the head losses due to pipe friction as a result of pumping at a rate of 30 mgd (4730 $m^3$/h) through 1050 ft (320 m) of 36-in diameter (914.4-mm) pipe having a friction factor of 130. From Table 2, $10^5K = 0.610$ or unit $K = 0.00000610$:

$$\text{Segmental } K = 0.00000610 \times 1050 = 0.006405$$

In USCS units
$$Q^{1.85} = 30^{1.85} = 540.3$$
$$h_f = 0.006405 \times 540.3 = 3.46 \text{ ft}$$

In SI units
$$Q^{1.85} = 4730^{1.85} = 6.29 \times 10^6$$
$$h_f = 2.618 \times 10^{-5} \times 0.006405 \times 6.29 \times 10^6 = 1.06 \text{ m}$$

Entrance and exit losses and losses through valves and fittings can be calculated from the data in Section 8.1.

STATIC HEAD AND PRESSURE DIFFERENTIAL In computing total system head, consideration must be given to the effects of static head and pressure differential. Static head can be calculated simply from the difference in elevation between supply level and discharge level, and differential pressure can be calculated from the difference between terminal pressure and suction pressure.

PUMP CHARACTERISTIC CURVES The shape of a centrifugal pump curve must be considered in selection of a specific pump. If, for example, the water level at the source of supply or at the point of discharge is subject to wide variation, a pump with a steep characteristic curve near the design point should be selected to minimize the effects of head variations on pump capacity. Additionally, the pump shutoff head (or head of impending delivery) must exceed the static head to ensure that the pump will operate upon opening of the discharge valve.

NET POSITIVE SUCTION HEAD As a final step in selection of a specific pump for a particular application, suction conditions should be investigated to determine the net positive suction head (*NPSH*) available. Failure to meet the *NPSH* requirements of the pump selected will result in cavitation of the pump impeller and very low pumping efficiency.

TOTAL SYSTEM HEAD The summation of all components of system head, as calculated for various flows, results in a graphical plot of the system-head curve (Figure 7). To determine the capability of a specific centrifugal pump operating under system conditions, the pump characteristic curve should be superimposed on the system-head curve. The intersection of the two curves then represents the capacity that the specific pump can deliver. The construction of system-head curves is further discussed in Section 8.1.

**TABLE 2** Computed valued of $10^5K$ for use in Eq. 1

| Pipe diameter, in. | Hazen-Williams $C$ value | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 70 | 80 | 90 | 100 | 110 | 120 | 110 | 135 | 140 |
| 6 | 11,800 | 9,240 | 7.420 | 6,100 | 5,100 | 4,350 | 3,750 | 3,590 | 3,280 |
| 8 | 2,900 | 2,270 | 1,823 | 1,500 | 1,240 | 1,070 | 924 | 881 | 805 |
| 10 | 982 | 767 | 617 | 507 | 425 | 362 | 312 | 298 | 272 |
| 12 | 404 | 315 | 253 | 209 | 175 | 149 | 128.5 | 122.6 | 112.1 |
| 14 | 190 | 149 | 119.7 | 98.4 | 82.5 | 70.4 | 60.5 | 57.8 | 52.9 |
| 16 | 99.6 | 77.8 | 62.6 | 51.6 | 43.3 | 36.8 | 31.6 | 30.3 | 27.7 |
| 18 | 56.1 | 43.9 | 35.2 | 29.0 | 24.3 | 20.7 | 17.84 | 17.04 | 15.6 |
| 20 | 33.6 | 26.2 | 21.1 | 17.33 | 14.53 | 12.4 | 10.67 | 10.17 | 9.30 |
| 21 | 26.4 | 20.7 | 16.6 | 13.67 | 11.47 | 9.77 | 8.43 | 8.05 | 7.35 |
| 24 | 13.8 | 10.3 | 8.68 | 7.13 | 5.99 | 5.09 | 4.39 | 4.19 | 3.83 |
| 27 | 12.4 | 6.08 | 4.89 | 4.02 | 3.37 | 2.87 | 2.47 | 2.36 | 2.16 |
| 10 | 4.66 | 3.64 | 2.91 | 2.41 | 2.02 | 1.717 | 1.48 | 1.412 | 1.291 |
| 51 | 2.94 | 2.29 | 1.964 | 1.516 | 1.269 | 1.081 | 0.933 | 0.890 | 0.814 |
| 16 | 1.92 | 1.50 | 1.206 | 0.993 | 0.832 | 0.708 | 0.610 | 0.583 | 0.534 |
| 19 | 1.298 | 1.016 | 0.816 | 0.670 | 0.563 | 0.480 | 0.413 | 0.395 | 0.361 |
| 42 | 0.906 | 0.706 | 0.570 | 0.469 | 0.392 | 0.334 | 0.287 | 0.276 | 0.251 |
| 45 | 0.646 | 0.504 | 0.406 | 0.334 | 0.280 | 0.238 | 0.206 | 0.1964 | 0.1796 |
| 48 | 0.462 | 0.379 | 0.290 | 0.239 | 0.200 | 0.1702 | 0.1470 | 0.1401 | 0.1280 |
| 51 | 0.352 | 0.275 | 0.221 | 0.1816 | 0.1522 | 0.1296 | 0.1119 | 0.1067 | 0.0975 |
| 54 | 0.266 | 0.208 | 0.1673 | 0.1377 | 0.1152 | 0.0982 | 0.0848 | 0.0807 | 0.0738 |
| 57 | 0.204 | 0.160 | 0.1285 | 0.1056 | 0.0886 | 0.0753 | 0.0650 | 0.0621 | 0.0567 |
| 60 | 0.1594 | 0.1244 | 0.1000 | 0.0823 | 0.0691 | 0.0587 | 0.0507 | 0.0484 | 0.0442 |
| 63 | 0.1256 | 0.0982 | 0.0789 | 0.0650 | 0.0545 | 0.0464 | 0.0400 | 0.0382 | 0.0349 |
| 66 | 0.1000 | 0.0785 | 0.0630 | 0.0518 | 0.0434 | 0.0370 | 0.0319 | 0.0304 | 0.0278 |
| 69 | 0.0805 | 0.0630 | 0.0507 | 0.0417 | 0.0349 | 0.0298 | 0.0256 | 0.0245 | 0.0224 |
| 72 | 0.0655 | 0.0511 | 0.0412 | 0.0339 | 0.0284 | 0.0242 | 0.0209 | 0.01991 | 0.01820 |
| 75 | 0.0538 | 0.0414 | 0.0339 | 0.0278 | 0.0233 | 0.01982 | 0.01710 | 0.01632 | 0.01493 |
| 78 | 0.0444 | 0.0347 | 0.0279 | 0.0229 | 0.01924 | 0.01637 | 0.01413 | 0.01348 | 0.01231 |
| 81 | 0.0314 | 0.0289 | 0.0232 | 0.01906 | 0.01600 | 0.01360 | 0.01173 | 0.01121 | 0.01024 |
| 84 | 0.0309 | 0.0242 | 0.01942 | 0.01600 | 0.01340 | 0.01141 | 0.00984 | 0.00939 | 0.00859 |
| 90 | 0.0222 | 0.01730 | 0.01390 | 0.01143 | 0.00957 | 0.00816 | 0.00704 | 0.00672 | 0.00614 |
| 96 | 0.01614 | 0.01262 | 0.01013 | 0.00834 | 0.00700 | 0.00596 | 0.00513 | 0.00491 | 0.00448 |
| 102 | 0.01200 | 0.00939 | 0.00756 | 0.00621 | 0.00520 | 0.00444 | 0.00381 | 0.00365 | 0.00334 |
| 108 | 0.00910 | 0.00711 | 0.00572 | 0.00471 | 0.00395 | 0.00336 | 0.00289 | 0.00276 | 0.00253 |
| 120 | 0.00545 | 0.00426 | 0.00343 | 0.00283 | 0.00235 | 0.00200 | 0.00173 | 0.00165 | 0.00151 |

Note: In Eq. 1a,

$K = (1594/C)^{1.85}\,(L/d^{4.87})(l/0.446)$

$C$ = Hazen-Williams coefficient of pipe friction

$D$ = pipe length, ft; $10^5K$ values are for $L = 1.0$ ft and must be multiplied by true line length to determine line segmental $K$

$d$ = pipe diameter, in

1 in = 25.4 mn

***Parallel and Series Operation*** The installation of multiple pumping units operating in parallel is common practice in the waterworks industry because, with proper design and regulation, it permits the most efficient use of pumping facilities and allows smooth transitions in pumping rates as demand fluctuates. This type of operation is particularly adaptable to pumpage from treatment facilities into a distribution system but is also applicable to raw water pumpage, which is generally required to match treated water pumpage. Special care must be taken in sizing the individual pumping units to ensure efficient operation and to prevent units from operating significantly above or below design rates during parallel operation. The principle upon which design must be based is that *total station discharge may be determined by adding the individual pump discharges associated with any particular head.* Obviously then, as additional pumps are placed in operation, the station flow will increase. However, because the system-head curve rises with

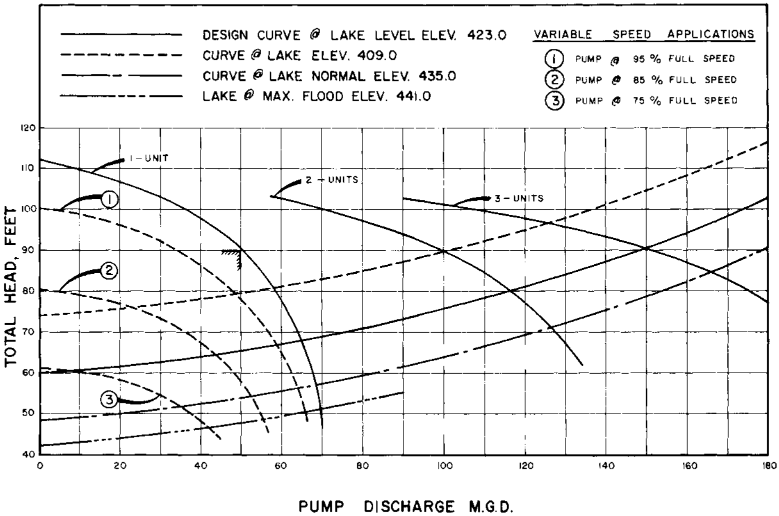

**FIGURE 7** System-head curve for the Forney raw water pumping station of Dallas (1 ft = 0.3048 m; 1 mgd = 157.7 $m^3/h$; elev. in ft × 0.5048 = elev. in m) (URS/Forrest and Cotton)

increasing flow, *the operation of two identical pumps in parallel will not produce a discharge equal to twice the capacity of one pump.* As more pumps are placed in operation, the incremental increase in pumping capacity becomes smaller.

It should be noted that, when only a portion of the pumps are in operation (total station flow is less than design capacity), the total system head is reduced and the individual pumping units are thus operating at a rate exceeding the design capacity.

If flows are increased substantially past the design point, the *NPSH* available may become inadequate and cavitation may occur. Additionally, the possibility of overloading the pump driver is introduced, particularly in pumps designed for high heads. In selecting a pumping unit, it is therefore necessary to check conditions at runout capacity (the maximum discharge and lowest head anticipated) in order to ensure proper pump operation.

The undesirable effects of operating a pump at capacities lower than design flow are similar to those resulting from overpumping, but for different reasons. Low discharge rates result in recirculation through the pump, causing cavitation, vibration, and noise. Moreover, the radial force on the impeller increases substantially, thus increasing the stress on the shaft and bearings (to an even greater extent than would result from overpumping). Drivers of pumps designed for low heads may be subjected to overload at low capacities (and thus high heads).

In determining pumping capacities for series operation, *heads are added.* Thus two identical pumps with capacity of 30 mgd (4730 $m^3/h$) at 200 ft (60 m) of system head would, if placed in series, discharge 30 mgd (4730 $m^3/h$) at 200 ft (60 m) of system head. This type of operation is frequently employed in raw water pumping stations in the form of multistage, vertical turbine pumps and is frequently utilized to boost pressures in a distribution system.

***Variable-Speed Applications*** Installation of two or more variable-speed pumping units will allow gradual increase or decrease of station discharge as dictated by demand. When the required discharge is less than the capacity of two pumps, the variable-speed units may be operated in parallel. Moreover, the installation of two variable-speed units permits operation at flows in excess of the minimum allowable flow and ensures satisfactory efficiency under all conditions. Figure 8 typifies the relationships between head, capacity,

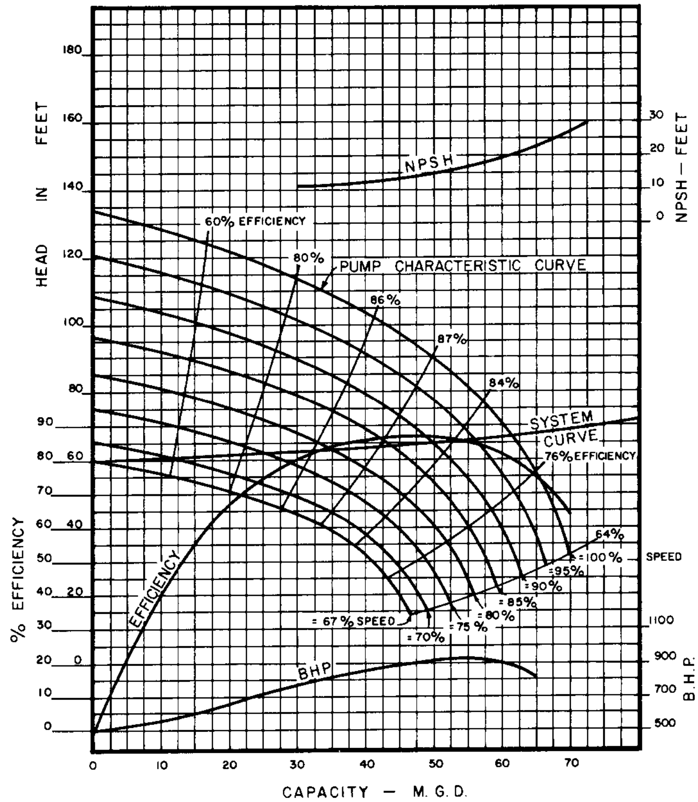

**FIGURE 8** System-head curves for variable-speed operation for the Forney raw water pumping station in Dallas (1 ft = 0.3048 m ; 1bhp = 0.746 bkW; 1 mgd = 157.7 m$^3$/h) (URS/Forrest and Cotton)

and efficiency at varying speeds. Typical procedure for an installation with two variable-speed units is as follows:

1. If station flow is less than the capacity of one pump, one variable-speed unit is operated.
2. If station flow is between one and two times the capacity of a single unit, both variable-speed units are operated (in lieu of operating one unit at full speed and the other at a speed less than that required to produce minimum allowable flow).
3. If station flow is more than two times the capacity of a single unit, the two variable-speed units are operated, along with as many constant-speed units as are required to ensure operation of all pumps at speeds that will produce flows exceeding minimum requirements.

## *USES OF PUMPS AT WATER TREATMENT PLANTS*

Pumps are an integral part of virtually every water treatment plant in existence and have a variety of uses, including low-lift service, coagulant feed, carbon slurry transfer and feed,

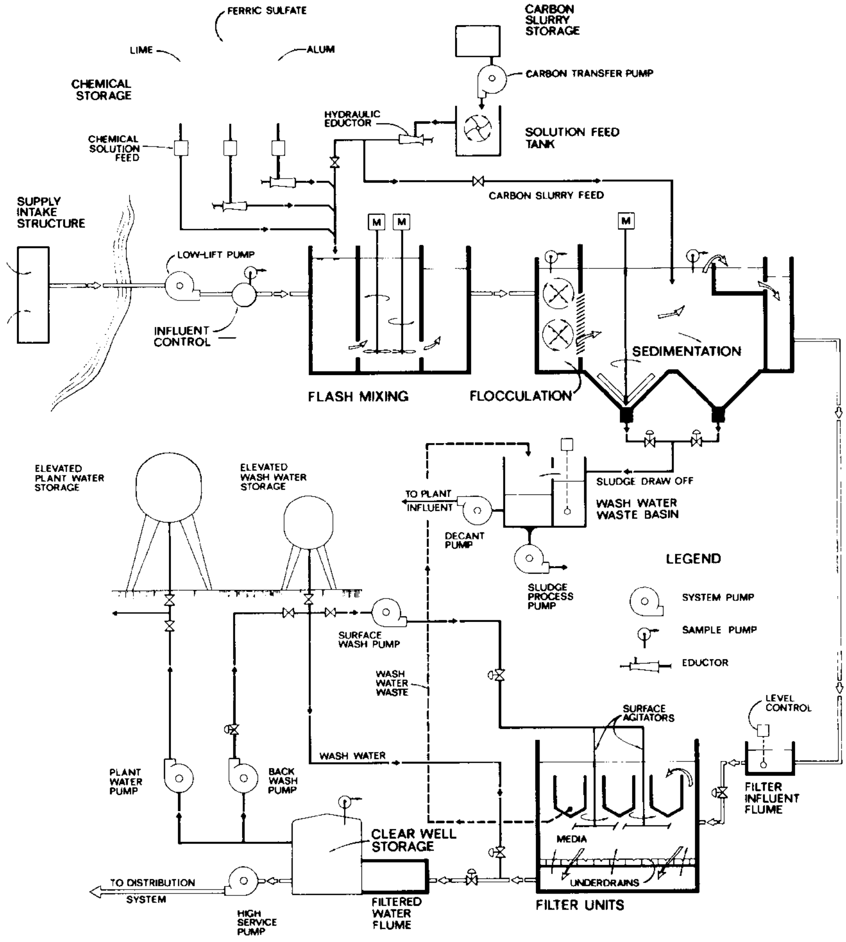

**FIGURE 9** Typical flow diagram of water treatment plant, including raw water supply

fluoride feed, delivery of samples from selected points to the chemical laboratory, plant water supply, wash water supply, surface wash supply, and high service pumpage to the distribution system (Figure 9).

***Low-Lift Pumps*** Low-lift pumps, located at either the source or the treatment site, are often outdoor, weatherproof vertical pumps (Figure 10). They may also be horizontal centrifugal pumps housed in a separate pumping station. Head and capacity requirements are as discussed previously.

***Coagulant Feed Pumps*** Pumps used in chemical feed applications are usually not centrifugal because of the kinds of materials handled. More often, chemicals are fed by a jet pump or hydraulic eductor that utilizes a moving stream of water to create a vacuum at the suction port of the eductor. This type of pump has no moving parts and is thus adaptable to the feeding of coagulants such as alum or ferric sulfate in solution. A constant-level solution tank is often used to maintain a constant head on the eductor suction. The

**FIGURE 10** Raw water pumping station for North Texas Municipal Water District, showing vertical turbine pumps with variable-speed drives (Flowserve Corporation)

eductor capacity is then a function of water supply pressure and frictional loss in the feed lines. Eductors are normally rated according to suction capacity, which must be added to the amount of flow contributed by the motive fluid in calculating head losses through the feed system. The manufacturer's literature should be consulted to determine the water supply requirements for various sizes of eductors.

***Carbon Slurry Pumps*** Treatment plants that receive raw water from surface sources often require the addition of activated carbon to combat taste and odor problems caused by suspended material and microorganisms carried into the supply by floodwaters. Consequently carbon must be stored in ample quantities to supply immediate needs. The activated carbon is often transferred from storage tanks to a constant-level solution tank in the form of a slurry. Progressing cavity-type pumps equipped with variable-speed drives are suitable for this transfer service, provided the proper construction materials are selected. The range of capacities required is equal to the difference between minimum and maximum carbon feed rates, and discharge head can be calculated as for any pumping system. However, selection of operating speed and power requirements must be based on estimates of the abrasive and viscous characteristics of the slurry.

***Fluoride Pumps*** The addition of hydrofluosilicic acid to drinking water is achieving growing acceptance in the United States as an effective preventative of tooth decay. Pumps used for addition of this material should be positive displacement, mechanical diaphragm, metering pumps constructed of special materials, such as Kralastic, Fenton, and Teflon. A relief valve should be installed on the discharge line to protect the pump in the event of a line blockage.

Diaphragm pumps operate on the principle of the linear motion of a flexible diaphragm, which pulls the solution through an intake port during the backward stroke and forces solution out the discharge port on the forward stroke. Feed rate can be varied by adjusting the stroke length or by a multistep pulley belt-connected to the motor driver. Hydrofluosilicic acid is usually supplied as a slurry that is 20 to 30% hydrofluosilicic acid. Of this acid, 79% is in the form of fluoride ion. In sizing the fluoride feed pumps, consideration must be given to the following factors:

1. Difference between the fluoride ion content of the raw water and that desired in the finished water
2. Strength of the slurry
3. Specific gravity of the slurry

For example, assume that the fluoride ion content of the raw water is 0.3 parts per million (ppm) and the desired concentration in the treated water is 0.8 ppm; that the slurry is 20% hydrofluosilicic acid with a specific gravity of 1.22; and that the plant raw water inflow is 100 mgd (15,800 $m^3/h$). The required dosage is then

$$\frac{0.8 - 0.3}{(0.79)(0.20)(1.22)} = 0.192 \text{ ppm of slurry}$$

and the amount of slurry needed is

in USCS units $\quad 0.192 \text{ ppm} \times 100 \text{ mgd} \times 8.34 \text{ lb/gal} = 160 \text{ lb/day}$

in SI units $\quad 0.192 \text{ ppm} \times 15{,}800 \text{ m}^3/\text{h} \times 10^{-6} \times 24 \text{ h/day} \times 998.3 \text{ kg/m}^3 = 72.7 \text{ kg/day}$

Head losses to the point of application can be calculated (with allowances for the viscosity of the slurry) and the proper feed rate accomplished by adjustment of the stroke length. A diaphragm pump is capable of providing a repeatable accuracy of ±1%, a desirable characteristic in light of the fact that excess fluoride in drinking water can produce harmful rather than beneficial effects on the teeth.

***Sampling Pumps*** Small-capacity centrifugal pumps are generally used for delivery of samples from various points in the plant to the chemical laboratory for analysis. Capacities required are generally in the vicinity of 5 to 10 gpm (1.1 to 2.3 $m^3/h$). The required discharge head can be determined from a schematic layout of the suction and discharge piping, with provision for some 10 to 15 $lb/in^2$ (70 to 100 kPa) pressure at the chemical laboratory faucet. Head losses through the system are computed as in any pumping system, and such computations are simplified somewhat by the fact that no interconnections are involved; that is, each sample pump must have a separate discharge line to the chemical laboratory.

***Plant Water Pumps*** Water used for various purposes throughout the treatment plant is usually taken from the treated water at the end of the process. Such water may be pumped back directly into the plant water system or to an elevated storage tank that supplies the head required for adequate pressures throughout the plant. In either case, a thorough study of the plant water system is necessary to determine the amount of water required. The plant water tank can be provided with automatic start and stop controls based on the water level in the tank to prevent complete draining or overflowing. Allowances should be made to ensure that the tank is sufficiently elevated to provide ample pressures at water-consuming devices. Plant water pumps will generally be of horizontal split-case construction and must be capable of filling the elevated tank at rates determined from analysis of the plant water system.

***Wash Water Pumps*** The procedure for selecting wash water pumps is much the same as that for plant water pumps. An elevated wash water tank should be sized large enough to permit backwashing of one filter at a time and should be elevated as necessary to provide the required flows through the wash water piping system. Required backwash rates vary from about 15 to 22.5 $gpm/ft^2$ (37 to 55 $m^3/h/m^2$) of filter surface area. In determining head losses from the elevated tank through the filters, consideration must be given not only to the head losses in piping, valves, and fittings, but also to the head losses in the filter underdrain system, which may range from 3 to 8 ft (0.9 to 2.4 m) at a backwash rate of 15 $gpm/ft^2$ (37 $m^3/h/m^2$), depending on the under-drain system installed and the filter bed. The wash water tank should be sized to allow backwashing of one filter for approximately 10 mm and should be equipped with controls for automatically starting and stopping the wash water pumps at predetermined levels. The required pumping capacity depends on the estimated frequency and rate of backwashing.

Wash water pumps may also be used to supply water directly to the backwash piping system. The head required in such cases is that needed to overcome all losses in the wash water piping, underdrain system, and filter bed, and the capacity should equal the maximum backwash rate. An air release valve, check valve, and throttling valve should be provided on the discharge side of the wash water pump, and standby service is highly recommended.

Because the wash water pumps generally use treated water from clear well storage, horizontal centrifugal pumps should be used only when positive suction head is available. Otherwise, a vertical pump unit may be suspended in the clear well.

***Surface Wash Pumps*** Manufacturers of rotary agitators for surface wash systems generally specify a minimum pressure for proper operation of their equipment. This pressure [generally from 40 to 100 lb/in$^2$ (280 to 690 kPa)] must be added to the system piping losses in determining head requirements for surface wash pumps. The required discharge may vary from 0.2 to 1.5 gpm/ft$^2$ (0.5 to 3.7 m$^3$/h/m$^2$) of surface area, depending on the supply pressure, size, and type of agitator supplied.

***High-Service Pumps*** High-service pumps at a water treatment plant are those pumps that deliver water to the distribution system. The term *water distribution system* as used herein is defined as embodying all elements of the municipal waterworks between the treatment facilities and the consumer. The function of the distribution system is to provide an efficient means of delivering water under reasonable pressure in volumes adequate to meet peak consumer demands in all parts of the area served.

High-service pumps may be of either vertical or horizontal construction, depending on the required capacity and the design and configuration of treated water storage facilities from which the pumps take suction. The high-service pumping station often houses the plant water and wash water pumps in addition to the high-service pumps because all such pumps utilize treated water to perform their required services (Figure 11).

Operating conditions in the distribution system play an important role in the determination of high-service pump capacities. In small municipalities, for example, it may be possible to pump from the treatment plant at a constant rate equal to the average daily demand and to supply peak demands from elevated storage tanks throughout the system. However, as systems become larger, the need for variable-rate pumping from the treatment plant increases. If sufficient storage is available in the distribution system for supplying peak hourly demands, it may be possible to provide variable-speed high-service pumps with total capacity equal to the maximum capacity of the treatment plant and to supply hourly peaks from storage. However, inasmuch as peak hourly demands may be two or more times as great as the peak daily demand and may be sustained for several hours, the required system storage for such operation can exceed 30% of the maximum daily demand. In very large systems, provision for this amount of storage is simply impractical. It may then become necessary to design treatment facilities for capacities in excess of the maximum daily demands and to supply only a portion of the peaking water from storage.

In any event, as distribution systems become larger, variable-speed pumping becomes more desirable and development of a system-head curve becomes more complex. In many cases, pumpage from treatment plants during off-peak hours exceeds pumpage during peak hours because storage tanks must be filled during off-peak hours. System-head curves must be derived for each of the previous conditions and also for a third condition, which represents those periods when storage tanks are full but are not being utilized to supply demands. Typical system-head curves for all three conditions are shown on Figure 12. Only a thorough analysis of the entire distribution system can provide the data necessary for the proper selection of high-service pumps.

## BOOSTER PUMPS IN DISTRIBUTION SYSTEMS

In order to maintain distribution system pressures within the desirable 40- to 90-lb/in$^2$ (275- to 620-kPa) range, booster pumps may be required at various locations, as dictated

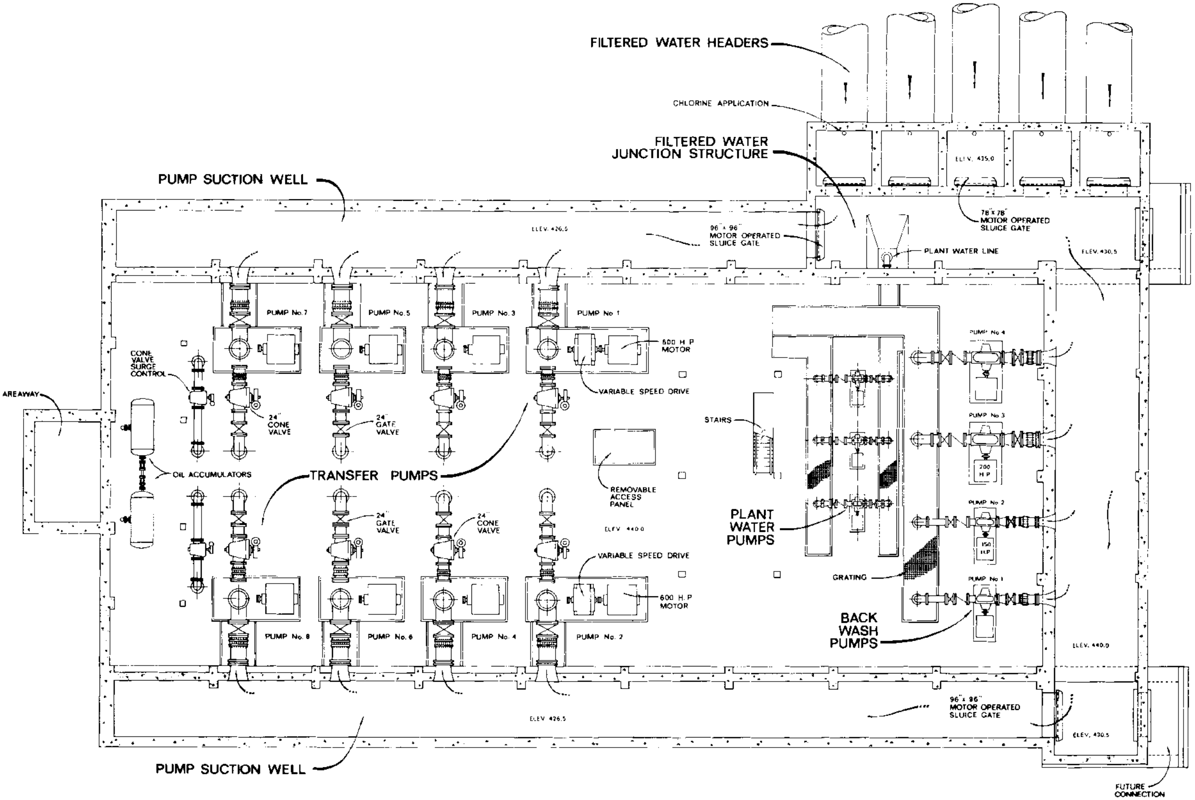

**FIGURE 11** Plan of the high-service pumping station in the East Side water treatment plant, Dallas (1 in = 2.54 cm; 1 ft 0.3048 m) (URS/Forrest and Cotton)

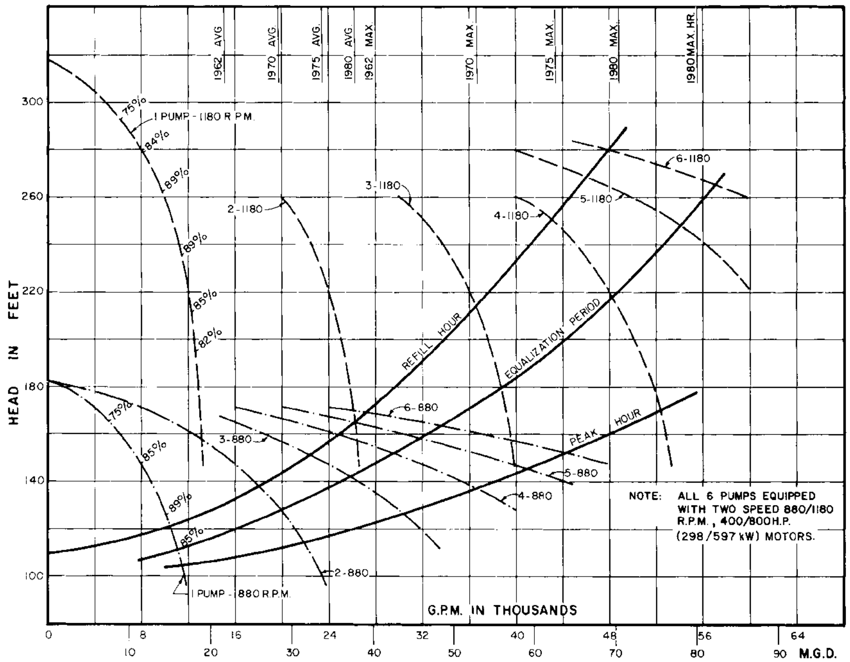

**FIGURE 12** Typical system-head curves for high-service pumpage to water distribution system (1 ft = 0.3048 m; 1 gpm = 0.227 m$^3$/h)

by topographical conditions and system layout. Booster stations may include in-line vertical or horizontal pumps connected directly to the pipeline or separate storage reservoirs and pumps. The latter method is preferred but is not always practicable because of land requirements for the storage reservoir.

In-line booster pumps should be sized to match the capacities of incoming pipelines and should be capable of supplying the additional head required to increase pressures to desirable ranges in the affected area of the distribution system. Determination of discharge head must take into account the pressure on the suction side of the pump as well as static head, frictional losses, and desired residual pressure on the discharge side.

Many water utilities refuse to accept in-line pumps as satisfactory for booster service and require construction of a pressure-equalizing storage reservoir. Horizontal or vertical booster pumps then take suction from the storage reservoir and return water at higher pressures to the mains. Pressure switches or floats automatically start and stop the booster pumps and thus eliminate the need for continuous attendance.

## GROUNDWATER WELLS

***Site Selection*** Foremost among the factors that must be considered in selection of a site for a proposed well are local regulations governing proximity to such potential contaminants as cesspools, privies, animal pens, or abandoned wells. Also to be considered is the effect on adjacent wells—if wells are located too close together, excessive head losses may result.

***Types of Pumps Used*** The two basic types of pump used in groundwater wells are vertical turbine, line shaft pumps, and submersible pumps. The vertical turbine pump consists of three basic components: the driving head, the column-pipe assembly, and the bowl assembly. The driving head is mounted above ground and consists of the pump discharge elbow, the motor support, and the stuffing box. The column-pipe assembly (consisting of shaft, bearings, and bearing retainers) and the bowl assembly (consisting of a suction head, impeller or impellers, discharge bowl, and intermediate bowl or bowls) are suspended from the driver head. Use of multiple bowls and impellers results in a form of series operation and permits pumpage against very high heads.

The submersible pump utilizes a waterproof electric motor located below the static level of the well to drive a series of impellers and produce a series operation similar to that of a line shaft pump. However, the length of shafting required is greatly reduced, and thus the shaft losses and total thrust are minimized. As a result, the submersible pump becomes economically competitive with the line shaft pump at great depths.

Air-lift pumps, which operate on the principle that a mixture of air and water will rise in a pipe surrounded by water, may be used in some cases. Such pumps are easy to maintain and operate and can be used in a crooked well or with sandy water. However, they are relatively inefficient (usually 30 to 50%) and allow very little system flexibility.

Reciprocating pumps are also used in some cases where small capacities are required from deep wells. Such pumps can be driven by electric motors or windmills, but they are generally noisy and are more expensive than centrifugal pumps.

***Determining Pump Capacity*** The capacity of any well is dependent on such factors as screen size, well development, aquifer permeability, recharge of groundwater supply from rainfall and streams, and available head. The basic procedure used in sizing a pump for well service involves drilling the well and performing a test operation. First the static head, or elevation of the groundwater table prior to pumping, is determined. Water is then pumped at various rates and the drawdown associated with each pumping rate determined. A plot of drawdown versus pumping rate can then be derived. Pumping rate is usually measured by a weir, orifice, or pilot tube, and drawdown is determined with a detector line and gage or with an electric sounder.

From the test data and from a preliminary layout of discharge piping, a system-head curve can be derived, with drawdown added to frictional losses for each pumping rate. The pump characteristic curve can then be superimposed on the system-head curve to determine the capacity that can be attained with a specific pump. It should be noted that pump curves for line shaft pumps are based on the results of shop tests, which do not allow for column frictional or line shaft and thrust losses. Consequently, the laboratory characteristic curve for any line shaft pump must be adjusted to field conditions.

Field pumping head can be determined by subtracting column frictional losses from the laboratory head. Field brake horsepower (brake kilowatts) is determined by adding shaft brake horsepower (brake kW), which depends on shaft diameter and length, and on rotative speed, to laboratory brake horsepower (brake kW). Field efficiency is determined from the formula

$$\text{In USCS units} \qquad \text{Field efficiency} = \frac{\text{gpm} \times \text{field head in feet}}{3960 \times \text{field brake horsepower}}$$

$$\text{In SI units} \qquad \text{Field efficiency} = \frac{\text{m}^3\text{/h} \times \text{field head in meters}}{367.5 \times \text{field brake kW}}$$

Because thrust loads cause additional losses in the motor bearing, it is necessary to determine the additional power required to overcome thrust losses. Total thrust load is equal to the sum of the shaft weight and the hydraulic thrust (which varies with laboratory head for any particular impeller), and losses due to thrust amount to approximately 0.0075 hp/100 rpm/1000 lb (0.00126 kW/100 rpm/1000 N) of thrust. Motor efficiency is then calculated by dividing the motor's full load power input (without thrust load) by the sum of full load power input and loss due to thrust. Overall efficiency then equals the product of field efficiency and motor efficiency.

As a result of the efficiency losses produced by shaft weight and length in line shaft pumps, it is usually more economical to use a submersible pump at depths of more than about 500 ft (150 m). Sizing a submersible pump requires calculations similar to those for a line shaft pump. However, the submersible pump installation requires a check valve in the column pipe, which must be considered in the determination of frictional losses. Moreover, the efficiency losses resulting from the motor cable (expressed as a percentage of input electric power) must be considered in determining overall efficiency, which can be calculated from the formula:

$$\text{Overall efficiency} = \frac{\text{water power} \times (\%\ \text{motor efficiency} - \%\ \text{cable loss})}{\text{shop brake power} \times 100}$$

where

$$\text{in USCS units} \qquad \text{Water power in hp} = \frac{\text{gpm} \times \text{field head in feet}}{3960}$$

$$\text{in SI units} \qquad \text{Water power in kW} = \frac{\text{m}^3\text{h} \times \text{field head in meters}}{367.5}$$

Cable size must be selected on the basis of motor power and motor input amperes, voltage, and cable length.

***Well Stations*** A typical well station generally includes a small building for housing the pump, pump controls, metering and surge-control facilities, and chemical feed equipment. Submersible pumps do not require a pump house for protection, but if pump controls or chemical feed equipment are provided, an enclosure of some type is required. Because well water supplies are often pumped directly into the distribution system, a differential producer is usually installed for metering. Moreover, chemicals may be added at the well station to minimize corrosion, control bacteria, decrease hardness, and inject fluorides into the water supply. Surges are usually controlled by installation of a surge valve in the pump discharge line. Controls may also be installed to permit starting and stopping of the pump from remote central locations and to provide for measurement and control of well drawdown.

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