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CALCULATING HORSEPOWER REQUIREMENTS AND SIZING IRRIGATION SUPPLY PIPELINES

Guy Fipps*

Pumping costs are often one of the highest individual expenses in irrigated agriculture. Table 1 shows typical fuel use and pumping costs in Texas, as measured by irrigation pumping plant tests conducted by Texas A&M AgriLife Extension Service. Properly sizing pipelines for each specific application will help minimize expenses. This publication will outline how to calculate the horsepower requirements of irrigation pumps and how to use this information in sizing supply pipelines.

PUMPING PLANT EFFICIENCY

An irrigation pumping plant has three major components:

1. Power unit,
2. Pump drive (or gear head), and
3. A pump.

For electric-powered plants, the motor shaft and the pump line shaft are generally connected directly, making a pump drive (gear head) unnecessary.

The *overall pumping plant efficiency* is a combination of the efficiencies of each individual component. The components of an individual pumping unit in good condition—when carefully matched to the specific requirements of a pumping situation—can have efficiencies similar to those provided in Table 2. However, numerous pumping units operate at efficiencies far below acceptable levels (Table 3).

Performance Standards

There are two primary methods of determining the efficiency of pumping plants. One is to measure the efficiency of each component of the plant (i.e., motor, shaft, and pump). Once the efficiencies of the components are known, the overall efficiency is easily calculated. This requires specialized equipment and considerable expertise.

Another method is to calculate the load on the motor or engine, followed by measuring how much fuel is consumed by the power unit. Then, the fuel usage can be compared to a standard. The most commonly used standards were developed by the Agricultural Engineering Department of the University of Nebraska (Table 4). The fuel consumption rates in Table 4 indicate the fuel use that can be *reasonably expected* from an accurately engineered irrigation pumping plant in good condition. The actual fuel consumption of a new or reconditioned plant should not be larger than what is in Table 4.

CALCULATING HORSEPOWER

Horsepower is a measurement of energy required to perform work. To determine the amount of horsepower needed to pump water, the operator must know the:

1. Pumping rate in gallons per minute (GPM); and
2. Total dynamic head (TDH) in feet.

Water horsepower (WHP) is the theoretical power needed for pumping water, which is calculated by:

(Equation 1) $$\text{WHP} = \frac{\text{GPM} \times \text{TDH (ft)}}{3{,}960}$$

Because no device or machine is 100 percent efficient, the power unit's horsepower output must be higher than that calculated with Equation 1. This horsepower, referred to as brake horsepower (BHP), is calculated by:

(Equation 2) $$\text{BHP} = \frac{\text{WHP}}{\text{(pumping plant efficiency)}}$$

TOTAL DYNAMIC HEAD (TDH)

TDH can be viewed as the total load on the pumping plant, which is usually expressed in feet of "head"—1 pound per square inch (psi) = 2.31 feet of head). TDH can be calculated with the following equation:

(Equation 3) TDH = (static head) + (friction loss) + (operating pressure) + (elevation change)

*Extension agricultural engineer, The Texas A&M University System.

Pumping lift is the vertical distance from the water level in the well to the pump outlet during pumping. In areas of a falling water table, the maximum depth to the water table expected during the pumping season is often used.

Friction loss occurs when water flows past the rough walls in a pipe, which creates friction, causing a pressure loss. Friction losses can also occur when water flows through pipe fittings—or, when the pipe diameter suddenly increases or decreases. There are numerous tables available with values for friction loss through pipe and fittings (similar to Tables 6 and 7).

Operating pressure requirements are provided by manufacturers for each water applicator, nozzle size, flow rate combination, along with other site-specific conditions. Operating pressure in *psi* is converted to *feet-of-head* by the relationship:

$$1 \text{ psi} = 2.31 \text{ ft}$$

Elevation change is the total change in elevation from the pump to the discharge point (e.g., end of the pipeline or sprinkler head). An elevation change may be positive (when the irrigation system is uphill from the pump) or negative (when it is downhill from the pump). Only use the difference in elevation between these two points—not the sum of each uphill or downhill section. Remember: Add the distance from the ground to the point of water discharge, particularly for center pivot systems.

For center pivot systems, elevation differences caused by slopes in the field generally are accounted for in the computer printout of the design. They are included in the operating pressure requirements. If not, then the elevation change in the field from the pivot point to the highest point should be added to the total elevation change.

SIZING IRRIGATION MAINLINES

In sizing irrigation water supply pipelines, two important factors are: *friction losses* and *water hammer,* which are both influenced by the relationship between the flow rate (i.e., velocity) and pipe size.

Water Hammer

Shock waves are produced when moving water is subjected to a sudden change in flow—referred to as *water hammer* or *surge pressure.* Water hammer is often caused by shock waves created by sudden increases or decreases in the water's velocity, created by the valves opening, pumps being started or stopped, or when water encounters directional changes due to fittings.

Controlling Water Hammer

Pressure relief valves are installed in the pipeline downstream of the pump to control surge pressure in situations where excessive pressures may develop by operating the pump with all of its valves closed. Also, pressure relief valves (or surge chambers) should be installed on the check valve's discharge side in situations where backflow may occur. Air trapped in a pipeline can contribute to water hammer. Air can also compress and expand in the pipeline, causing velocity changes. To minimize these issues, install air-relief valves at the high points of the pipeline and at other locations as needed to prevent air from accumulating in the system.

Other recommendations for minimizing water hammer include:

1. Install "non-slam" check valves for long pipelines sloping up from the pump (designed to close at zero velocity and before the column of water above the pump so it can move back).
2. When filling a long pipeline, control the flow with a gate valve (set at approximately 3/4 of the operating capacity). Once the lines have filled, the valve should be slowly opened until full operating capacity and pressure is attained.

"5-Feet-per-Second" Rule

To minimize water hammer, specifically in polyvinyl chloride plastic pipe (PVC), water velocities should be limited to 5 feet/s (feet per second)—unless specific considerations are given to control water hammer. Many experts agree that the velocity should never exceed 10 feet/s. Also, in centrifugal pumps, the velocity of flow in the suction pipe should be kept between 2 and 3 feet/s to inhibit cavitation. Table 5 illustrates the maximum flow rates recommended for different internal diameter (ID) pipe sizes using the 5-Feet-per-Second Rule. Most friction loss tables give both the friction loss and velocity for any given GPM and pipe size.

Velocity (V) in feet per second (feet/s) can be calculated based on the flow rate in gallons per minute (GPM) and internal pipe diameter in inches as:

(Equation 4) $$V \text{ (ft/s)} = \frac{\text{Flow (GPM)}}{2.45 \, ID^2 \text{ (inches)}}$$

Friction Loss

Pumping plants must provide sufficient energy to overcome friction losses in pipelines. Excessive friction loss will lead to high horsepower requirements and correspondingly high fuel usage for pumping. Often, the additional cost of a larger pipe will be recovered quickly from lower fuel costs. Both undersized and oversized pipes should be avoided.

Smooth pipe produces less friction loss and has lower operating expenses than rough pipe. In order from smoothest to rougher pipe: plastic pipe (e.g., PVC), aluminum, steel, and concrete. Typical friction losses in commonly used pipe can be found in Table 6.

The friction losses displayed are for pipes with these internal diameters (this table is presented for information purposes only). Actual pipe diameters vary widely, and more precise data from manufacturers' specifications should be used for design purposes.

Pump Selection

Do not select pumps based on horsepower. Pumps are selected based on the required flow rate, the total dynamic head, and the rated revolutions per minute (RPM) of the engine where applicable. There will be several options for pumps that meet the specific pumping requirements. Therefore, select the pump with the highest efficiency possible for the specific pumping conditions. Pump curve charts have been used for this purpose for years. However, dealers and manufacturers now use computer software to quickly sort through all of the pump possibilities and select the one with the highest efficiency for the specific pumping requirements.

SELECTING PVC PIPE

PVC (thermoplastic pipe) is precisely manufactured by a continuous extruding process that produces a strong, seamless pipe, which is chemically resistant, lightweight, and minimizes friction loss. PVC pipe is produced in various sizes, grades, and specifications.

PVC Terminology

Low pressure pipelines – Underground thermoplastic pipelines with a 4 to 24-inch nominal diameter used in systems subject to pressures of 79 psi or less.

High pressure pipelines – Underground thermoplastic pipelines of a 1/2 to 27-inch nominal diameter that are closed to the atmosphere and subject to internal pressures (including surge pressures, from 80 to 315 psi).

Class or pounds per square inch (psi) designation – Refers to a pressure rating in pounds per square inch (psi) (see Table 8).

Schedule – Refers to a plastic pipe with the same outside diameter and wall thickness as iron or steel pipe of the same nominal size (see Table 9).

Standard Dimension Ratio (SDR) – Refers to the outside pipe diameter ratio to the wall thickness. Table 9 gives the pressure rating for pipes of various SDR.

Iron Pipe Size (IPS) – Refers to plastic pipe with the same outside diameter as iron pipe of the same nominal size.

Plastic Irrigation Pipe (PIP) – This is an industry size designation for plastic irrigation pipe.

Working Pressure

The recommended maximum operating pressures of various classes and schedules of PVC pipe are shown in Tables 8 and 9. Actual operating pressure may be equal to these pressure ratings as long as **surge pressures** are included. Be sure to account for **all** surges.

To determine which pipe to use, combine the pipe's total head with the surge pressures and select the closest larger class. Be aware: Surge pressures should not exceed 28 percent of the pipe's pressure class rating.

When surge pressures are unknown, the actual operating (or "working") pressure should not exceed the maximum allowable working pressures given in Table 11.

Estimating Surge Pressure

As previously discussed, keeping the velocity at or below 5 feet/s will help minimize surge pressure (or water hammer). Please note: The sudden opening and closing of valves will produce a surge pressure, which increases with higher velocities. The maximum surge pressure produced in a PVC pipe with the sudden opening or closing of a valve can be determined from Table 10. For example, the surge pressure from a sudden valve closure with a water velocity of 7 feet/s in a SDR 26 PVC pipe is:

$$7 \times 14.4 = 100.8 \text{ psi}$$

This pressure is then added to the operating pressure to determine which class of PVC pipe to use.

EXAMPLE PROBLEM 1 – COMPLETE ANALYSIS

Determine the horsepower difference requirements and annual fuel costs for 6-inch and 8-inch mainlines (e.g., plastic pipe) for the following system:

System Data

1. Type of power plant	Diesel
2. Cost of energy	$2.65 per gal.
3. Pumping lift	250 ft
4. Pump column pipe distance to pump in column pipe	8-in. steel pipe 350 ft (or 3.5 × 100-ft sections)
5. System flow rate	750 GPM
6. Yearly operating time	2,000 hrs.
7. Distance from pump to pivot	4,000 ft (or 40 × 100-ft sections)
8. Required operating pressure	45 psi
9. Elevation change from pump to pivot	+37 ft
10. Types of fittings in system	Check valve, gate valve, two standard elbows

(Equation 3) Step 1 – Calculate Total Dynamic Head (TDH)

TDH = (*pumping lift*) + (*elevation change*) + (*operating pressure*) + (*friction losses*)

1. **Pumping lift** (item 3) = 250 ft
2. **Elevation change** (item 9) = +37 ft
3. **Operating pressure** (item 8) = 45 psi × (2.31 ft/psi) = 104 ft
4. **Friction loss: Pump column pipe**
    a. Friction loss in 8-in. well casing (from Table 6) = 1.8 ft/100 ft
    b. Total friction loss = 1.8 × 3.5 = 6.3 ft
5. **Friction loss in plastic mainline (Case 1: 6-in. pipe)**
    a. Friction loss in pipe (from Table 6) = 3.4 ft/100 ft × 40 = 136 ft
    b. Friction loss in fittings (from Table 7)
    Equivalent pipe length = 30 + 3.5 + (2 × 16) = 65.5 ft of pipe
    Friction loss = 3.4 ft/100 ft × (65.5/100) = 2.2 ft
    c. Total friction loss = 136 + 2.2 = 138.2 ft
6. **Friction loss in plastic mainline (Case 2: 8-in. pipe)**
    a. Friction loss in pipe (from Table 5) = 0.8 ft/100 ft × 40 = 32 ft
    b. Friction loss in fittings
    Equivalent pipe length = 40 + 4.5 + (2 x 14) = 72.5 ft of pipe
    Friction loss = 0.8 ft/100 ft × (72.5/100) = 0.6 ft
    c. Total friction loss = 32 + 0.6 = 32.6 ft
7. **TDH (Case 1)** = (1) + (2) + (3) + (4) + (5) = 250 + 37 + 104 + 6.3 + 138.2 = 535.5 ft
8. **TDH (Case 2)** = (1) + (2) + (3) + (4) + (6) = 250 + 37 + 104 + 6.3 + 32.6 = 429.9 ft

(Equation 2) Step 2 – Calculate Water Horsepower (WHP)

$$\textbf{(Case 1)}\ \text{WHP} = \frac{(750\ \text{GPM}) \times (535.5\ \text{ft})}{3{,}960} = 101\ \text{WHP}$$

$$\textbf{(Case 2)}\ \text{WHP} = \frac{(750\ \text{GPM}) \times (429.9\ \text{ft})}{3{,}960} = 82\ \text{WHP}$$

Note: The power plant's output must be larger than the WHP due to the pump's efficiency. Typically, a pump efficiency of 75 percent is used in the design. However, the actual pump selection is based on pump performance curves available from manufacturers.

(Equation 2) Brake Horsepower (BHP)

(Case 1) BHP = 101/.75 = 135 BHP

(Case 2) BHP = 81/.75 = 108 BHP

Step 3 – Calculate Annual Fuel Use

Note: The Nebraska Performance Standards (Table 4) can be used to estimate annual fuel consumption. From Table 4, each gallon of diesel will provide 12.5 WHP-hours.

$$\textit{Fuel use} = \textit{WHP} \times \frac{1}{(\textit{performance criteria})} \times (\textit{hours of operation})$$

$$\textbf{(Case 1)}\ \text{Fuel use} = 101\ \text{WHP} \times \frac{\text{gal.}}{12.5\ \text{WHP} - \text{hrs.}} \times \frac{2{,}000\ \text{hrs.}}{\text{yr.}} = \frac{16{,}160\ \text{gals.}}{\text{yr.}}$$

$$\textbf{(Case 2)}\ \text{Fuel use} = 81\ \text{WHP} \times \frac{\text{gal.}}{12.5\ \text{WHP} - \text{hrs.}} \times \frac{2{,}000\ \text{hrs.}}{\text{yr.}} = \frac{12{,}960\ \text{gals.}}{\text{yr.}}$$

Step 4 – Calculate Annual Fuel Costs

$$\textbf{(Case 1)}\ \frac{16{,}160\ \text{gals.}}{\text{yr.}} \times \frac{\$2.65}{\text{gal.}} = \$42{,}824\ \text{per year for diesel}$$

$$\textbf{(Case 2)}\ \frac{12{,}960\ \text{gals.}}{\text{yr.}} \times \frac{\$2.65}{\text{gal.}} = \$34{,}344\ \text{per year for diesel}$$

DIFFERENCE = $42,824 – $34,344 = $8,480

Step 5 – Calculated Total Water Pumped per Year

Note: The conversion rate used is: 325,851 gal. = 1 ac.-ft

$$\frac{750\ \text{gals.}}{\text{min.}} \times \frac{60\ \text{mins.}}{\text{hr.}} \times \frac{2{,}000\ \text{hrs.}}{\text{yr.}} = 90\ \text{million gals.} = 276\ \text{acre-feet of water}$$

EXAMPLE PROBLEM 2: SIMPLIFIED ANALYSIS

In the previous example, the friction losses in the pump column pipe (due to the fittings) are minimal. The only significant difference between Case 1 and Case 2 is the friction loss in the pipeline. Thus, the difference in horsepower requirements and annual fuel costs between the 6-inch and 8-inch pipelines in the previous example can be approximated by considering only the pipe's friction loss.

Step 1 – Calculate Pipeline Friction Loss Difference

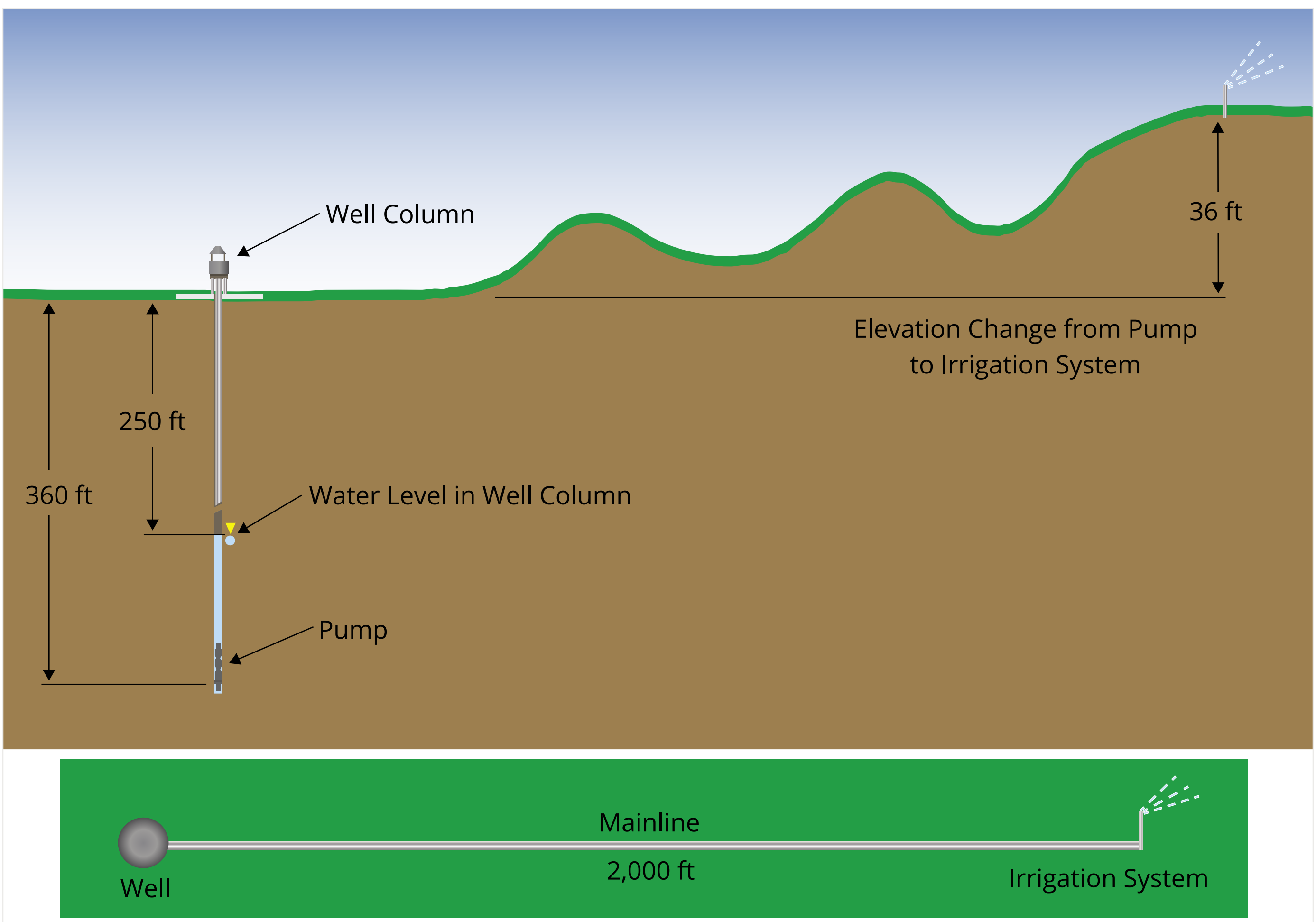
(Friction loss in 6-in.) - (Friction loss in 8-in.) = 136 - 32 ft = 104 ft

Step 2 – Calculate Increase in Horsepower and Annual Fuel Use

$$\text{WHP} = \frac{750 \times 104}{3{,}960} = 19.7 \text{ WHP}$$

$$\text{Fuel use} = 19.7 \text{ WHP} \times \frac{\text{gal.}}{12.5 \text{ WHP} - \text{hrs.}} \times \frac{2{,}000 \text{ hrs.}}{\text{yr.}} = \frac{3{,}151 \text{ gals.}}{\text{yr.}}$$

Note: This means that 3,151 more gallons of diesel would be required if a 6-inch mainline was used instead of an 8-inch mainline.



Adapted from a drawing by Ed Wilson

Table 1. Pumping costs in the Texas High Plains (THP) and in South/Central Texas (SCT) per acre-inch of water at 100 feet total head from irrigation pumping plant efficiency tests conducted by the Texas A&M AgriLife Extension Service.

Type and price[1]	Region	Cost ($) per ac.-in. per 100 ft head		
		Lowest	Highest	Average
Natural Gas @ $3.00 MCF	THP SCT	0.40 0.31	3.93 1.96	0.81 0.76
Electricity @ $0.10/KWH	THP SCT	0.70 0.41	4.43 28.89	1.93 2.13
Diesel @ $2.65/gal.	THP SCT	2.33 1.43	7.79 13.82	3.14 3.35

[1]Assumed price—actual prices varied in each region.

Table 2. Irrigation pumping equipment efficiency.

Equipment	Attainable Efficiency, Percent
Pumps (centrifugal, turbine)	75–82
Right-angle pump drives (gear head)	95
Automotive-type engines	20–26
Industrial engines	
Diesel	25–37
Natural gas	24–27
Electric motors	
Small	75–85
Large	85–92

Table 3. Typical values of overall efficiency for representative pumping plants, expressed as percent.*

Power Source	Recommended as Acceptable	Average Values from Field Tests†
Electric	72–77	45–55
Diesel	20–25	13–15
Natural gas	18–24	9–13
Butane, propane	18–24	9–13
Gasoline	18–23	9–12

*Ranges are given because of the variation in efficiencies of both pumps and power units. The difference in efficiency for high and low-compression engines used for natural gas, propane, and gasoline must be considered. The higher value of efficiency can be used for higher compression engines.

†Typical average observed values reported by pump efficiency test teams.

Table 4. Nebraska performance criteria for pumping plants. Fuel use by new or reconditioned plants should equal or exceed these rates.

Energy Source	Water Horsepower-hours[1] per unit of Energy	Energy Units
Diesel	12.5	gal.
Gasoline[2]	8.7	gal.
Natural gas	66.7[3]	1,000 ft^3
Electricity	0.885[4]	kwh

[1] Based on 75 percent efficiency.

[2] Includes drive losses and assumes no cooling fan.

[3] Assumes natural gas content of 1,000 BTU per cubic foot. 4Direct connection—no drive.

[4] Direct connection—no drive.

Table 5. Approximate maximum flow rate in different pipe sizes to keep velocity ≤ 5 feet per second.

Pipe Diameter	Flow Rate (GPM)
1/2	6
3/4	10
1	15
1 1/4	25
1 1/2	35
2	50
3	110
4	200
5	310
6	440
8	780
10	1,225
12	1,760
16	3,140

Table 6. Friction losses in feet-of-head per 100 feet of pipe (for pipes with internal diameters shown).															
	4-inch			6-inch			8-inch			10-inch			12-inch		
Pipe size	Steel	Alum.	PVC	Steel	Alum.	PVC	Steel	Alum.	PVC	Steel	Alum.	PVC	Steel	Alum.	PVC
Flow rate (GPM)															
100	1.2	0.9	0.6	—	—	—	—	—	—	—	—				
150	2.5	1.8	1.2	0.3	0.2	0.2	—	—	—	—	—	—			
200	4.3	3.0	2.1	0.6	0.4	0.3	0.1	0.1	0.1	—	—	—			
250	6.7	4.8	3.2	0.9	0.6	0.4	0.2	0.1	0.1	0.1	0.1	—	—	—	
300	9.5	6.2	4.3	1.3	0.8	0.6	0.3	0.2	0.1	0.1	0.1	—	—	—	—
400	16.0	10.6	7.2	2.2	1.5	1.0	0.5	0.3	0.2	0.2	0.1	0.1	0.1	—	—
500	24.1	17.1	11.4	3.4	2.4	1.6	0.8	0.6	0.4	0.3	0.2	0.1	0.1	0.1	0.1
750	51.1	36.3	24.1	7.1	5.0	3.4	1.8	1.3	0.8	0.6	0.4	0.3	0.2	0.1	0.1
1000	87.0	61.8	41.1	12.1	8.6	5.7	3.0	2.1	1.4	1.0	0.7	0.5	0.4	0.3	0.2
1250	131.4	93.3	62.1	18.3	13.0	8.6	4.5	3.2	2.1	1.5	1.1	0.7	0.6	0.4	0.3
1500	184.1	130.7	87.0	25.6	18.2	12.1	6.3	4.5	3.0	2.1	1.5	1.0	0.9	0.6	0.4
1750	244.9	173.9	115.7	34.1	24.2	16.1	8.4	6.0	4.0	2.8	2.0	1.3	1.2	0.9	0.6
2000	313.4	222.5	148.1	43.6	31.0	20.6	10.8	7.7	5.1	3.6	2.6	1.7	1.5	1.1	0.7

NOTE: Flow rates below horizontal line for each pipe size exceed the recommended 5-feet-per-second velocity.

Table 7. Friction loss in fittings. Friction loss in terms of equivalent length of pipe (feet) of same diameter.						
	Inside Pipe Diameter (inches)					
Type of fitting	4	5	6	8	10	12
45-degree elbow	5	6	7	10	12.5	15
Long-sweep elbow	7	9	11	14	17	20
Standard elbow	11	13	16	20	25	32
Close return bend	24	30	36	50	61	72
Gate value (open)	2	3	3.5	4.5	5.5	7
Gate value (1/2 open)	65	81	100	130	160	195
Check valve	100	110	30	40	45	35

Table 8. Pressure rating for class and SDR non-threaded PVC pipe.*	
Pipe Designation	Maximum Working Pressure Including Surges (psi)
Class 80	80
Class 100	100
Class 125	125
Class 160	160
Class 200	200
Class 250	250
Class 315	315
SDR 81	50
SDR 51	75
SDR 41	100
SDR 32.5	125
SDR 26	160
SDR 21	200
SDR 17	250
SDR 13.5	315

*For pipes of standard code designation: PVC 1120, PVC 1220, and PVC 2120.

Table 9. Pressure rating for schedule 40 and schedule 80 PVC pipe.*		
Diameter (inches)	Maximum Operating Pressure (psi)	
	Schedule 40	Schedule 80
3	840	1200
4	710	1040
6	560	890
8	500	790
10	450	750
12	420	730

*For Type I, Grade I at 73.4 degrees F.

Table 10. Maximum surge pressures associated with sudden changes in velocity in psi per feet/s. water velocity (for 400,000 psi modulus of elasticity PVC materials).	
SDR	Maximum Surge Pressure (psi) per each feet/s. of Water Velocity
13.5	20.3
17.0	18.0
21.0	16.1
26.0	14.4
32.5	12.9
41.0	11.4
51.0	10.2
64.0	9.1
81.0	8.1

Example: The surge pressure from a sudden valve closure with a water velocity of 7 feet/s. in a SDR 26 PVC pipe is **7 × 14.4 = 100.8 psi.**

Table 11. Maximum allowable working pressure for non-threaded PVC pipe when surge pressures are not known and for water temperatures of 73.4 degrees F.	
SDR	Maximum Working Pressure (psi)
13.5	227
17.0	180
21.0	144
26.0	115
32.5	90
41.0	72
51.0	58
64.0	45
81.0	36

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