Appendix 10-B

Pump Station Hydraulic Design Example

10.B.1 Introduction

The following is a systematic procedure which integrates the hydraulic design variables involved in wet pit design. It incorporates the recommended design criteria and yields the required number and capacity of pumps as well as the wet well and storage dimensions.

Theoretically, an infinite number of designs are possible for a given site. Therefore, to initiate design, constraints must be evaluated and a trial design formulated to meet these constraints. Then, by routing the inflow hydrograph through the trial pump station, its adequacy can be evaluated.

The hydraulic analysis of a pump station involves the interrelationship of three components:

- the inflow hydrograph,
- the storage capacity of the wet well and the outside storage, and
- the discharge rate of the pumping system.

The inflow hydrograph is determined by the physical factors of the watershed and regional climate factors. The discharge of the pump station is often controlled by local regulations or physical factors. Therefore, the main objective in pump station design is to store enough inflow (volume of water under the inflow hydrograph) to allow station discharge to meet specified limits. Even if there are no physical limitations to pump station discharge, storage should always be considered since storage permits the use of smaller and/or fewer pumps.

10.B.2 Pump Station Hydraulic Design

The procedure for pump station design is illustrated in the following 10 steps:

Step 1 Inflow to Pump Station

Develop inflow hydrograph to the pump station using the procedures presented in Chapter 3, Hydrology.

Step 2 Estimate Pumping Rate, Volume of Storage, and Number of Pumps

Because of the complex relationship between the variables of pumping rates, storage, and pump on-off settings, a trial and error approach is usually necessary for estimating the pumping rates and storage required for a balanced design. A wide range of combinations will produce an adequate design. The goal is to develop an economic balance between volume and pumping capacity.

Some approximation of all three parameters is necessary to produce the first trial design. One approach is shown in Figure 10-3, Estimating Required Storage. In this approach, the peak pumping rate is assigned and a horizontal line representing the peak rate is drawn across the top of the hydrograph. The shaded area above the peak pumping rate represents an estimated volume of storage required above the last pump turn on point. This area is measured to give an estimated starting size for the storage facility. Once an estimated storage volume is determined, a storage facility can be estimated. The shape, size, depth, etc., can be established to match the site and a stage-storage relationship can be developed.

The total pumping rate may be set by stormwater management limitations, capacity of the receiving system, the desirable pump size, or available storage. Two pumps would be the minimum number of pumps required (MDOT typically uses three as a minimum). However, as many as five pumps may be needed in the case of a continuously depressed highway. Size and, thus, numbers of pumps may be controlled by physical constraints such as portable standby power.

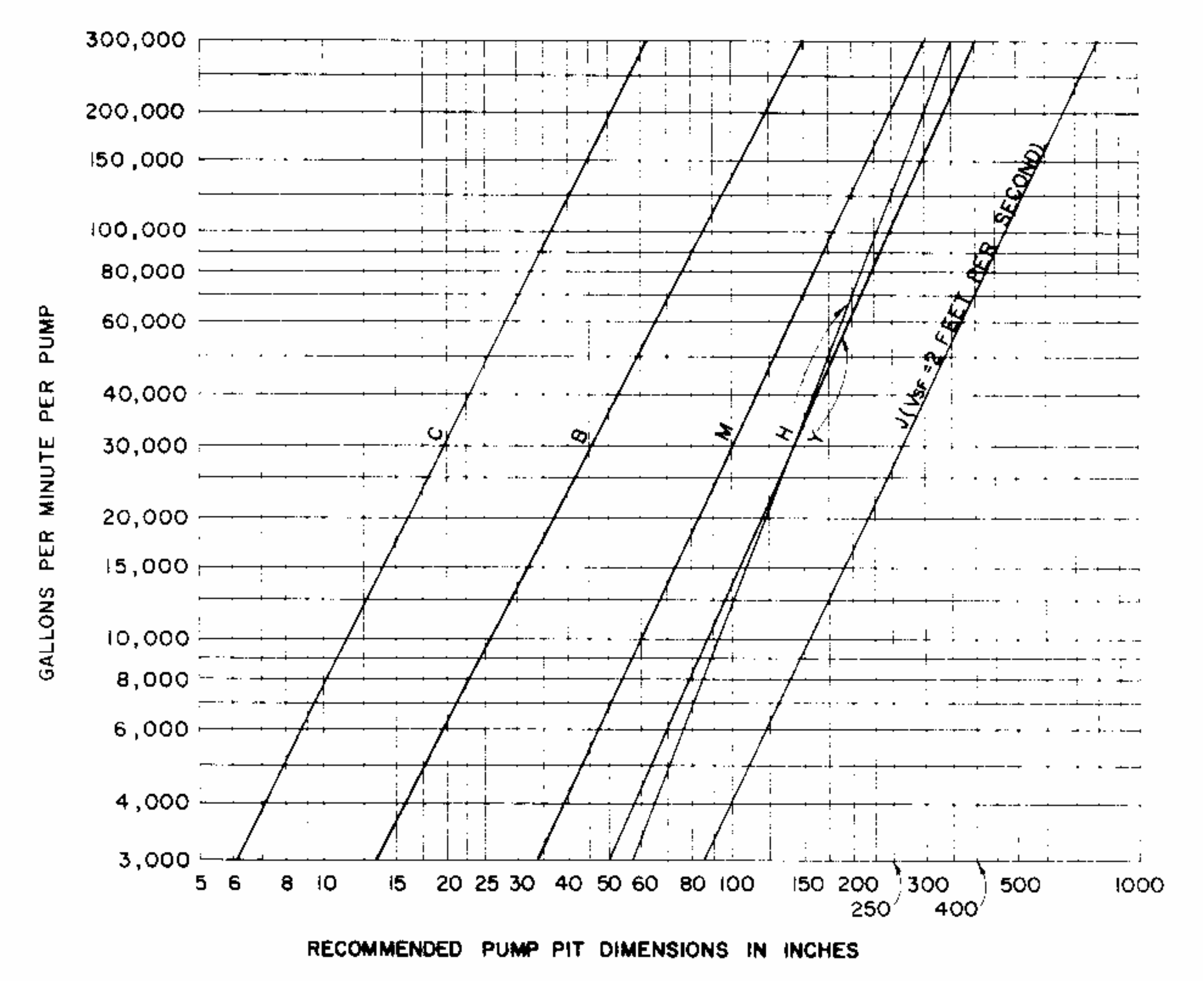
Step 3 Design High Water Level

The highest permissible water level in the wet well must be set as 2 feet or more below the gutter pan. The lower the elevation, the more conservative the design.

At the design inflow, some head loss will occur through the pipes and appurtenances leading to the pump station.

Step 4 Determine Pump Pit Dimensions

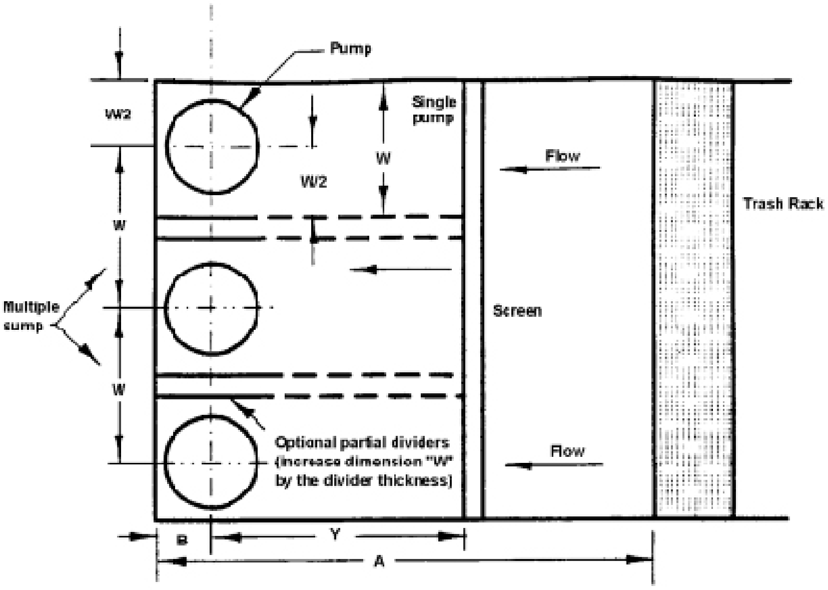
Determine the minimum required plan dimensions for the pump station from manufacturer's literature or from dimensioning guides such as those provided by the Hydraulic Institute (see Figure 10-B-1, Recommended Pump Pit Dimensions, and Figure 10-B-2, Sump Dimensions, Plan, and Elevation View, Wet-Pit Type Pumps). The dimensions are usually determined by locating the selected number of pumps on a floor plan keeping in mind the guidance given in the Station Type and Depth section for clearances and intake system design. Keep in mind the need for clearances around electrical panels and other associated equipment that will be housed in the pump station building.



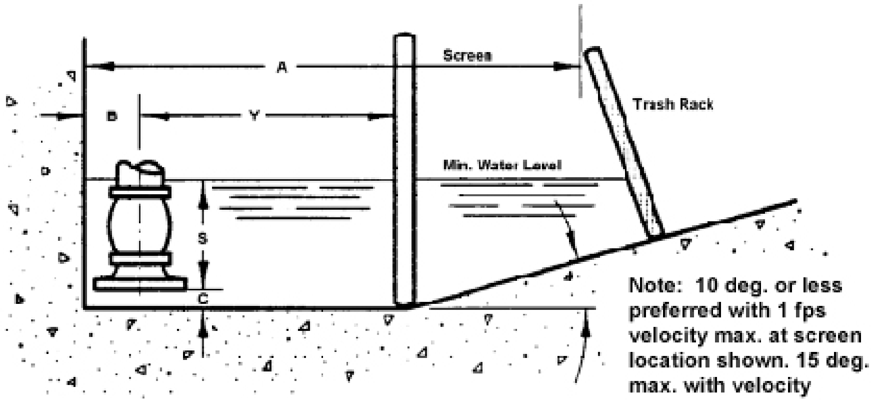
The above graph is reproduced from Hydraulic Institute Standards.

A = Minimum distance from trash rack to backwall (length of pump pit).
B = Maximum distance from centerline of pump to backwall.
C = Average dimension from underside of bell to bottom of pit.
S = Minimum dimension from minimum water level to underside of bell.
W = Minimum center-to-center spacing of pumps.
Y = Minimum distance to pump centerline from downstream end of any obstruction in sump (obstruction must be streamlined).

Figure 10-B-1 Recommended Pump Pit Dimensions



Plan View



Note: 10 deg. or less preferred with 1 fps velocity max. at screen location shown. 15 deg. max. with velocity reduced to 0.5 fps

Elevation View

Figure 10-B-2 Wet Pit Dimensions, Plan, and Elevation View, Wet-Pit Type Pumps

Step 5 Stage-Storage Relationship

Routing procedures require that a stage-storage relationship be developed. This is accomplished by calculating the available volume of water for storage at uniform vertical intervals.

Having roughly estimated the volume of storage required and trial pumping rate by the approximate methods described in the preceding sections, the configuration and elevations of the storage chamber can be initially set. Knowing this geometry, the volume of water stored can be calculated for its respective depth. In addition to the wet-pit, storage will also be provided by the inflow pipes and exterior storage if the elevation of water in the wet-pit is above the inflow invert. If the storage pipe is circular, the volume can be calculated using the ungula of a cone formula as discussed in Table 10-B-1. Table 10-B-1, Figure 10-B-3, and Figure 10-B-4 give examples of the calculation and plotting of the storage in a circular pipe and a circular wet-pit. A similar procedure would be followed for other storage configurations. Volume in a storage chamber can be calculated below various elevations by formulas, depending on the shape of the chamber. A storage versus elevation curve can then be plotted and storage below any elevation can readily be obtained.

Step 6 Pump Cycling and Usable Storage

One of the basic parameters addressed initially was that the proper number of pumps must be selected to deliver the design Q. Also, the correct elevations must be chosen to turn each pump on and off. Otherwise, rapid cycling (frequent starting and stopping of pumps) may occur causing undue wear and possible damage to the pumps.

Before discussing pump cycling calculations, operation of a pump station will be described. Initially, the water level in the storage basin will rise at a rate depending on the rate of the inflow and physical geometry of the storage basin. When the water level reaches the stage designated as the first pump start elevation, the pump will be activated and discharge water from storage at its designated pumping rate. If this rate exceeds the rate of inflow, the water level will drop until it reaches the first pump stop elevation. With the pump stopped, the basin begins to refill and the cycle is repeated. This scenario illustrates that the cycling time will be lengthened by increasing the amount of storage between pump on and off elevations. This volume of storage between first pump on and off elevations is termed usable volume.

For a given pump with a capacity Q_p, cycling will be a maximum (least time between starts) when the inflow Q_i to the usable storage is one-half the pump capacity. The proof is as follows:

t = time between starts
t = time to empty + time to fill usable storage volume, V_t

$$\mathbf{t = V_t/(Q_p - Q_i) + V_t/Q_i \qquad When\ Q_i = Q_p/2,\ m^3/s,\ t = 4V_t/Q_p,\ s} \qquad \textbf{(10.B.1)}$$

or t in minutes $t = 4V_t/60Q_p = V_t/15Q_p$

Generally, the minimum allowable cycling time, t, is designated by the pump manufacturer based on electric motor size. In general, the larger the motor, the larger is the starting current required, the larger the damaging heating effect, and the greater the cycling time required. Pump manufacturers should always be consulted for allowable cycling time during the final design phase of project development.

Ungula Volume: $V_3 = L(0.67a^3 \pm cA) / (D/2 \pm c)$

If base is greater than a semicircle, use (+) sign. If base is less than a semicircle, use (-) sign.

Where: L = length of ungula, feet
D = diameter of base, feet
A = area of base, sf
a = $(D^2/4 - c^2)^{1/2}$
c = (d - D/2)
d = water depth, feet

For determining Area A of the cross-section of a circular conduit flowing part full, Table 10-B-1, Storage in Ungula, may be used.

Let (depth of water)/(diameter of channel) = D/d and C_a = the tabulated value.
Then $A = C_a d^2$

D/d	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.0000	0.0013	0.0037	0.0069	0.0105	0.0417	0.0192	0.0242	0.0294	0.0350
0.1	0.0409	0.0470	0.0534	0.0600	0.0668	0.0739	0.0811	0.0885	0.0961	0.1039
0.2	0.1118	0.1199	0.1281	0.1365	0.1449	0.1535	0.1623	0.1711	0.1800	0.1890
0.3	0.1982	0.2074	0.2167	0.2260	0.2355	0.2450	0.2546	0.2642	0.2739	0.2836
0.4	0.2934	0.3032	0.3130	0.3229	0.3328	0.3428	0.3527	0.3627	0.3727	0.3827
0.5	0.393	0.403	0.413	0.423	0.433	0.443	0.453	0.462	0.472	0.482
0.6	0.492	0.502	0.512	0.521	0.531	0.540	0.550	0.559	0.569	0.578
0.7	0.587	0.596	0.605	.0614	0.623	0.632	0.640	0.649	0.657	0.666
0.8	0.674	0.681	0.689	0.697	0.704	0.712	0.719	0.725	0.732	0.738
0.9	0.745	0.750	0.756	0.761	0.766	0.771	0.775	0.779	0.782	0.784

Source: King and Brater, Handbook of Hydraulics

Table 10-B-1 Storage in Ungula

Source: FHWA IP-82-17, Vol. 1

Stage-Storage Tabulation
48-Inch Pipe at 0.40 percent, 21-foot Diameter Wet Well

Elevation, (feet)	Pipe, (cf)	Wet Well, (cf)	Total, (cf)
0.0	0	0	0
0.5	45	173	2.18
1.0	250	346	596
1.5	672	519	1,191
2.0	1,332	692	2,024
2.5	2,211	865	3,076
3.0	3,185	1,038	4,223
3.5	4,165	1,211	5,376
4.0	5,068	1,384	6,452
4.5	5,768	1,558	7,326
5.0	6,229	1,730	7,959
5.5	6,463	1,903	8,366
6.0	6,529	2,076	8,605
6.5	6,529	2,249	8,778
7.0	6,529	2,422	8,951

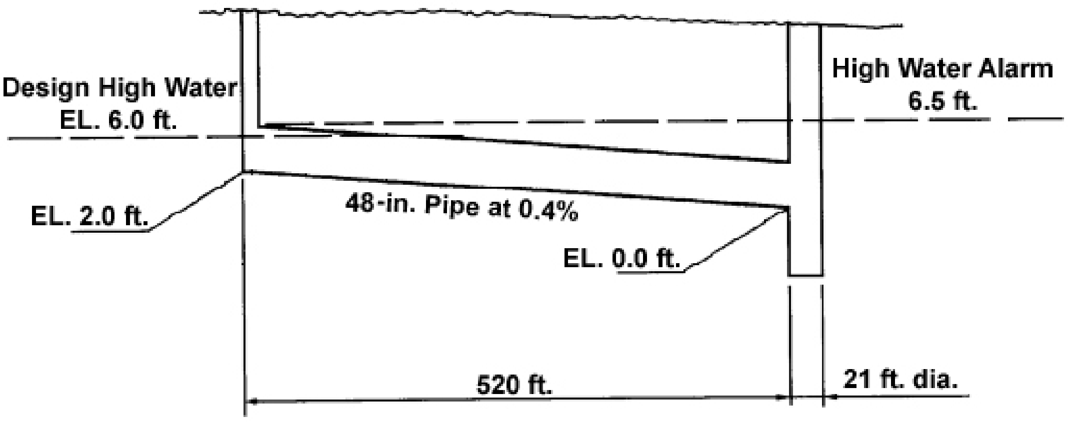


Figure 10-B-3 Storage Pipe Sketch and Calculation Table

Source: FHWA IP-82-17, Vol. 1

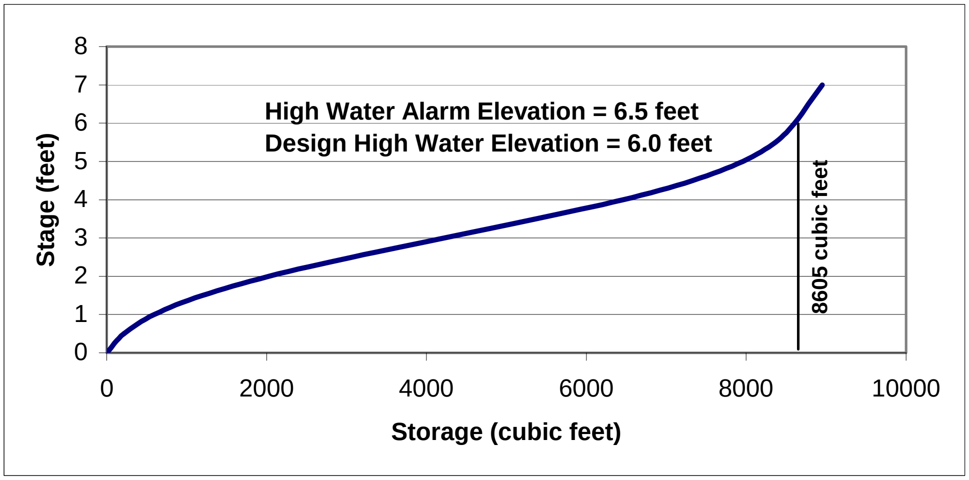


Figure 10-B-4 Stage-Storage Curve

Source: FHWA IP-82-17, Vol. 1

However, the following limits may be used for estimating allowable cycle time during preliminary design:

Motor Hp	Cycling Time (t), min.
0 - 15	5.0
20 - 30	6.5
35 - 60	8.0
65 - 100	10.0
150 - 200	13.0

Knowing the pumping rate and minimum cycling time, the minimum necessary allowable storage, V, to achieve this time can be calculated by:

$$\mathbf{V = 15\, Q_p t} \qquad \textbf{(10.B.2)}$$

Having selected the trial wet-pit dimensions, the pumping range, Δh, can then be calculated. The pumping range represents the vertical height between pump start and pump stop elevations. Usually, the first pump stop elevation is controlled by the minimum recommended bell submergence criteria specified by the pump manufacturer or the minimum water level, H, specified in the design. The first pump start elevation will be a distance, Δh, above H.

When the only storage provided is in the wet-pit, the pumping range can be calculated by dividing the allowable storage volume by the wet-pit area.

Δh = V/wet pit area **(10.B.3)**

When larger volumes of storage are available, the initial pump start elevations can be selected from the stage-storage curve. Since the first pump turned on should typically have the ability to empty the storage facility, its turn-off elevation would be the bottom of the storage basin. The minimum allowable storage would be calculated by the equation $V=15\ Q_pt$. The elevation associated with this volume in the stage-storage curve would be the lowest turn-on elevation that should be allowed for the starting point of the first pump. The second and subsequent pump start elevations will be determined by plotting the pump performance on the mass inflow curve.

This distance between pump starts may be in the range of 1 to 3 feet for stations with a small amount of storage and 3 to 6 inches for larger storage situations.

Step 7 Trial Pumps and Pump Station Piping

The designer must select a specific pump in order to establish the size of the discharge piping needed. This is done by using information previously developed or established. Though the designer will not typically specify the manufacturer or a specific pump, he must study various manufacturers' literature in order to establish reasonable relationships between total dynamic head (TDH), discharge, efficiency, and energy requirements. Discharge pipes should be horizontal and discharge freely without submergence into the surge chamber. Discharge pipe diameter should be selected to maintain velocity at peak flow below 10 fps.

Any point on an individual performance curve identifies the performance of a pump for a specific TDH that exists in the system. It also identifies the horsepower required and the efficiency of operation of the pump. It can be seen that for either an increase or decrease in TDH, the efficiency is reduced as the performance moves away from the eye of the performance curve (typically identified as the Best Efficiency Point). The designer must make certain that the motor specified is adequate over the full range of TDHs that will exist. The range of the pump performance should not extend into areas where substantially reduced efficiencies exist.

Step 8 Total Dynamic Head

TDH is the sum of the static head, velocity head, and various head losses in the pump discharge system due to friction. Knowing the range of water levels in the storage pit and having a trial pump pit design with discharge pipe lengths, diameters, and appurtenances, such as elbows and valves designated, TDH for the discharge system can be calculated. To summarize, the TDH is equal to:

$TDH = H_s + H_f + H_v + H_p$

Where: H_s = static head or height through which the water must be raised, feet
H_f = loss due to friction in the pipe, feet
H_v = velocity head, feet
H_p = loss due to friction in water passing through the pump valves, fittings and other items, feet

The Hazen Williams formula, expressed as follows is generally used for from friction losses in discharge lines.

$$H_f = L/(D^{4.8704}) \times (4.727) \times (Q/C)^{1.852}, \text{ feet} \tag{10.B.4}$$

Where: Q = discharge, cfs
L = length of pipe, feet
D = pipe diameter, feet
C = Loss Coefficient (typically assumed to equal 100)

In general, the following minor loss coefficients should be used:

Entrance, K = 0.5
Exit, K = 1.0
Gate Valve, K = 0.2
Check Valve, K = 2.5
90 Degree Bend, K = 0.3

The Hydraulic Institute and others have produced line loss tables and charts that make determination of losses quite easy and accurate. The tables and charts have been developed for a variety of pipe materials and are recommended for use in determining line and fitting losses for the discharge side of the pumping system.

Step 9 Pump Design Point

Using methods described in the previous step, the TDH of the outlet system can be calculated for a specific static head and various discharges. These TDHs are then plotted versus discharge. This plot is called a system head curve. A system head curve is a graphical representation of TDH plotted against discharge Q for the entire pumping and discharge system. The required design point of a pump can be established after the pump curve is superimposed to give a visual representation of both system and pump. As usually drawn, the system head curve starts from a low point on the Y-ordinate representing the static head at zero discharge. It then rises to the right as the discharge and the friction losses increase. A design point can be selected on the system head curve and a pump can be selected to match that point. The pump will always operate at the intersection of the system curve and the pump curve. System head curves are often drawn for several different static heads, representing low, design, and maximum water levels in the sump. One, two, or more pump curves can be plotted over the system head curves and conditions examined. If a change of discharge line size is contemplated, a new system head curve for the changed size (and changed head loss) is easily constructed. Figure 10-B-5, System Head Curves, shows the same system with one pump and then with two identical pumps (in parallel) delivering into the same system. Note the increased head loss and reduced capacity of each pump when both are operating. This condition will only exist when a common discharge pipe is shared by both pumps. In highway design, it is common practice to provide individual discharge lines for each pump, thereby reducing the risk of backflow and preserving the design point of each pump. Therefore, the additional loss from a shared pipe is not experienced.

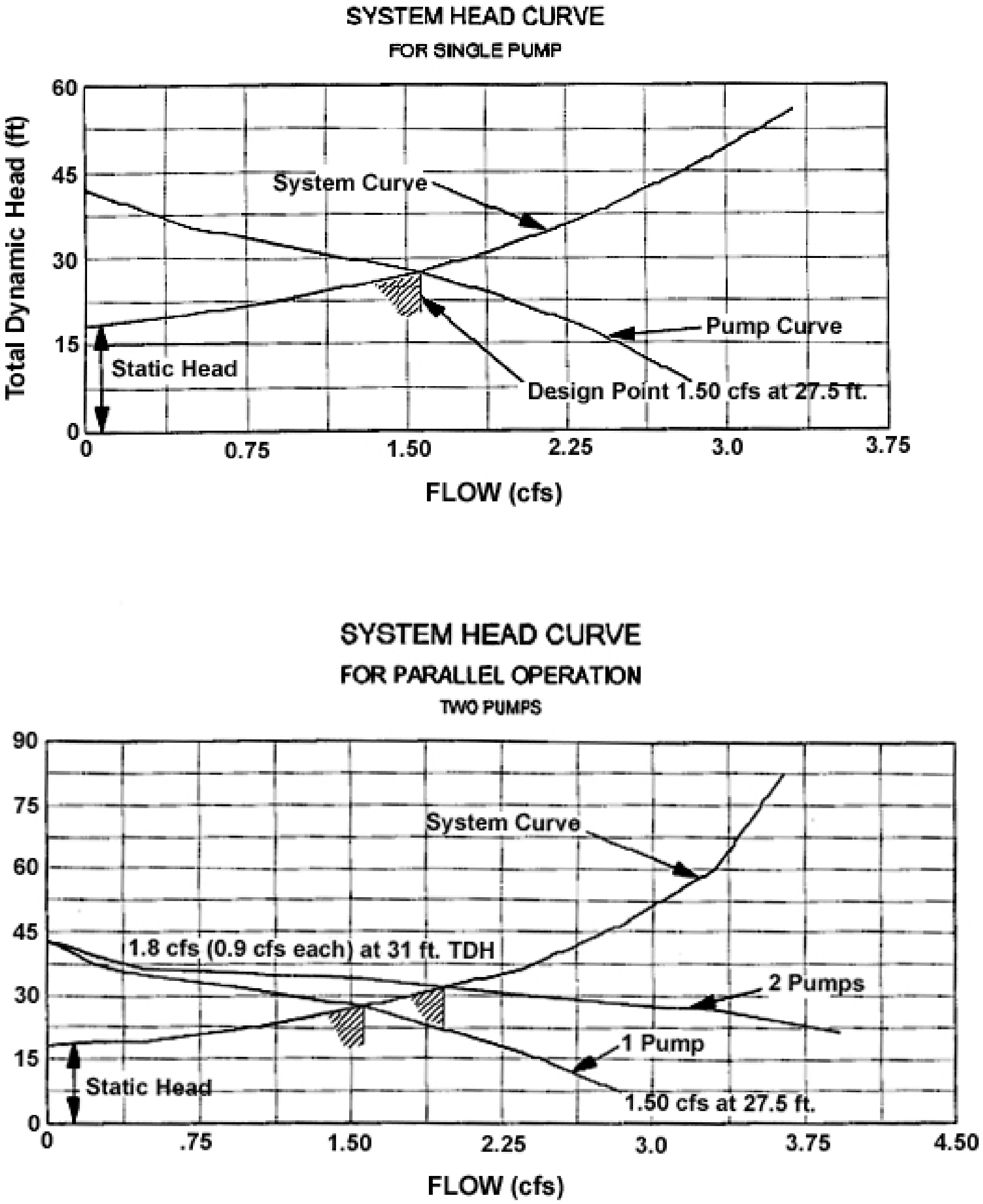


Figure 10-B-5 System Head Curves

Source: FHWA IP-82-17, Vol. 1

Each pump considered will have a unique performance curve that has been developed by the manufacturer. More precisely, a family of curves is shown for each pump, because any pump can be fitted with various size impellers. These performance curves are the basis for the pump curve plotted in the system head curves discussed above. The designer must have specific information on the pumps available in order to be able to specify pumps needed for the pump station.

Any point on an individual performance curve identifies the performance of a pump for a specific TDH that exists in the system. It also identifies the power required and the efficiency of operation of the pump. It can be seen that for either an increase or decrease in TDH, the efficiency is reduced as the performance moves away from the eye of the performance curve. It should also be noted that as the TDH increases, the power requirement also increases. The designer must make certain that the motor specified is adequate over the full range of TDHs that will exist. It is desirable that the design point be as close to the eye as possible, or else to the left of the eye rather than to the right of or above it. The range of the pump performance should not extend into the areas where substantially reduced efficiencies exist.

It is necessary that the designer correlate the design point discussed above with an elevation at about the mid-point of the pumping range. By doing this, the pump will work both above and below the TDH for the design point and will thus operate in the best efficiency range.

Step 10 <u>Power Requirements</u>

To select the proper size of pump motor, compute the energy required to raise the water from its lowest level in the pump pit to its point of discharge. This is best described by analyzing pump efficiency. Pump efficiency is defined as the ratio of pump energy output to the energy input applied to the pump. The energy input to the pump is the same as the driver's output and is called water horsepower.

$$\mathbf{whp = Q\Upsilon H/550} \tag{10.B.5}$$

Where: whp = water horsepower
Q = pump capacity, cfs
Υ = specific weight of liquid (62.4-lb./cf)
H = head, feet

The horsepower required to drive the pump is referred to as brake horsepower (bhp).

$$\text{bhp} = \text{whp}/e$$

where: e = efficiency of the pump and motor (e = whp/bhp)

Efficiency can be broken down into partial efficiencies -- hydraulic, mechanical, etc. The efficiency as described above, however, is a gross efficiency used for the comparison of centrifugal pumps. The designer should study pump performance curves from several manufacturers to determine appropriate efficiency ranges. A minimum acceptable efficiency should be specified by the designer for each performance point specified.

Step 11 Mass Curve Routing

The procedures described thus far will provide all the necessary dimensions, cycle times, appurtenances, etc., to design the pump station. A flood event can be simulated by routing the design inflow hydrograph through the pump station by methods described in Section 10.3.1.9. In this way, the performance of the pump station can be observed at each hydrograph time increment and pump station design evaluated. Then, if necessary, the design can be "fine-tuned."

10.B.3 Example: Storage to Reduce Peak Flow

Example: Determine the required storage to reduce the peak flow of 22 cfs to 14 cfs as shown in Figure 10-B-6, Estimating Required Storage. Using the assumed storage pipe shown in Figure 10-B-7, Storage Pipe Sketch, the stage-storage curve in Figure 10-B-8, Stage-Storage Curve, the stage discharge curve in Figure 10-B-9, Stage-Discharge Curve, and the inflow hydrograph in Figure 10-B-10, Development of Inflow Mass Curve, the storage can be determined.

The inflow mass curve is developed in Figure 10-B-10. Since 14 cfs was to be pumped, it was assumed that two 7 cfs pumps would be used. The pumping conditions are as follows:

	Pump-Start Elevation (feet)	Pump-Stop Elevation (feet)
Pump No. 1 (7 cfs)	2.0 feet (2,011 cf)	0.0 (0)
Pump No. 2 (7 cfs)	3.0 feet (4,224 cf)	1 foot (596 cf)

The numbers in parentheses are the storage volume (cf) associated with the respective elevations.

Figure 10-B-11, Mass Curve Routing Diagram, shows the plotting of the pump discharge curve on the inflow mass diagram. Note that the first pump is turned on at about hour 11.4 when a storage volume of 2,011 cf has accumulated. At about hour 11.5, pump No. 1 has emptied the storage basin and the pump turns off. At about hour 11.7, the storage volume has again reached 2,011 cf and a pump is turned on. If an alternating start plan had been developed, this would be the second pump that would turn on at this point. If an alternating start plan had not been designed, the first pump would again be started. At about hour 11.8, the volume in storage has increased to 4,224 cf, which is associated with a turn-on elevation of 3 feet. Both pumps operate until about hour 12.4 when the volume in the storage basin has

been essentially pumped out. The pumps will continue to start and stop until the hydrograph has receded and the inflow stops.

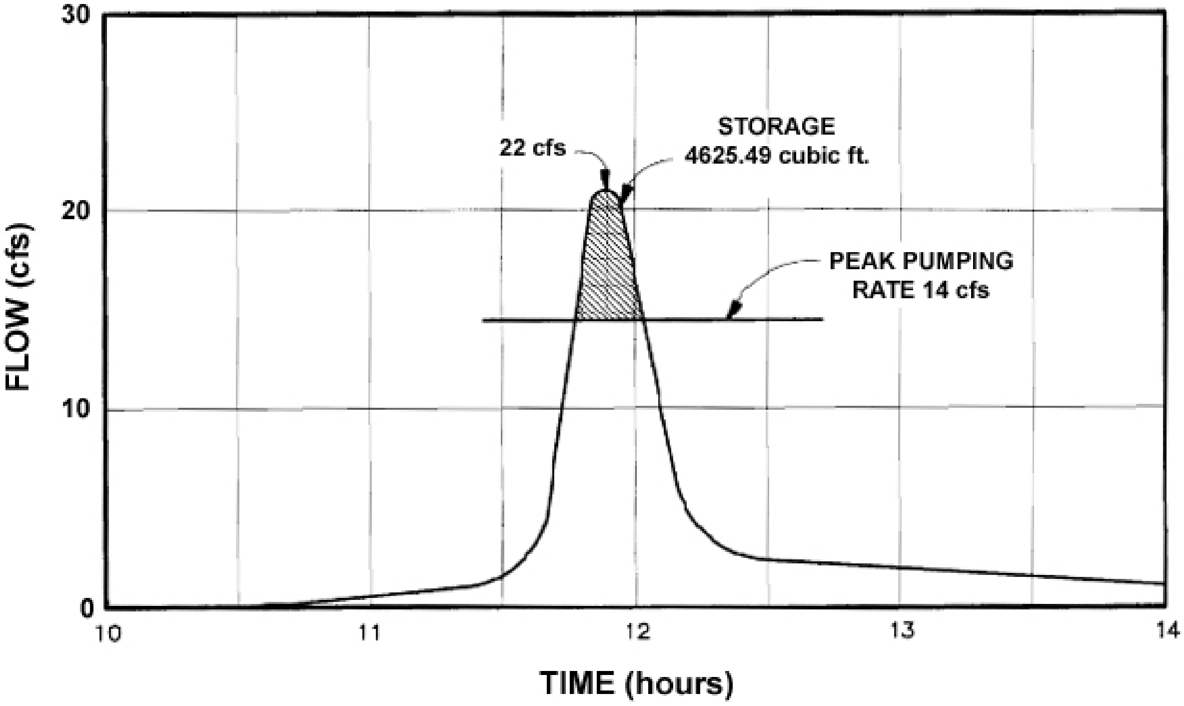


Figure 10-B-6 Estimating Required Storage

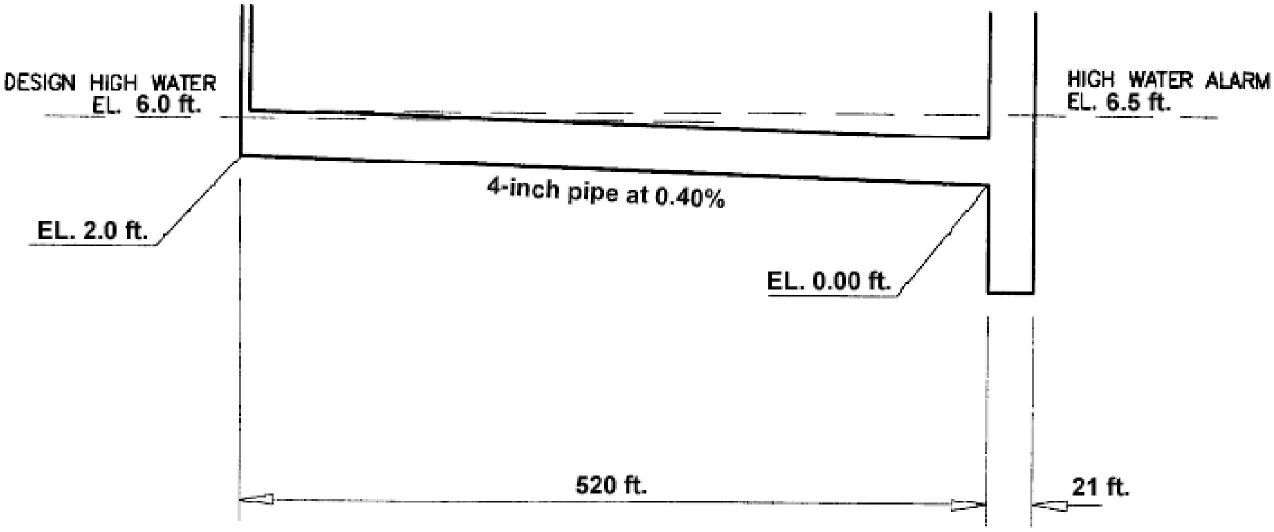


Figure 10-B-7 Storage Pipe Sketch

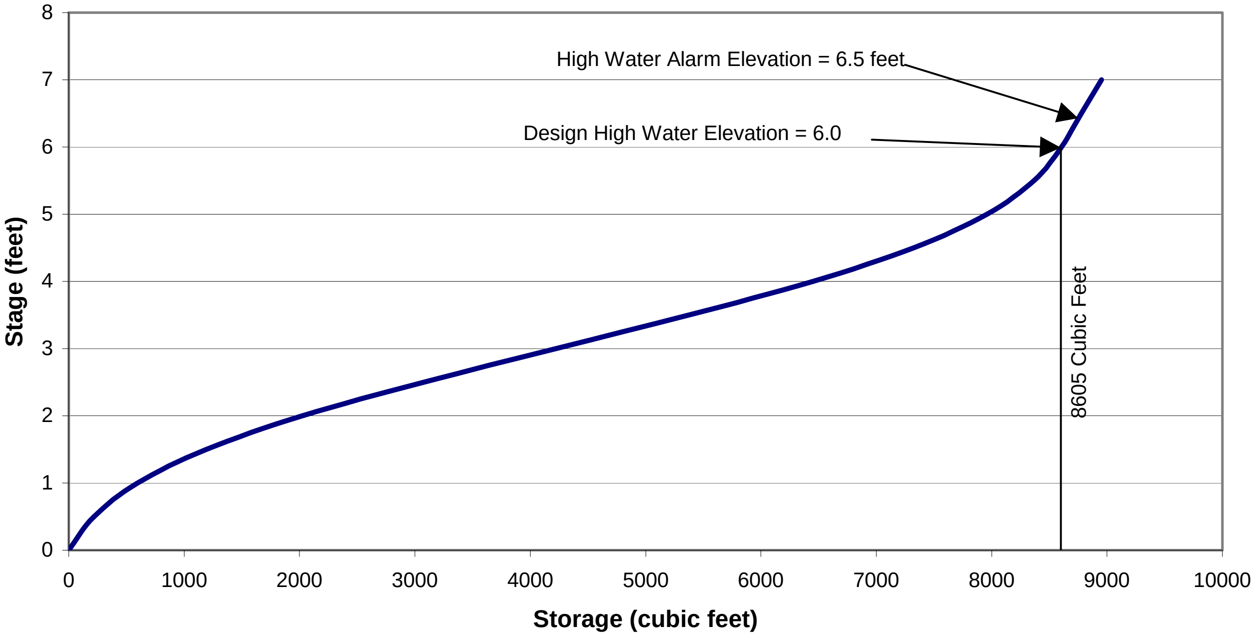


Figure 10-B-8 Stage-Storage Curve

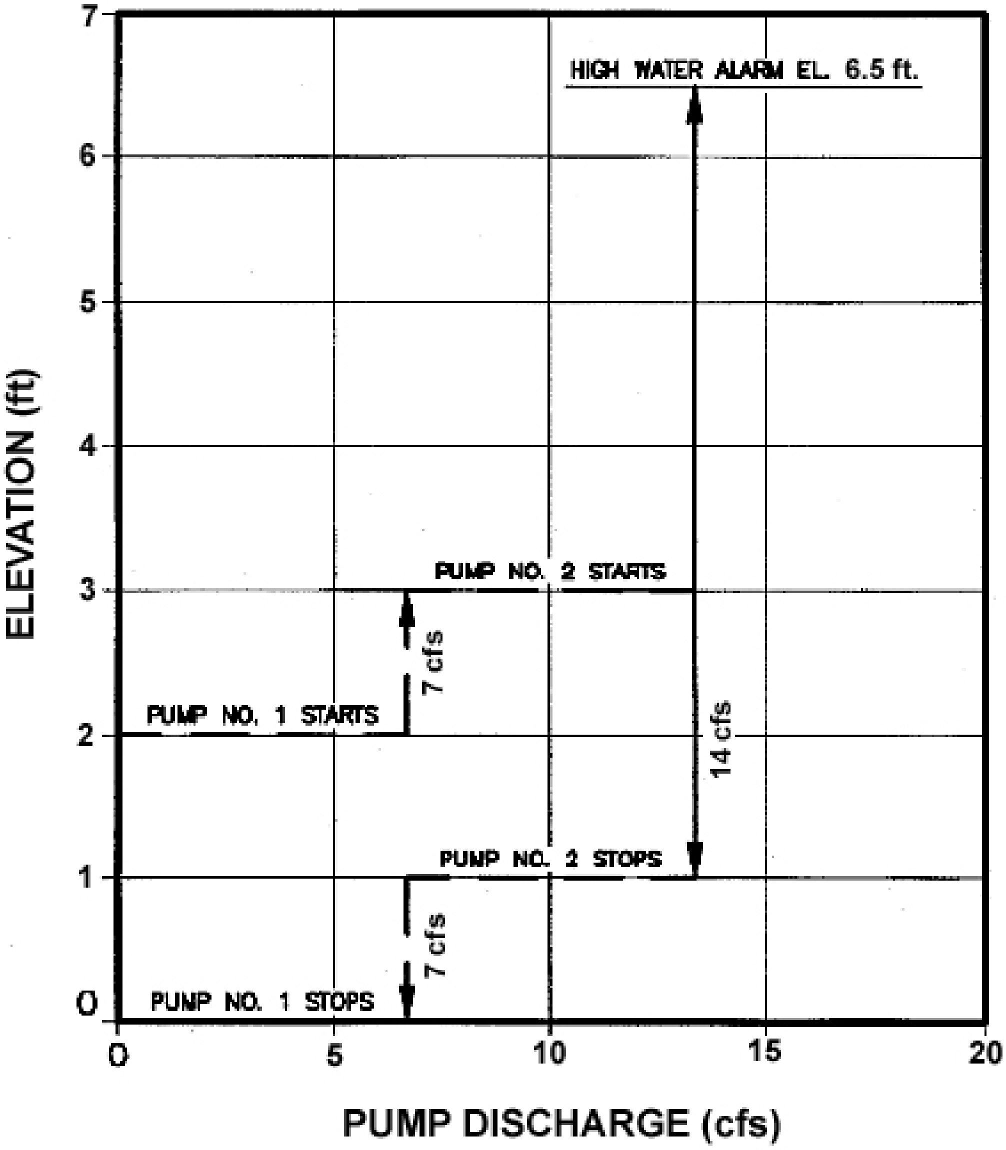


Figure 10-B-9 Stage-Discharge Curve

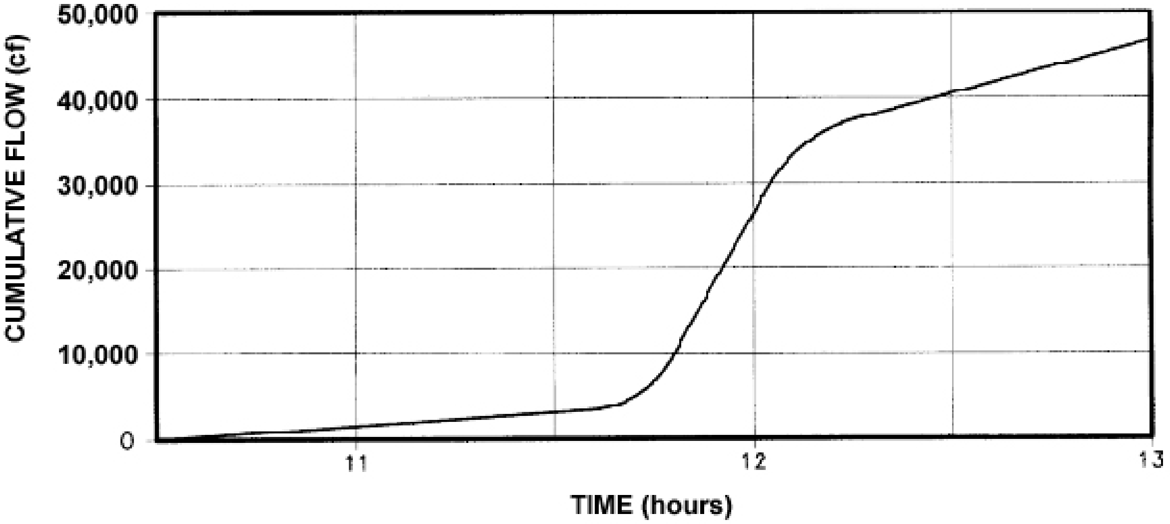


Figure 10-B-10 Development of Inflow Mass Curve

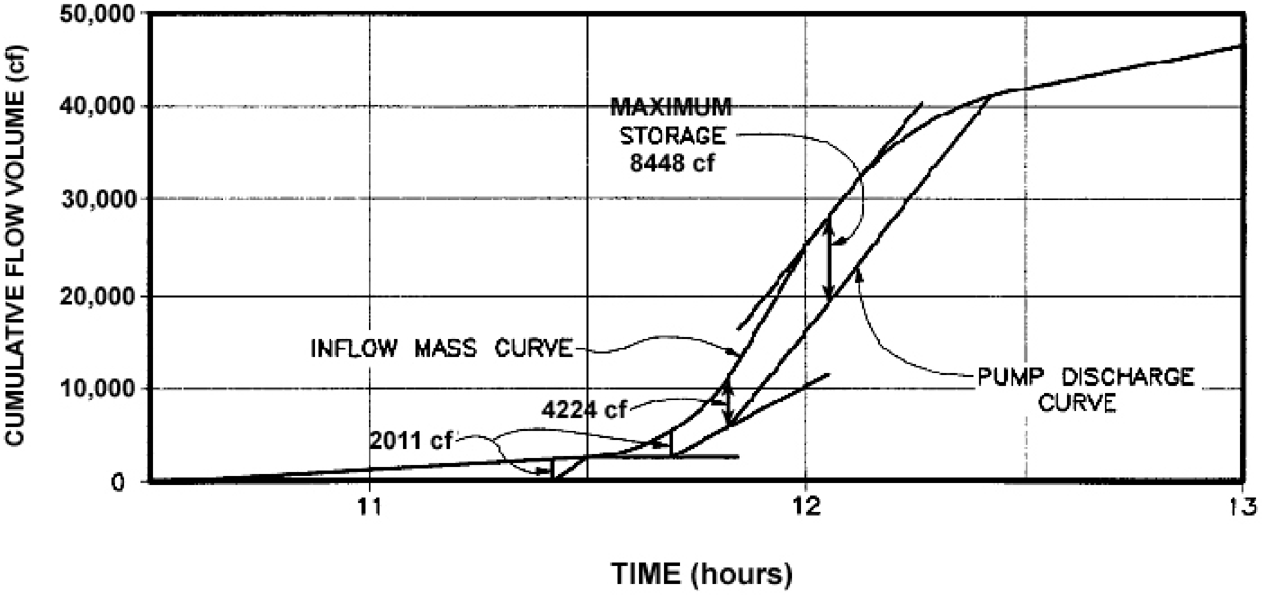


Figure 10-B-11 Mass Curve Routing Diagram

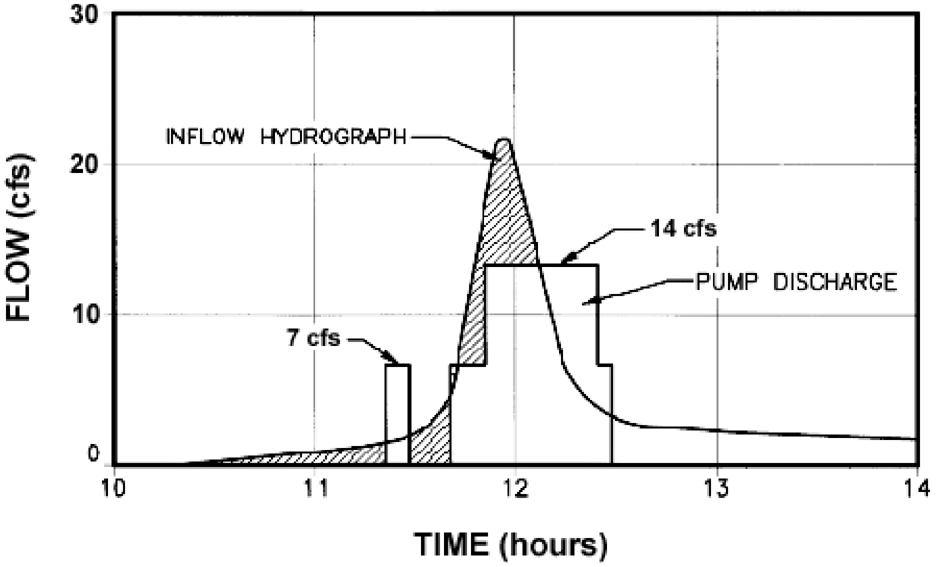


Figure 10-B-12 Pump Discharge Components

The shaded area between the curves (see Figure 10-B-12) represents stormwater that is going into storage. Pump cycling at the end of the storm has been omitted in order to simplify the illustration. When the stored volume remaining is equal to the volume (600 cf) associated with pump No. 2 stop elevation (1 foot), pump No. 2 shuts off; pump No. 1 shuts off when the storage pipe is emptied at pump No. 1 stop elevation (0.0).

The maximum vertical distance between the pump discharge curve and the inflow mass hydrograph is 8,448 cf. This represents the maximum storage required for the reduction of the 22 cfs peak to 14 cfs for the defined conditions, i.e., the storage volume as defined, the start elevations defined, and the pump rates defined. The design is adequate since the available storage at the high water alarm is 8,790 cf. It should be noted that a reduction of the starting elevations would have reduced the required storage volume. The designer must make these adjustments on a trial basis until a satisfactory operating condition is developed. Other pumping rates could have also been plotted on the inflow mass curve to determine their performance. Once the mass inflow curve has been developed, it is a relatively easy process to try different pumping rates and different starting elevations until a satisfactory design is developed. It should be noted that number of starts per hour can be determined by looking at the plots on the inflow mass curve. The system should be designed so that the allowable number of starts per hour for the selected pump size is not exceeded.

The designer now has a complete design that allows the problem to be studied in-depth. The peak rate of runoff has been reduced from 22 cfs, the inflow hydrograph peak, to 14 cfs, the maximum pump discharge rate. A reduction of 46.5 percent is accomplished by providing for 8,470 cf of storage. This is only one possible design option. The designer may wish to reduce the pumping rate further by providing more storage, and additional combinations of pump discharge and storage can be considered.

To aid the designer in visualizing what is happening during the peak design period in this process, the pump discharge curve can be superimposed on the design inflow hydrograph as shown in Figure 10-B-12, Pump Discharge Components.