12.6 Design Procedure

12.6.1 Introduction

The following is a systematic procedure which integrates the hydraulic design variables involved in sump design. It incorporates the above recommended design criteria and yields the required number and capacity of pumps as well as the wet well and storage dimensions. The final dimensions can be adjusted as required to accommodate non-hydraulic considerations such as maintenance. Though the recommended station is a wet-pit, this procedure can be adapted for use in designing dry-pit stations.

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 3 components:

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

The inflow hydrograph is determined by the physical factors of the watershed and regional climatological 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 use of smaller and/or fewer pumps.

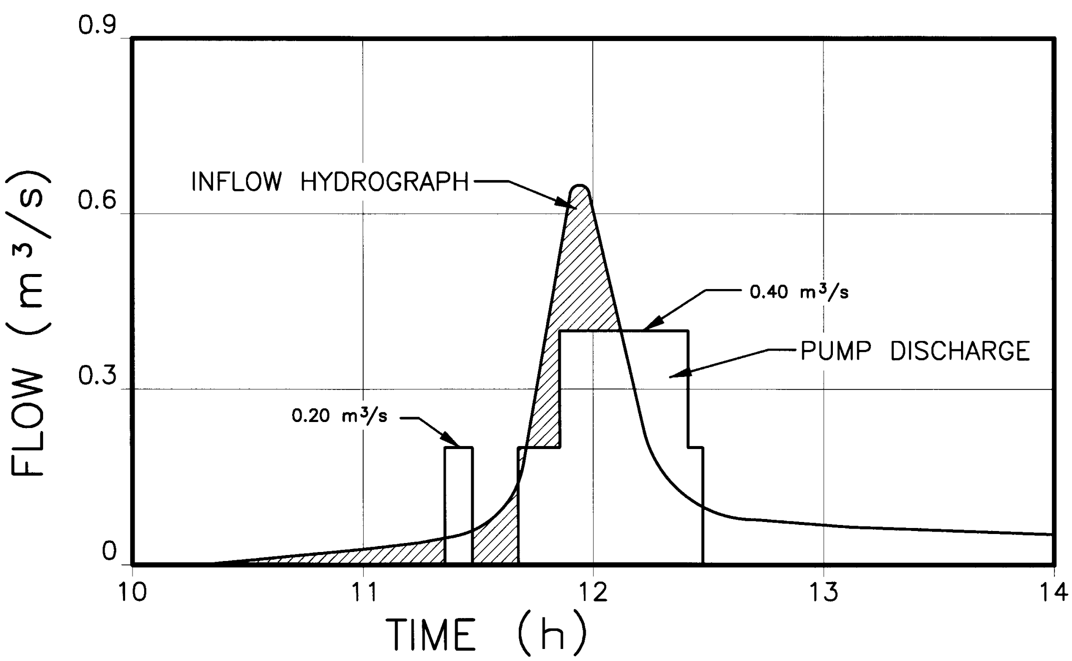


Figure 12-16 Pump Discharge

12.6.2 Pump Station Design

The procedure for pump station design is illustrated in the following 10 steps (metric units).

Step 1 Inflow to Pump Station

Develop inflow hydrograph to the pump station using the procedures presented in Chapter 6, 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 12-6. 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. However, as many as five pumps may be needed in the case of a continuously depressed highway situation. Size and thus numbers of pumps may be controlled by physical constraints such as portable standby power as discussed in Section 12.5.3.

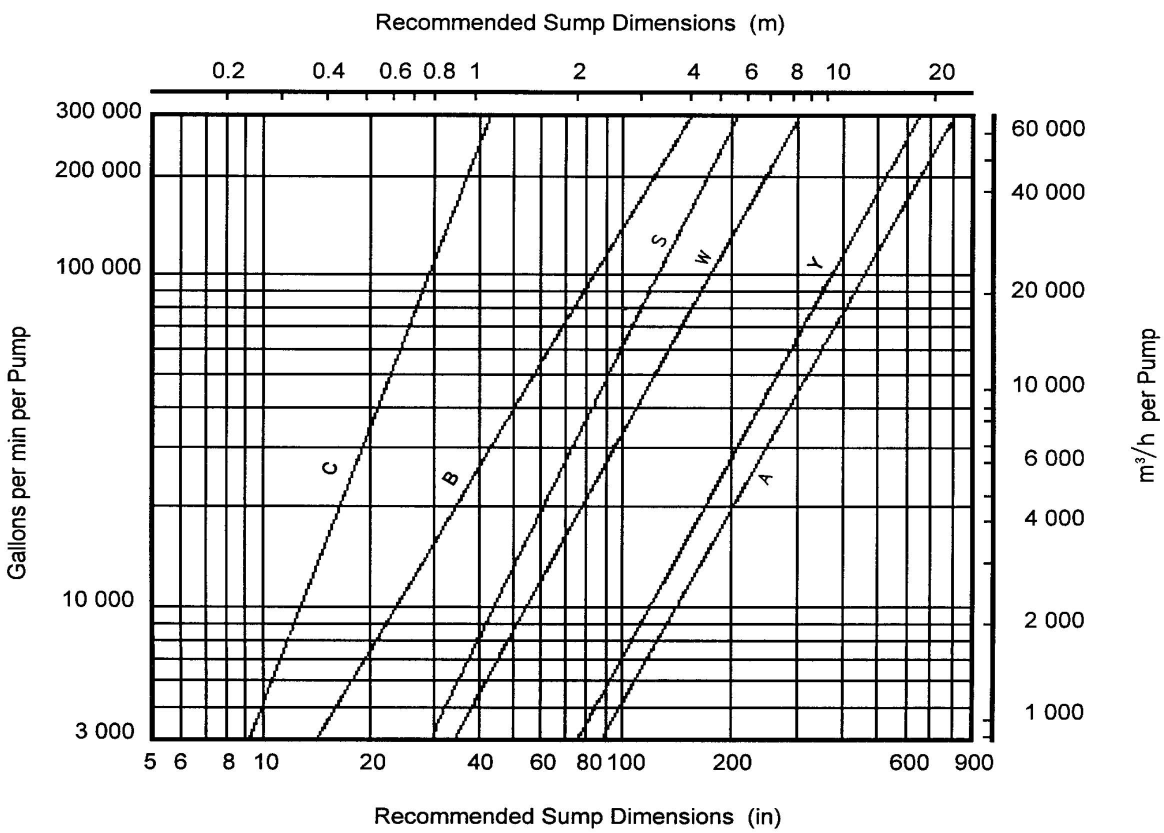
Step 3 Design High Water Level

The highest permissible water level must be set as 0.3 to 0.6 m (1 to 2 ft.)below the finished pavement surface at the lowest pavement inlet. 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. Therefore a hydraulic gradient will be established and the maximum permissible water elevation at the station will be the elevation of the hydraulic gradient. This gradient will be very flat for most wet well designs with exterior storage because of the unrestricted flow into the wet well.

Step 4 Determine Pump Pit Dimensions

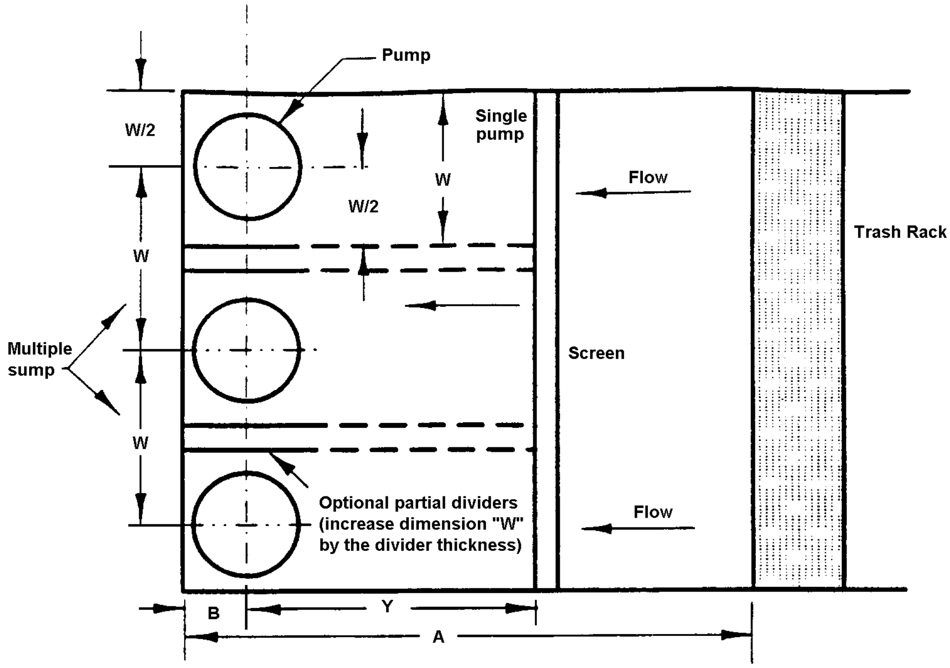
Determine the minimum required plan dimensions for the pump station from manufacturer's literature or from dimensioning guides such as those provided by the Hydraulic Institute, see Figures 12-17 and 12-18. The dimensions are usually determined by locating the selected number of pumps on a floor plan keeping in mind the guidance given in Section 12.5.9 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.



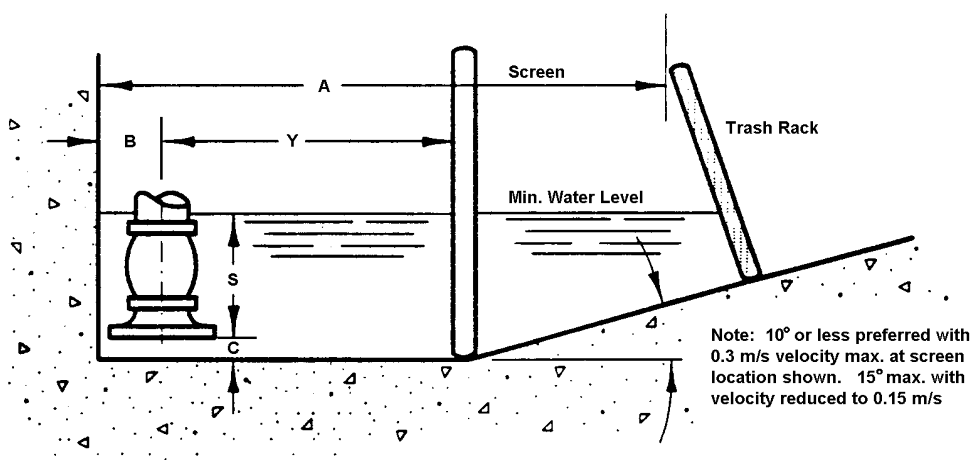
The above graph is reproduced from Hydraulic Institute Standards.

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 12-17 Recommended Pump Pit Dimensions



Plan View



Elevation View

Figure 12-18 Sump 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 Figure 12-19. Figures 12-19, 12-20 and 12-21 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 vs. elevation curve can then be plotted and storage below any elevation can readily be obtained.

Ungula Volume: $V_3 = H(0.67a^3 \pm cB) / (r \pm c)$

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

Where: H = length of ungula, m
r = radius of base, m
B = area of base, m^2

May use King & Brater table, for determining area B of the cross section of a circular conduit flowing part full.

Let (Depth of water)/(Diameter of channel) = D/d and C_a = the tabulated value.
Then $B = C_a d^2$

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

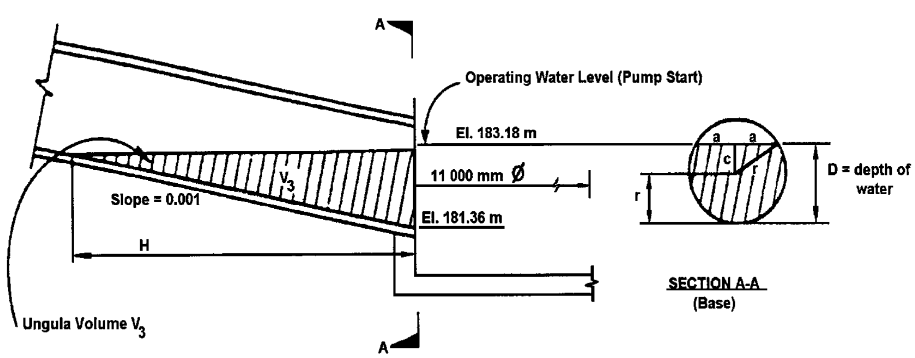


Figure 12-19 Storage in Ungula

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

Stage-Storage Tabulation
1200 mm Pipe at 0.40%, 6400 mm Diameter Wet Well

Elevation (m)	Pipe (m^3)	Wet Well (m^3)	Total (m^3)
0.00	0.00	0.00	0.00
0.15	1.27	4.90	6.17
0.30	7.11	9.80	16.91
0.46	19.03	14.70	33.73
0.61	37.75	19.60	57.35
0.76	62.67	24.52	87.19
0.91	90.25	29.42	119.67
1.07	118.02	34.32	152.34
1.22	143.62	39.22	182.84
1.37	163.47	44.15	207.62
1.52	176.41	49.04	225.45
1.68	183.15	53.94	237.09
1.83	185.02	58.84	243.86
1.98	185.02	63.74	248.76
2.13	185.02	68.64	253.66

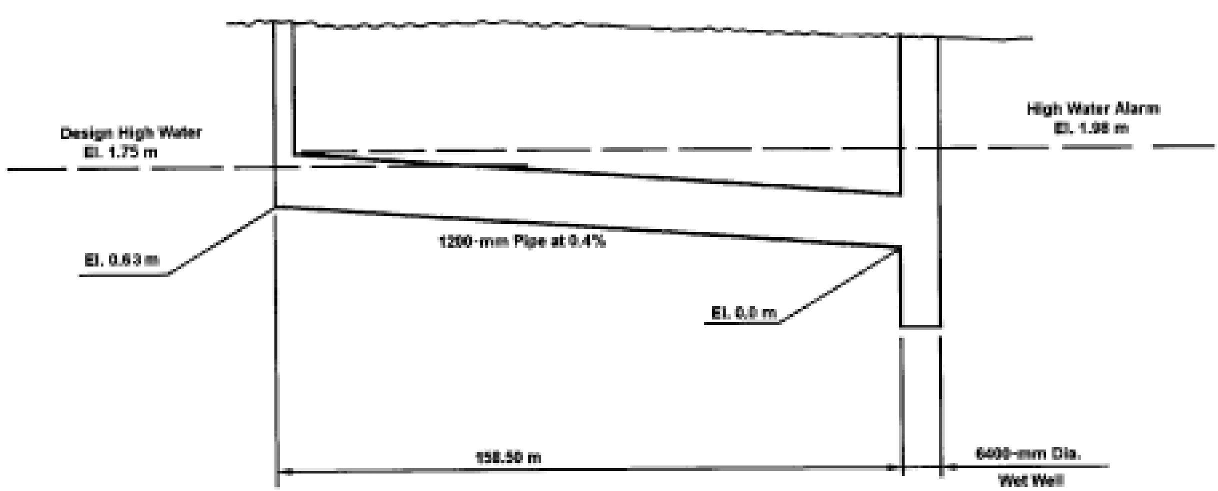


Figure 12-20 Storage Pipe Sketch

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

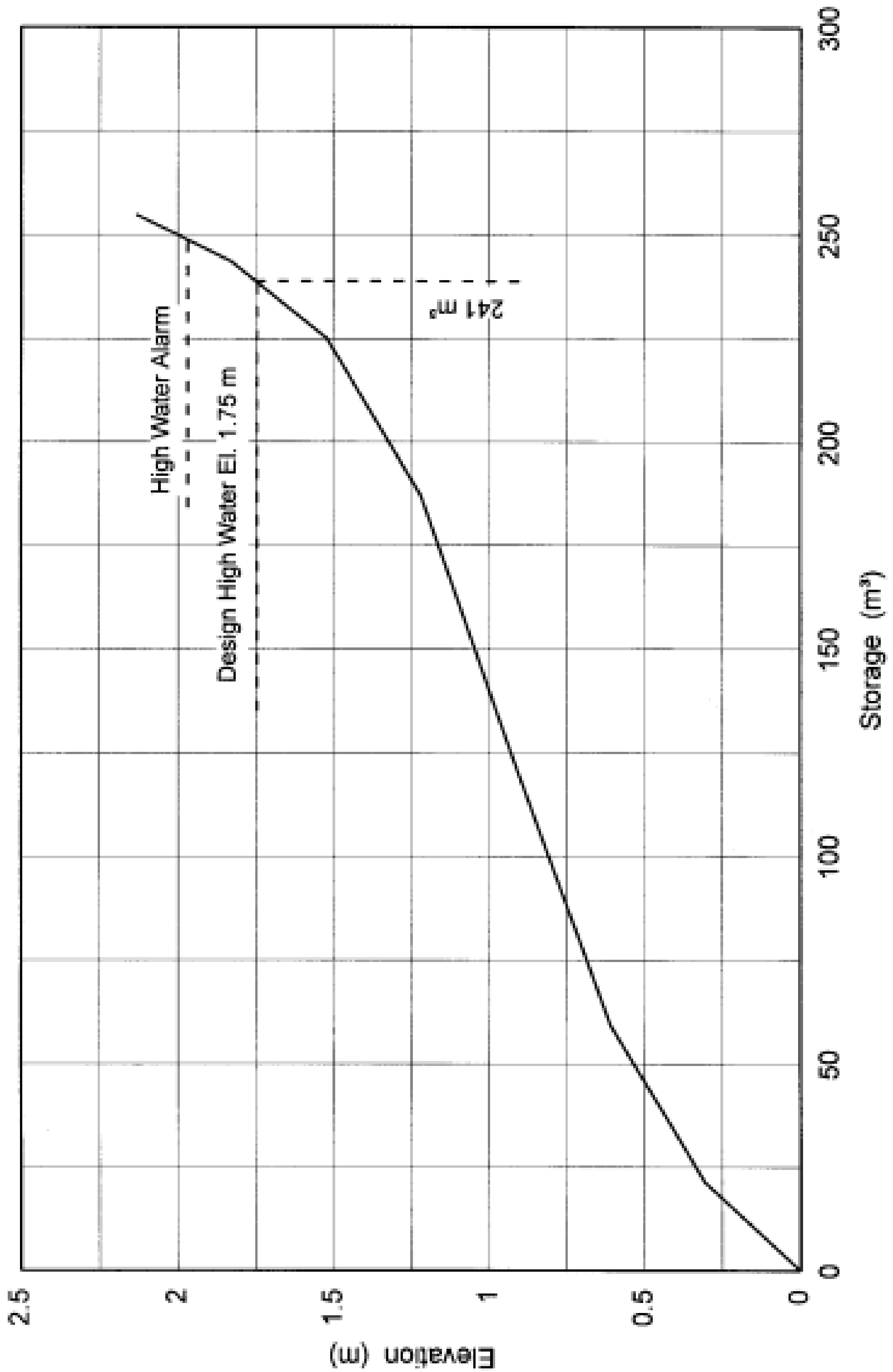


Figure 12-21 Stage-Storage Curve

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

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. In theory, the minimum cycle time allowable to reduce wear on the pumps will occur when the inflow to the usable storage volume is one-half the pump capacity. Assuming this condition, cycling time can be related to 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

$$t = V_t/(Q_p - Q_i) + V_t/Q_i \qquad \text{When } Q_i = Q_p/2,\ m^3/sec,\ (ft^3/sec)\quad t = 4V_t/Q_p,\ sec \qquad (12.4)$$

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. The pump manufacturer should always be consulted for allowable cycling time during the final design phase of project development.

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

Motor kW	Cycling Time (t), min
0 - 11	5.0
15 - 22	6.5
26 - 45	8.0
48 - 75	10.0
112 - 149	13.0

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

$V = 15\ Q_p t$ (12.5)

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.

$\Delta h = V/\text{wet pit area}$ (12.6)

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 $V=15\ Q_p t$. 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 0.3 to 1 m (1 to 3 ft) for stations with a small amount of storage and 0.07 to 0.15 m (0.2 ft to 0.5 ft) 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 that will be needed. This is done by using information either previously developed or established. Though the designer will not typically specify the manufacturer or a specific pump, he/she must study various manufacturers' literature in order to establish reasonable relationships between total dynamic head, discharge, efficiency and energy requirements. This study will also give the designer a good indication of discharge piping needed since pumps that produce the desired results will have a specific discharge pipe size.

Any point on an individual performance curve identifies the performance of a pump for a specific Total Dynamic Head (TDH) that exists in the system. It also identifies the horse 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 horse 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 areas where substantially reduced efficiencies exist.

Step 8 Total Dynamic Head

Total Dynamic Head 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 and diameters and appurtenances such as elbows and valves designated, total dynamic head for the discharge system can be calculated. To summarize the Total Dynamic Head (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, m (ft)
H_f = loss due to friction in the pipe, m (ft)
H_v = velocity head, m (ft)
H_p = loss due to friction in water passing through the pump valves, fittings and other items, m (ft)

The Manning's formula expressed as follows is generally used for discharge lines.

$$\mathbf{H_f = [L(Q \times n)^2]/[(A \times R)^{2/3}]} \qquad \textbf{(12.7)}$$

Where: Q = discharge, m^3/s (ft^3/s)
L = length of pipe, m (ft)
n = Manning’s roughness value
A = cross sectional area of discharge pipe, m^2 (ft^2)
R = hydraulic radius of discharge pipe, m (R = diameter/4 for line running full)

Friction losses can also be computed by the Darcy Formula. This requires computation of the relative roughness of the pipe, the Reynold’s number and the friction factor. 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.

Consult the Storm Drainage System Chapter for methods of determining head loss in various components of the system. Standard textbooks and manufacturers’ catalogs should also be consulted.

Step 9 Pump Design Point

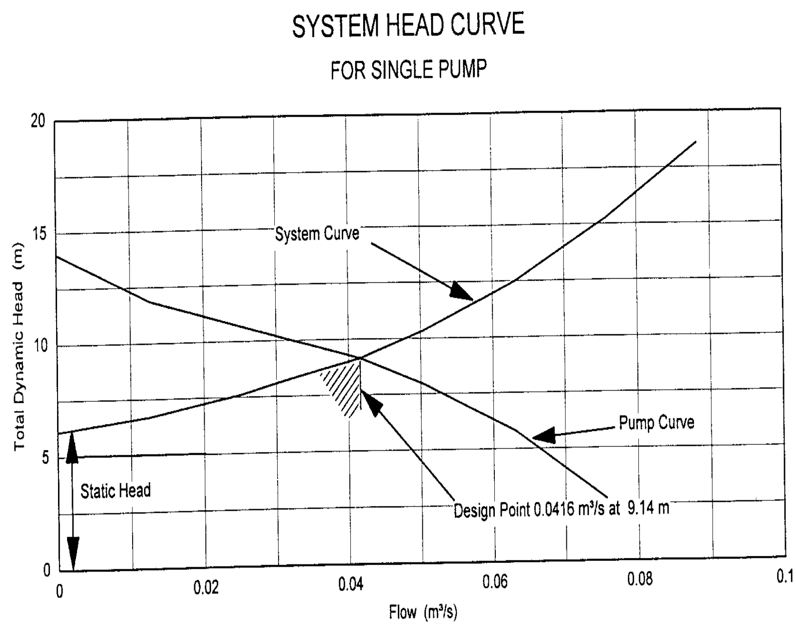
Using methods described in the previous step, the Total Dynamic Head of the outlet system can be calculated for a specific static head and various discharges. These TDHs are then plotted vs. discharge. This plot is called a system head curve. A system head curve is a graphical representation of total dynamic head 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 usual pump curve is the reverse of the system head curve so the point of intersection is clearly identifiable. 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 12-22 shows the same system with one pump and then with two identical pumps 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.

Therefore, the additional loss from a shared pipe is not experienced. It should be noted that the pump will always operate at the intersection of the system curve and the pump curve.

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. A study of pump performance curves should be made by all designers.

Any point on an individual performance curve identifies the performance of a pump for a specific Total Dynamic Head (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.



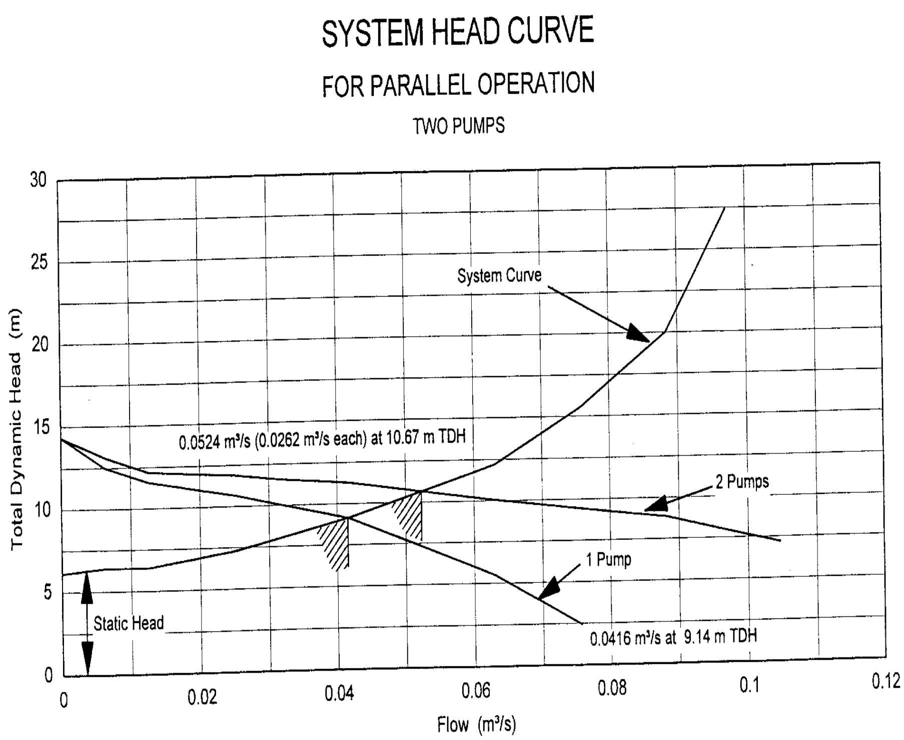


Figure 12-22 System Head Curves

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

Step 10 Power Requirements

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 brake kilowatts.

$$\textbf{Efficiency, } e = \textbf{pump output/brake kilowatts} = Q\gamma H/1000 \textbf{ brake kW} \quad \textbf{(12.8)}$$

Where: Q = pump capacity, m^3/s (ft^3/s)
γ = specific weight of liquid (1000 kg/m^3 x 9.81 m/s^2 for cold water) (62.42 lb/ft^3)
H = head, m (ft)

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.

To compute the energy required to drive a pump, assume that the pump will operate at 80% efficiency. The above equation can then be solved for brake kilowatts.

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 12.5.10. 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."

12.6.3 Documentation

The following items shall be included in the documentation file. (See Chapter 1, Section 1.6). The intent is not to limit data to only those items listed, but rather establish a minimum requirement consistent with the pump station design procedures as outlined in this chapter. If circumstances are such that the pump design is prepared other than the normal procedures or is governed by factors other than recommended in this chapter, a narrative summary detailing the design basis shall appear with the other data.

The following items should be included in the documentation file:

- inflow design hydrograph from drainage area to pump
- flood frequency curve for the attenuated peak discharge
- maximum allowable headwater elevations and related probable damage
- starting sequence and elevations
- sump dimensions

- available storage amounts
- pump sizes and operations
- pump calculations and design report
- line storage and pit storage capacity
- maintenance plan