Hydraulic Design of Stormwater Pumping Stations: The Effect of Storage

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In the design of stormwater pumping stations, skillful design can reduce both the initial cost and operating costs. The initial cost can be reduced by providing storage to reduce the peak pump rate. Savings can be achieved by reducing the size of the pump, the pump motor, piping, and valves, and substantial savings can accrue if the number of pumps is reduced. Most electrical utilities assess a fixed charge for the electrical capacity that the utility must maintain to provide service. Because horsepower is directly proportional to the pumping rate, any reduction in the pumping rate will be reflected in the fixed charge. By providing storage to reduce the peak pumping rate, operating costs can be considerably reduced. The effect of storage can be evaluated by using a mass curve routing procedure. This design procedure combines three independent components—the inflow hydrograph, the stage-storage relationship, and the stage-discharge relationship. The mass curve routing procedure identifies the amount of storage required to reduce the peak rate of flow to the fixed discharge rate. Design guidance is also provided for estimating the amount of storage required to accomplish a given reduction, and formulas are provided for calculating the volume of storage basins.

In most localities stormwater pumping stations only operate for a relatively short period of time during a year. This means that a substantial capital investment must sit idle for long periods of time. Therefore, the design and operation of stormwater pumping stations provide a most promising opportunity for cost reduction. Potential savings are even more promising in areas where storms are less frequent.

The merits of providing storage to reduce the peak pumping rates of pumping stations have long been recognized by engineers. To control the costs of stormwater projects, engineers are now examining potential savings much more closely. To achieve meaningful cost reductions, savings must be accomplished in both construction cost and maintenance and operations costs.

Initial costs can be reduced by providing storage to reduce the peak pumping rate; this will produce savings in the cost of the pump, the pump motor, and the instrumentation. Additional savings can be achieved by reducing the size of piping and valves. Substantial savings can accrue if the number of pumps is reduced. These savings will be offset by the cost of providing storage, but in many cases a net savings will occur if the storage can be provided at a low cost.

Maintenance and operating costs can be lowered by reducing the fixed electrical charge assessed by most electrical utilities. This charge is basically for the electrical capacity that the utility must maintain to service the pumping station and is usually proportional to the horsepower of the station. Because the horsepower is directly proportional to the pumping rate, any reduction in the pumping rate will be reflected in the fixed electrical charge.

This paper provides design guidance for sizing storage facilities used to reduce peak rates of flow at stormwater pumping stations.

DESIGN PROCEDURE

The merits of using storage to reduce peak flows are illustrated here by using a generalized case because the case of an actual pumping station may be complicated by the varying pumping rates and discontinui-

ties as the pumps turn on and off. This is shown in Figure 1, where the shaded area between the curves represents the volume of stormwater that must be stored to reduce the peak flow rate. Storage exists in natural channels, storm drain systems, constructed basins or forebays, and storage boxes. Engineers must be able to identify and analyze the effect of storage on the discharge rates from the pumping station.

Designers must establish the interrelationship of three separate components:

1. The inflow hydrograph must be determined for the contributing watershed.
2. The volumetric storage capability of the storage facility must be identified.
3. The stage-discharge curve of the pumps must be determined.

Once these three components have been established, a mass curve routing procedure can be used to analyze the problem.

The mass curve routing procedure is based on the assumption that the storage facility acts as a reservoir. Figure 2 helps to illustrate two shortcomings of this assumption. First, the velocity in the pipe is not zero (this shortcoming should be minor because the velocities should be low). Second, the water depth of the reservoir decreases to zero as the water surface approaches the invert of the pipe. During peak flow conditions the pipe will be flowing full and the design conditions shown in Figure 2 will not exist.

The second shortcoming can be eliminated by providing an isolated depressed storage facility that is independent of the storm drain system; however, in most systems it is quite cost effective to use the storm drain system as the storage facility. If a boundary is drawn around the storage facility and
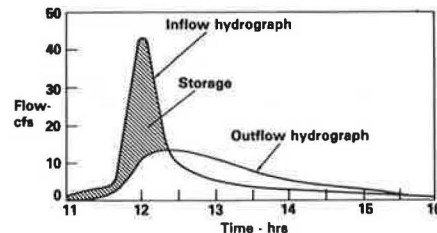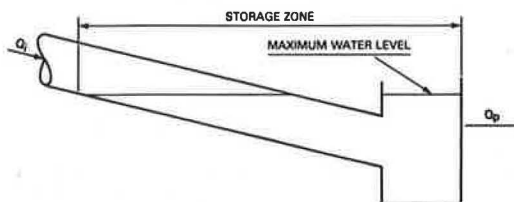
Figure 1. Generalized storage case.

Figure 2. Reservoir routing.

the pumping station so that they act as a unit, the reservoir assumption is valid because the design conditions conform to the general storage equation:

$$(\overline{I} - \overline{O}) \Delta t = \Delta S \tag{1}$$

where

$\overline{I}$ = average inflow rate,
$\overline{O}$ = average outflow rate,
Δt = time increment, and
ΔS = change in storage.

The inflow rate is defined by the design hydrograph, the outflow rate by the pumping discharge rates, and storage by the stage-storage curve. Because Equation 1 is valid inside the boundary, the reservoir assumption is an adequate representation of design conditions.

An example problem is used to illustrate the development of the routing procedure. The inflow hydrograph used for this example problem is shown in Figure 3.

ESTIMATING REQUIRED STORAGE AND PUMPING RATES

Because of the complex relationship among 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 can be used to produce an adequate design. A desirable goal is to maximize storage capacity so as to minimize pumping capacity.

The relationship between storage and the pump discharge curve for one pump is shown in Figure 4. The area between the curves to the left of the pump-on point represents the storage available in the system below the pump-on elevation, and the remaining area above the pump discharge curve represents the storage volume required above the pump-on elevation.

Some approximation is necessary to produce the first trial design. In one approach, shown in Figure 5, 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 the volume of storage required above the last pump-on elevation. This area is then measured to size the storage facility.

The number of pumps and their respective pumping rates are selected along with the pump on-off settings, and the trial dimensions of the storage basin are assigned to produce the required volume of storage, represented by the shaded area in Figure 5, above the last pump-on elevation.

For the example problem, a peak pumping rate of 14 ft^3/sec was assigned; this can be achieved by using two 7-ft^3/sec pumps. The pumping rate is plotted as a horizontal line and the shaded area is measured to determine the required volume (4,500 ft^3) above the last pump-on elevation.

STAGE-STORAGE RELATIONSHIP

Engineers have a wide range of tools available to them for providing the necessary storage at a pumping station. Natural or constructed earth basins are the most cost effective; however, at most highway pumping stations the stormwater must be stored underground. This can be done by oversizing the storm drain or providing a concrete storage box.

Routing procedures require the development of a stage-storage relationship. This is done by calculating the available volume of water for storage at uniform vertical intervals. Usually, the stage-storage curve is developed by using 0.25- to 0.50-ft intervals.

Two important points should be remembered:

1. The stage-storage curve must be developed for the entire range of elevations encountered.
2. To be cost effective, all of the pipes should be filled at peak conditions.

Natural Earth Basins

Storage provided by irregular natural terrain is calculated by determining the area of horizontal planes associated with the vertical intervals. The areas of adjacent planes are averaged and multiplied by the vertical increment to determine an incremental volume. Starting at the bottom of the basin, the volumes are summed to obtain the stage-storage curve.

Trapezoidal Basins

The stage-storage curve can be developed by using the prismoidal formula; however, because most engineers will want to develop computer programs for determining the volumes, the following equation is more useful:

$$V = LWD + (L + W)Z D^2 + (4/3)Z^2 D^3 \tag{2}$$

where

V = volume of the basin (ft^3),
L = length of the basin at the base (ft),

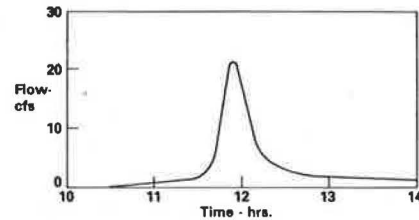Figure 3. Design inflow hydrograph.
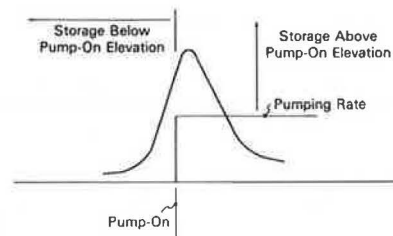

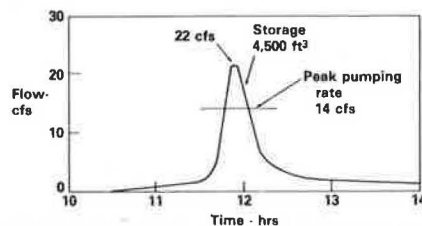Figure 4. Relation between storage and pump-on.

Figure 5. Estimating required storage.

W = width of the basin at the base (ft),
D = depth of the basin (ft), and
Z = side-slope factor, ratio of horizontal to
    vertical.

The equation, developed in Figure 6, is based on the premise that all of the sloping surfaces have the same slope. If different side slopes are required, the equation can be adjusted. A special case occurs when the basin is square (pyramid) and the equation for calculating the volume can be simplified:

$$V = L^2 D + 2LZD^2 + (4/3)Z^2 D^3 \qquad (3)$$

Storm Drains

Whenever the pump start elevation is above the invert of the storm drain, the storm drain will perform more as a storage basin than as a means of conveyance. By oversizing the storm drain, a true storage basin can be created to provide a meaningful reduction in pumping rates. One length of pipe could be designed to act as a storage basin, or the storage zone could be extended into several lengths of the storm drainage system.

The volumes for establishing the stage-storage curve can be calculated by using the prismoidal formula:

$$V = (L/6)(A_1 + A_2 + 4M) \qquad (4)$$

where

V = volume of water in pipe (ft³),
L = wetted length of pipe (ft),

A_1 = wetted cross-sectional area of lower end
    of pipe (ft²),
A_2 = wetted cross-sectional area of upper end
    of pipe (ft²), and
M = wetted cross-sectional area of midsection of
    pipe (ft²).

Relative area-depth curves or tables for the particular storm drain shape must be consulted to determine the cross-sectional areas. An FHWA report (1) provides relative area-depth tables for various cross-sectional shapes. Because the invert of the pipe should be sloped to aid in sediment removal, calculating the cross-sectional areas becomes more difficult. If the pipe is circular, a special case exists and the volume can be determined by the ungula of a cone formula (see Figure 7):

$$V = H [(2/3 a^3 \pm cB)/(r \pm c)] \qquad (5)$$

where

H = wetted length of the pipe (ft),
a = one-half of the water surface width (ft),
c = distance from the center of the pipe to
    the water surface (ft),
B = wetted cross-sectional area of the base
    (ft²), and
r = radius of pipe (ft).

When the water surface is above the center of the pipe, + is used; when the water surface is below the center of the pipe, - is used. Relative depth-area values for a circular section are given in Table 1.
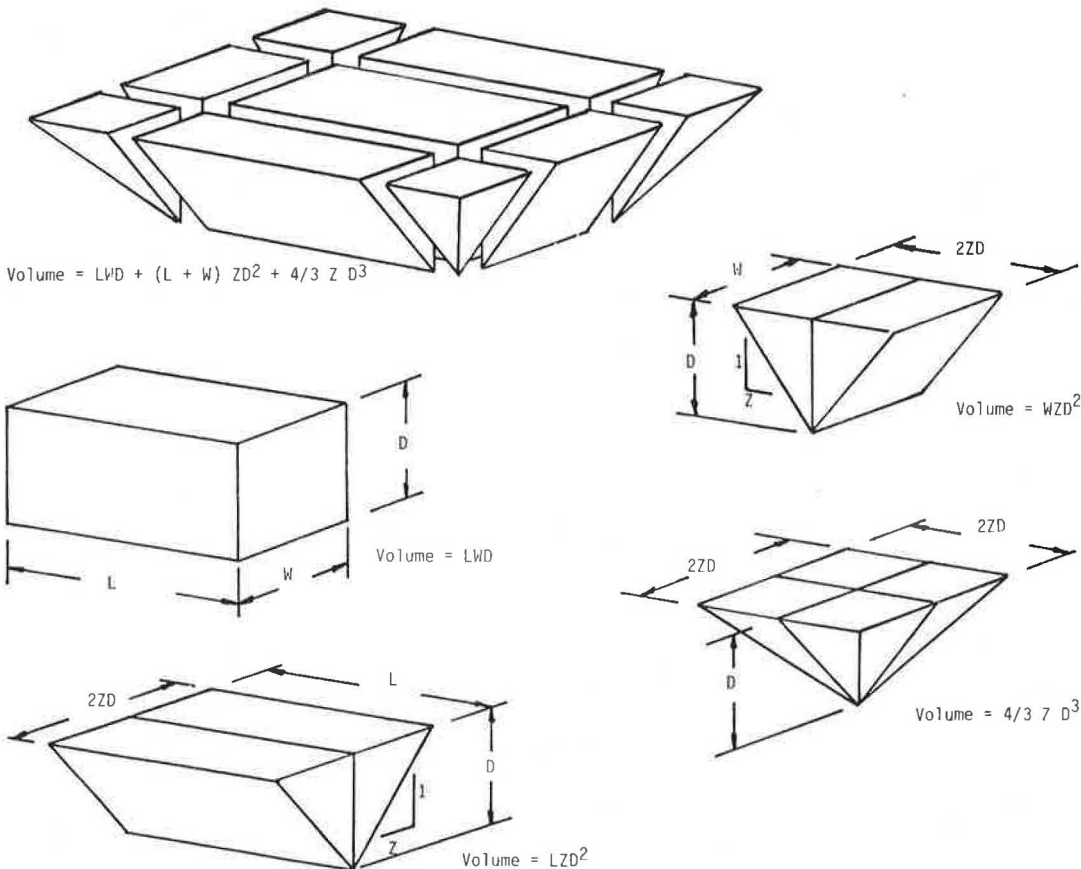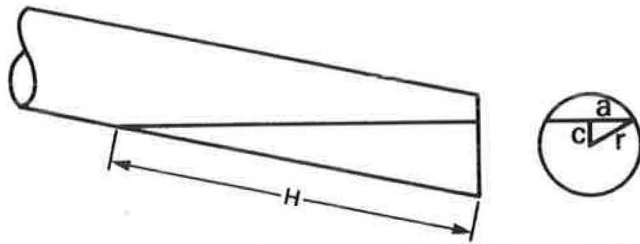
Figure 6. Volume of trapezoidal basin.

Volume = LWD + (L + W) ZD² + 4/3 Z D³

Volume = LWD

Volume = WZD²

Volume = LZD²

Volume = 4/3 Z D³

Figure 7. Ungula of a cone.

Storage Boxes

Underground storage boxes would most likely be rectangular reinforced concrete boxes. The volumes at the various stages can be calculated by using a combination of formulas for regular prisms and triangular wedges. Procedures for determining the volume of storage boxes are provided in Figure 8.

EXAMPLE PROBLEM

In the example problem, a 520-ft-long, 48-in.-diameter circular concrete pipe with a 0.40 percent slope is provided as a storage pipe, as shown in Figure 9; a 21- ft-diameter wet well is also provided. The storage volumes for the respective elevations are given in Table 2, and the stage-storage curve is plotted in Figure 10.

Stage-Discharge Relationship

Mass curve routing procedures require that a stage-discharge relationship be established. For the example problem presented here, the following stage-discharge relationship was developed:

Pump	Discharge Rate (ft^3/sec)	Elevation (ft)	
		Pump Start	Pump Stop
1	7	2.0	0.0
2	7	3.0	1.0

This stage-discharge relationship is based on three design assumptions: (a) pump 1 stops at 0.0-ft elevation, (b) the pumping range = 2 ft, and (c) there is a 1-ft difference in elevation between pump starts.

Figure 11 shows the pumping arrangement. Because pumping station design is basically a trial-and-error approach, this pumping arrangement should be considered a first attempt.

INFLOW MASS CURVE

To obtain an inflow mass curve, the inflow rates at the limits of a time increment are averaged and multiplied by the time increment to obtain an incremental volume. These incremental volumes are then totaled to obtain a cumulative inflow and plotted versus time to create an inflow mass curve. The inflow hydrograph for the example problem (Figure 3) is totaled in Table 3 and plotted in Figure 12 as the inflow mass curve.

MASS CURVE ROUTING

After the three components, the inflow hydrograph, the stage-storage relationship, and the stage-discharge relationships, have been determined, a graphical mass curve routing procedure can be used. In actual design practice, the inflow hydrograph, which is developed by an acceptable hydrologic method, is a fixed design component; however, the storage and pumping discharge rates are variable. The designer may wish to assign a pumping discharge rate based on environmental or downstream capacity considerations. The required storage is then determined by various trials of the routing procedure.

As the stormwater flows into the storage basin, it will accumulate until the first pump-start elevation is reached. The first pump is activated and, if the inflow rate is greater than the pump rate, the stormwater will continue to accumulate until the elevation of the second pump start is reached. As the inflow rate decreases the pumps will shut off at their respective pump-stop elevations.

These conditions are modeled in the mass curve diagram by establishing the point at which the cumulative flow curve has reached the storage volume associated with the first pump-start elevation. This storage volume, 2,025 ft^3 (Figure 10), is represented by the vertical distance between the cumulative flow curve and the base line as shown in Figure 13. A vertical storage line is drawn at this point because it establishes the time at which the first pump starts.

The pump discharge line is drawn from the intersection of the vertical storage line and the base line upward toward the right; the slope of this line is equal to the discharge rate of the pump. The pump discharge curve represents the cumulative discharge from the storage basin, and the vertical distance between the inflow mass curve and the pump discharge curve represents the amount of stormwater stored in the basin.

If the rate of inflow is greater than the pump capacity, the inflow mass curve and the pump dis-

**Table 1. Relative depth-area values for circular pipes.**

d/D	C									
	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0		0.0013	0.0037	0.0069	0.0105	0.0147	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	0.614	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
1.0	0.785									

Note: $B = C D^2$, where B = flow area, C = coefficient, D = diameter of the pipe, and d = depth of flow.
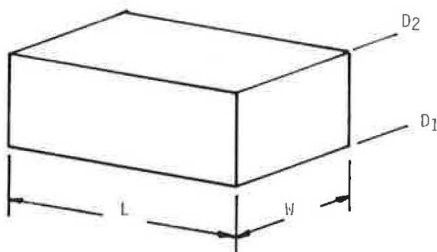
Figure 8. Volume of storage box.
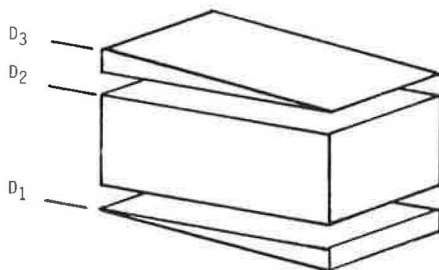
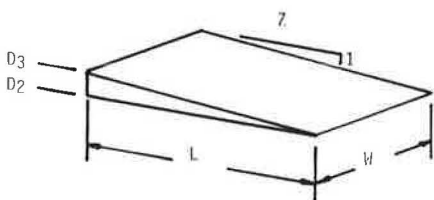1. Volume for depths less than D_1
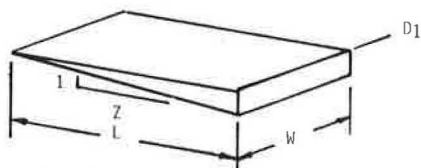
$$V_1 = 1/2 \ WZ \ D^2$$

2. Volume for depths between D_1 and D_2.
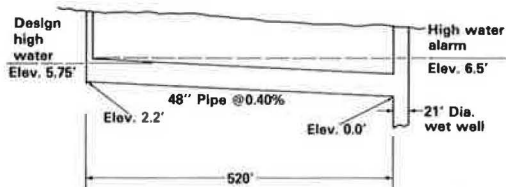

$$V_2 = LW \ (D - D_1)$$

Total $V = V_1 + V_2$

3. Volume for depths between D_2 and D_3.

$$V_3 = 1/2 \ WZ \ (D - D_2)^2 + W \ (L - Z \ (D - D_2)) \ (D - D_2)$$

Total $V = V_1 + V_2 + V_3$

Figure 9. Storage pipe used in example problem.

Table 2. Stage-storage volumes for 48-in.-diameter pipe at 0.40 percent slope with 21-ft diameter wet well.

Elevation (ft)	Volume (ft³)		
	Pipe	Wet Well	Total
0.0	0	0	0
0.5	45	173	218
1.0	251	346	597
1.5	672	519	1,191
2.0	1,333	692	2,025
2.5	2,213	866	3,079
3.0	3,187	1,039	4,226
3.5	4,168	1,212	5,380
4.0	5,072	1,385	6,457
4.5	5,773	1,559	7,332
5.0	6,230	1,732	7,962
5.5	6,468	1,905	8,373
6.0	6,534	2,078	8,612
6.5	6,534	2,251	8,785
7.0	6,534	2,424	8,958

charge curve will continue to diverge until the volume of water in storage is equal to the storage associated with the second pump-start elevation (4,226 ft³). At this point the second pump starts, and the slope of the pump discharge line is increased to equal the combined pumping rate.

The procedure continues until peak storage conditions are reached. At some point on the inflow mass curve, the inflow rate will decrease and the slope of the inflow mass curve will flatten. To determine the maximum amount of storage required, a line is

Figure 10. Stage-storage curve.

Table 3. Development of inflow mass curve.

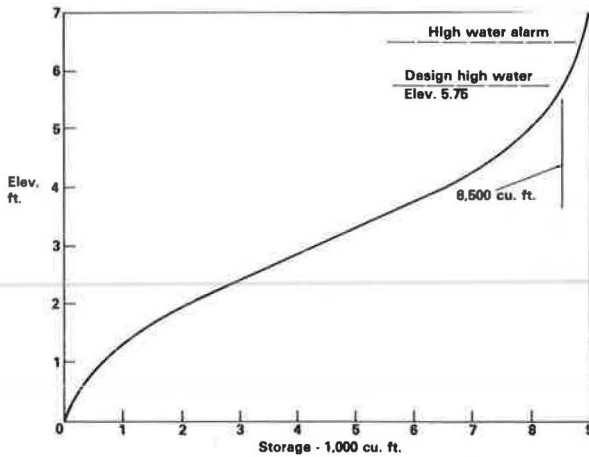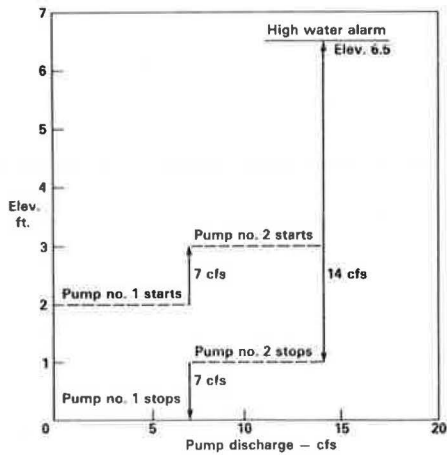| Time	Inflow (ft^3/sec)	Average Inflow (ft^3/sec)	Incremental Flow (ft^3)	Cumulative Flow (ft^3)
10:30	0			0
		0.05	15	
10:35	0.1			15
		0.15	45	
10:40	0.2			60
		0.25	75	
10:45	0.3			135
		0.35	105	
10:50	0.4			240
		0.45	135	
10:55	0.5			375
		0.55	165	
11:00	0.6			540
		0.65	195	
11:05	0.7			735
		0.75	225	
11:10	0.8			960
		0.85	255	
11:15	0.9			1,215
		0.95	285	
11:20	1.0			1,500
		1.05	315	
11:25	1.1			1,815
		1.15	345	
11:30	1.2			2,160
		1.85	550	
11:35	2.5			2,710
		3.5	1,050	
11:40	4.5			3,760
		8.0	2,400	
11:45	11.5			6,160
		15.2	4,560	
11:50	19.0			10,720
		20.2	6,060	
11:55	21.5			16,780
		19.2	5,760	
12:00	17.0			22,540
		14.5	4,350	
12:05	12.0			26,890
		9.2	2,760	
12:10	6.5			29,650
		5.8	1,740	
12:15	5.0			31,390
		4.5	1,350	
12:20	4.0			32,740
		3.8	1,140	
12:25	3.5			33,880
		3.4	1,020	
12:30	3.3			34,900
		3.0	900	
12:35	2.7			35,800
		2.6	780	
12:40	2.5			36,580
		2.4	720	
12:45	2.3			37,300
		2.2	660	
12:50	2.1			37,960
		2.05	620	
12:55	2.0			38,580
		1.95	580	
13:00	1.9			39,160

Note: Time increment = 300 sec.

Figure 11. Stage-discharge curve.

drawn parallel to the pump discharge curve tangent to the inflow mass curve as shown in Figure 13. The vertical distance between the lines represents the maximum amount of storage required.

The routing procedure continues until the pump discharge curve intersects the inflow mass curve. At this point the storage basin has been completely emptied and a pumping cycle completed. As the storm recedes, the pumps will cycle to discharge the remaining runoff.

In developing the pump discharge curve, the engineer should remember that the pump performance curve is quite sensitive to changes in head and that the static head will fluctuate as the water level in the storage basin fluctuates. The designer should also recognize that the pump discharge rate represents an average pumping rate.

The storage volumes for the two 7-ft³/sec pumps described earlier in the example problem are as follows:

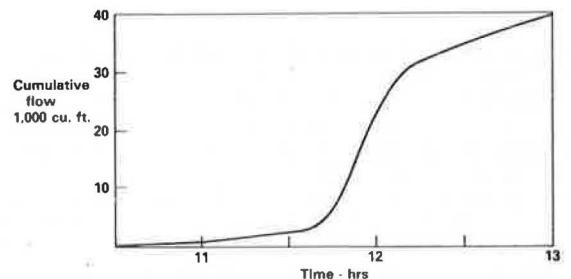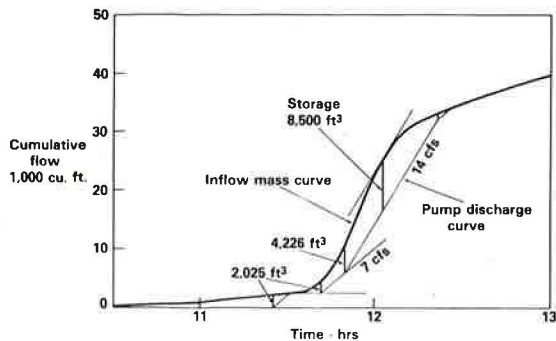|	Pump Start		Pump Stop	
Pump	Elevation (ft)	Storage Volume (ft^3)	Elevation (ft)	Storage Volume (ft^3)
1	2	2,025	0	0
2	3	4,226	1	597

Figure 12. Inflow mass curve.

Figure 13. Mass curve routing.

As shown in Figure 13, pump 1 is activated when the cumulative flow fills the storage basin to an elevation of 2.0 ft (2,025 ft³). The pump discharge curve is drawn from the base line at a rate of 7 ft³/sec. Because the rate of discharge is greater than the inflow rate, the basin will quickly empty and pump 1 will shut off. The pump discharge curve will be horizontal because there is no pumped discharge until the inflow builds up to the pump 1 start elevation again.

Pump 1 comes on again as the inflow builds up. Because the inflow rate is greater than the discharge rate, the curves will diverge until the available storage (4,226 ft³) is reached at the pump 2 start elevation. The combined discharge rate is plotted, and a line is drawn parallel to the discharge curve through the point of tangency of the inflow mass curve to determine the maximum amount of storage required, as shown in Figure 13. The vertical distance between the lines represents the maximum amount of storage required (8,500 ft³).

The peak storage conditions have now been reached and storage decreases. The routing continues until the two curves intersect, at which time the basin will have emptied. Pump 2 will shut off when the storage volume is equal to the volume (597 ft³) associated with the pump 2 stop elevation (1.0 ft); pump 1 will shut off when the storage pipe has been emptied at the pump 1 stop elevation (0.0 ft). Subsequent inflows will cause the pumps to cycle as the storm flow recedes; for purposes of simplicity this additional cycling is not shown.

The design is adequate because the available storage at the high-water alarm is 8,785 ft³. High-water design conditions are plotted on the stage-storage curve (Figure 10) for reference.

In the final design, the mass curve routing procedure can be fine-tuned after the pumps have been selected. For example, if two equal pumps are selected, the pumping rate when only one pump is pumping most likely would be greater than half the combined rate. Another refinement can be made for the condition that prevails when all of the pumps have come on line and peak pumping conditions have been reached. The pump discharge curve can be adjusted to reflect changes in the pumping caused by changes in the static head. However, it should be noted that these refinements do not act on the side of safety.

DISCUSSION OF RESULTS

Pumping Design

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 ft³/sec, the inflow hydrograph peak has been reduced to 14 ft³/sec, and the maximum pump discharge rate has been reduced by 46.5 percent by providing for 8,500 ft³ 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.

It is important that the designer visualize what is happening during the peak design period. To aid in this process, the pump discharge curve developed in Figure 13 can be superimposed on the design inflow hydrograph of Figure 3, as shown in Figure 14, to obtain another picture of the routing process. The shaded area between the curves represents stormwater that is going into storage. Again, pump cycling at the end of the storm has been omitted to simplify the illustration.

To complete the design the designer should investigate more frequent storms (storms with a 2- to 10-year recurrence interval) and evaluate pumping cycles during these storms. Less frequent storms (a 100-year recurrence interval) should also be investigated to determine the amount of flooding that will occur.

Stormwater pumping station design is one of the most promising areas in which cost reductions can be achieved by good engineering. Engineers will want to analyze a wide range of storage and pumping rate combinations to obtain the most economical design. To assist in design calculations, a programmable calculator program (2) has been prepared for the routing procedure.

Sediment Problems

The handling of sediment remains a difficult problem in pumping station design. Mechanical engineers prefer that as much sediment as possible be deposited in the storage boxes and the wet well to minimize wear on the pumps, whereas maintenance engineers prefer that the sediment be passed through the system so that the station is as maintenance-free as possible. Although both of these goals may have merit, they are at cross-purposes, and some trade-off must be made.

Because the velocity in the storage pipe is quite low (1 to 2 ft/sec), sediment will tend to settle out in the storage pipe. Some engineers recommend a relatively steep slope of 1 to 2 percent to pass the sediment into the wet well. As a general statement, the steeper the grade the better is the sediment removal; however, the steeper grade may cause the station wet well to be driven deeper into the ground and thus increase its cost. A steep grade may also limit the length of pipe that would otherwise be available for storage.
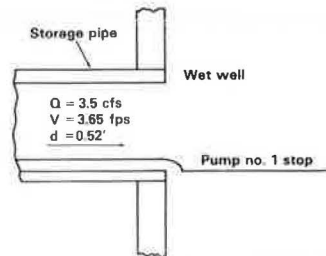
It is difficult to analyze flow and sediment conditions in the storage pipe; one approach would be

Figure 14. Pump discharge.
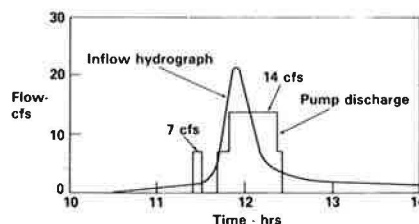
to investigate the flushing case. Design publications recommend a minimum velocity of 3 ft/sec when the pipes are flowing full; however, in the pumping station case the pumping rates determine the pipe velocity. For the flushing case, it is assumed that all main pumps have stopped and that the inflow rate is half the smallest pumping rate to ensure pump cycling. The slope of the storage pipe is then selected to provide a velocity of at least 3 ft/sec. The flushing case for the example problem is shown in Figure 15.

Table 4. Trial slopes for flushing concrete pipe.

Pipe Size (in.)	Pipe Slope (ft/ft)	Pipe Size (in.)	Pip Slope (ft/ft)
24	0.0083	54	0.0028
27	0.0071	60	0.0024
30	0.0062	66	0.0021
33	0.0054	72	0.0019
36	0.0048	78	0.00172
42	0.0039	84	0.00156
48	0.0033	90	0.00142
		96	0.00130

Note: Velocity of 3 ft/sec, 1/8 full flow, n = 0.013.

Figure 15. Flushing conditions for storage pipe.

The selection of the size and slope of the storage pipe is an important element in the trial-and-error design procedure. Table 4 gives design slopes for concrete pipes of various sizes that will produce a velocity of 3 ft/sec when flow is at a depth of 1/8 of the pipe diameter. Although these criteria are quite rigorous, the resulting slopes for the larger pipes are still quite flat. If the storage pipe is depressed or isolated from the upstream storm drainage, a minimum pipe grade of 0.35 percent is suggested to prevent low spots in the pipe.

In summary, the storage pipe and wet well should be designed to handle sediment; however, the pumping system should be designed to carry sediment-laden stormwater in case sediment removal does not occur in the wet well.

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