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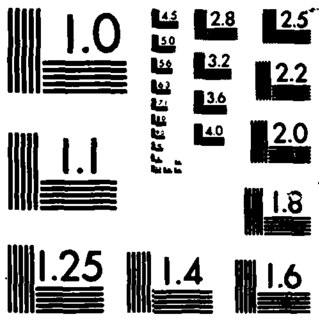

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TECHNICAL REPORT EL-85-11

WATER DISTRIBUTION SYSTEM OPTIMIZATION

by

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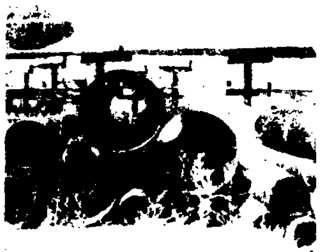

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This report describes the development of a computer program WADISO (Water Distribution Systems Optimization) which can be used to optimally size pipes in water distribution systems and select optimal pipes for cleaning and lining. The program can also be used as a steady-state simulation program to calculate flows and pressures in pipe networks.

The simulation portion of the program uses the node method with sparse matrix techniques to reduce computations. The optimization portion uses a
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20. ABSTRACT (Continued).

bounded enumeration technique, based on minimizing the sum of pipe installation, pipe cleaning and lining, and present worth of pumping energy costs. Only discrete commercially available pipe sizes are considered. The program can handle ~~virtually~~ any typical water distribution system and includes pumps, pressure reducing valves, multiple pressure zones, and check valves. To use the optimization, the user must also specify costs as a function of pipe diameter (or use default costs in the program), minimum pressures, up to five water use loadings, a list of which pipes are to be sized, and a range of sizes to be considered.

The program user's guide is included as an appendix to the report. Other appendices address how to access the program, how to obtain detailed documentation, the nature of pipe sizing, existing literature on pipe optimization, and a discussion of the relationship of pipe sizing and water distribution performance criteria.

PREFACE

The computer program described in this report was developed under the MAPS (Methodology for Areawide Planning Studies) Work Unit under the Water Supply and Conservation Research Program. The technical monitors for the program at the Office of the Chief of Engineers were Mr. Jim Ballif (DAEN-ECE-BU) and Mr. Robert Daniel (DAEN-CWP-D).

The work was performed in the Water Resources Engineering Group (WREG), Environmental Engineering Division (EED), Environmental Laboratory (EL), at the US Army Engineer Waterways Experiment Station (WES) in Vicksburg, Miss. Dr. Johannes Gessler, Civil Engineering Department of Colorado State University, developed the computer program, prepared the user's guide and documentation for the program, and wrote Parts I, II, and III and Appendix A of this report. Dr. Gessler worked in the WREG under an Intergovernmental Personnel Act. Dr. Thomas M. Walski, WREG, prepared Parts IV and V and Appendices B through F. The report was reviewed by Mr. M. John Cullinane, Water Supply and Waste Treatment Group, EED, and Ms. Jan S. Condra, WREG. The report was edited by Ms. Jamie W. Leach of the WES Publications and Graphic Arts Division.

The study was conducted under the direct supervision of Dr. Michael R. Palermo, Chief, WREG, and under the general supervision of the late Mr. Andrew J. Green, Chief, EED; Dr. Raymond L. Montgomery, Acting Chief, EED; and Dr. John Harrison, Chief, EL.

During the preparation of this report, COL Tilford C. Creel, CE, and COL Robert C. Lee, CE, were the Commanders and Directors of WES and Mr. Fred R. Brown was Technical Director. At the time of publication, COL Allen F. Grum, USA, was Director and Dr. Robert W. Whalin was Technical Director.

This report should be cited as follows:

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CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet per second	0.02831685	cubic metres per second
feet	0.3048	metres
feet per second	0.3048	metres per second
gallons per minute	3.785412	cubic decimetres per minute
inches	25.4	millimetres
miles (US statute)	1.609347	kilometres
pounds (force) per square inch	6894.757	pascals
square miles	2.589998	square kilometres

WATER DISTRIBUTION SYSTEM OPTIMIZATION

PART I: INTRODUCTION

Background and Purpose

1. Pipe network optimization in the mid 1980s is about where pipe network steady-state simulation was in the early 1970s. Some tools have been developed, but their use is highly experimental and very few practicing engineers use them as part of their standard design procedures. Many engineers in the early 1970s claimed that network simulation was really not necessary and that the numerous constraints imposed on the design and not directly related to the hydraulic performance of the system made simulation meaningless. Today, network simulation has become a standard tool in network design. Even small engineering firms or water districts routinely simulate system performance using one of many available computer programs written for a variety of computers. In the past few years the availability of such programs for microcomputers has brought this tool into the offices of many small engineering firms. The criticisms of the early 1970s have disappeared.

2. Today, many practicing engineers insist that network optimization is not feasible, and that there are too many constraints beyond the strictly physical and economic aspects which cannot or are very hard to build into the optimization procedures. But this criticism is about as well founded as the one heard in regard to pipe network simulation some time ago. Availability of user friendly software, reasonably flexible in regard to the constraints the engineer would like to impose, and use of an approach the engineer can more or less follow and trust will lead to general acceptance of computer optimization of pipe networks.

3. The purpose of this report is to describe the development of a simulation and optimization computer program called WADISO (Water Distribution Simulation and Optimization). The purpose of WADISO is to assist engineers in designing least-cost improvements to water systems to meet performance standards.

Organization of Report

4. The remainder of this part describes the need for network optimization. Part II discusses a network balancing technique, developed for the optimization procedure. Part III describes an optimization algorithm which is easy to understand, provides for great flexibility, and guarantees globally minimum cost within the user-specified constraints. The drawback of the algorithm is the fact that it may require considerable computer time. But the nature of the algorithm is such that as more constraints are imposed, performance of the technique improves. Part IV describes cost data required to use on optimization model.

5. Appendix A to the report is the user's guide for the WADISO program. Appendix B describes how to access the program on the CDC Cybernet computer system, while Appendix C describes how to obtain listings and detailed documentation of the program. Appendix D presents a discussion of pipe sizing methods with an emphasis on the differences between solutions treating pipe size as discrete and continuous variables. Appendix E reviews other approaches available in the literature. Finally, Appendix F presents an analysis of the sensitivity of model results to design assumptions made in applying the model.

Need for Optimization

6. It is rare that a very large and complex pipe network is designed and constructed at one given point in time. Systems usually grow over many years in relatively small increments. For instance, once the main supply grid of an existing city water distribution system is in place, new development of a square mile or so requires the sizing of only a few main lines, perhaps roughly 1/2 mile apart.* Somewhere around 10 to 15 miles of pipes may need to be sized for a single construction project. Cost of the part of the system to be sized may be in the range of a few million dollars. The sizing of the pipes within subdivisions is typically not part of such an optimization since minimum sizes specified by state regulations are usually used in these cases.

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 4.

7. A second example of needs for pipe network optimization is the improvement of an existing distribution system. Due to increased per capita water usage, or due to the continuous addition of more and more subdivisions to an existing grid, pressure conditions in a network may become unsatisfactory and the utility decides to reinforce the existing grid to meet the projected needs for some time. An alternative to adding new pipes to the main grid, typically running parallel to existing lines, is the cleaning and lining of existing lines. Typical project costs start around one million dollars and may reach tens of millions of dollars. One example is the reinforcement of the major New York City water supply tunnels, which has been cited in the literature several times (Lai and Schaake 1969; Quindry, Brill, and Liebman 1981; Gessler 1982).

8. Gessler (1982) discussed some of the reasons why engineers may think optimization is not necessary. One widespread misconception is that if the minimum pressure in a system is close to the desired minimum pressure, system cost is also close to the minimum cost. Because it is very easy using a simulation program to design a "reasonable" system which will just meet the pressure requirement, optimization then does not seem to be essential. The example of the New York City water supply tunnels may serve again to illustrate how wrong this assumption is and how surprising the results of an optimization can be. The optimization by Lai and Schaake (1969) led to total system cost of $73.3 million. The optimization by Quindry, Brill, and Liebman reduced this figure (using the same demands and minimum pressure requirements) to $63.6 million. Gessler (1982) showed that there was indeed a technically feasible solution for $41.2 million (all amounts in 1969 dollars). There are even less expensive solutions, yet the additional savings are relatively minor and operational considerations (redundancy) make the solutions unattractive.

Desirable Properties of an Optimization Technique

9. It is difficult to list desirable capabilities of an optimization algorithm without biasing the list toward a particular technique. It is clear that some techniques can handle certain situations better than others. Nevertheless a "minimum list" of such capabilities is offered here:

- a. The algorithm should guarantee that the global minimum will be reached or at least should permit a search for the global minimum with relative ease. Looped networks may have multiple local minima which make the search for the global minimum more difficult.

b. Pipe sizes must be treated as discrete variables throughout the algorithm. To use a procedure which works with pipe sizes as a continuous variable and "rounds to the nearest available size" only at the very end is not acceptable. Such rounding can result in costly and/or infeasible solutions.

c. No restrictions should be imposed on the unit cost function for the discrete sizes. Because of the highly arbitrary way the cost function may increase with size, it is difficult to accurately "interpolate" cost. This is another reason why the algorithm must work with the discrete sizes and the associated discrete cost. Similarly, it should be possible to specify different unit prices for the same diameter pipe laid in different locations.

10. In addition to these basic requirements for an optimization procedure listed above, some other desirable properties of an optimization procedure are:

a. The algorithm should guarantee that actual pressure exceeds minimum pressures at any node in the system. This minimum may vary from node to node.

b. Optimization should guarantee minimum pressures for several loading patterns. The various loading patterns may have different minimum pressure requirements at the same node. For instance, for average daily consumption a pressure of 50 psi could be required throughout the system. During fire conditions a pressure of 25 psi at all nodes may be sufficient except at the location of the fire load itself where 15 psi may be acceptable.

c. It is not customary to vary pipe size along a leg of pipe. The size should remain constant between the two user-defined end nodes of a pipe (i.e. pipe length should not appear as a variable).

d. It is easy to show that cleaning and lining of existing pipes can be an economically attractive alternative to adding new pipes to an existing system. The algorithm should allow the user to consider this alternative.

11. A third set of requirements for an optimization procedure relates to the amount of control the user retains over the design. Engineers who have worked with a particular piece of software and understand its internal working frequently learn how to control program performance, sometimes in indirect ways. No specific requirements are listed here. Rather, some general remarks are offered. It would be very desirable if the user could somehow control

which pipes become the major conveyance components. Or it seems highly desirable that the user can prevent the program from offering a solution which shows a different pipe size for every block. Such "random" size changes are typically the result of a specific (and most of the time arbitrary) loading pattern.

PART II: AN EFFICIENT BALANCING ALGORITHM

Node Method

12. This part begins with a discussion of why the node method for determining heads was selected for WADISO and then gives the more important equations used by the program in balancing networks. It then describes how the equations are solved and gives some examples of balancing flows in networks (which is also referred to as "simulation").

Node method versus loop method

13. Part III will discuss an optimization procedure which will require the repeated determination of pressure and flow distribution for selected sets of diameters for pipes to be sized. In the typical simulation program the efficiency of the algorithm may not be too important. Time for input and output (or the computer cost associated with these operations, like connect time to a time share computer) may dominate the total time (or cost) required. But if the pressure and flow distribution must be evaluated many times, it becomes imperative that a very fast algorithm be employed which specifically takes into account the needs of the optimization scheme.

14. Historically, flow and pressure distributions were most often calculated using a loop method, i.e. a procedure in which the flow rates in the pipes are the primary unknowns (Jeppson 1976). After the flow rates were calculated, a second part of the algorithm determined the pressures at all nodes. The reason for using the loop method rather than a node method was that there are typically fewer loops in a system than nodes. The percent difference is especially large in small systems. The use of a loop method was logical because in the early stages of computer analysis of networks, hardware limitations restricted the analysis to small systems (say less than 20 loops or less than 30 nodes). With the increasing capabilities of the hardware, it has become possible to analyze much larger systems. Because loop programs were already developed there was a distinct tendency in network analysis to stay with this technique. But the percent advantage in the number of loops over the number of nodes decreases rapidly with system size.

15. A node method offers interesting advantages over a loop method. The primary unknowns are the total hydraulic heads at each node. The head corrections from iteration to iteration typically follow a geometric series.

This permits the development of reliable estimates for the head error, iteration by iteration. Since system requirements are usually spelled out in terms of pressures, it is much easier to know when to terminate the computations in a node method than in a loop method. A second reason for preferring the node method over the loop method is the much simpler network topology. There is no need to determine a loop topology, which may change as pipes to be sized are eliminated. A third reason for using a node method is related to pressure controlled devices like some pumps, pressure reducing valves (PRV), and check valves. The operational mode of a PRV is only known when the pressures at its end nodes are known. Such pressures in a loop method are not known iteration by iteration without a significant increase in computational time.

Node equations

16. The node method expresses the flow rate in each leg of pipe in terms of the total hydraulic heads at each end of the pipe. Using the Hazen-Williams formula, this relationship is

$$HE_B - HE_E = CP * Q^{1.85} \tag{1}$$

where

HE = total hydraulic head, ft

B = beginning node number of the pipe

E = ending node number of the pipe

CP = characteristic pipe coefficient, ft/cfs$^{1.85}$

Q = the flow rate in the pipe, cfs

and the characteristic pipe coefficient CP is defined as

$$CP = 4.72 * L/(HW^{1.85} * DI^{4.87}) \tag{2}$$

where

L = length of pipe, ft

HW = Hazen-Williams coefficient

DI = pipe diameter, ft

17. Equation 2 is now linearized. While it is customary to do such linearization in the vicinity of estimated heads, it is done here in the vicinity of an estimated flow QO . The flow rate Q can then be expressed as

$$Q = 0.46 * Q0 + 0.54 * (HE_B - HE_E)/(CP * Q0^{0.85}) \tag{3}$$

where Q0 = estimated flow rate, cfs.

18. The continuity equation at a node is now formulated with the sign convention that flow away from the node is positive. This is illustrated using the small system shown in Figure 1. Flow is assumed from 1 to 2, 2 to 3, and 2 to 4.

```
         6           7
   O-----------O-----------O
   1           |2          4
             8 |
               |
               O
               3
```

Figure 1. Small network

$$\begin{aligned} &-0.46 * Q0_6 - 0.54 * (HE_1 - HE_2)/\left(CP_6 * Q0_6^{0.85}\right) \\ &+0.46 * Q0_8 - 0.54 * (HE_2 - HE_3)/\left(CP_8 * Q0_8^{0.85}\right) \\ &\qquad + 0.46 * Q0_7 - 0.54 * (HE_2 - HE_4)/\left(CP_7 * Q0_7^{0.85}\right) + QD_2 = 0 \end{aligned} \tag{4}$$

where

HE = total hydraulic head, ft

CP_i = characteristic pipe coefficient of pipe i, $ft/cfs^{1.85}$

$Q0_i$ = estimated flow in pipe i

QD_j = output at node j, cfs

19. This continuity equation can be simplified by assuming reasonably good estimates for $Q0_i$, i.e.

$$-Q0_6 + Q0_8 + Q0_7 + QD_2 = 0 \tag{5}$$

20. This assumption is permissible no matter how unrealistic the estimates are. It is, for instance, possible to start with flow rates estimated to be 1 cfs in all pipes of a system. In subsequent iterations the flow calculated in the previous iteration is used.

21. Using the notation

$$A_i = 1/\left(CP_i * QO_i^{0.85}\right) \tag{6}$$

where A_i = matrix coefficient for pipe i, cfs/ft. The continuity equation can now be written as

$$-A_6 * HE_1 + (A_6 + A_7 + A_8) * HE_2 - A_8 * HE_3 - A_7 * HE_4 = -QD_2 \tag{7}$$

22. It is important to observe that in Equation 7 there is no formal difference between adjacent nodes from which water comes and those toward which water flows. The coefficients for all heads are negative, except for the coefficient on the diagonal which is positive. Also, the diagonal member is the negative sum of all the off-diagonal members.

23. Writing the continuity equation for all n nodes in the network results in a system of n equations with n unknown heads. In order to meet the boundary conditions at the tanks and reservoirs where the total hydraulic head is prescribed, the coefficient on the diagonal is replaced by a very large number, say 1E10. On the right-hand side of the equation, instead of the negative output at the node, a value of the same very large number times the desired head at this node is used. If the tank level is for instance at elevation 1580 ft, one would use 1580 * 1E10. No matter how many pipes exit from the tank, the equation will have the trivial solution of the node head equal to 1580 since all off-diagonal terms are small compared with the term on the diagonal.

24. The coefficient matrix is sparse and symmetrical. Both of these characteristics can be used to reduce computer time required to solve the set of linear equations. Symmetry will be retained even in the presence of pumps or PRV's.

Pumps

25. In many networks pumps are important components. If the continuity equation alone dictates the pump flows (i.e. pumping into a dead end with no tanks), it is possible to break the network at the pumps. Each subnetwork can then be analyzed individually. If the pump flow cannot be implied by continuity alone, it is important that the pumps be handled automatically by the program.

26. The characteristic curve of a centrifugal pump can usually be approximated by a parabola

$$H_p = a * Q_p^2 + b * Q_p + c \tag{8}$$

where

H_p = pump head, ft (downstream head minus upstream head), $H_p > 0$

a = coefficient of square term (a < 0)

Q_p = pump flow, cfs

b = coefficient of linear term (b < 0)

c = constant term (c > 0)

A negative value for b is necessary. A positive value for b would result in a maximum of the characteristic curve, and there would no longer be a unique solution for flow given the head.

27. This equation can be linearized using an estimated pump flow rate

$$Q_p = H_p/(2 * a * Q0_p + b) + \left(a * Q0_p^2 - c\right)/(2 * a * Q0_p + b) \tag{9}$$

where $Q0_p$ = estimated pump flow, cfs. For the first iteration any value for the estimated pump flow could be used. In WADISO the pump curve is defined using three points, and the middle point is used as a first guess of the pump flow. This allows the user to execute some control over the initial estimate of flow.

28. For a pump the continuity equation of the upstream node of the pump will now show an additional term on the diagonal of

$$-1.85/(2 * a * Q0_p + b)$$

In the same continuity equation the coefficient of the head at the downstream side of the pump is

$$+1.85/(2 * a * Q0_p + b)$$

Note that $2 * a * Q0_p + b < 0$; i.e., the sign of the coefficient due to the pump is the same as for a pipe.

29. The small pipe and pump combination shown in Figure 2 is used to illustrate the format of the continuity equation, both at the upstream node and downstream node of a pump. The flow in the pump is assumed to go from node 2 to node 3. The continuity equation for node 2 reads

```
    7           8           9
0----------0--(Pump)--0----------0
1          2    ->    3          4
```

Figure 2. Small network with pump

$$-0.46 * QO_7 - 0.54 * (HE_1 - HE_2)/\left(CP_7 * QO_7^{0.85}\right) + (HE_3 - HE_2)/ (2 * a * QO_p + b) + \left(a * QO_p^2 - c\right)/(2 * a * QO_p + b) + QD_2 = 0 \tag{10}$$

With the assumption that the sum of the estimated flow rates and the domestic load at node 2 approximately balance,

$$-QO_7 + QO_p + QD_2 = 0 \tag{11}$$

the continuity equation for node 2 takes the final form

$$-A7 * HE_1 + (A_7 - 1.85/(2 * a * QO_p + b) * HE_2 + 1.85/(2 * a * QO_p + b) * HE_3 = -QD_2 + 0.46 * QO_p - 1.85(a * QO_p^2 - c)/(2 * a * QO_p + b) \tag{12}$$

and the equivalent equation for node 3 is

$$1.85/(2 * a * QO_p + b) * HE_2 + \left(A_9 - 1.85/(2 * a * QO_p + b)\right) * HE_3 - A_9 * HE_4 = -QD_3 + 0.46 * QO_p - 1.85\left(a * QO_p^2 - c\right)/(2 * a * QO_p + b) \tag{13}$$

30. From the above example it is clear that with this treatment of the pumps, the symmetry of the coefficient matrix is not affected. Convergence characteristics of the numeric solution of the equations are essentially unaffected or even slightly improved by the presence of pumps. This is different from the approach used by Jeppson (1976) who found that in order to guarantee convergence it was necessary to perform a variable transformation which led to a nonsymmetrical matrix and slightly worsened the convergence characteristics.

Check valves

31. Check valves are frequently used in water systems in combination

with pumps in order to prevent backflow around the pump or to prevent backflow from private water users with storage. The status of the check valve is not known when the program starts.

32. In the first iteration the check valve is assumed to be open. Based on the calculated heads upstream and downstream of the valve, the status of the check valve is tested, iteration by iteration. Should the downstream pressure exceed the upstream pressure, the pipe which includes the check valve is eliminated by setting its entry in the coefficient matrix equal to zero. The status of a check valve may change several times during the course of convergence. Therefore, the status of the check valve must be tested at the end of every iteration.

Pressure-reducing valves

33. A simple PRV has three different modes of operation. In the standard (active) mode of operation, the PRV reduces the downstream pressure to a selected value in order to protect part of a network from high pressures. If all PRV's feeding into a low pressure zone are known to operate in the standard mode, it is possible to analyze the low pressure zone first. Each PRV can be treated as a supply point with known total hydraulic head. From such an analysis the amount of water entering through each PRV into the low pressure zone can be obtained. In a second step the high pressure zone can be analyzed, introducing the flow through the PRV's as loads on the system. Such a two-step analysis does not require more computer time than the analysis in one single step. However, the mode of operation of the PRV is not typically known a priori. The PRV's then may operate in one of the following three modes:

a. Active mode. Water flows through the PRV and the pressure on the downstream side of the valve is reduced to the preset level.

b. Open mode. If the upstream pressure of the PRV drops below the preset level, the pressure on both sides of the PRV is equal. Water flows essentially unrestricted through the PRV.

c. Check valve mode. If the downstream pressure exceeds the preset level or if the downstream pressure exceeds the upstream pressure, the valve will close and act like a check valve.

34. Topologically, a PRV can be represented as a link between two nodes. In its active mode of operation, the downstream node is treated like a supply point with known pressure. The flow from this pseudo-reservoir into the low pressure zone of the network is added to the output at the upstream node of the PRV. In the computer representation, the physical connection between the

two nodes is eliminated; i.e. the coefficient in the matrix is set to zero.

35. Should, in the course of the iterative procedure, the upstream pressure drop below the pressure setting of the valve, the valve is made "transparent": the coefficient in the matrix is set to a very large value and the supply point at the downstream side of the valve is removed. In this mode the PRV is treated exactly like a pipe.

36. If the downstream pressure exceeds the pressure setting of the PRV, or the downstream pressure exceeds the upstream pressure, the connection between the upstream and downstream node is completely eliminated by setting the coefficient in the matrix to zero. The downstream node is permitted to find its own pressure level. If only one pipe leads from the PRV into the low pressure zone, this pipe will now show a zero flow rate.

37. In the first iteration the PRV is set as if it were open. At the end of each iteration the status of the PRV's is checked, and if necessary adjusted.

38. Two aspects are important in the way PRV's are handled in WADISO. First, the topology of the network may change from one iteration to the next. In the node method used here, this poses no difficulties. Network topology is only defined by the location of the nonzero entries in the coefficient matrix of the linearized continuity equation. Second, this treatment of PRV's does not affect the symmetry of the coefficient matrix. Chandrashekar (1980) proposed quite a different method of handling the PRV's in the context of a node method. It had the distinct disadvantage of creating a nonsymmetrical matrix.

Solution of Node Equations

39. After the coefficient matrix of the node equations is established, a Gaussian elimination procedure is used to solve the equations for the head at each node. Whether the procedure takes advantage of symmetry and sparseness is only important from the point of view of computer time and memory requirement. To take advantage of symmetry is easy. Instead of working with the total matrix, one can work with the upper half only. Sparseness is more difficult to take advantage of, especially since the matrix may not be well banded.

40. The algorithm employed in this program stores the locations of the nonzero entries in a double subscripted array. The coefficients themselves

are stored in a single subscripted array. Since exploitation of sparseness is not essential to the algorithm, the reader is referred to Rose and Willoughby (1972) and Jennings (1977).

41. After the linearized equations are solved, the flow rates are calculated in all pipes and pumps. These flow rates are used to reevaluate the coefficient matrix in order to execute the next iteration.

42. It is important to realize that continuity in this procedure is not automatically met. Convergence can be checked in two relatively independent ways. First, corrections on the heads should become smaller from iteration to iteration. On the average these corrections reduce from one iteration to the next by a factor of 1.85. Second, convergence can be checked by observing the net outflow at each node from one iteration to the next. In most water distribution systems, pressure accuracy (i.e. differences in pressure from one iteration to the next) in general becomes acceptable much earlier than flow accuracy (i.e. amount by which the sum of the inflows and outflows differs from zero). It is quite common to have the pressure accuracy reach values better than 1 psi, while the flow accuracy can still be in the range of 10 to 100 gpm. Pressure accuracy is considered to be more important since system requirements are typically specified in the form of pressures. High flow accuracy is then achieved by minor adjustments of the pressures. Both of these accuracies are available iteration by iteration in WADISO. The algorithm initially checks the pressure accuracy by recording the largest absolute correction and if this correction is less than a specified value, the algorithm then checks the flow accuracy. Computations continue until the flow accuracy reaches the specified value for flow accuracy.

43. The regularity with which the iterative procedure reaches the final answer makes it possible to overrelax the head corrections. Overrelaxation of the head corrections by a factor of 1.85 has proven to give the best convergence. Such overrelaxation only takes place after the third iteration. If it is applied earlier, it can lead to nonconvergence. In the presence of PRV's and/or check valves, overrelaxation cannot be employed since it frequently results in nonconvergence. If the rate of convergence is significantly below average, the overrelaxation scheme is bypassed thus avoiding nonconvergence in the case of ill-conditioned networks.

44. It is typical for the algorithm to reach a pressure accuracy of 1 psi in three to four iterations, and a flow accuracy of 1 gpm in a total of

five to seven iterations, if overrelaxation is employed after the third iteration. In the presence of PRV's and/or check valves, it takes typically about twice as many iterations to reach the same flow accuracy. The number of iterations is usually independent of system size, except for very small systems where the number of iterations can be one to two iterations less for similar accuracy.

45. The number of iterations required to reach a certain accuracy is only slightly dependent of the initial guess of flow rates.

Examples

46. Convergence characteristics are illustrated herein by means of two examples. The system to be used is shown in Figure 3. It has two supply reservoirs. From one reservoir the flow enters the system through a supply pump. Two booster pumps provide for sufficient pressure at the south end of the system. The system has 32 nodes and 42 pipes in addition to the three pumps already mentioned. The system has the equivalent of 15 loops, although a loop count is not a good measure for system size in an algorithm which employs a node method.

47. Convergence is illustrated in Table 1 by listing the heads at four selected nodes, iteration by iteration. The initial estimate for flow rates is 1 cfs (448 gpm) in all pipes, 1,750 gpm in pump 2, and 1,200 gpm in pumps 4 and 5. No overrelaxation is employed. Table 2 shows the data for the same case, with initial flow estimates in all pipes set to 10 cfs (4,480 gpm). The estimated flow rates for the pumps are the same as for the data in Table 1. In Table 3 the data are shown for the same case as in Table 1, except that an overrelaxation scheme is employed after the second iteration.

48. Tables 1-3 demonstrate that the algorithm is not sensitive to the initial guesses of flow rates and that the employment of overrelaxation reduces the number of iterations required to reach a certain accuracy by about a factor of 2. The heads are listed to three digits beyond the decimal point only to illustrate the convergence characteristic. For the same reason the accuracies for pressure and flow rate were set to 0.01 psi and 0.1 gpm, respectively. Due to the uncertainty in Hazen-Williams coefficients and outputs, such a high degree of accuracy is not meaningful in real systems.

49. In a last test run all pumps have been removed and replaced by

Characteristic pump curves

	Discharge (gpm)	Head (ft)
Pump # 2	1500	237
	1750	231.5
	2000	225.5
Pumps # 4 and 5	1000	120
	1200	110
	1400	99

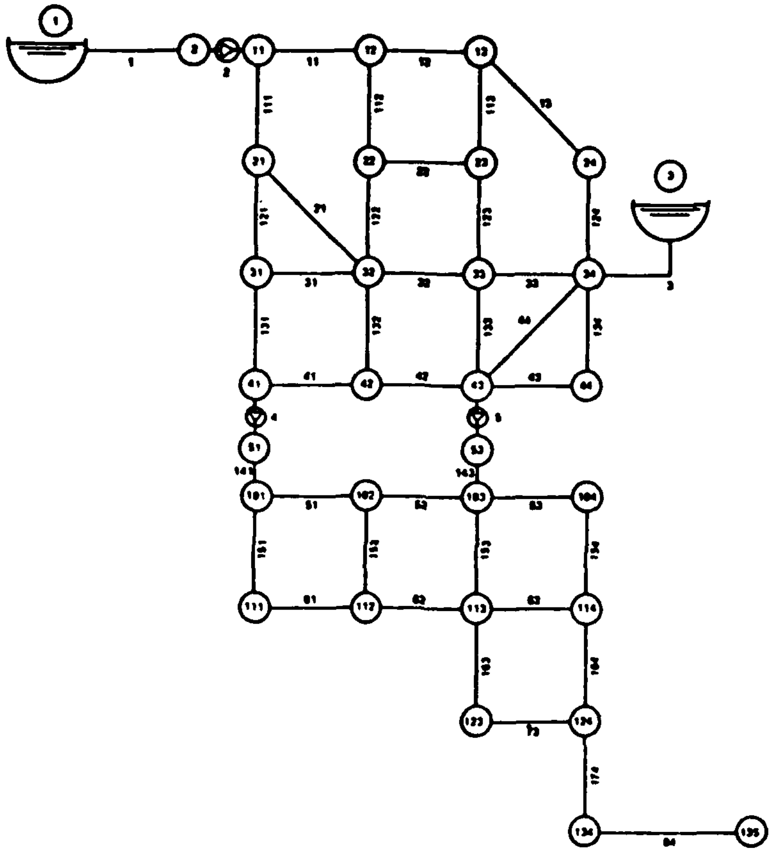

Figure 3. Example 1 pipe network

short legs of pipe. The water level in reservoir 1 was set at 731.0 ft in order to provide about the same flow distribution in the network. No over-relaxation took place. The purpose of this run was to show that the presence of pumps does not significantly affect the rate of convergence. The data are provided in Table 4. Due to the removal of the pumps the heads are different. But it is quite clear that the rate of convergence is not significantly different.

Table 1

Calculated Heads at Selected Nodes, Iteration by Iteration, for Example 1; Estimated Pipe Flow 1 cfs in all Pipes; No Overrelaxation

Iter. No.*	Node 33	Node 41	Node 103	Node 135	Max. Pressure Corr.	Max. Flow Imbalance
1	672.446	639.892	621.281	542.827	71.2	8191.
2	683.895	656.576	692.426	594.504	46.8	1452.
3	689.520	671.273	748.918	637.976	25.7	602.
4	692.129	675.999	766.086	648.606	8.1	276.
5	693.296	677.869	772.600	651.948	3.2	127.
6	693.822	678.669	775.336	653.188	1.3	58.
7	694.062	679.025	776.542	653.698	0.6	27.
8	694.172	679.186	777.085	653.920	0.3	12.
9	694.222	679.259	777.333	654.019	0.1	6.
10	694.245	679.293	777.446	654.064	0.1	3.
11	694.256	679.309	777.498	654.084	0.0	1.
12	694.260	679.316	777.522	654.094	0.0	1.

* Fifteen iterations to reach accuracy of 0.01 psi and 0.1 gpm.

Table 2

Calculated Heads at Selected Nodes, Iteration by Iteration, for Example 1; Estimated Pipe Flow 10 cfs in All Pipes; No Overrelaxation

Iter. No.*	Node 33	Node 41	Node 103	Node 135	Max. Pressure Corr.	Max. Flow Imbalance
1	683.281	664.121	676.911	667.831	74.0	8171.
2	687.885	663.245	734.528	700.122	43.9	1300.
3	691.051	673.653	763.188	695.030	14.6	602.
4	692.772	676.986	772.025	678.167	7.3	280.
5	693.579	678.303	775.232	666.422	5.1	130.
6	693.950	678.865	776.528	660.051	2.8	60.
7	694.120	679.114	777.086	656.900	1.4	27.
8	694.198	679.227	777.335	655.402	0.6	13.
9	694.234	679.278	777.447	654.703	0.3	6.
10	694.251	679.302	777.499	654.379	0.1	3.
11	694.258	679.313	777.522	654.229	0.1	1.
12	694.262	679.318	777.533	654.160	0.0	1.

* Fifteen iterations to reach accuracy of 0.01 psi and 0.1 gpm.

Table 3

Calculated Heads at Selected Nodes, Iteration by Iteration, for Example 1; Estimated Pipe Flow 1 cfs in All Pipes; With Overrelaxation after 2nd Iteration

Iter. No.*	Node 33	Node 41	Node 103	Node 135	Max. Pressure Corr.	Max. Flow Imbalance
1	672.446	639.892	621.281	542.827	71.2	8191.
2	683.895	656.576	692.426	594.504	46.8	1452.
3	694.301	683.766	796.935	674.928	25.7	924.
4	694.981	679.286	778.719	655.403	4.6	384.
5	693.981	679.367	777.705	654.136	0.4	183.
6	694.338	679.346	777.512	654.120	0.2	147.
7	694.260	679.329	777.547	654.107	0.1	2.
8	694.265	679.322	777.542	654.102	0.0	0.

* Eight iterations to reach accuracy of 0.01 psi and 0.1 gpm.

Table 4

Example as in Table 1 but Without Pumps

Iter. No.*	Node 33	Node 41	Node 103	Node 135	Max. Pressure Corr.	Max. Flow Imbalance
1	704.158	696.205	692.594	614.675	118.7	977.
2	700.191	690.395	683.292	584.111	13.2	633.
3	697.427	686.480	677.272	565.549	8.0	343.
4	695.870	684.313	674.006	555.796	4.2	170.
5	695.084	683.226	672.382	551.021	2.1	81.
6	694.707	682.705	671.607	548.760	1.0	38.
7	694.530	682.461	671.245	547.706	0.5	18.
8	694.447	682.348	671.077	547.219	0.2	8.
9	694.410	682.296	671.000	546.994	0.1	4.
10	694.392	682.272	670.964	546.890	0.0	2.
11	694.384	682.261	670.947	546.842	.0	1.
12	694.380	682.256	670.940	546.820	.0	0.

* Fourteen iterations to reach accuracy of 0.01 psi and 0.1 gpm.

Table 5 shows the complete computer output from the program for the example including the pumps (E.G.L. = energy grade line).

50. A small second example is provided in order to illustrate the behavior of PRV's during the iterative scheme. The system is shown in Figure 4. It consists of 14 nodes including 2 reservoirs, 12 pipes, and 3 PRV's which protect an area of 5 nodes from high pressures.

51. The heads at the upstream and downstream side of each PRV are listed iteration by iteration in Table 6. The initial flow rate in all pipes is set to 1 cfs. No overrelaxation is permitted.

Table 5

System Data for Balanced System, Example 1

NODE DATA

NODE NO.	ELEV. FT.	OUTPUT GPM	E.G.L. FT.	PR.HEAD FT.	PRESSURE PSI	
1	500.0	-1758.	500.0			RESERVOIR
2	450.0		482.4	32.4	14.0	
3	710.0	-3042.	710.0			RESERVOIR
11	550.0	100.	713.7	163.7	70.9	
12	560.0	150.	698.3	138.3	59.9	
13	565.0	150.	697.2	132.2	57.3	
21	550.0	150.	694.8	144.8	62.7	
22	570.0	200.	693.9	123.9	53.7	
23	570.0	200.	694.4	124.4	53.9	
24	550.0	150.	701.2	151.2	65.5	
31	550.0	150.	689.1	139.1	60.3	
32	565.0	200.	691.7	126.7	54.9	
33	560.0	200.	694.3	134.3	58.2	
34	550.0	150.	707.2	157.2	68.1	
41	550.0	150.	679.3	129.3	56.0	
42	545.0	150.	688.2	143.2	62.0	
43	540.0	150.	692.0	152.0	65.9	
44	530.0	100.	698.4	168.4	72.9	
51	550.0		794.6	244.6	106.0	
53	550.0		793.6	243.6	105.6	
101	625.0	100.	783.7	158.7	68.8	
102	620.0	150.	777.5	157.5	68.2	
103	615.0	150.	777.5	162.5	70.4	
104	610.0	100.	769.7	159.7	69.2	
111	620.0	100.	768.6	148.6	64.4	
112	625.0	150.	765.3	140.3	60.8	
113	625.0	200.	756.3	131.3	56.9	
114	620.0	150.	753.3	133.3	57.7	
123	600.0	100.	728.7	128.7	55.8	
124	600.0	100.	721.9	121.9	52.8	
134	580.0	150.	695.2	115.2	49.9	
135	550.	1000.	654.1	104.1	45.1	

PIPE DATA

PIPE NO.	NODES FROM	TO	DIAM. IN.	LENGTH FT.	COEF	FLOW GPM	VEL. FT/SEC	HEAD LOSS
1	1	2	15.0	5280.0	110.	1758.	3.2	17.6
2	2	11	PUMP HEAD	231.3	FT	1758.	POWER	103. HP
3	3	34	15.0	300.0	110.	3042.	5.5	2.8
4	41	51	PUMP HEAD	115.3	FT	1097.	POWER	32. HP
5	43	53	PUMP HEAD	101.7	FT	1353.	POWER	35. HP
11	11	12	10.0	2640.	100.	744.	3.0	15.4
12	12	13	10.0	2640.0	100.	178.	.7	1.1
13	24	13	10.0	3735.0	100.	298.	1.2	4.0
21	21	32	10.0	3735.0	110.	286.	1.2	3.1
22	23	22	8.0	2640.0	110.	70.	.4	.5
31	32	31	10.0	2640.0	110.	312.	1.3	2.6
32	33	32	10.0	2640.0	110.	311.	1.3	2.6
33	34	33	10.0	2640.0	110.	746.	3.0	13.0
41	42	41	10.0	2640.0	110.	606.	2.5	8.8
42	43	42	10.0	2640.0	110.	386.	1.6	3.8
43	44	43	10.0	2640.0	110.	508.	2.1	6.4
44	34	43	12.0	3735.0	110.	1090.	3.1	15.2
51	101	102	10.0	2640.0	115.	525.	2.1	6.2
52	103	102	10.0	2640.0	115.	44.	.2	.1
53	103	104	10.0	2640.0	115.	593.	2.4	7.8
61	111	112	10.0	2640.0	115.	371.	1.5	3.3
62	112	113	10.0	2640.0	115.	641.	2.6	9.0
63	113	114	10.0	2640.0	115.	355.	1.5	3.0
73	123	124	10.0	2640.0	115.	551.	2.3	6.8
84	134	135	10.0	5280.0	115.	1000.	4.1	41.1
111	11	21	10.0	2640.0	110.	914.	3.7	18.9
112	12	22	10.0	2640.0	110.	416.	1.7	4.4
113	13	23	10.0	2640.0	110.	327.	1.3	2.8
121	21	31	10.0	2640.0	110.	478.	2.0	5.7
122	22	32	10.0	2640.0	110.	286.	1.2	2.2
123	23	33	10.0	2640.0	110.	57.	.2	.1
124	34	24	10.0	2640.0	100.	448.	1.8	3.0
131	31	41	10.0	2640.0	110.	641.	2.6	9.8
132	32	42	10.0	2640.0	110.	370.	1.5	3.5
133	33	43	10.0	2640.0	110.	292.	1.2	2.3
134	34	44	10.0	2640.0	110.	608.	2.5	8.9
141	51	101	12.0	2640.0	110.	1097.	3.1	10.9
143	53	103	12.0	2640.0	110.	1353.	3.8	16.1
151	101	111	8.0	2640.0	115.	471.	3.0	15.1
152	102	112	8.0	2640.0	115.	419.	2.7	12.2
153	103	113	8.0	2640.0	115.	566.	3.6	21.3
154	104	114	8.0	2640.0	115.	493.	3.1	16.5
163	113	123	8.0	2640.0	115.	651.	4.2	27.6
164	114	124	8.0	2640.0	115.	699.	4.5	31.4
174	124	134	10.0	2640.0	115.	1150.	4.7	26.6

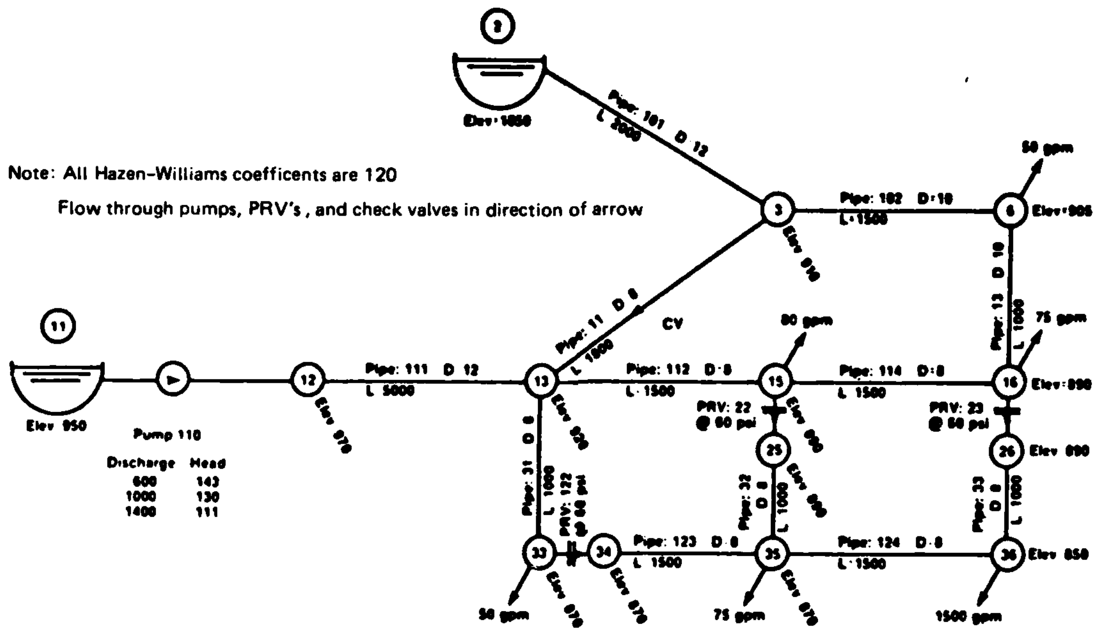

Figure 4. Example 2 pipe network

Table 6

Calculated Heads at Selected Nodes, Iteration by Iteration, for Example 2; Estimated Pipe Flow 1 cfs in All Pipes; No Overrelaxation

Iter. No.*	Node 15	Node 25	Node 16	Node 26	Node 33	Node 34
1	1010.25	1010.25	1019.91	1019.91	1006.35	1006.35
2	1030.43	1030.43	1029.27	1029.27	1042.48	1023.23
3	1035.18	1028.48	1034.58	1028.48	1049.87	1020.58
4	1037.89	1028.48	1036.45	1028.48	1059.07	1020.05
5	1037.88	1028.48	1035.90	1028.48	1062.79	1019.79
6	1037.33	1028.48	1035.11	1028.48	1064.25	1019.67
7	1036.83	1028.48	1034.51	1028.48	1064.80	1019.62
8	1036.49	1028.48	1034.12	1028.48	1065.00	1019.59
9	1036.28	1028.48	1033.89	1028.48	1065.06	1019.58
10	1036.16	1028.48	1033.77	1028.48	1065.08	1019.57
11	1036.09	1028.48	1033.70	1028.48	1065.08	1019.57
12	1036.06	1028.48	1033.66	1028.48	1065.08	1019.57

* Six iterations to reach an accuracy of 1 psi.
Sixteen iterations to reach accuracy of 0.01 psi and 0.1 gpm.

52. Table 7 shows the complete system data for Example 2. Pressure reducing valve 122 is closed because the downstream pressure at node 34 (64.8 psi) exceeds the pressure setting (60 psi). As a consequence, the flow in pipe 123 is zero. In Table 6 one can see how the pressure at node 34 finds its own level even though the node is downstream of a PRV.

Table 7

System Data for Example 2

NODE DATA

NODE NO.	ELEV. FT.	OUTPUT GPM	E.G.L. FT.	PR.HEAD FT.	PRESSURE PSI	
2	1050.0	-830.	1050.0			RESERVOIR
3	910.0		1045.8	135.8	58.8	
6	905.0	50.	1038.2	133.2	57.7	
11	950.0	-1000.	950.0			RESERVOIR
12	970.0		1080.0	110.0	47.7	
13	920.0		1065.2	145.2	62.9	
15	890.0	80.	1036.0	146.0	63.3	
16	890.0	75.	1033.6	143.6	62.2	
25	890.0		1028.5	138.5	60.0	
26	890.0		1028.5	138.5	60.0	
33	870.0	50.	1065.1	195.1	84.5	
34	870.0		1019.6	149.6	64.8	
35	870.0	75.	1019.6	149.6	64.8	
36	850.0	1500.	1009.0	159.0	68.9	

PIPE DATA

PIPE NO.	NODES FROM	TO	DIAM. IN.	LENGTH FT.	COEF	FLOW GPM	VEL. FT/SEC	HEAD LOSS
11	3	13	CHECK VALVE			CLOSED		
13	6	16	10.0	1000.0	120.	780.	3.2	4.5
22	15	25	PRV AT	60.0 PSI		ACTIVE		
23	16	26	PRV AT	60.0 PSI		ACTIVE		
31	13	33	8.0	1000.0	120.	50.	.3	.1
32	25	35	8.0	1000.0	120.	624.	4.0	8.9
33	26	36	8.0	1000.0	120.	951.	6.1	19.5
101	2	3	12.0	2000.0	120.	830.	2.4	4.2
102	3	6	10.0	1500.0	120.	830.	3.4	7.6
110	11	12	PUMP HEAD	130.0 FT		1000.	POWER	33. HP
111	12	13	12.0	5000.0	120.	1000.	2.8	14.8
112	13	15	8.0	1500.0	120.	950.	6.1	29.1
114	15	16	8.0	1500.0	120.	247.	1.6	2.4
122	33	34	PRV AT	60.0 PSI		CLOSED		
123	35	34	8.0	1500.0	120.	0.	.0	.0
124	35	36	8.0	1500.0	120.	549.	3.5	10.5

PART III: OPTIMIZATION USING DISCRETE METHOD

53. In this part, the enumeration technique used to select the optimal solution is presented. First, the selection of an enumeration technique is justified, then some methods to reduce the number of times the network needs to be balanced are presented. The algorithm is then described.

54. One advantage of the algorithm is that it not only selects the optimal solution but also presents other solutions which are almost as good as the optimal solution and may be selected for other reasons. Pipe rehabilitation, described next, is an alternative to new pipes and may be considered by the program, as well as pumping energy cost. The data required for optimization are then described followed by an example.

Reasons for an Enumeration Algorithm

55. The optimization of pipe networks is complicated by several practical considerations that make it very difficult to apply standard optimization techniques without contorting the problem to fit the technique. These are discussed below.

56. The discrete character of the variables to be selected (i.e. pipe sizes with their associated cost) makes the use of standard optimization procedures difficult. Such procedures typically assume that the variables to be selected are continuous. Of particular concern in connection with treating the pipe sizes as continuous variables is the fact that the discrete cost function may be quite erratic and difficult to approximate by a continuous function. In addition to these difficulties, some optimization procedures (Lai and Schaake 1969; Quindry, Brill, and Liebman 1981) require that the cost function have some specific characteristics (i.e. cost per unit length had to be proportional to the diameter to the power 2.63). Appendix D shows that for two parallel pipes to be sized, a solution with a single pipe is less expensive if this power is less than 2.63, and that a solution with two equally sized pipes is less expensive if the power is larger than 2.63. An algorithm for the optimization of looped pipe networks which requires a power of 2.63 for diameter in the diameter versus cost relationship cannot provide a meaningful answer.

57. Most of the optimization procedures proposed so far are essentially

gradient search techniques, some in a continuous variable space, some in a discrete space. Such algorithms can only guarantee local minima. Gessler (1982) has shown that such a simple problem as the sizing of the New York City water supply tunnels (a problem with two loops) has two minima which differ from each other in cost by more than 10 percent.

58. Finally, a solution developed in a continuous space requires an additional step after the execution of the optimization algorithm, in which the pipe sizes are "rounded" to commercially available pipe sizes. This step is not trivial. Indeed, it is possible that the globally optimal, discrete solution may not even be in the neighborhood of the globally optimal solution using continuous pipe sizes, but could be associated with a local minimum. An exhaustive search among the discrete solutions in the neighborhood of the global minimum of the continuous solution does not guarantee the globally optimal solution in discrete space.

59. If the transition from a continuous solution to a discrete solution poses such significant difficulties, it is then quite logical to explore the feasibility to work in the discrete space from the very beginning. Optimization by exhaustive enumeration of all possible size combinations within user-specified constraints overcomes several shortcomings of the traditional optimization procedures. Most important it guarantees the globally optimal solution in the discrete domain of pipe sizes. There are no requirements associated with the discrete cost function. It is also relatively easy to account for pumping cost as part of the optimization, or to consider cleaning of old pipes as an alternative to the addition of new pipes. The inclusion of multiple loading patterns is possible as well, a point which addresses the problem of system redundancy. Finally, the exhaustive enumeration can be used for the generation of a queue of Pareto optimal solutions (noninferior) which are described later. Such a queue is most valuable in the decisionmaking process since pressure constraints and water demands are in many cases somewhat arbitrary.

60. The most important drawback of an algorithm based on exhaustive enumeration may be the computer time required to find the optimum. In its most general formulation such a procedure is NP-hard (i.e., the computer time required to find the optimum solution increases exponentially with system size). This observation deserves two comments.

61. First, if a problem is formulated in the most general format (i.e.

sizing every pipe individually), exhaustive enumeration would have to be limited to "relatively small" systems. Since many optimization problems are in fact, topologically speaking, small, this in itself does not rule out the usefulness of the procedure.

62. Second, the most general formulation may indeed not even be desirable. In the most general formulation each leg of pipe is sized individually. Such an approach may well lead to very arbitrary size selection, dictated to a large degree by specific loading patterns, and the peculiarities of the cost function. The optimized system may in the end no longer show a clear conveyance concept. (Conveyance concept refers to the overall flow pattern from the source to the users, e.g. most of the flow is carried in pipe along Walnut St. while pipe along Cherry St. merely closes the loop.) From an operational point of view such a clear concept is an important requirement. By combining several pipes to be sized into one group of pipes, with the ultimate goal that all pipes in the same group be assigned the same size, the optimization can be forced to provide a simple and easy to understand conveyance concept.

63. If the number of pipes can be limited say to less than 10 in real sizing problems, independent of total system size, and if the number of candidate sizes for each group can be limited to say less than 6, the problem is no longer NP-hard. Computer time now increases only with system size (number of nodes) to a power somewhat smaller than two if a sparse matrix technique is used in the computation of the pressure distributions.

Reducing the Number of Candidate Solutions

64. As mentioned in the previous paragraph, the only major potential drawback of an enumeration algorithm is computer time. In order to minimize the number of size combinations for which the pressure distribution is to be calculated, four techniques are employed: grouping pipes, test on size range, cost test, and size test.

Grouping pipes

65. Pipe diameters do not change at every block in a distribution system. For example, one does not find a 12-in. pipe from First St. to Second St., a 6-in. pipe from Second St. to Third St., etc. In WADISO, it is possible to combine links in the model into a single group. For example, treating the pipe from First St. to Tenth St. as a single pipe (called a "group" in WADISO)

instead of as nine pipes greatly reduces the number of combinations of solutions.

Test on size range

66. The number of combinations to be tested is equal to the product of the number of sizes in each group. It is therefore appropriate to establish the fact that the smallest pipe size specified for each group can meet the pressure requirement when combined with the maximum pipe sizes in all other groups. If the smallest size in a group fails this test, that size in the group is eliminated, the number of sizes in the group is reduced by one, and the second smallest size is tested.

Cost test

67. After a size combination is found which meets all pressure requirements (this will be called a "functional size combination"), there is no need to compute the pressure distribution for any other system which is more expensive than the least expensive functional size combination. It is beneficial to have a routine in front of the enumeration routine which has the purpose to find a relatively inexpensive functional size combination. This routine should be fast and there is no need for this solution to be "near optimal." Of course, the less expensive this first size combination, the more effective it is in reducing the number of combinations which need additional testing.

Size test

68. If a certain pipe size combination does not meet the pressure requirements, no pipe size combination will meet the pressure requirements which has all sizes equal to or less than the pipe sizes of this combination. In order to execute the size test, the program maintains a queue of nonfunctional pipe size combinations. If a pipe size combination passes the cost test, it will enter the size test, in which the present combination is compared with previous combinations which have failed the pressure requirement. If the queue of nonfunctional combinations reaches a certain length, this test will require more time than the cost test. Indeed, if the queue gets too long, the program may spend more time performing this test than it would require to compute the pressure distribution in the first place. Therefore, the maximum length of this queue should be limited.

69. If a pipe size combination has passed all four of the tests described above, the pressure distribution is computed. In the pressure test the pressure distribution is calculated for all loading patterns. In order

for the combination to pass the pressure test, a combination must meet the pressure requirements of all loading patterns. It is permissible for each loading pattern to have its own required minimum pressures which may vary from node to node.

Enumeration Algorithm

70. The tests described above can be combined into an enumeration algorithm as shown in Figure 5. The grouping of pipes is done by the user.

71. The first part of the algorithm performs the test on size ranges, and selects a relatively inexpensive solution. If in the course of this search a nonfunctional solution is encountered, it is entered into the queue of nonfunctional solutions. The last task in this first part of the algorithm is to initialize the queue of nonfunctional solutions.

72. The second part of the algorithm enumerates all size combinations.

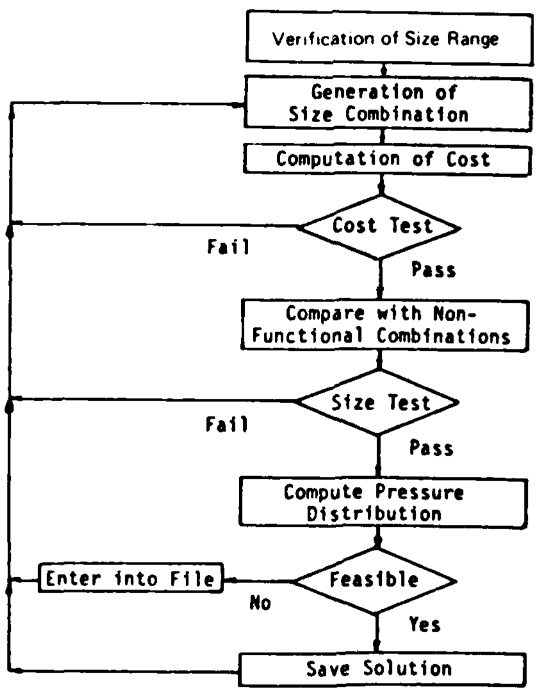

Figure 5. Enumeration algorithm

For each combination the total cost (excluding energy to overcome friction which is not known until the system is balanced) is calculated. If such cost is higher than the cost of the so far best functional combination, i.e. if the combination fails in the cost test, the combination is discarded. If the combination passes the cost test, the combination is compared with previously generated combinations which did not meet the pressure requirement. If a combination is found in the queue of nonfunctional solutions which has all sizes larger or equal to the sizes in the combination presently being tested (i.e. if the combination fails the size test), the combination is discarded. If the combination passes the size test, the pressure distribution is calculated for one loading pattern at a time. If the combination does not meet the pressure requirement of a loading pattern, the combination is entered into the queue of nonfunctional solutions, and the algorithm proceeds with the next combination. If the combination meets the pressure requirements for all loading patterns, it becomes the least expensive functional combination.

73. The node method employed in the computation of the pressure distribution makes it easy to test the effects of elimination of pipes. To accomplish this, the list of candidate pipe sizes for a group includes a diameter of zero at zero cost.

Pareto optimal solutions

74. In a slight variation of the algorithm as described above the cost test and the pressure test can be somewhat relaxed to yield a set of good solutions. A solution can belong to this set if it has the property of being Pareto optimal (noninferior). This means that there must not be another combination which can produce greater pressure at less cost. This concept is shown in more detail in Appendix F, Table F4 and Figure F3.

75. Using this concept, functional combination is allowed to pass the cost test even if its cost is higher than the cost of the previous best solution, but remains within a certain tolerance (expressed as a percentage) from the cost of this best solution. The idea is to look for size combinations for which no solution offering a higher minimum pressure is less costly. Such a combination is said to be Pareto optimal. If the combination is indeed Pareto optimal, it is compared with a queue of previously found Pareto optimal combinations. If appropriate, the combination is entered into the queue, and if the combination makes other entries in this queue inferior, they are eliminated from the queue.

76. A functional combination may also be allowed to pass the pressure test even if the minimum pressure is less than the required pressure, but within a certain pressure tolerance from the pressure requirement. This enables solutions which barely fail the pressure test to be included in the Pareto optimal set even though they will not be the globally optimal solution.

77. The fact that a solution is slightly more expensive may not automatically exclude it from consideration. It is possible that minor additional expenditures may result in significantly better system performance. Considering the fact that the pipe network is designed for a projected (estimated) water output, a pressure slightly below the specified requirement does not necessarily imply that the combination of pipe sizes is unacceptable. The queue of Pareto optimal solutions is helpful because of the uncertainties associated with the planning goals.

78. It is important to understand that the larger the allowable cost and pressure margins, the more combinations will meet the pressure test. This in turn increases computer time requirements.

Pipe cleaning as an alternative to adding new pipes

79. If an existing system can no longer meet the pressure requirements for a present or projected water demand, one option for reinforcing the system is to add new pipes. If the existing system includes rough pipes (i.e. low Hazen-Williams coefficients), however, it may be more economical to clean the old pipes or clean some of the old pipes and add some new pipes. The enumeration algorithm can easily handle the evaluation of these alternatives. In order to simplify the program's internal bookkeeping when testing the cleaning option, the program does not eliminate the new pipe and change the Hazen-Williams coefficient of the old pipe. Rather it assigns to the new pipe a diameter such that the old pipe and the new pipe combined have the same conveyance capacity as the cleaned old pipe alone.

Including pumping cost into the optimization

80. As a result of the computation of the pressure distribution, the flow rates through the pump and the pump head are obtained. This permits the computation of pumping cost if the percentage of time the pump is running at this operating point is specified. It is again possible to specify several loading patterns, each with its own percentage of time. The program

will then calculate and accumulate the pumping cost and add it to the pipe cost.

81. Pumping energy cost can be divided into lift energy and friction energy. For the purpose of the program, lift energy is the pumping energy required when the largest pipe sizes in each group are used. As smaller pipe sizes are used, energy to overcome friction increases. This extra friction energy is not included in the cost test described earlier because it is not known until the pressures are balanced. This total energy cost is used for final comparisons. In most water systems, this extra friction energy is small compared with other costs. Pumping cost is discussed in more detail in Part IV.

Data Required for Optimization

82. For a detailed discussion of the data required to run the optimization program the reader is referred to the User's Manual (Appendix A). Only the general aspects of data requirements are discussed below.

83. Pipes to be sized must be identified. This is done in the WADISO program by assigning them to a group. All pipes within one group are assigned the same diameter. These assignments allow the user to control the nature of the final solution. Using groups the computer time involved in optimizing the system is reduced. However, two pipes in the same group could be assigned the same diameter even though some savings may result from using two different diameters.

84. For each group a list of candidate pipe sizes must be assigned. The list can be different for different groups. The list for a group does not need to include all pipe sizes available. The user can specify that elimination of pipes in a group is permissible, and/or that cleaning of an existing parallel pipe should be considered. Size selection again allows the user to exercise some control over the nature of the solution. Careful selection of sizes will also minimize computer time.

85. The user specifies one or several loading patterns by specifying the water used (outputs) and the required minimum pressure at one, several, or all nodes. Careful selection of multiple loading patterns will help in establishing redundancy. If pumps are present for which the present worth of pumping cost must be considered, the efficiency and the percent of time the pump is

running under each loading pattern must be entered for energy cost calculations.

86. If cleaning is an alternative to be considered, the Hazen-Williams coefficient of the cleaned pipe needs to be specified. In order to generate a queue of Pareto optimal pipe size combinations, the pressure and cost tolerance need to be entered.

Examples

Example 3

87. The purpose of this example is to illustrate pipe size selection for multiple loading patterns and the queue of Pareto optimal size combinations. The system layout is shown in Figure 6. The grouping of pipes and the candidate pipe sizes for each group are shown in Table 8. Note that the pipe in group 7 has been assigned only one pipe size. This forces the program to include the cost of this pipe in the total cost computation. Of course, in the optimal solution this single size will be assigned to group 7 (pipe 131). The minimum pipe sizes in the range of 6 through 10 in. make sure no group is

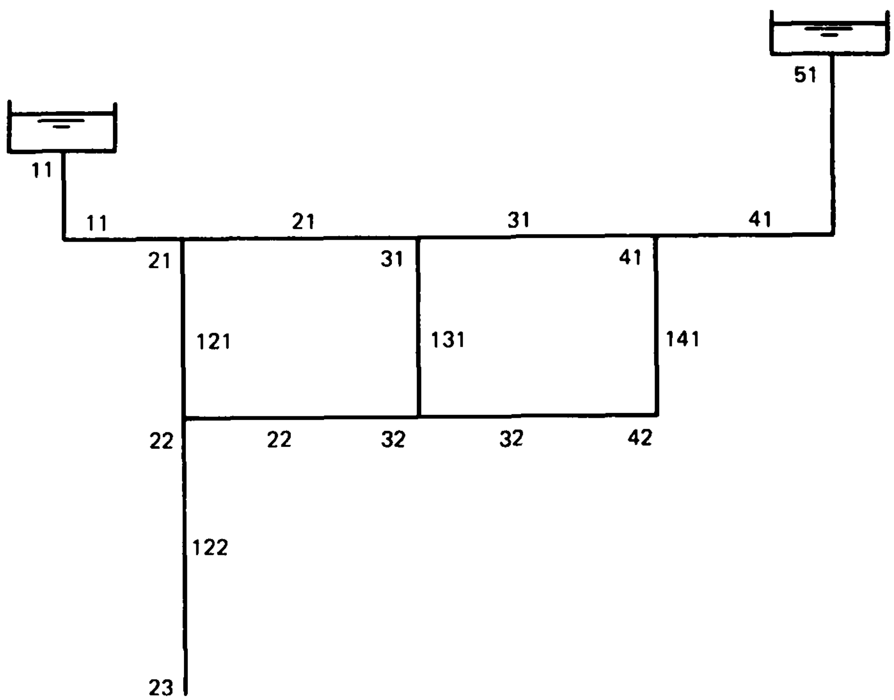

Figure 6. Example 3 pipe network

Table 8

Grouping of Pipes

Group No.	Pipes Included In Group	Candidate Pipe Sizes, in.
1	11	8 10 12 14 16
2	41	8 10 12 14
3	21 31	6 8
4	32 141	6 8 10
5	22 121	8 10 12
6	122	10 12 14
7	131	8

eliminated. The user could have specified that a group could be eliminated.

88. Though the program permits the user to assign different cost functions to each pipe, in this example all pipes are assigned to a single cost function. The costs used are listed in Table 9.

Table 9

Pipe Size and Cost

	Pipe Size, in.						
	6	8	10	12	14	16	18
Cost (in dollars per foot)	15.1	19.3	28.9	40.5	52.1	59.4	68.6

89. The pressure requirement must be met for four different loading patterns. Pattern 1 represents a normal load under which the pressure must be at least 40 psi throughout the system. In patterns 2 through 4 a fire flow of 1,000 gpm is added in turns to nodes 23, 32, and 42, respectively. In these cases, a pressure of at least 20 psi must be maintained throughout the system.

90. In a first run the program was instructed not to generate a queue of Pareto optimal size combinations.

91. There are 1,080 size combinations for the candidate sizes as listed in Table 8. But the 6-in. size in group 4 and the 10-in. size in group 6 are eliminated in the size range test, leaving only 480 combinations to be tested. Since there are four loading patterns, the optimization may consider as many as 4 * 480 = 1,920 pressure distributions. Yet the program actually calculated the pressure distribution only 98 times because of the cost and size test. This constitutes about 5 percent of all distributions.

92. The optimal size combination is:

Group No.	1	2	3	4	5	6	7
Size, in.	14	10	6	8	10	12	8

at a cost of $1,203,588 and a minimum pressure of 21.1 psi in loading pattern 4.

93. In a second run, the program was requested to generate a queue of Pareto optimal combinations by considering combinations which are as much as 5 percent more expensive than the best combination, and those with pressures as much as 3 psi below the required minimum. Now it becomes necessary to calculate 317 pressure distributions. The queue of Pareto optimal solutions is given in Table 10. Observe that by giving up 1.2 psi at the location of the fire flow, about 2.5 percent of the tctal cost can be saved. Conversely, by investing an extra 1.6 percent, the minimum pressure can be raised to 2.3 psi above the requirement.

Table 10

Queue of Pareto Optimal Solutions

Solution	Group No. 1	2	3	4	5	6	7	Minimum Pressure psi	Cost
1	12	10	6	10	10	12	8	24.3	1,257,252
2	12	12	6	8	10	12	8	23.6	1,234,212
3	16	10	6	8	10	12	8	22.3	1,222,860
4	14	10	6	8	10	12	8	21.1	1,203,588
5	12	10	6	8	10	12	8	18.8	1,172,964

94. Input data and final size combination for the critical loading pattern are shown in Table 11.

Example 4

95. The next example illustrates elimination of pipes and cleaning of old pipes which run parallel to new pipes to be sized. The system layout is given in Figure 7. Pipe grouping and candidate pipe sizes are listed in Table 12. Cleaning of old pipe 11 instead of adding the new pipe 211 appears attractive because pipe 11 has a Hazen-Williams coefficient of 70. The coefficient of the other four old pipes is 110 and cleaning will therefore not

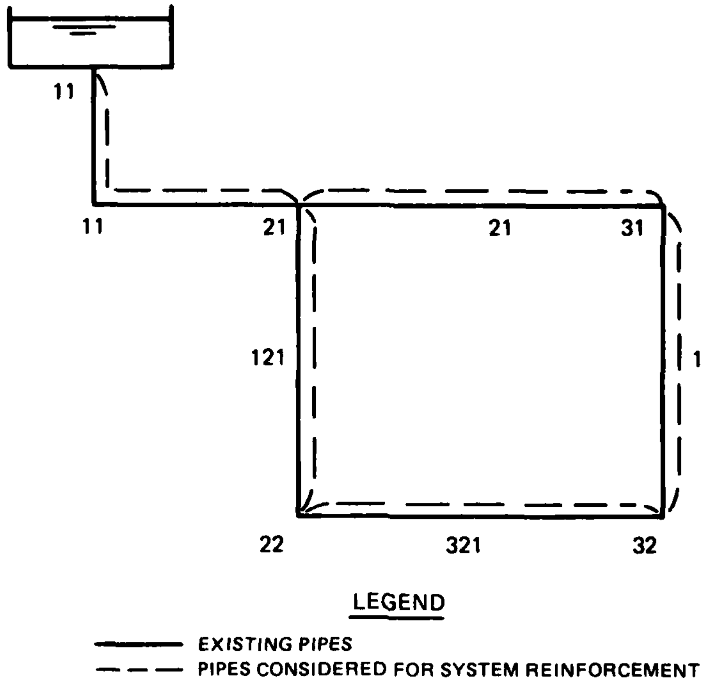

Figure 7. Example 4 pipe network

result in significant improvements. The cost of new pipes is assumed to be the same as in the previous example (see Table 9). Cleaning costs are listed in Table 13 and the C-factor for pipe 11 is 120 after cleaning.

96. Pressure and cost tolerances for generation of the Pareto optimal solutions are set at 3 psi and 5 percent, respectively. Besides the optimal solution there is only one combination listed in the queue. The two combinations are listed in Table 14. The final pipe size selection together with the input data are listed in Table 15.

Table 11

System Data for Example 3

NODE DATA

NODE NO.	ELEV. FT.	OUTPUT GPM	E.G.L. FT.	PR.HEAD FT.	PRESSURE PSI	
11	900.0	-1439.	900.0			RESERVOIR
21	780.0	500	889.8	109.8	47.6	
22	770.0	150.	867.8	97.8	42.4	
23	750.0	250.	865.7	115.7	50.1	
31	785.0		867.5	82.5	35.7	
32	770.0	150.	859.1	89.1	38.6	
41	790.0	100.	875.2	85.2	36.9	
42	770.0	1200.	818.4	48.4	21.0	
51	920.0	-911.	920.0			RESERVOIR

PIPE DATA

PIPE NO.	NODES FROM	TO	DIAM. IN.	LENGTH FT.	COEF	FLOW GPM	VEL. FT/SEC	HEAD LOSS
11	11	21	14.0	2640.0	100	1439.	3.0	10.2
12	21	31	6.0	5280.0	100.	163.	1.9	22.4
22	22	32	10.0	5280.0	100.	376.	1.5	8.7
31	41	31	6.0	5280.0	100.	92.	1.0	7.7
32	32	42	8.0	5280.0	100.	481.	3.1	40.7
41	51	41	10.0	5280.0	100.	911.	3.7	44.8
121	21	22	10.0	3500.0	100.	776.	3.2	22.1
122	22	23	12.0	6500.0	100.	250.	.7	2.1
131	31	32	8.0	3500.0	100.	255.	1.6	8.4
141	41	42	8.0	3500.0	100.	719.	4.6	56.8

Table 12

Grouping of Pipes

Group No.	Pipe No.	Candidate Pipe Sizes*				
1	211	8	10	12	C	E
2	221	8	10	12	E	
3	222	8	10	12	E	
4	321	8	10	12	E	
5	331	8	10	12	E	

* C = clean, E = eliminate.

Table 13

Pipe Size and Cleaning Cost

	Pipe Size, in.						
	6	8	10	12	14	16	18
Cost (in dollars per foot)	14.5	15.7	16.8	17.7	18.5	19.2	20.0

Table 14

Queue of Pareto Optimal Solutions

	Group No.					Minimum	
Solution	1	2	3	4	5	Pressure psi	Cost
1	C	E	E	10	E	40.1	355,344
2	C	E	E	8	E	39.3	304,656

Table 15

System Data for Example 4

NODE DATA

NODE NO.	ELEV. FT.	OUTPUT GPM	E.G.L. FT.	PR.HEAD FT.	PRESSURE PSI	
11	900.0	-2500.	900.0			RESERVOIR
21	760.0	250	857.9	97.9	42.4	
22	750.0	750.	845.8	95.8	41.5	
31	750.0	500.	842.5	92.5	40.1	
32	740.0	1000.	838.9	98.9	42.9	

PIPE DATA

PIPE NO.	NODES FROM	TO	DIAM. IN.	LENGTH FT.	COEF	FLOW GPM	VEL. FT/SEC	HEAD LOSS
11	11	21	16.0	10560.0	120	2500.	4.0	42.1
21	21	31	12.0	5280.0	110.	911.	2.6	15.5
22	22	32	12.0	5280.0	110.	589.	1.7	6.9
121	21	22	12.0	5280.0	110.	799.	2.3	12.1
131	31	32	12.0	5280.0	110.	411.	1.2	3.5
321	21	22	10.0	5280.0	100.	540.	2.2	12.1

PART IV: COST DATA FOR NETWORK OPTIMIZATION

Introduction

97. The results of any optimization method are only as meaningful and accurate as the cost data used. Ideally, for any application of a network optimization model, the user should determine a relationship between the cost of each pipe segment and the diameter of that segment. Each of these relationships will depend on a wide variety of factors such as pipe material and depth of excavation.

98. The engineer attempting to optimally size a network must accurately estimate the cost of pipes yet cannot afford to spend a great deal of effort developing the estimates. The effort required to generate the required cost data can be fairly large and sometimes not justifiable in a planning study. Cost functions for pipe installation are available in the literature, but these data are often site specific and the assumptions made in developing the functions are not well documented.

99. The purpose of this part is to present data for determining the cost of water main installation, and cleaning and lining of water mains, and to discuss how pumping energy cost can be included in network optimization. Cost data are presented to assist those using the model. The data represent typical costs for projects under typical conditions. Users must realize that there can be considerable variation from these costs due to site-specific conditions. In running the program to select optimal pipe sizes, the user should enter cost data based on local site-specific information or, at a minimum, verify the applicability of data presented in this report before using the program.

100. The WADISO program requires that cost data for a given pipe be entered as a function of diameter. Some of the other factors in addition to diameter that affect cost include type of cover, amount of rock excavation, amount of dewatering, depth of pipe, land use, pipe material, pressure class, number of service connections and hydrant laterals, interference with other buried utilities, and overall size of the project, to name just a few. Therefore, it is highly unlikely that the same cost function will be applicable for all pipes studied in the system. The program can store up to 12 different cost functions for pipe installation and pipe cleaning and lining. Users are

encouraged to take advantage of this feature of the program and specify several cost functions to arrive at a good solution. The default cost data are included in the program to assist those who want to learn how to use the program and do not want to take the time to generate their own cost data.

101. The costs presented in the following sections have been adjusted to an Engineering News Record (ENR) construction cost index of 4500. These values and any other cost data will need to be adjusted to local price levels before the program can be applied.

Pipe Cost Data

102. The most important entries in the optimization program are the pipe cost functions. Some default values are stored in the program but actual values will fluctuate widely about these "typical" values. Several other cost functions are also presented in this section to give the model user an appreciation for the variability in costs.

103. Costs are presented in Table 16 for pipe construction costs. All costs given are for total construction costs which include the pipe and installation. The following assumptions were made in developing Table 16: (a) the pressure rating of the pipe is 200 psi; (b) pipes are sufficiently long so that mobilization costs are small; (c) cathodic protection and surge protection are not included; (d) cost of hydrants, valves, and fittings must be added separately; (e) river crossings are not considered; and (f) right-of-way costs are not included. The columns in Table 16 are described individually below.

104. The costs given in the column labeled "Aver" were generated using the MAPS computer program (Headquarters, Army Corps of Engineers 1980). They correspond to polyvinyl chloride (PVC) pipe in diameters 12 in. and less, ductile iron pipe for diameters of 14 to 48 in., and prestressed concrete embedded cylinder pipe for diameters of 54 in. and larger. The pipe is laid in a rectangular trench with 5 ft of overburden and no rock excavation. Dewatering is not required and there is negligible interference with other buried utilities.

105. The costs given in the column titled "Rock" correspond to the costs given in the Aver column except that the excavation is primarily in rock.

Table 16

Typical Pipe Cost Data for ENR = 4500

Pipe No.	Pipe Diameter in.	Cost, $/ft Aver*	Rock*	Rural*	Urban*	Tunn*
1	2	6.29	12.0	2.30		
2	3	8.57	14.7	3.28		
3	4	10.8	17.4	5.50		
4	6	15.1	22.6	7.57	78.	
5	8	19.3	27.8	11.7	95.	
6	10	28.9	38.4	14.1	110.	
7	12	40.5	51.0	17.9	125.	
8	14	52.1	63.8	24.5	135.	
9	16	59.4	72.2	31.8	143.	
10	18	68.6	82.6	40.0	151.	
11	20	80.1	95.3		157.	
12	24	106.	128.		171.	
13	30	147.	176.		495.	
14	36	192.	228.		560.	
15	42	242.	285.		687.	
16	48	295.	247.			
17	54	331.	404.			
18	60	396.	485.			
19	66	477.	569.			
20	72	554.	662.			771.
21	78	642.	762.			845.
22	84	734.	870.			921.
23	96	941.	1,100.			1,073.
24	108	1,170.	1,370.			1,228.
25	120	1,420.	1,630.			1,387.

* See text for explanation of columns.

106. The costs given in the column labelled "Rural" are based primarily on data presented by Lindsey and Walski (1980). The costs are based on simple installation of PVC pipe in soil with no special bedding and no paving. Costs were verified against data presented by the National Park Service (1980) and Whitlach and Asplund (1981) and were in reasonable agreement.

107. The costs given in the column labelled "Urban" are based on data presented by Walski (1985) from earlier studies performed in Buffalo, N.Y., New York, N.Y., and Philadelphia, Pa. Costs correspond to relatively small projects in congested urban areas, with numerous service connections and hydrant laterals. Ductile iron pipe is used and significant repaving is involved with each project. These costs are most appropriate for replacing or paralleling existing lines.

108. The costs given in the column titled "Tunn" are based on tunnel cost data developed by Bennett (1981) and used in the MAPS computer program (Headquarters, Army Corps of Engineers 1980). The costs are for a circular moled tunnel with cast in-place linings through rock with an unconfined compressive strength of 10,000 psi, a rock quality designation of 70, and negligible seepage into the tunnel so that dewatering is not required. These conditions are good for tunneling and represent fairly low cost. Tunnel costs can fluctuate widely depending on lining, tunneling method, rock conditions, and seepage. The costs presented here do not include shafts, inlets, and outlets. In urban areas tunnels can often be competitive with cut-and-cover pipe laying in the larger diameters.

109. The costs presented above should give the reader an appreciation of the magnitude of costs for different size pipes and of the variation in costs even for a single size. The costs were verified against data presented by Dickson (1978). Data published by Dickson show, for example, that costs for a 24-in. pipe can vary from $46.8/ft to $128/ft for steel or concrete main, depending on the conditions.

110. The values stored in the "Aver" column correspond to the default values stored in the WADISO program.

<u>Cost of valves and fittings</u>

111. The cost data presented in Table 16 (except for the Urban column) correspond to straight runs of pipe with no valves, bends, crosses, or tees. These costs could be used directly for long, straight pipelines. However, for typical water main networks laid on a typical distribution grid pattern, the

extra cost of valves and fittings can be significant.

112. Table 17 gives cost for ductile iron valves, bends, and tees. The costs are based primarily on the Dodge Guide to Public Works and Heavy Construction Costs. Cost data are not presented for very large items (>48 in.) since cost data are not readily available.

113. There are several ways in which these costs can be included into the cost function given earlier. The simplest is to note that for a typical urban grid, two gate valves are placed every 1,000 ft, and there is one tee or cross every 1,000 ft. With this assumption, the costs of valves, crosses, and tees are roughly 10 percent of the pipe cost in the diameter range of 4 to 12 in. As the diameter increases beyond 12 in., the costs of valves and fittings increase disproportionately, but the distance between such devices also increases.

114. A more precise way to modify the unit cost of pipe is to use the following formula

$$\bar{C} = C + [N_v(C_v) + N_t(C_t)]/L \tag{14}$$

where

$\bar{C}$ = corrected unit cost of pipe, \$/ft

C = uncorrected cost of pipe, \$/ft

N_v = number of valves in a segment, 0

C_v = unit cost of a valve, \$

N_t = number of tees and crosses in a segment, 0

C_t = unit cost of a tee or cross, \$

L = length of segment, ft

Such calculations must be made for each diameter for each pipe segment.

115. The cost of tees and crosses can be handled in a similar way. The cost of tees given in Table 17 is based on all outlets being the same diameter (e.g. all 36-in. pipe). Such fittings often have different diameters in the runs and branches. To estimate the cost, the largest diameter should be used in Table 17, but this cost should be reduced by up to 25 percent if the branches are much larger than the runs (e.g. a 12 × 36 tee costs 78 percent of a 36 × 36 tee).

116. The cost of hydrants is independent of the diameter of the pipe. However, the tee or tap connecting the hydrant lateral to the main is slightly

Table 17

Cost of Valves and Fittings for ENR = 4500

Pipe Diameter in.	Cost, $/item Gate Valve	90-deg Bend	Tee
2	200.	95.	105.
3	283.	130.	153.
4	404.	168.	188.
6	530.	234.	262.
8	694.	262.	305.
10	996.	343.	428.
12	1,120.	389.	500.
14	1,280.	472.	611.
16	4,730.	661.	864.
18	6,180.	955.	1,230.
20	7,110.	1,260.	1,680.
24	10,600.	2,030.	2,770.
30	15,500.	3,220.	4,670.
36	26,700.	4,990.	7,180.
42	37,600.	7,090.	12,400.
48	49,700.	10,100.	17,600.

dependent on the main diameter. Air release valves, pressure relief valves, blowoffs, etc., are quite independent of the diameter of the main and can generally be ignored in network optimization. It may be desirable however to limit velocities to reduce the magnitude of transients.

Application of pipe cost data

117. The cost data entered to the program must include all capital costs associated with the pipe segment. Costs which are not dependent on diameter (e.g. right-of-way) can be omitted if the optimization is based only on capital costs. If energy costs are to be included and pipe rehabilitation by cleaning and lining is an alternative to new pipes, then total (rather than relative) costs are important and all costs must be included.

118. The total unit capital cost for pipe can be given by

$$TC = \left(\frac{ENR}{4500}\right)\bar{C} + K \tag{15}$$

where

TC = total unit capital cost of a pipe, \$/ft

ENR = ENR construction cost index corresponding to price level for study

$\bar{C}$ = unit pipe cost corrected for valves and fittings, \$/ft

K = costs which are independent of pipe diameter, \$/ft

119. Use of Equation 15 can be illustrated by an example. Suppose a 2,000-ft, 12-in. pipe is to be laid with two gate valves and one tee, at a time in which the ENR index is 4800. The right-of-way cost is \$5/ft.

120. Based on values in Tables 16 and 17, the cost of the pipe corrected for valves and fittings

$$\begin{aligned}\bar{C} &= 40.5 + [2(1120) + 1(500)]/2000 \\ &= 41.9\end{aligned}$$

This can then be corrected using

$$TC = \frac{4800}{4500}\left(41.9\right) + 5 = 49.7 \ \$/\text{ft}$$

Cleaning and Lining Cost

121. The cost of cleaning and cement mortar lining is highly influenced by factors other than the diameter of the pipe. Among the more important factors are the ease of access to the pipe, the amount of temporary bypass piping to be installed, and the type of paving required.

122. Walski (1985) presented data on pipe cleaning and lining. Ranges of values for cleaning and lining pipes are given as a function of diameter in Table 18. The column entitled "Low" contains costs for very simple large jobs, while the column entitled "High" contains costs for projects complicated by extensive bypass piping and valve replacement. On some occasions, costs can fall out of this range. The column titled "Average" contains default data used in the WADISO program.

123. The most striking point about the cleaning and lining data is that conditions other than diameter can greatly affect cost. One can use a constant value for cost over a range of diameters with very little error.

Table 18

Unit Cost for Pipe Cleaning and Lining at ENR = 4500

Pipe Diameter in.	Cost, $/ft Low*	Average*	High
6	8.7	14.5	24.6
8	9.1	15.7	26.7
10	9.4	16.8	28.6
12	9.6	17.7	30.1
14	10.1	18.5	31.4
16	10.6	19.2	32.6
18	11.0	20.0	34.0
20	11.3	20.5	34.8
24	11.9	21.6	36.7
30	12.7	23.1	39.3
36	13.4	24.3	41.3
42	14.0	25.4	43.2
48	14.5	26.4	44.9

* See text for explanation of columns.

Energy Cost

124. Accurately calculating pumping energy cost is fairly difficult because pump discharge varies with time, and head and efficiency vary with discharge and tank water levels. The price of energy also changes with the time of energy use. The present worth of energy cost is therefore

$$PWE = k \int_0^T \frac{Q(t)\ h(t)\ p(t)\ PWF(t)}{e(t)/100}\, dt \qquad (16)$$

where

- PWE = present worth of energy cost, $
- k = unit correction factor
- $Q(t)$ = discharge, cfs
- $h(t)$ = head produced by pump, ft
- $p(t)$ = price of energy, $/kwhr
- $PWF(t)$ = present worth factor
- $e(t)$ = wire-to-water efficiency of pumps, percent
- T = length of planning period, years

Equation 16 is unworkable for practical purposes because: (a) there is no easy way to determine $Q(t)$ and enter it to a computer program, and (b) it would be computationally infeasible to perform the flow balancing calculations for each value of $Q(t)$ to determine $h(t)$ and $e(t)$. Therefore, some simplifications must be made to Equation 16.

125. First the integral in Equation 16 must be approximated by a summation of the energy cost at a few representative flow rates (loadings). Secondly, the price of energy and the wire-to-water efficiency will be treated as constants for a given pump. Equation 16 can then be rewritten for a single pump or pump station as

$$PWE = \frac{kps}{e} \sum_{I=1}^{n} Q(I)\ H(I)\ PER(I) \qquad (17)$$

where

s = series present worth factors

n = number of loadings specified

Q(I) = pump discharge during I-th loading, cfs

H(I) = pump head during I-th loading, ft

PER(I) = percent of time I-th loading occurs

126. The key to using Equation 17 effectively in the program is to chose one or two loadings which are representative of average, actual conditions during the planning horizon. The number of computations carried out by the program increases almost proportionately with the number of loadings, so a wise user will keep the number of loadings to a minimum.

127. In general, it is best to specify a single loading on which energy costs are based. According to Walski (1984), this should be the average loading at approximately one third of the way through the project planning horizon. Using a single loading will not result in serious errors for most water distribution systems since, in most systems, most of the head is for lift rather than for overcoming friction losses. Therefore, H(I) does not vary greatly with time. This would not be the case for long pipelines.

128. The price of energy will also vary during the design life. This will not cause significant problems since the price of energy will not usually change significantly with regard to overall price levels, and, therefore, the opportunity cost for energy will not vary greatly. (Another major energy crisis could alter this.)

PART V: SUMMARY

129. The WADISO computer program, described in this report, enables engineers to optimally size pipes and select pipes to be cleaned and lined. The enumeration algorithm used in the program guarantees that the globally optimal solution will be identified, although computer time may be large for complex systems. In addition to optimizing pipe networks, the program can be used as a steady-state simulation model.

130. The program is divided into three parts: (a) simulation, which balances flows and heads in the system using the node method and sparse matrix techniques; (b) cost function development, which enables the user to build up to 12 cost functions for pipes laid under different conditions; and (c) optimization, which optimizes the system using a bounded enumeration.

131. The program is written in CDC Extended Fortran V (sequential format) and should be compatible with Fortran 77 compatible compilers. Availability of the program is addressed in Appendix C.

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APPENDIX A: USER'S GUIDE FOR WADISO PROGRAM

This appendix consists of the user's guide for the WADISO (Water Distribution Simulation and Optimization) computer program as published in Chapter 28 of Engineer Manual 1110-2-502, "Methodology for Areawide Planning Studies." Because of this, paragraph, page, and figure numbers are preceded by the number 28. This appendix reflects the status of the program in the spring of 1985.

CHAPTER 28

WATER DISTRIBUTION SYSTEM ANALYSIS AND OPTIMIZATION

Section 1

Introduction

28-1. Purpose. This MAPS chapter provides guidance on the use of the WADISO (Water Distribution System Analysis and Optimization) Computer Module for the MAPS program. WADISO is a user friendly computer program which aids the engineer in finding optimum pipe sizes during planning studies, for constructing, reinforcing, expanding and rehabilitating water distribution systems.

28-2. Scope of Chapter. The WADISO module is intended to help the user in the selection of pipe sizes when sizing water distribution systems. WADISO has been developed at the U. S. Army Engineer Waterways Experiment Station (WES) for the Office, Chief of Engineers. This chapter explains how to use the module and interpret the results. It assumes that the user is familiar with the basic principles of flow in pipe networks as they apply to the computation of flow and pressure distribution. In part two of this manual, Documentation, a description of the program code is provided. Reading the User's Guide and using the program do not require knowledge of computer programming. But appreciation of the Documentation requires programming experience. Features of the program are described in paragraphs 28-1 through 28-6; program control for simulation is described in paragraphs 28-11 through 28-18; program control for optimization is described in paragraphs 28-19 through 28-20; and running the optimization is described in paragraphs 28-21 through 28-32.

28-3. WADISO and MAPS. Though WADISO was developed under MAPS work unit of Water Supply and Conservation Research Program, it is a stand alone program. Instructions for accessing the program are provided in Appendix B of this manual.

28-4. Description of WADISO. The WADISO module consists of two major parts. The first part computes pressure and flow distribution in pipe networks (simulation routine). The second part calculates cost and some pressure distribution for a set of user selected pipe sizes and changes the sizes for selected pipes within user specified limits until it finds the most economical arrangement which meets the pressure requirement (optimization routine). Both parts allow for the presence of pumps, pressure reducing valves and check valves within the water distribution system as well as multiple supply points. There are no limitations to the layout of the system except that there must be at least one constant head node (tank or reservoir) for each network. The least one constant head node (tank or reservoir) for each network. The optimization part of the program is intended to be used for the sizing of a limited number of pipes. Typically this part of the program is used to size the pipes in an expansion of an existing system, or to improve the pressure conditions in an existing system by reinforcing the system through the cleaning of selected pipes or addition of pipes parallel to existing pipes. The program is not intended for the sizing of all pipes in large systems. Such sizing is possible with the employed methodology, but the computer time required for the optimization would be prohibitive.

28-5. Features of WADISO. While WADISO is a very complex computer program, it is designed such that it is easy to use. Those users familiar with MAPS (Methodology for Areawide Planning Studies) Computer Program will find a considerable amount of similarity between the two programs. Nevertheless there are differences and the user should not automatically assume that things work always the same in the WADISO program as they do in the MAPS program.

a. Hardware and Program. The only equipment required for the use of the WADISO module is a terminal, or a microcomputer which can serve as a terminal and a telephone to connect the user with the host computer on which the program is located. Because of the large amount of data output, printing capability at the terminal is highly desirable. The program is written in FORTRAN V. The commands as presented here are the ones used when running the program on the CDC Cybernet system. Implementation on other hardware may require modifications.

b. Computer Experience. No prior experience with computer programming is required in order to use WADISO. All of the commands used during program operation are explained in this manual. System commands required to manage data files are described in Appendix B.

c. Interactive Use of the Program. The WADISO module is designed to be used in an interactive mode. Prompts will appear at the terminal to guide the user through the program. If the program detects an error or inconsistency, it will print a warning. Output is provided immediately after each run. If the user wishes, it is possible to run WADISO in batch mode. This allows the user to take advantage of lower computer cost for batch mode processing.

d. Modular Structure. The module can be run in two ways, as a steady state simulation or as an optimization routine. For simulation the user does not need to enter data for cost and optimization constraints related to the optimization routine.

e. Data Files. Simulation and optimization of water distribution systems require a considerable amount of data. Data for the simulation portion of the program can be stored from one run to the next in user specified files. Additional files can be used to store optimization data and cost data. The files are built while using the program and saved using commands as described in Appendix B.

28-6. Status of WADISO. This manual reflects the status of WADISO as of 1 January 1985. But it is the intent to continuously revise and update the program to meet the needs of the users. A potential user should check with the program developers at WES, phone number 601-634-3931 or FTS 542-3931 to determine whether any revisions have been issued since this version of the manual was prepared.

Section 2

Program Control of Simulation Routine

28-7. Introduction. Program execution is controlled from six menus using an interactive format. One menu controls access to the three major routines of the program: simulation, optimization, and cost data entry. Two menus each control the simulation and cost data routines. And one menu controls the optimization routine. Figures 28-1 and 28-2 show the overall layout of the program. Figures 28-1 emphasizes the program steps involving simulation while Figure 28-2 emphasizes optimization.

28-8. Program Start Up. After starting the program, the user sees the following menu:

```
PROGRAM CONTROL:

     SIMULATION        :  ENTER 1  PRESS RETURN
     OPTIMIZATION      :        2
     COST DATA         :        3
     TERMINATE PROGRAM :        4
```

To enter the simulation routine the user selects option 1. The user can respond with NOM (for NO MENU). In this case the program will suppress the printing of all menus and prompts. This option is convenient when running the program in batch mode. After NOM is entered the program returns to the program control menu. In the menu which follows the user can select between two options. Option 1 will permit the user to enter a new system. Option 2 lets the user retrieve the data from a local file containing data of a system previously entered and stored:

```
SIMULATION ROUTINE

SELECT PROGRAM OPTION :

  TO ENTER NEW SYSTEM :  ENTER  1  PRESS RETURN
  TO RETRIEVE DATA    :         2
```

If option 1 is selected the program will start to request data (see 28-13, Data Input). If option 2 is selected the program will request the file name (see 28-17, Storing Data).

28-9. Option Menu. The main option menu is accessed after an option previously selected is completed (i.e. when a new system has been entered and the user has typed "END" or an old system has been retrieved). The menu allows the user to select from balancing the network (calculation of flow and pressure distribution), modifying the network (including change of individual parameters, expansion of system, or deletion of part of the system), printing the input data, storing the data under a user selected file name, retrieving data from a file in which the data was previously stored, printing the output (this option is only available if the system was previously balanced), returning to the

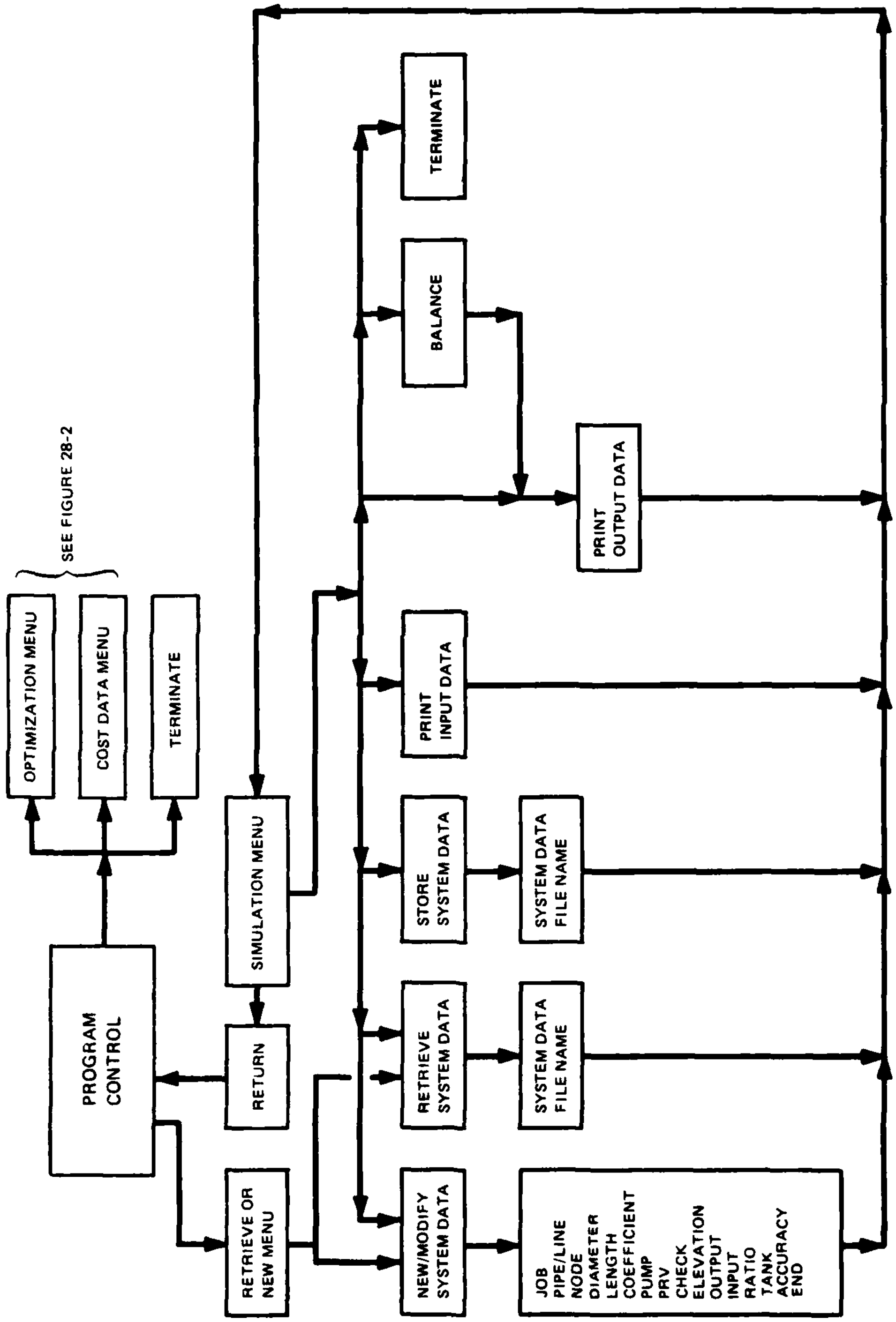

Figure 28-1. Flow Chart, Simulation Routine

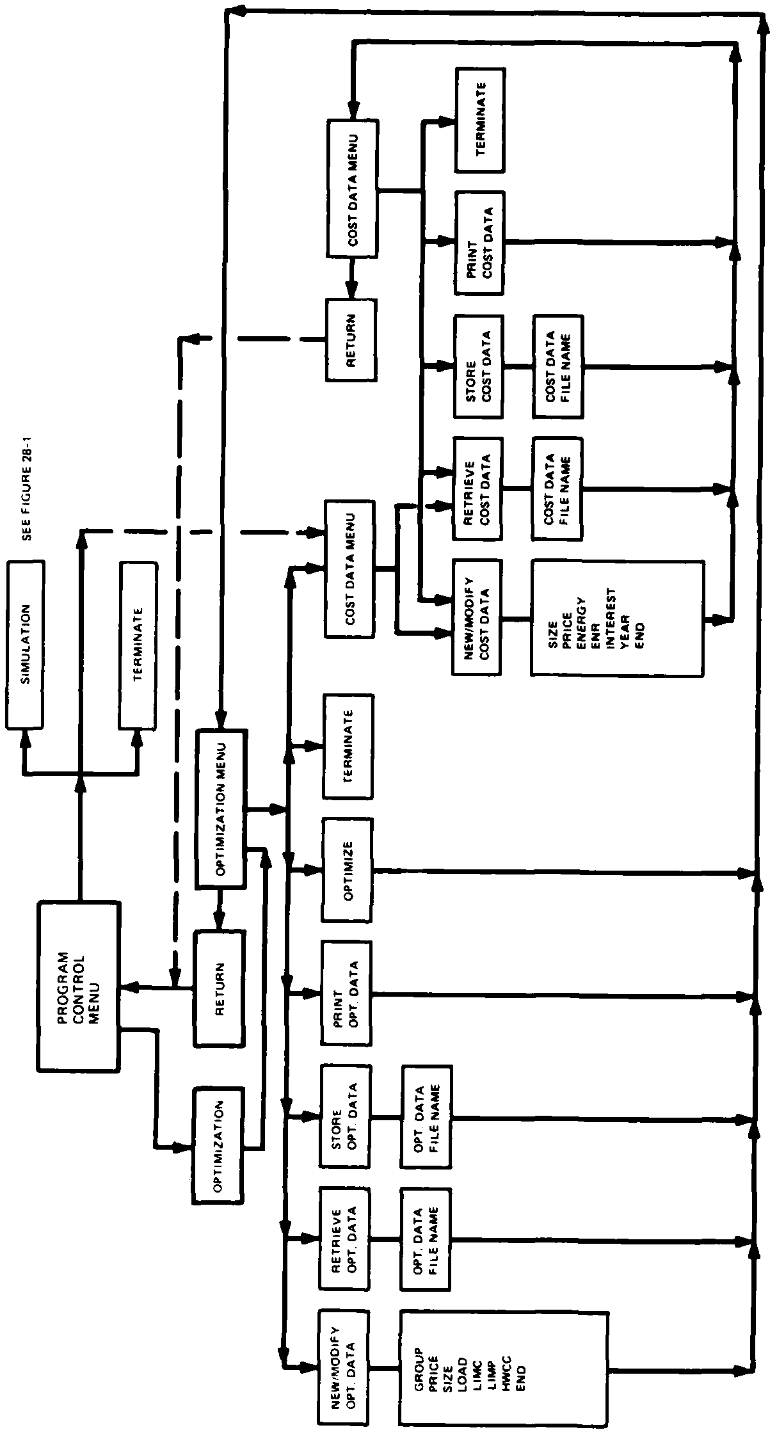

Figure 28-2. Flow Chart, Optimization Routine

program control menu, and terminating the program. The option menu as displayed at the terminal is reproduced below.

```
SELECT PROGRAM OPTION:

   BALANCE           :  ENTER  0 OR OC  PRESS RETURN
   MODIFY SYSTEM     :         1
   PRINT INPUT       :         2    2C
   STORE DATA        :         3
   RETRIEVE DATA     :         4
   PRINT OUTPUT      :         6    6C
   PROGRAM CONTROL   :         8
   TERMINATE PROGRAM :         9
```

The options with a C behind the number refer to the format in which input or output is to be printed. Without the C the program will pause after the printing of one screen (input) or one page (output). This is used for reviewing the input data and the output data on a CRT terminal. The option with a C (for Continuous) is used for producing a hard copy at a printer (i.e. no stop after the printing of each page). If the user is viewing data one page at a time, the user enters any character (except C and E) to view the next page. If the user enters a C, the program will switch to continuous output. If the user enters an E (for Exit) during the printing of the node table, the program will advance immediately to the top of the pipe table. If E is entered during the printing of the pipe table, printing is terminated. Since option 0 automatically accesses option 6 (i.e. output is always printed after balancing) this convention also applies to option 0. After an option is completed program control returns to the main option menu, except for option 9.

28-10. Description of Options. A general description of each of the options displayed in the menu follows.

a. BALANCE. Under this option the program calculates the pressure and flow distribution in the water distribution system and prints the results.

b. MODIFY SYSTEM. This option allows the user to return to the data input routine where any system parameter can be changed, or a system can be expanded, or part of a system can be deleted.

c. PRINT INPUT. This option permits the user to view the data which was entered or modified in the input routine.

d. STORE DATA. In order to store data in a local file the user must access the store routine. The program does not store the data automatically after each run.

e. RETRIEVE DATA. This option enables the user to retrieve data which was stored under d. above. The data must be in a local file. This option is equivalent to option 2 at the time of program start up (see 28-8.).

f. PRINT OUTPUT. This option is only available if the system is balanced. It will print two tables, one for the node data and one for the link data. This option is automatically accessed after balancing a system (see 28-10.a).

g. PROGRAM CONTROL. This option enables the user to return to the program control menu. If a pipe network is to be optimized (sizing of a set of user selected pipes) the user must return to the program control menu before the optimization routine can be accessed.

h. TERMINATE PROGRAM. This option will terminate the computer run.

Section 3

Simulation of Distribution Systems

28-11. Introduction. The water distribution system analysis part of the program calculates the level of the energy grade line and pressure at each node, the flows and head losses in each pipe, flow and head for each pump, and mode of operation for each PRV and check valve for steady state conditions. The program works for looped and branched networks. There is no need for the user to identify loops in the network. The program can be run as a stand alone program or in combination with the optimization routine.

28-12. Definition of Terms. Throughout this chapter a number of terms are used which may appear to be standard in connection with water distribution system analysis. Yet their precise definition may be important in the context of WADISO and this Section on water distribution systems.

a. Pipe Network. While this term is used interchangeably with water distribution system, a pipe network consists of links and nodes and refers more to the mathematical representation of a water distribution system.

b. Link. Links are elements which connect two nodes. A link can be a pipe, with or without a check valve, a pump, or a pressure reducing valve. A link is defined by its link number, and the numbers of the two nodes it connects.

c. Node. Nodes are the end points of links. One or more links connect a node to the network. Supply points (reservoirs, tanks) are also nodes since they are end points of links. A node is identified by its node number.

d. Pipe. A pipe is a link. It is assumed to have a constant diameter between the two nodes it connects. The diameter is expressed in inches and the length is expressed in feet. The program uses the Hazen-Williams head los equation and the corresponding Hazen-Williams coefficient. The term 'line' is equivalent to 'pipe'.

e. Pump. A pump is a link. It has a characteristic curve which defines the relationship between pump discharge (in gallons per minute) and pump head (in feet). The user specifies three points on the characteristic curve. The program will then fit a parabola through the three points. The constant term of the parabola must be positive. The first derivative at zero flow must be negative, and the second derivative must be negative, see Figure 28-3. As an option the user can enter only one point on the curve (e.g. the rated capacity and head). In this case the program will default to a characteristic curve described in paragraph 28-13.1 and shown in Figure 28-3. A pump link has no

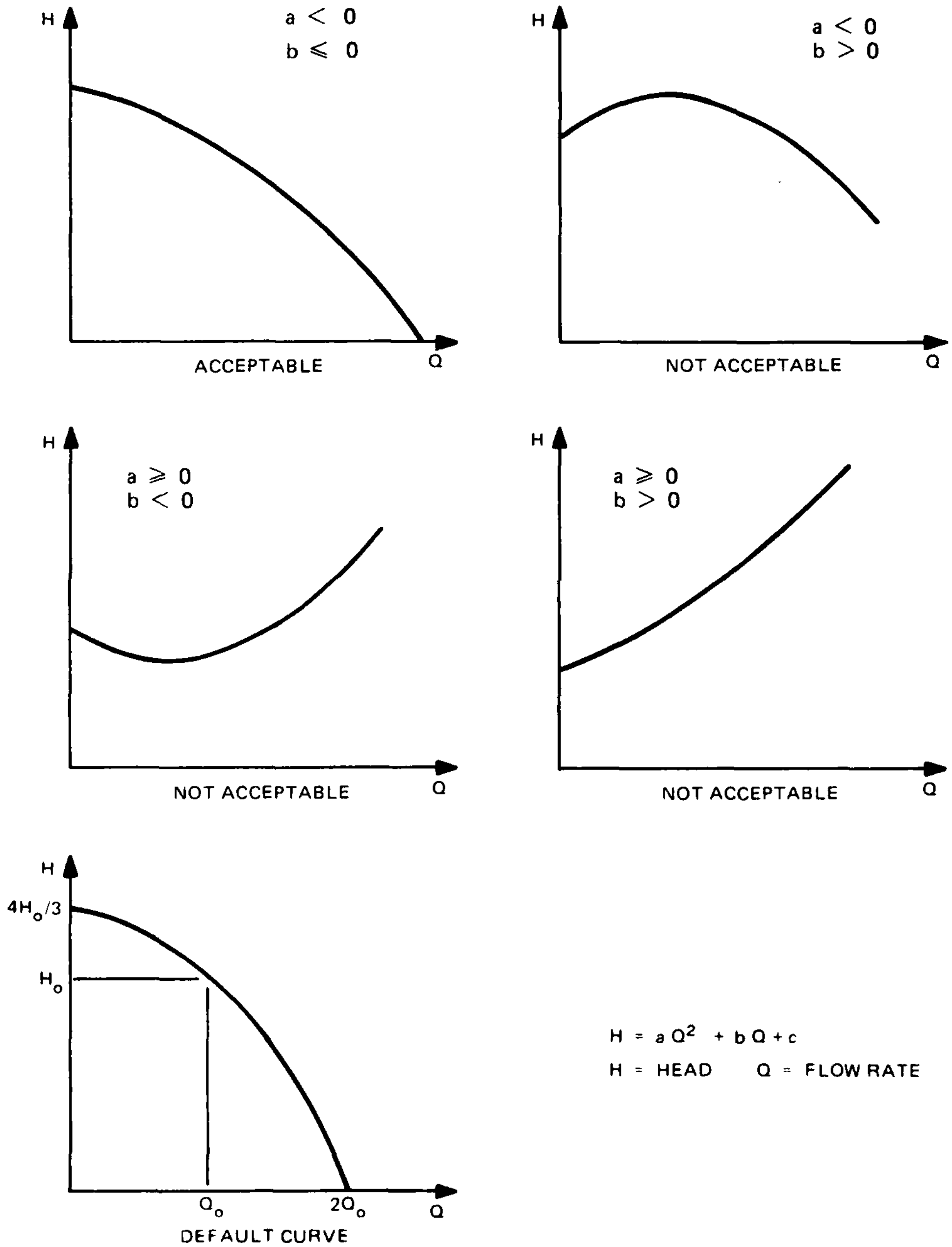

Figure 28-3. Acceptable, Unacceptable and Default Pump Curve

length associated with it. Elevation of beginning and ending node of the pump link should be the same.

f. Pressure Reducing Valve. A pressure reducing valve (PRV) is another type of link. The pressure setting (in psi) for a PRV is the pressure which the valve will try to maintain on the downstream side of the PRV. If the downstream pressure can be maintained at the pressure setting, the valve is ACTIVE. If for some reason the downstream pressure exceeds the valve setting, the valve is CLOSED. If the upstream pressure is less than the pressure setting, the valve is completely OPEN. PRVs also act as check valves (i.e. reversed flow is not possible). In this case the valve is CLOSED. The operational mode of the PRVs, ACTIVE, CLOSED, and OPEN is indicated in the program output. A PRV link has no length associated with it. Elevation of beginning and ending node of the PRV link should be the same. Two PRVs cannot have the same ending node. The ending node of a PRV cannot be the beginning node of another PRV. In these cases the two PRVs must be separated by at least one leg of pipe, no matter how short.

g. Check Valve. A check valve limits the flow direction in a pipe. A check valve is always associated with a pipe and is therefore not a link by itself. If the check valve is open the output will show the standard pipe information, followed by the letters CV (for Check Valve). If the check valve is closed, the word CLOSED is printed in the output instead of the flow data.

h. Reservoir. A reservoir is a node with a fixed water level (hydraulic grade line). The elevation of the node is at the free surface, that is node elevation (in ft) and elevation of the water surface coincide. The pressure at such a node is zero.

i. Tank. A tank is a node with a fixed water level (hydraulic grade line). The node elevation (in ft) is the elevation of the foot of the tank. The tank water level indicates the vertical distance from the foot of the tank to the free surface. A tank shows a pressure larger than zero. It cannot be assigned an output or input. The net inflow from, or outflow to, the tank is computed by the program.

j. Output. Output refers to the amount of water (in gallons per minute) which is withdrawn from the system at a node. Domestic or industrial usage and fire flows are examples of output. Output is treated to be independent of local pressure. Output is the same as negative input. A node with output cannot be assigned a constant head.

k. Input. Input refers to the amount of water (in gallons per minute) which is forced into the system at a node. Input is treated to be independent of local pressure. Input is the same as negative output. A node with input cannot be assigned a constant head.

28-13. Data Input. Data for the distribution system analysis is entered interactively from the terminal. The keywords used during data entry are summarized in Table 28-1 and are described in detail below. Data is requested with the following prompt:

Table 28-1. Keywords for Water Distribution Simulation
(S. prompt)

```
ACCURACY       xx.x           xx.x           ( xx )
          Press. Accur.   Flow Accur.   Max. Number of Inter.
-------------------------------------------------------------------
CHECK VALVE   xxx       xxx       xxx
             Link #    Node #    Node #
-------------------------------------------------------------------
COEFFICIENT     xxx            xxx          xxx.x
           First Link #   Last Link #    Coef.
or
COEFFICIENT   xxx       xxx.x
             Link #     Coef.
or
COEFFICIENT   xxx.x
              Coef.
-------------------------------------------------------------------
DIAMETER    xxx      xx.x
          Link #  Diam. in.
-------------------------------------------------------------------
END
-------------------------------------------------------------------
ELEVATION   xxx        xxx.x
          Node #      Elev. ft.
-------------------------------------------------------------------
INPUT     xxx       xxx.x
        Node #     Input gpm.
-------------------------------------------------------------------
JOB     text
-------------------------------------------------------------------
LENGTH    xxx       xxxx.x
        Link #     Length ft.
-------------------------------------------------------------------
LINE      xxx       xxx       xxx      xx.x       xxxx.x      ( xxx.x )
        Link #    Node #    Node #  Diam. in.   Length ft.     Coef.
-------------------------------------------------------------------
NODE
     followed by prompt:  FOR NODE xx ENTER   ELEVATION OUTPUT
     response:            xxxx.x      (xxx.x)
                         Elev. ft.  Output gpm.
-------------------------------------------------------------------
OUTPUT     xxx       xxx.x
         Node #    Output gpm.
-------------------------------------------------------------------
PIPE     xxx       xxx       xxx      xx.x       xxxx.x      ( xxx.x )
       Link #    Node #    Node #  Diam. in.   Length ft.     Coef.
-------------------------------------------------------------------
PRV      xxx      xxx      xxx
       Link #   Node #   Node #
     followed by prompt:  ENTER PRESSURE SETTING
     response:            xx.x
                      Press.Setting psi.
-------------------------------------------------------------------
PUMP     xxx      xxx      xxx
       Link #   Node #   Node #
     followed by prompt:  POINT x ON CHARACTERISTIC CURVE:  ENTER
                                                 DISCHARG,  HEAD
     response:            xxx.x         xxx.x
                      Discharge gpm.    Head ft.
           or:  E for point 2 (default curve)
-------------------------------------------------------------------
RATIO      xxx           xxx         x.xx
      First Node #   Last Node #   Ratio
or
RATIO    x.xx
         Ratio
-------------------------------------------------------------------
TANK     xxx        xxx.x
       Node #   Tank Height ft.
-------------------------------------------------------------------
```

Values in ( ) indicate optional entry.

S. KEYWORD IS xxxx ENTER (KEYWORD) DATA LIST

The S. indicates that the user is in the simulation routine. At xxxx appears the current default keyword. For example, when the program expects pipe input, it would prompt S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST. The format of the user's input is then

Keyword value1 value2 ... valuen

For example, to change the diameter of pipe 101 to 10 in., the user enters

DIAMETER 101 10.0

If data is entered without a keyword, the current keyword as displayed in the prompt ("pipe" in the above example), will be used, and will remain unchanged. If a different keyword is to be entered it must be included and will override the previous one. Under certain conditions the keyword may default to a new keyword. For instance after the keyword JOB the keyword defaults to PIPE. Or after the program detects an error in the input data the keyword will default to PIPE. All the keywords can be abbreviated with the first four letters. Numeric values behind the keyword can be separated by blanks or by commas. There must be a space or comma between the keyword and the first numeric value.

a. JOB. The alphanumeric characters entered after this keyword become the title of the job. It is printed at the top of every page of output. The length of the job name is limited to 60 characters.

b. PIPE. This keyword is used to enter the data for a pipe. Diameter is in inches. Length is in feet. The format for this keyword is given below.

	Line #	Node #	Node #	Diameter (in)	Length (ft)	Hazen-William Coefficient
PIPE	121	160	165	6.0	3756.0	120

Remember that the keyword need not be entered if the present keyword is PIPE. The numeric values can be separated by blanks or commas. The Hazen-Williams coefficient is optional. The program defaults to a value of 100, unless the default value is changed with the keyword COEF (see 28-13.j). The order of the node numbers connected by a pipe does not matter. If the user attempts to reenter a pipe, line, pump or PRV, which was previously entered, the program issues the message

```
ELEMENT xxx WAS PREVIOUSLY ENTERED FROM x TO x
TO CONTINUE ENTER 1 PRESS RETURN
TO EXIT           0
```

where xxx is current line, pump or PRV number and
x are node numbers for the link.

If the user enters 1, the link is modified with the new data. If the user enters zero, the data is not accepted and the link remains as it was before.

c. LINE. This keyword is equivalent to the keyword PIPE.

d. ELEVATION. This keyword is used to enter the elevation of the nodes. It is the elevation at which the pressure of a node is to be determined. Elevation is given in feet and must be greater than zero. The format for this keyword is given below.

	Node #	Elevation (ft)
ELEVATION	115	867.6

Elevations also can be entered when using the keyword NODE (see 28-13.o).

e. OUTPUT. This keyword is used to enter a constant output of water, for instance a domestic load, which is independent of pressure to be calculated by the program. Output is entered in gallons per minute. The format for this keyword is given below.

	Node #	Output (gpm)
OUTPUT	271	535.0

If output is assigned to a node previously declared a constant head node (with the keyword TANK) the output assignment overrides the constant head assignment. Output also can be entered when using the keyword NODE (see 28-13.o). If later the user attempts to redefine an input or output node as a tank, the program asks

```
x  WAS ENTERED WITH OUTPUT/INPUT
TO CONTINUE ENTER 1 PRESS RETURN
TO EXIT            0
```

where x is the node number.

If the user enters 1, the node becomes a tank. I the user enters 0, the node remains an input or output node.

f. INPUT. This keyword is used to enter a constant input of water into the system, which is independent of pressure to be calculated by the program. Input is entered in gallons per minute. The format is the same as for output.

	Node #	Input (gpm)
INPUT	317	525.0

Using the INPUT keyword is equivalent to using the OUTPUT keyword with a negative value for the output. If input is assigned to a node previously declared a constant head node (with the keyword TANK) the input assignment overrides the constant head assignment.

g. TANK. This keyword is used to designate a node with constant head. The format for this keyword is given below.

	Node #	Tank Height (ft)
TANK	7	85

The tank height is given in feet above the elevation of the node. If a tank height of zero is specified, the program will label the node as reservoir. If a tank is assigned to a node previously declared a node with input or output (with the keyword INPUT or OUTPUT), the tank assignment will override the input or output assignment. If the user later attempts to enter an input or output for a node that was previously entered as a tank, the program responds

```
x  WAS ENTERED AS A SUPPLY POINT
TO CONTINUE ENTER 1 PRESS RETURN
TO EXIT          0
```

where x is the node number.

If the user enters 1, the node becomes an input or output node. If the user enters 0, the node remains a tank.

h. DIAMETER. This keyword is used to indicate the diameter of a pipe. Diameter is given in inches. The format for this keyword is given blow.

	Link #	Diameter (in)
DIAMETER	17	8.0

This keyword is typically used only when changing a diameter, since usually the diameter is specified under the keyword PIPE. If a user attempts to enter a diameter for a pipe not yet entered under the keyword PIPE, the program will print an error message. If the pipe size is to be determined during the optimization, any pipe size can be entered for diameter.

i. LENGTH. This keyword is used to enter the length of a pipe. Length is given in feet. The format for this keyword is given below.

	Link #	Length (ft)
LENGTH	38	5260.0

This keyword is typically used only when changing a length, since usually the length is specified under the keyword PIPE. If the user attempts to enter a length for a pipe not yet entered under the keyword PIPE, the program will print an error message.

j. COEFFICIENT. This keyword is used to enter the Hazen-Williams coefficient of a pipe, or group of pipes, or to change the default value. Which one of these three options is used depends on the number of numeric values provided. To enter the coefficient of a single pipe the format is

	Link #	Coefficient
COEFFICIENT	11	95

This will override the coefficient previously entered for the indicated pipe link, either under the keyword PIPE or COEF. To enter the coefficient of a group of pipes the format is

	Link #	Link #	Coefficient
COEFFICIENT	11	37	95

In this case the Hazen-Williams coefficient of all the existing pipes with numbers in the range 11 through 37 (inclusive) will be changed to 95. Links other than pipes in the indicated range (pumps, PRVs) are not affected. To change the default value the format is

	Coefficient
COEFFICIENT	120

In this case the C-factor for all pipes which were assigned the default value are changed to the new default value. Note that in all three cases the last value is the new coefficient.

k. ACCURACY. This keyword is used to specify the accuracy to which computations should be carried and (as an option) the maximum number of iterations which are to be performed. The user specifies a pressure accuracy in psi and a flow accuracy in gallons per minute. The largest error in the system will be less than the value entered under this keyword. For an exact definition of the term 'accuracy' see part two of this manual, Documentation. If the ACCURACY keyword is not used the program uses the following default values: pressure accuracy 2 psi, flow accuracy 10 gallons per minute, number of iterations 25. The format for this keyword is given below.

	Pressure accuracy (psi)	Flow accuracy (gpm)	Number of iterations (optional)
ACCURACY	4	20	10

The number of iterations is optional. The program uses a numeric technique in which the head loss equations of all pipes (or characteristic curve of the pumps) are linearized and solved simultaneously with the continuity equation of all nodes. Such a technique shows excellent convergence. The number of iterations required is independent of the number of nodes and pipes in the system. A system without PRVs and without check valves typically converges within 5 - 7 iterations for a flow accuracy of 1 gallon per minute and pressure accuracy of 1 psi (typically the flow accuracy is the controlling factor). Systems with PRVs and/or check valves require roughly twice as many iterations. After the use of the keyword ACCU the keyword will be changed back to PIPE.

l. PUMP. This keyword is used to enter data for a pump. First the link number and its end nodes are entered. Note that pumps are numbered as part of the same sequence (links) which includes the pipe and PRV numbers. Do not use the same link number for a pipe and a pump or PRV.

	Link #	Node #	Node
PUMP	78	81	82

While the order of the node numbers does not matter when entering data under the keyword PIPE the order here is important. The pump is assumed to pump from the first node number listed to the second one. This entry is followed by the prompt:

POINT xx ON CHARACTERISTIC CURVE: ENTER DISCHARGE, HEAD

This prompt appears three times. At xx the numbers 1, 2, and 3 will appear respectively. The discharge is to be entered in gallons per minute and the head is entered in ft. If the quadratic equation fitted through the three points does not meet the requirements listed in paragraph 28-12.e the program will print an error message and reject the data. If the user enters only the first point and responds to the second request with the letter E (for EXIT), the program will default to a characteristic curve which has a head of 133.3% of the head entered for point 1 at flow zero and a head of zero at a discharge twice the discharge entered for point 1 (see Figure 28-3). After the three points are entered the program will print the coefficients and return to the standard input prompt under the keyword PUMP. The units of the coefficients are such that flow is in cfs and head is in feet.

m. PRV. Note that this keyword has only three characters. It is used to enter data for pressure reducing valves. First the link number and its end nodes are entered. Note that PRVs are numbered as part of the same sequence (links) which includes the pipe and pump numbers. The format for this keyword is given below.

	Link #	Node #	Node
PRV	278	113	101

The PRV is assumed to allow flow only from the first node number listed to the second one since PRVs act as check valves. The constant pressure, if possible, will be maintained at the second node listed. This entry is followed by the prompt:

ENTER PRESSURE SETTING

The pressure setting is given in psi. After the pressure setting is entered the program will return to the input prompt under the keyword PRV.

n. CHECK. This keyword is used to insert a check valve into a previously entered pipe. The format for this keyword is given below.

	Link #	Node #	Node
CHECK	27	97	84

The program will assume that the check valve will allow flow only from the first to the second node. I the indicated pipe number was not previously entered or the node numbers do not match those previously entered for this pipe the program will print an error message and reject the data.

o. NODE. This keyword offers an alternative to the use of the keywords ELEVATION and OUTPUT for entering data pertaining to a node. It is most conveniently used if the user enters first all the pipe, pump, and PRV data. He can then enter the keyword NODE without any numeric values:

NODE

The program will now respond with the following prompt:

FOR NODE xx ENTER ELEVATION OUTPUT

At xx the node number for which data is requested will appear, starting with the lowest node number used for a beginning or ending node of a link. The numeric value for OUTPUT is optional. For instance nodes with constant head will require only the elevation on this line of data. After the data for all nodes is entered the program returns to the standard prompt with the keyword TANK. If the keyword NODE is used after some node elevations were already entered under the keyword ELEVATION, these nodes will be skipped. The keyword NODE can also be used if at a later time the system is expanded. The program will then prompt only for those nodes just added. For example, if a user entered a pipe from node 7 to 10, and the elevation for node 10 had not been specified, the user could enter NODE to which the program would respond FOR NODE 10 ENTERED ELEVATION OUTPUT and the user would respond 150 25.

p. RATIO. This keyword is used to multiply the present output (entered under the keyword OUTPUT or NODE) at a sequence of nodes or all nodes by the indicated factor. For example this keyword is used to simulate peak day flows if the output data entered under the keyword OUTPUT corresponds to average day flow. Note that there are two formats for this keyword. The format for changing the output at a sequence of nodes is

	Node #	Node #	Ratio
RATIO	10	47	1.8

The present output at all nodes with numbers between 10 and 47 (inclusive) will be multiplied by the indicated ratio. The format to change the output at all nodes is

	Ratio
RATIO	1.8

In both cases nodes which were designated as constant head nodes (reservoirs, tanks) and nodes which were assigned an input are not affected. Note that in both formats the last value is the ratio.

q. Deleting Elements. The user can delete links. If the deletion of a link results in a completely disconnected node, the program will automatically delete this node and all data associated with it. The link is deleted using any one of the regular link keywords (PIPE, LINE, PUMP, or PRV) followed by the link number and a 0 (zero). For instance

PUMP 117 0

would delete the pump with number 117. Since the program does not check on the type of element being deleted, in the above example PIPE 117 0 would accomplish the same thing, as would PRV 117 0. Check valves are removed from a pipe by reentering the complete pipe.

r. END. This keyword will terminate the data entry routine. The program will return to the main simulation option menu.

s. Printing the Input Data. Upon entering the keyword END, program control returns to the main option menu. The user can select option 2 or 2C in order to review the input data. The program will print two tables. The first table is a node table and give

(1) node number,
(2) elevation, ft,
(3) output, gpm, and
(4) comment.

The comment column is used to flag the constant head points with either the word RESERVOIR or TANK. A negative value in the output column indicates a flow input. The second table is a link table (including pipes with check valves, pumps, and PRVs) and gives

(1) link number,
(2) beginning node,
(3) ending node,
(4) diameter, in.,
(5) length, ft,
(6) Hazen-Williams coefficient (* indicates default value), and
(7) comment.

For pipes with a check valve the words CHECK VALVE appear in the comment column. In the case of pumps the word PUMP is printed in this column. And in the case of PRVs the words PRV AT xx PSI are printed in the comment column. At xx the pressure setting of the PRV is printed. After printing the input data program control returns to the main option menu (see 28-9).

28-14. Balancing of System. To balance the system (compute pressure and flow distribution) the user takes option 0 or 0C in the main option menu. The program will first list the pressure and flow accuracy limits. It then prints the estimated maximum error at the end of every iteration. For example:

```
ACCURACY LIMITS:   2.0 PSI;   10.0 GPM
ESTIMATED MAXIMUM ERRORS:
ITERATION #  1:  61.7 PSI AT NODE 14;     3312. GPM AT NODE 5
   etc.
SYSTEM IS BALANCED
```

The program proceeds with printing the output. If the system is not properly balanced after the specified maximum number of iterations, the program prints a warning message.

28-15. Output. Output is provided automatically after balancing (option 0 or 0C). Also, if a system is balanced when the main option menu is displayed option 6 or 6C is available and will access the output routine.

a. Node Table. The first table printed lists all nodes. The table gives

(1) node number,
(2) elevation of node, ft,
(3) output, gpm,
(4) elevation of hydraulic grade line, ft,
(5) head, ft,
(6) pressure, psi, and
(7) comment.

The output column shows the output (positive value) or input (negative value) as specified under the keyword OUTPUT and INPUT respectively. At constant head nodes (tanks or reservoirs) a negative value indicates the net inflow from the tank or reservoir into the system, a positive value indicates the net outflow from the system into the tank or reservoir. The comment column flags the constant head nodes with either the word RESERVOIR or TANK.

b. Link Table. The second table printed lists all pipes (including those with check valves), pumps, and pressure reducing valves. The table gives

(1) link number,
(2) node number from which the flow comes,
(3) node number toward which the flow goes,
(4) diameter, in.,
(5) length, ft,
(6) Hazen-Williams coefficient (* indicates default value),
(7) flow, gpm,
(8) velocity, ft/sec, and
(9) head loss, ft.

Note that the flow direction is indicated by the order in which the node numbers are listed. In the case of pumps the word PUMP appears in column 4 followed by the pump head, and the discharge of the pump in column 7 again followed by the (hydraulic) power produced by the pump in HP. In the case of PRVs the word PRV appears in column 4 followed by the pressure setting, and one of the words ACTIVE, CLOSED, or OPEN, depending on the mode in which the PRV operates (see 28-12.f). For pipes with check valves the information is the same as for a regular pipe if the check valve is open, with the letters CV printed in the right margin of the table. If the check valve is closed the words CHECK VALVE CLOSED is printed, starting in column 4.

28-16. Consecutive Runs. After a system is balanced and output is printed control returns to the main option menu. If at this point option 0 or 0C is selected, the program will continue balancing the system to a higher degree of accuracy even if the accuracy requested is not changed. This is because the program will always go through at least three iterations unless the user has set the maximum number of iterations to less than 3 (which is not recommended).

The user can also select option 1 which returns control to the input routine as described in 28-13. At this point the user can change any parameter in the system, expand the system, or delete part of the system. The keywords used are the same as described in paragraph 28-13. Upon entering the keyword END control returns to the main option menu and the user can balance the system again or select any other option available.

28-17. Storing Data. In the main option menu the user can select option 3 in order to store the data, either before or after balancing. The program will respond with the prompt

```
ENTER FILE NAME
```

The user enters any file name which conforms with the file name requirements of the computer system. If a balanced system is stored the output is stored with all the system parameters. The only exception is the net outflow at constant head tanks which is not stored. On the CYBERNET this data file becomes a LOCAL file. In order to make the file a PERMANENT file the user must execute a SAVE or REPLACE command after program execution is terminated (option 9 in the main option menu). The user is reminded of this when taking option 9 by a message

```
IF YOU CREATED NEW DATA FILES, YOU WILL LOSE THESE FILES, UNLESS YOU
TRANSFER THEM TO PERMANENT STORAGE WITH A SAVE OR REPLACE COMMAND.
```

Data stored that way can be retrieved again through option 2 in the start-up menu (see 28-8) or option 4 in the main option menu.

28-18. Example 1. The network for this example is shown in Figure 28-4. The purpose of the example is to illustrate first the data input routine. The program will then be rerun a number of times to illustrate some of the options available. Below a run of the program is shown, from the point when the program has begun. Lines without a question mark are the prompts printed by the program. The user's input appears behind the question mark.

```
PROGRAM CONTROL :
     SIMULATION         : ENTER  1  PRESS RETURN
     OPTIMIZATION       :        2
     COST DATA          :        3
     TERMINATE PROGRAM  :        9
? 1
SIMULATION ROUTINE

SELECT PROGRAM OPTION :
     TO ENTER NEW JOB :  ENTER  1  PRESS RETURN
     TO RETRIEVE DATA :         2
? 1
S. KEYWORD IS JOB ENTER (KEYWORD) DATA LIST
? EXAMPLE 1
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST     ---
? 101 2 3 12 2000                                   )
```

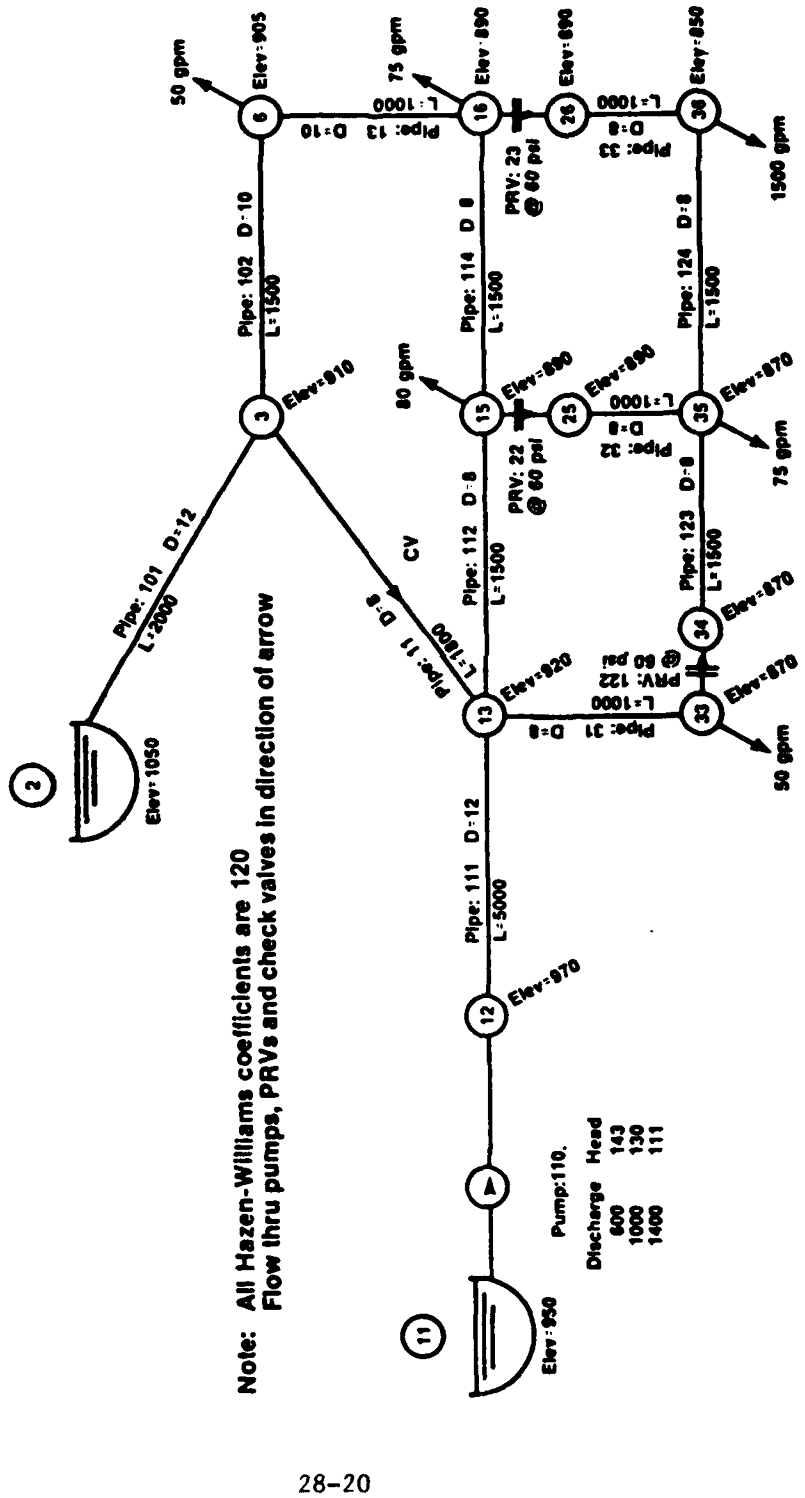

Figure 28-4. System Layout Example

```
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST        )
? 102 3 6 10 1500                                   )
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST        )
? 111 12 13 12 5000                                 )
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST        )
? 112 13 15 8 1500                                  )
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST        )
? 114 15 16 8 1500                                  )
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST        )
? 123 34 35 8 1500                                  )     Pipe Data
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST        )
? 124 35 36 8 1500                                  )
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST        )
? 11 3 13 8 1800                                    )
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST        )
? 13 6 16 10 1000                                   )
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST        )
? 31 13 33 8 1000                                   )
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST        )
? 32 25 35 8 1000                                   )
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST        )
? 33 26 36 8 1000                                   )
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST      ---
? PRV 22 15 25                                      )
ENTER PRESSURE SETTING                              )
? 60                                                )
S. KEYWORD IS PRV ENTER (KEYWORD) DATA LIST         )
? 23 16 26                                          )     PRV Data
ENTER PRESSURE SETTING                              )
? 60                                                )
S. KEYWORD IS PRV ENTER (KEYWORD) DATA LIST         )
? 122 33 34
ENTER PRESSURE SETTING                              )
? 60                                                )
S. KEYWORD IS PRV ENTER (KEYWORD) DATA LIST         -------
? PUMP 110 11 12                                          )
POINT 1 ON CHARACTERISTIC CURVE:  ENTER DISCHARGE, HEAD   )
? 600 143                                                 )    Pump
POINT 2 ON CHARACTERISTIC CURVE:  ENTER DISCHARGE, HEAD   )    Data
? 1000 130                                                )
POINT 3 ON CHARACTERISTIC CURVE:  ENTER DISCHARGE, HEAD   )
? 1400 111
S. KEYWORD IS PUMP ENTER (KEYWORD) DATA LIST        -------
? NODE                                              )
FOR NODE  2  ENTER  ELEVATION OUTPUT                )
? 950                                               )
FOR NODE  3  ENTER  ELEVATION OUTPUT                )
? 910                                               )
FOR NODE  6  ENTER  ELEVATION OUTPUT                )
? 905 50                                            )     Node Data
FOR NODE 11  ENTER  ELEVATION OUTPUT                )
? 950                                               )
```

```
FOR NODE 12  ENTER  ELEVATION OUTPUT                 )
? 970                                                )
FOR NODE 13  ENTER  ELEVATION OUTPUT                 )
? 920                                                )
FOR NODE 15  ENTER  ELEVATION OUTPUT                 )
? 890 80                                             )
FOR NODE 16  ENTER  ELEVATION OUTPUT                 )
? 890 75                                             )
FOR NODE 25  ENTER  ELEVATION OUTPUT                 )     Node Data
? 890                                                )
FOR NODE 26  ENTER  ELEVATION OUTPUT                 )
? 890                                                )
FOR NODE 33  ENTER  ELEVATION OUTPUT                 )
? 870 50                                             )
FOR NODE 34  ENTER  ELEVATION OUTPUT                 )
? 870                                                )
FOR NODE 35  ENTER  ELEVATION OUTPUT                 )
? 870 75                                             )
FOR NODE 36  ENTER  ELEVATION OUTPUT                 )
? 850 1500                                           )
S. KEYWORD IS TANK ENTER (KEYWORD) DATA LIST        ---
? 11 0                                               )
S. KEYWORD IS TANK ENTER (KEYWORD) DATA LIST         )     Tank Data
? 2 100                                              )
S. KEYWORD IS TANK ENTER (KEYWORD) DATA LIST         )
? END                                               ---
```

After the menu appears, select option 2, PRINT INPUT. The node and link table for the input data are shown in Table 28-2. In the menu select option 0, BALANCE. The program will respond with printing the accuracies, iteration by iteration, as shown below.

```
ACCURACY LIMITS:     2.0 PSI;    10.0 GPM
ESTIMATED MAXIMUM ERRORS:

ITERATION #  1 :    61.7 PSI AT NODE 14:     3312. GPM AT NODE  5
ITERATION #  2 :    31.0 PSI AT NODE  5:      625. GPM AT NODE  6
ITERATION #  3 :     9.1 PSI AT NODE 12:      663. GPM AT NODE 11
ITERATION #  4 :     3.4 PSI AT NODE 12:      228. GPM AT NODE  7
ITERATION #  5 :     1.4 PSI AT NODE  7:      126. GPM AT NODE  7
ITERATION #  6 :     1.9 PSI AT NODE  9:       58. GPM AT NODE  7
ITERATION #  7 :      .6 PSI AT NODE 14:       27. GPM AT NODE  7
ITERATION #  8 :      .3 PSI AT NODE 14:       12. GPM AT NODE  7
ITERATION #  9 :      .1 PSI AT NODE 14:        6. GPM AT NODE  7

SYSTEM IS BALANCED
```

The output is shown in Table 28-3. Note that PRVs 22 and 23 are OPEN because the upstream pressure is below the pressure setting. PRV 122 is CLOSED because the downstream pressure is larger than the pressure setting. Consequently pipe 123 as exactly zero flow. If the network would be perfectly balanced, pump 110 and pipe 111 should show the same flow. But the accuracy for flow rates defaulted to 10 gpm. In the last iteration the model had actually reached a flow accuracy of 6 gpm. To show how the accuracy can be further improved, once more enter option 0 in the main option menu. With the accuracy limits unchanged the program will execute three iterations. The output is shown in Table 28-4.

```
ACCURACY LIMITS:    2.0 PSI;    10.0 GPM
ESTIMATED MAXIMUM ERRORS:

ITERATION #  1 :      .1 PSI AT NODE 14;        3. GPM AT NODE  7
ITERATION #  2 :      .0 PSI AT NODE 14;        1. GPM AT NODE  7
ITERATION #  3 :      .0 PSI AT NODE 14;        1. GPM AT NODE  7

SYSTEM IS BALANCED
```

The output is shown in Table 28-4. After the system was balanced the first time the largest change in any flow rate was 4 gpm and the largest change in pressure .1 psi, both consistent with the estimated accuracies. A check valve is now inserted into pipe 11 limiting the flow from 3 to 13. This change should result in a considerable change in the system since at present 247 gpm are flowing through this pipe toward the tank. Also the Hazen-Williams coefficient is to be changed for all pipes to 120. From the option menu take option 1. The prompts and responses are reproduced below.

```
KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? CHECK 11 3 13
KEYWORD IS CHEC ENTER (KEYWORD) DATA LIST
? COEF 120
KEYWORD IS COEF ENTER (KEYWORD) DATA LIST
? END
```

In Table 28-5 the output for this run is reproduced. The accuracies after the last iteration are estimated to be .2 psi and 9 gpm. Note that the PRVs 22 and 23 have switched to active mode. The check valve in pipe 11 is closed. In the last change the output is reduced by 10% (multiplication factor .9) and then an output of 1800 gpm is assigned to node 36. Also output at node 35 is to be eliminated. From the main option menu select option 1.

```
KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? RATIO .9
KEYWORD IS RATI ENTER (KEYWORD) DATA LIST
? OUTPUT 36 1800
KEYWORD IS OUTP ENTER (KEYWORD) DATA LIST
? 35 0
KEYWORD IS OUTP ENTER (KEYWORD) DATA LIST
? END
```

The output for the balanced system is shown in Table 28-6. The accuracies are estimated at .3 psi and 7 gpm. This concludes Example 1.

Table 28-2. Input Data for Example 1

PIPE NETWORK ANALYSIS AND OPTIMIZATION

JOB: EXAMPLE 1

NODE NO	ELEV. FT.	OUTPUT GPM	
2	950.0		TANK HEIGHT: 100.0
3	910.0	0.	
6	905.0	50.	
11	950.0		RESERVOIR
12	970.0	0.	
13	920.0	0.	
15	890.0	80.	
16	890.0	75.	
25	890.0	0.	
26	890.0	0.	
33	870.0	50.	
34	870.0	0.	
35	870.0	75.	
36	850.0	1500.	

PIPE CONNECTIONS

PIPE NO	B NODE	E NODE	DIAM. IN.	LENGTH FT.	H-W-C	
11	3	13	8.0	1800.0	100.*	
13	6	16	10.0	1000.0	100.*	
22	15	25				PRV AT 60.0 PSI
23	16	26				PRV AT 60.0 PSI
31	13	33	8.0	1000.0	100.*	
32	25	35	8.0	1000.0	100.*	
33	26	36	8.0	1000.0	100.*	
101	2	3	12.0	2000.0	100.*	
102	3	6	10.0	1500.0	100.*	
110	11	12				PUMP
111	12	13	12.0	5000.0	100.*	
112	13	15	8.0	1500.0	100.*	
114	15	16	8.0	1500.0	100.*	
122	33	34				PRV AT 60.0 PSI
123	34	35	8.0	1500.0	100.*	
124	35	36	8.0	1500.0	100.*	

PUMP COEFFICIENTS FOR PUMP 110

Q*Q	Q	CONSTANT
-3.7772	-1.1221	151.3

Table 28-3. First Output for Example 1

PIPE NETWORK ANALYSIS AND OPTIMIZATION

JOB: EXAMPLE 1

NODE DATA

NODE NO.	ELEV. FT.	OUTPUT GPM	E.G.L. FT.	PR.HEAD FT.	PRESSURE PSI	
2	950.0	-720.	1050.0	100.0	43.3	SUPPLY
3	910.0		1045.5	135.5	58.7	
6	905.0	50.	1030.6	125.6	54.4	
11	950.0	-1109.	950.0			RESERVOIR
12	970.0		1075.4	105.4	45.7	
13	920.0		1050.3	130.3	56.5	
15	890.0	80.	1022.0	132.0	57.2	
16	890.0	75.	1021.6	131.6	57.0	
25	890.0		1022.0	132.0	57.2	
26	890.0		1021.6	131.6	57.0	
33	870.0	50.	1050.2	180.2	78.1	
34	870.0		1009.4	139.4	60.4	
35	870.0	75.	1009.4	139.4	60.4	
36	850.0	1500.	994.5	144.5	62.6	

PIPE DATA

PIPE NO.	NODES FROM	TO	DIAM. IN.	LENGTH FT.	COEF	FLOW GPM	VEL. FT/SEC	HEAD LOSS
11	13	3	8.0	1800.0	100.*	273.	1.7	4.9
13	6	16	10.0	1000.0	100.*	941.	3.8	9.0
22	15	25	PRV AT	60.0 PSI	OPEN			
23	16	26	PRV AT	60.0 PSI	OPEN			
31	13	33	8.0	1000.0	100.*	51.	.3	.1
32	25	35	8.0	1000.0	100.*	627.	4.0	12.6
33	26	36	8.0	1000.0	100.*	947.	6.0	27.1
101	2	3	12.0	2000.0	100.*	720.	2.0	4.5
102	3	6	10.0	1500.0	100.*	991.	4.0	14.9
110	11	12	PUMP HEAD	125.4 FT		1109.	POWER	35. HP
111	12	13	12.0	5000.0	100.*	1107.	3.1	25.1
112	13	15	8.0	1500.0	100.*	780.	5.0	28.4
114	15	16	8.0	1500.0	100.*	79.	.5	.4
122	33	34	PRV AT	60.0 PSI	CLOSED			
123	35	34	8.0	1500.0	100.*	0.	.0	.0
124	35	36	8.0	1500.0	100.*	551.	3.5	14.9

Table 28-4. Output for Example 1 after Second Balancing

PIPE NETWORK ANALYSIS AND OPTIMIZATION

JOB: EXAMPLE 1

NODE DATA Page 1

NODE NO.	ELEV. FT.	OUTPUT GPM	E.G.L. FT.	PR.HEAD FT.	PRESSURE PSI	
2	950.0	-722.	1050.0	100.0	43.3	SUPPLY
3	910.0		1045.5	135.5	58.7	
6	905.0	50.	1030.5	125.5	54.4	
11	950.0	-1108.	950.0			RESERVOIR
12	970.0		1075.5	105.5	45.7	
13	920.0		1050.3	130.3	56.5	
15	890.0	80.	1021.8	131.8	57.1	
16	890.0	75.	1021.4	131.4	56.9	
25	890.0		1021.8	131.8	57.1	
26	890.0		1021.4	131.4	56.9	
33	870.0	50.	1050.2	180.2	78.1	
34	870.0		1009.2	139.2	60.3	
35	870.0	75.	1009.2	139.2	60.3	
36	850.0	1500.	994.3	144.3	62.5	

PIPE DATA

PIPE NO.	NODES FROM	TO	DIAM. IN.	LENGTH FT.	COEF	FLOW GPM	VEL. FT/SEC	HEAD LOSS
11	13	3	8.0	1800.0	100.*	274.	1.7	4.9
13	6	16	10.0	1000.0	100.*	945.	3.9	9.1
22	15	25	PRV AT	60.0 PSI	OPEN			
23	16	26	PRV AT	60.0 PSI	OPEN			
31	13	33	8.0	1000.0	100.*	50.	.3	.1
32	25	35	8.0	1000.0	100.*	627.	4.0	12.6
33	26	36	8.0	1000.0	100.*	948.	6.1	27.1
101	2	3	12.0	2000.0	100.*	722.	2.0	4.5
102	3	6	10.0	1500.0	100.*	995.	4.1	15.0
110	11	12	PUMP HEAD	125.5	FT	1108.	POWER	35. HP
111	12	13	12.0	5000.0	100.*	1108.	3.1	25.1
112	13	15	8.0	1500.0	100.*	784.	5.0	28.6
114	15	16	8.0	1500.0	100.*	78.	.5	.4
122	33	34	PRV AT	60.0 PSI	CLOSED			
123	35	34	8.0	1500.0	100.*	0.	.0	.0
124	35	36	8.0	1500.0	100.*	552.	3.5	14.9

Table 28-5. Output for Example 1 after Adding Check Valve and Changing Pipe Coefficients

PIPE NETWORK ANALYSIS AND OPTIMIZATION

JOB: EXAMPLE 1

NODE DATA Page 1

NODE NO.	ELEV. FT.	OUTPUT GPM	E.G.L. FT.	PR.HEAD FT.	PRESSURE PSI	
2	950.0	-816.	1050.0	100.0	43.3	SUPPLY
3	910.0		1045.9	135.9	58.9	
6	905.0	50.	1038.5	133.5	57.8	
11	950.0	-998.	950.0			RESERVOIR
12	970.0		1080.1	110.1	46.7	
13	920.0		1065.4	145.4	63.0	
15	890.0	80.	1036.5	146.5	63.5	
16	890.0	75.	1034.1	144.1	62.4	
25	890.0		1028.5	138.5	60.0	
26	890.0		1028.5	138.5	60.0	
33	870.0	50.	1065.3	195.3	84.6	
34	870.0		1019.6	149.6	64.8	
35	870.0	75.	1019.6	149.6	64.8	
36	850.0	1500.	1009.1	159.1	68.9	

PIPE DATA

PIPE NO.	NODES FROM	TO	DIAM. IN.	LENGTH FT.	COEF	FLOW GPM	VEL. FT/SEC	HEAD LOSS
11	13	3	CHECK VALVE			CLOSED		
13	6	16	10.0	1000.0	120.*	767.	3.1	4.4
22	15	25	PRV AT	60.0 PSI		ACTIVE		
23	16	26	PRV AT	60.0 PSI		ACTIVE		
31	13	33	8.0	1000.0	120.*	50.	.3	.1
32	25	35	8.0	1000.0	120.*	623.	4.0	8.9
33	26	36	8.0	1000.0	120.*	950.	6.1	19.4
101	2	3	12.0	2000.0	120.*	816.	2.3	4.1
102	3	6	10.0	1500.0	120.*	817.	3.3	7.4
110	11	12	PUMP HEAD	130.1 FT		998.	POWER	33. HP
111	12	13	12.0	5000.0	120.*	996.	2.8	14.7
112	13	15	8.0	1500.0	120.*	945.	6.0	28.8
114	15	16	8.0	1500.0	120.*	249.	1.6	2.4
122	33	34	PRV AT	60.0 PSI		CLOSED		
123	35	34	8.0	1500.0	120.*	0.	0.0	0.0
124	35	36	8.0	1500.0	120.*	548.	3.5	10.5

Table 28-6. Output for Example 1 after Changing the Outputs

PIPE NETWORK ANALYSIS AND OPTIMIZATION

JOB: EXAMPLE 1

NODE DATA Page 1

NODE NO.	ELEV. FT.	OUTPUT GPM	E.G.L. FT.	PR.HEAD FT.	PRESSURE PSI	
2	950.0	-972.	1050.0	100.0	43.3	SUPPLY
3	910.0		1044.4	134.4	58.2	
6	905.0	45.	1034.1	129.1	55.9	
11	950.0	-1043.	950.0			RESERVOIR
12	970.0		1078.2	108.2	46.9	
13	920.0		1062.2	142.2	61.6	
15	890.0	72.	1030.3	140.3	60.8	
16	890.0	68.	1027.9	137.9	59.7	
25	890.0		1028.5	138.5	60.0	
26	890.0		1027.9	137.9	59.7	
33	870.0	45.	1062.1	192.1	83.2	
34	870.0		1017.8	147.8	64.1	
35	870.0		1017.8	147.8	64.1	
36	850.0	1800.	1001.9	151.9	65.8	

PIPE DATA

PIPE NO.	NODES FROM	NODES TO	DIAM. IN.	LENGTH FT.	COEF	FLOW GPM	VEL. FT/SEC	HEAD LOSS
11	13	3	CHECK VALVE			CLOSED		
13	6	16	10.0	1000.0	120.*	927.	3.8	6.3
22	15	25	PRV AT	60.0 PSI		ACTIVE		
23	16	26	PRV AT	60.0 PSI		OPEN		
31	13	33	8.0	1000.0	120.*	45.	.3	.1
32	25	35	8.0	1000.0	120.*	687.	4.4	10.6
33	26	36	8.0	1000.0	120.*	1112.	7.1	26.0
101	2	3	12.0	2000.0	120.*	972.	2.8	5.6
102	3	6	10.0	1500.0	120.*	972.	4.0	10.2
110	11	12	PUMP HEAD	128.2	FT	1043.	POWER	34. HP
111	12	13	12.0	5000.0	120.*	1043.	3.0	16.0
112	13	15	8.0	1500.0	120.*	998.	6.4	31.9
114	15	16	8.0	1500.0	120.*	247.	1.6	2.4
122	33	34	PRV AT	60.0 PSI		CLOSED		
123	35	34	8.0	1500.0	120.*	0.	0.0	0.0
124	35	36	8.0	1500.0	120.*	686.	4.4	16.0

Section 4

Program Control for Optimization Routine

28-19. Introduction. The optimization routine is accessed from the program control menu (see 28-8) by selecting option 2. This routine is then controlled from three menus. One menu provides for the main options of the routine. Two more menus are used when accessing the cost data option. Note that the cost data option can be accessed directly from the program control menu.

28-20. Option Menu. The option menu of the optimization routine is accessed either from the program control menu, or after an option previously selected in this menu is completed. The menu allows the user to select from optimizing the network, entering and/or modifying the optimization parameters, printing the optimization data, storing the data under a user selected file name, retrieving the optimization data from a file in which the data was previously stored with the preceding option, returning to the program control menu, and terminating the program. The option menu as displayed at the terminal is shown below.

```
SELECT PROGRAM OPTION:

     OPTIMIZE                 : ENTER  0  PRESS RETURN
     ENTER/MODIFY OPT. DATA :        1
     PRINT OPT. DATA          :        2
     STORE OPT. DATA          :        3
     RETRIEVE OPT. DATA       :        4
     ENTER/MODIFY COST DATA :        5
     PROGRAM CONTROL          :        8
     TERMINATE PROGRAM        :        9
```

After the completion of options 0 through 5 control returns to this option menu.

a. OPTIMIZE. This option starts the optimization procedure. For more details see paragraph 28-29.

b. ENTER/MODIFY OPT. DATA. This option allows the user to return to the data input routine as described in paragraph 28-26. There, any of the optimization parameters can be changed.

c. PRINT OPT. DATA. This option prints a list of all optimization data. See paragraph 28-27.

d. STORE OPT. DATA. In order to store the optimization data in a local file the user must access the store routine using this option. The program does not store the data automatically. See paragraph 28-28.

e. RETRIEVE OPT. DATA. This option allows the user to retrieve data which was stored under d. above. This option is equivalent to option 2 at the time of start of the optimization routine.

f. ENTER/MODIFY COST DATA. This option allows the user to enter a new cost data file or to update a previously entered cost data file.

g. PROGRAM CONTROL. This option will transfer program control back to the program control menu.

h. TERMINATE PROGRAM. This option will terminate the computer run.

Section 5

Optimization of Distribution System

28-21. Introduction. Optimization is carried out under a set of constraints (e.g. minimum pressures, ranges of pipe sizes) provided by the user. The intent of the optimization routine is to use these constraints to size specific pipes in the system. The program will implicitly enumerate all possible size combinations and select the solution with the lowest total cost within the constraints specified (including energy cost for pumping if desired). The procedure guarantees the global minimum within the specified constraints. The optimization can be carried out for more than one output/input pattern of flows. An overview of the steps required to optimize a network are given below.

a. Enter or retrieve network simulation data;

b. Run simulation to set up internal tables;

c. Enter or retrieve cost data;

d. Enter or retrieve optimization data; and

e. Run optimization.

Entering data under step d. can be further divided into the following steps.

a. Identify pipes to be optimized by assigning them to groups;

b. Identify price function for each pipe to be sized;

c. Identify allowable sizes for new pipes;

d. Identify loadings to be analyzed; and

e. Identify pressure constraints.

28-22. Definition of Terms. The following terms will be used in connection with the optimization routine:

a. Group. A group consists of one or several pipes with the same diameter, to be sized in the optimization routine. The user indicates which pipes are to be optimized by assigning the pipes to a group. Pipes not assigned to a group have a fixed diameter specified during the simulation.

b. Price Functions. In the cost data file the user can enter different price functions for a discrete set of pipe sizes. For example one price function may refer to the cost for 'average conditions', a second function for shallow pipes, a third one for deep pipes, a fourth one for typical city conditions, etc. Each pipe to be sized is assigned to a price function. Pipes in the same group may be assigned to different price functions.

c. Sizes. In the context of the optimization routine sizes (in inches) refer to a list of discrete pipe sizes from which the program selects the optimum size for a particular group. Each group can have a different set of sizes. Only those pipe sizes identified for a group will be considered.

d. Minimum Pressure. Pipe sizes will be selected such that at all nodes (excluding reservoirs and the nodes at the foot of tanks), the pressure is equal to or larger than the minimum pressure (in psi) specified for the particular node.

e. Loading. A set of flow outputs or inputs to be applied simultaneously is defined as a loading. For example average day use and fire flow at node 101 are two loadings.

f. Redundancy. Redundancy in a system refers to the fact that there is more than one path for water to take to a particular node.

28-23. Optimization Parameters. The optimization routine uses five types of optimization parameters.

a. Pipe Grouping. Each pipe to be sized is assigned to one group. All pipes in the same group will be assigned the same diameter during the optimization routine. This constraint is very important in three ways. First, for reasons of constructing a distribution system it is not desirable to have each leg of pipe with a potentially different size. Such solutions are the result of a particular loading pattern. Slight changes in the pattern could result in different sizes. Grouping allows the user to control where pipe size changes may occur. Second, grouping of pipes provides the user with a powerful tool to control to some degree the optimization, that is the direction in which to look for an answer. On the other hand careless usage of the tool may result in excessively expensive solutions. Third, because of the two reasons listed above which make grouping desirable, the methodology employed by the optimization routine takes advantage of the grouping in order to keep computer time within reason. A large number of groups may result in excessive computer time.

b. Cost Information. The user may enter cost data in the cost data input portion of the program or use default cost data stored in the program. The data includes costs for each size for one or several price functions (see 28-22.b). The user also indicates which pipe belongs to which price function. Costs are represented by a discrete function. The program does not need to interpolate points between sizes. Therefore no continuous price function needs to be fitted through the points. The price function does not need to meet any particular mathematical requirements (e.g. concave, linear, etc). The user can build up to 12 price functions. The default data for pipe cost is stored as price function 1 while default data for cleaning and lining is stored as price function 2. These default prices can be overwritten by the user.

c. Size List. The user specifies the pipe sizes to be considered for each group. For example pipe selection for a group may be limited to 6, 8, 10, and 12 inches. One can only specify sizes which are included in the discrete price function. Each group can have a different set of sizes. In addition to specifying possible pipe sizes to be considered, the user can specify that the program can consider eliminating all pipes in a group, or cleaning and lining the existing pipe(s), if there exists a parallel pipe (not to be sized) to each pipe in the group.

d. Loading Pattern. The user specifies up to five loading patterns to be used in the optimization. A solution is required to meet the pressure constraint for all loading patterns.

e. Pressure Constraint. The user specifies minimum pressures to be met or exceeded in the final solution at as many nodes as desired.

28-24. Redundancy. The importance of redundancy in the part of the system to be sized depends on the particular system. Redundancy is important in the sizing of an entire addition to an existing system. It may be less important, or indeed unnecessary in the case where the reinforcement to an existing system is to be sized since the existing system may already provide the necessary redundancy. Redundancy can be controlled in this optimization routine in several ways. First: it is possible in the size list to limit the search for alternatives to specific pipe diameters and not to allow the program to consider cleaning or no new pipe (elimination) (i.e. not to specify 0 nor C in the size list). The selected size in the group will then be at least the minimum listed. Redundancy is also controlled through the multiple loading constraint, by assigning the fire load to various nodes. Pipes which could be eliminated under one loading pattern may be essential in another one in order to meet the pressure constraint. Alternately, two pipes serving a node can be placed in the same group which would force both pipes to be included with positive diameters.

28-25. Cost Data File. The cost data file is a local file in which the user stores one or more price functions to be used in the optimization routine. This paragraph describes how to enter data into the data file and how to update the data file. The routine can be accessed from the option menu of the optimization routine (28-20.f.) or directly from the program control menu (28-8).

a. Option Menus. The user first sees the menu:

```
COST DATA ROUTINE
SELECT PROGRAM OPTION :

    TO ENTER NEW OPT. DATA  :  ENTER  1  PRESS RETURN
    TO RETRIEVE OPT. DATA   :         2
```

If option 1 is selected the program will start to request data. If option 2 is selected the program will request the file name:

ENTER FILE NAME OF COST DATA FILE

The user enters the name under which the data was previously stored. The program will then print the option menu of the cost data routine:

SELECT PROGRAM OPTION:

ENTER/MODIFY COST DATA	: ENTER	1	PRESS RETURN
PRINT COST DATA	:	2	
STORE COST DATA	:	3	
RETRIEVE COST DATA	:	4	
PROGRAM CONTROL	:	8	
TERMINATE PROGRAM	:	9	

b. Description of Options. The options operate analogous to the ones discussed in the simulation routine. A brief description of each option follows:

(1) ENTER/MODIFY COST DATA. This option is accessed by taking option 1 in either one of the two menus listed above. It allows the user to enter or modify cost data (see 28-25c).

(2) PRINT COST DATA. This option allows the user to view the data which was entered or modified under (1). (See 28-25d).

(3) STORE COST DATA. This option allows the user to store the cost data under a user selected file name. (See 28-25e).

(4) RETRIEVE COST DATA. This option is accessed either by taking option 2 in the first menu, or option 4 in the second menu. It allows retrieval of data previously stored under option (3). (See 28-25f).

(5) PROGRAM CONTROL. This option returns program control to the menu from which the cost data routine was accessed, i.e. either the program control menu, or the menu of the optimization routine.

(6) TERMINATE PROGRAM. This option will terminate the computer run.

c. Data Input. The keywords used during data entry are summarized in Table 28-7. Data is requested with the following prompt:

C. KEYWORD IS xxxx ENTER (KEYWORD) DATA LIST

The C. indicates that the user is in the cost data routine. At xxxx appears the current keyword. Below the keywords are listed with the corresponding format for the data list. The first keyword displayed is SIZE.

(1) SIZE. This keyword is used to indicate the pipe sizes for which cost data is to be entered (i.e. the domain of the price function). The format is shown below. Up to 25 different sizes can be specified for a given function.

Table 28-7. Keywords for Cost Data File
(C. prompt)

```
END
-----------------------------------------------------------
ENERGY     x.xxx
      Energy Cost $/kWh
-----------------------------------------------------------
INTEREST       x.x
           Interest in %
-----------------------------------------------------------
PRICE     xx
      Price Fct. #
      followed by prompt: FOR SIZE xx.x
      response:           xx.x    (or END)
                       Price $/ft
or
PRICE    xx            xx.x        xx.x
      Price Fct. #    Size in.   Price $/ft
or
PRICE    xx    DELETE
      Price Fct. #
-----------------------------------------------------------
SIZE    xx.x    xx.x    xx.x    ...
      List of Sizes in.
or
SIZE    xx.x    DELETE
      Size in.
-----------------------------------------------------------
YEAR    xx
      Number of Years
```

```
          List of diameters
          (in.)
     SIZE 2 4 6 8
```

This entry would enter sizes 2, 4, 6, and 8 inches into the data file. If one of the sizes specified already exists in the data file this size is not repeated. If the keyword displayed in the prompt is SIZE the keyword is optional. In order to delete a size from the data file the format is

```
     SIZE 6 DELETE
```

If the keyword displayed in the prompt is SIZE the keyword is optional. DELETE can be abbreviated to DELE. Do not specify a size of 0 (zero).

(2) PRICE. This keyword is used to enter the cost data per linear foot of pipe for sizes specified earlier under the keyword SIZE. There are two formats. In the first format the user enters only the price function number after the keyword and the program will then prompt the user for price of each size entered.

```
          Function #
     PRICE 4
```

This will cause the program to prompt the user for entry of price data for all sizes. The program will print

    FOR PRICE FUNCTION 4 ENTER COST/FT FOR SIZES

followed for all sizes in the data file by the prompt

    FOR SIZE xxx

where xxx stands for the diameter in inches. Enter the cost for this size. For instance:

    FOR SIZE 8
    ? 19.3

The program will then request the data for the next size. Sizes will appear in the order they were entered into the data file. Entering END will let the user exit this loop at any time. The second format for entering cost data enables the user to enter or change one single cost figure

	Function #	Size in.	Price $/ft
PRICE 4		8	19.3

This entry assigns in price function 4 to size 8 inches the cost of 19.3 $/ft. Price function 1 contains the default function, while price function 2 contains the default function for cleaning.

(3) ENERGY. This keyword is used to enter the energy cost in $/kWh. The format is

	Energy cost $/kWh
ENERGY	0.083

(4) ENR. This keyword is used to multiply a entire price function by a factor. The format is:

	Function #	Multiplication factor
ENR	2	1.08

This entry multiplies all cost data in price function 2 by the factor 1.08, and stores the prices in function 2.

(5) INTEREST. When calculating the present worth of pumping cost, the program requires an interest rate. This keyword is used to enter this rate. The format is

	Interest %
INTEREST	7.5

(6) YEAR. When calculating the present worth of pumping cost the program requires the number of years of operation. This keyword is used to enter this time period in years. The format is:

	Years
YEARS	25

(7) END. This keyword will terminate the cost data input. Program control will return to the menu of the cost data routine.

d. PRINT COST DATA. The program will print all data which are part of the cost data routine (that is entered under c above or retrieved). In particular a table of all pipe sizes with the prices for the various price functions is printed, followed by energy cost, the interest rate, and the numbers of years used in computing the present worth of pumping cost. Program control then returns to the menu of the cost data routine.

e. STORE COST DATA. When selecting option 3 in the menu the program will respond with the prompt:

ENTER FILE NAME FOR COST DATA FILE

The user enters the file name. Control will return to the menu of the cost data routine.

f. RETRIEVE COST DATA. This option is accessed from either the first or second menu of the cost data routine (option 2 or option 4, respectively). See paragraph 28-25a. Program control returns to the menu of the cost data routine.

28-26. Data Input. Input of the optimization parameters is similar to the data input in the water distribution system analysis part of the program. It is controlled by a set of keywords which are summarized in Table 28-8 and which are described in detail below. Data is requested with the following prompt:

O. KEYWORD IS (xxx nn) ENTER (KEYWORD) DATA LIST

The O. indicates that the prompt refers to optimization data. At xxx nn appears the present keyword (e.g. Group 2). It consists of a word and a numeric value. The format of the input is then

Keyword value1 value2 ... valuen

or

Keyword value 1 Keyword value2 ... valuen

where value 1 is part of the keyword. For example the first format

GROUP 2 201 205 203

states that pipes 201, 203, and 205 should be added to group 2. While

GROUP 2 ALL 209 220

Table 28-8. Keywords for Optimization
(O. prompt)

END	
GROUP	xx xxx xxx xxx ... Group # List of Link #
or	
GROUP	xx ALL xxx xxx Group # First Link # Last Link #
HWCC	xxx.x Coef. for Cleaning
LIMC	x.x $ of Minimum Cost
LIMP	x.x Pressure Increment psi.
LOAD	xx MINIMUM xx.x Pattern # Min. Press. psi
or	
LOAD	xx MINIMUM xxx xx.x Pattern # Node # Min. Press. psi
or	
LOAD	xx MINIMUM xxx xxx xx.x Pattern # First Node Last Node $ Min. Press. psi.
or	
LOAD	xx OUTPUT xxx xxx.x Pattern # Node $ Output gpm.
or	
LOAD	xx PUMP xxx xx.x (xx.x) Pattern # Link $ Time Running % Efficiency %
or	
LOAD	xx RATIO x.xx Pattern # Ratio
or	
LOAD	xx RATIO xxx xxx x.xx Pattern # First Node # Last Node # Ratio
PRICE	xx xxx xxx xxx ... Price Fct. # List of Link #
PRICE	xx ALL xxx xxx Price Fct. # First Link # Last Link #
SIZE	xx xx.x xx.x xx.x ... Group # List of Sizes in.

says that all previously defined pipes with numbers in the range 209 to 220 should be added to group 2. If data is entered without a keyword, the present keyword (word and numeric value) as displayed in the prompt, will be used. The first numeric value after the word is considered part of the keyword. It can only be changed if the keyword is included. In the above example the value 2 refers to group 2. The entry

217 219 255

would leave the keyword and the group number unchanged. The word ALL serves as a secondary keyword. First and second keyword can be abbreviated with the first four letters. The numeric value behind the keyword can be separated by blanks or by commas. There must be a space or comma between the keyword and the numeric value after the keyword as well as in front of the second keyword.

a. GROUP. All pipes to be assigned to groups for sizing must already be part of the system when accessing the optimization routine (i.e. at the time option 2 is selected in the program control menu). That is, all pipes to be sized must have previously been entered in the simulation part of the program (i.e. pipe number, beginning and ending node numbers, diameter, length and friction coefficient were assigned under the keyword PIPE or LINE). The pipe sizes used at the time of data entry are immaterial but should be 'reasonable' because the system must be balanced once with these diameters. The Hazen-Williams coefficient should correspond to that of new pipes. The keyword group is used to identify the pipes to be sizes. All pipes in the same group will be assigned the same diameter in the optimization. A group can consist of one pipe. The keyword consists of the word GROUP followed by the group number. The format for the keyword is given below.

	Group #	List of Pipe numbers
GROUP	2	201 205 203

GROUP 2 is the present keyword. (GROU 2 is equivalent). If the displayed keyword in the prompt is GROU 2 the entry

201 205 203

is equivalent to the previous entry. An alternative format is

	Group #		Pipe #	Pipe #
GROUP	3	ALL	117	128

This statement would assign all pipes with numbers in the range 117 through 128 (inclusive) to group 3. Links in this range which are pumps or PRVs are not affected. Again the keyword and group number are optional. If the present keyword is GROUP 3

ALL 117 128

is equivalent to the previous entry. If the group number is to be changed the total keyword (word and numeric value) must be included. If the present keyword is not GROUP the keyword must be included in order to assign pipes to groups. A pipe can only be assigned to one group. If a pipe is assigned to a group more than once, the last entry will override previous entries. Assigning group number 0 (zero) to a pipe will remove the pipe from the group to which it is presently assigned. For instance if pipes 128 and 144 were previously assigned to group 3 (or any other group) the entry

GROUP 0 128 144

would eliminate pipes 128 and 144 from the list of pipes to be sized. An example for how pipes can be grouped is given in Figure 28-5. Pipes 221, 231, and 241 could form group 1. Pipes 222 and 233 could form group 2.

b. PRICE. This keyword is used to assign a pipe to be sized to a specific price function. The cost functions are part of the cost data file. An assignment of price function 3 to a pipe means that the pipe prices of function 3 in the cost data file will be used for this pipe in the calculation of total cost. The keyword consists of the word PRICE followed by the price function number. The format is the same as for the keyword GROUP.

	Function #	List of Pipe numbers
PRICE	3	201 55 117

This entry would assign pipes 55, 117 and 201 to price function 3. If the present keyword is PRICE and the present price function number is 3 the entry

201 55 117

is equivalent to the previous entry. The use of the word ALL to assign a range of pipe numbers is again available.

	Function #		Pipe #	Pipe #
PRICE	2	ALL	28	44

This entry assigns all pipes with numbers in the range 28 through 44 to price function 2. Again if the keyword in the prompt is PRICE 2 the first two items are optional. If the price function number needs to be changed the entry must include the total keyword (word and numeric value). Not all pipes in the same group need to belong to the same price function. Assigning one pipe in a group to a particular function does not affect any other pipe in the group. If a pipe is assigned more than once to a function, the last entry will override previous entries. A pipe can only be assigned to one function. Pipes not assigned to a function but assigned to a group will default to price function 1. Assigning function number 0 (zero) to a pipe will remove the pipe from any function. For instance

PRICE 0 114

would eliminate the assigned price function from pipe 114. If no other assignment is made for pipe 114 and this pipe is included in a group, it would default to function 1. If cleaning is an option to adding a new pipe, the cleaning cost

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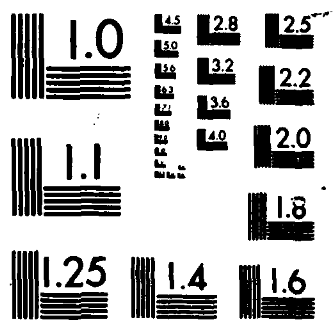
UNCLASSIFIED F/G 13/2 NL

END


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0

of the old pipe will default to price function 2 unless the old pipe was assigned to a different price function. To indicate that an existing pipe is to be considered for cleaning, the user must enter a parallel new pipe for which one of the possible sizes is C.

c. SIZES. This keyword is used to designate the sizes for a particular group to be considered during the optimization. The keyword consists of the word SIZE followed by a group number. The format is given below.

	Group #	List of Sizes
SIZES	6	10 12 14 16

This entry assigns to group 6 the sizes 10, 12, 14, and 16 inches. If the keyword in the prompt is SIZE 6

10 12 14 16

is equivalent to the previous entry. The sizes listed must be a subset of the sizes included in the cost data file. Entering a 0 (zero) as a possible size will permit elimination of all pipes in the group as an alternative. Enter a C (for Cleaning) if cleaning and lining of the parallel old pipe(s) instead of adding new parallel pipes is to be considered as an alternative. In the case of cleaning as an option, all pipes in the group must have pipes with different pipe numbers but the same beginning and ending nodes which are to be considered for cleaning and are not to be sized. In Figure 28-5 two groups are shown. Group 1 consists of pipes 221, 231, and 241. Existing pipes 21, 31, and 141 are parallel to the three previously listed pipes, respectively. Cleaning and lining of pipes 21, 31, and 141 is permissible. Therefore listing of C as a size option of group 1 is possible. Group 2 consists of pipe 222 and 233. There is no pipe parallel to 222 (i.e. no pipe has same beginning and ending nodes). For this group cleaning cannot be specified. An example of size assignments to group 1, which would permit elimination of the group as well as cleaning the existing pipes with the same beginning and ending nodes would be

SIZES 1 0 C 6 8 10

Within the size range specified, one does not need to list all sizes included in the data file. For instance

6 10 14

is a legitimate response, even though the cost data file may include 8 and 12 inch pipe sizes as well. Rather than specifying all 5 sizes from 6 to 14 inches the user can specify sizes 6, 10, and 14 in a first run. If the program selects the 12 inch size the user then could rerun the program for sizes 10, 12, and 14. Since computer time is roughly proportional to the product of the number of sizes in all groups this procedure may dramatically reduce computer time. But the procedure may not be totally equivalent to listing all five sizes in the first run. If the group number needs to be changed the keyword (word and group number) must be included. If one enters sizes for the same group twice, with (partially) different sets of sizes, the program

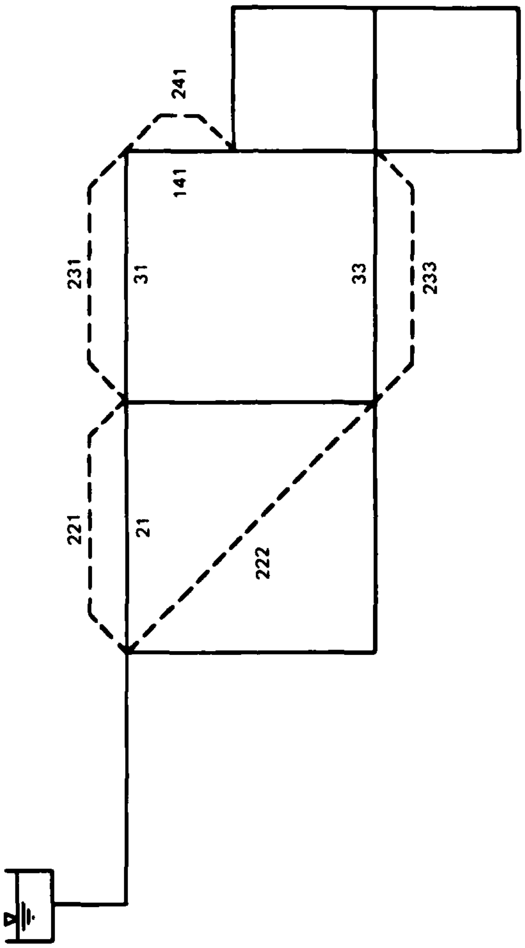


Figure 28-5. Sample System with Parallel Pipes

will use the union of the two (or more) sets. To clear a group from all assigned sizes enter the word DELETE after the group number.

SIZES 3 DELETE

would clear group 3 of all previously assigned sizes.

d. LOAD. The first loading pattern used in the optimization routine is the one entered in the simulation routine of the program. This keyword is used to assign additional loading patterns. Any assignments made with this keyword start out from the first loading pattern. The keyword consists of the word LOAD followed by the pattern number. The format is

	Pattern #		Node #	Output (gpm)
LOAD	3	OUTPUT	38	1200

This entry assigns in loading pattern number 3 an output of 1200 gallons per minute to node 38 regardless of the previous load at this node. OUTPUT is the second keyword in this entry. Input format after the second keyword OUTPUT follows the same format as described in paragraph 28-13.e. The last numeric value can be negative (input). Another alternative to this format is

	Pattern #		Ratio
LOAD	2	RATIO	1.5

If the second keyword is RATIO the format follows the same format as described in paragraph 28-13.p. The above assignment would multiply the output at all nodes by a factor 1.5. The format

	Pattern		Node #	Node #	Ratio
LOAD	2	RATIO	25	53	1.25

is also available as described in paragraph 28-13.p. It would multiply the output at all nodes with numbers in the range 25 through 53 by a factor 1.25 for loading pattern 2. Any nodes not included in the assignment for a loading pattern will have the same output or input as in loading pattern 1. It is important to remember that when a loading pattern is entered, the program will first set all inputs and outputs to the same value as in pattern 1. Any subsequent changes are to the present loading pattern. For instance subsequent entries for the same loading pattern of RATIO 1.2 and RATIO 1.5 would result in outputs 1.8 times larger than the values in pattern 1. But entering RATIO 1.2 for loading pattern 2 and RATIO 1.5 for loading pattern 3 would yield a flow of 1.5 times the load of pattern 1 for pattern 3.

e. PUMP. The user can flag to the program which pumps should be included in determining energy cost. PUMP is a second keyword used in connection with the keyword LOAD. Also entered under this keyword is the percentage of time during which the pump operates and the expected wire-to-water efficiency of the pump. The format for this keyword is shown below.

	Pattern #		Link #	Percent Time Running	Efficiency (%)
LOAD	2	PUMP	109	60	78

This entry causes the pump with link number 109 to be included in the energy cost computation. It is assumed the pump runs 60% of the time under load pattern 2 and its wire-to-water efficiency is 78%. Pumps not listed under this keyword are assumed to operate according to the characteristic pump curve entered in the simulation part of the program but their energy costs are not considered in the optimization. Pumps listed under this keyword are assumed to operate with the characteristic curve specified in the simulation part of the program unless continuity dictates the flow rate o the pump (no reservoir or tank on the downstream side of the pump). In this latter case the characteristic curve is ignored and the head is selected such that the minimum pressure requirement downstream of the pump is exactly met.

f. MINIMUM. This is a second keyword used in connection with the keyword LOAD. It is used to assign the minimum pressure which is to be maintained at nodes. The format is shown below.

	Min. Pressure (psi.)
LOAD 2 MINIMUM	35

This entry assigns a minimum pressure of 35 psi to all nodes except constant head nodes for loading pattern 2. An alternative format is

	Node #	Min. Pressure (psi.)
LOAD 3 MINIMUM	16	40

This entry assigns a minimum pressure of 40 psi to node 16 in loading pattern 3. The third format is

	Node #	Node #	Min. Pressure (psi.)
LOAD 1 MINIMUM	28	76	32

This entry assigns a minimum pressure of 32 psi to all nodes with numbers in the range 28 through 76 (inclusive) for loading pattern 1. If a minimum pressure is assigned to a constant head node the assignment is ignored. If a node is assigned more than one minimum pressure only the last entry is retained. Nodes which are not assigned a minimum pressure are not checked.

g. LIMC. This keyword lets the user specify a percentage of the (present) minimum cost. If, during the optimization procedure, a solution is encountered which is within this percentage difference from the cost of the current least cost solution, this solution will be kept in a solution queue of Pareto Optimal solutions, even though it is more expensive than the current best solution as long as this solution provides a higher pressure than the required minimum. The format is shown below.

	% of Minimum Cost
LIMC	5

This entry would keep any solution in the queue of Pareto Optimal solutions which is not more expensive than 105% of the best solution found to this point. The default value is 3%.

h. LIMP. This keyword lets the user specify a pressure differential in psi. If, during the optimization procedure, a solution is encountered which fails the pressure requirement by less than the specified differential, this solution will be kept in the solution queue of Pareto Optimal solutions as long as the solution offers lower cost. The format is shown below.

	Pressure Differential (psi)
LIMP	3

This entry would keep any solution on file which fails the pressure requirement by less than 3 psi. The default value is 3 psi.

i. HWCC. This keyword lets the user specify the Hazen-Williams coefficient for pipes which are to be cleaned and lined, if applicable. All pipes in the system to be cleaned will have the same coefficient. The format is shown below.

	Coefficient
HWCC	110

This entry assigns an after cleaning Hazen-Williams coefficient of 110 to all pipes to be cleaned. The default value is 120.

j. END. This keyword will terminate the data entry routine. Program control returns to the main option menu of the optimization routine.

28-27. Printing of Optimization Data. All optimization data as entered under paragraph 28-26 (or retrieved) is printed when the user selects option 2 in the optimization menu. This output consists of a table which lists the group number and pipes assigned to the group, the sizes assigned to each group, the loading patterns with the assigned outputs and minimum pressures, the loading patterns with the pump numbers and the percentage of time running under each pattern, and the parameters for the Pareto Optimal solution queue. Control returns to the option menu of the optimization routine.

28-28. Storing and Retrieving of Optimization Data. The optimization parameters as entered under paragraph 28-26 and printed in paragraph 28-27 can be stored under a user selected file name. When selecting option 3 in the menu the program will respond with the prompt

ENTER FILE NAME FOR OPTIMIZATION PARAMETER FILE

The user enters any file name which conforms with the file name requirements of the computer system. Data stored under this option can be retrieved again through option 4 in the menu of the optimization routine.

28-29. Optimization. To perform the optimization the user takes option 0 (zero) in the menu of the optimization routine. The program will determine the least expensive combination of pipe sizes which meets the minimum pressure requirement for each loading pattern. At the same time the program will generate alternate solutions which are Pareto Optimal (or non-inferior). It includes solutions which are not more than X % more expensive than the minimum cost solution on file at the time the Pareto Optimal solution is encountered. The value of X is specified under the keyword LIMC. Other solutions included are those which have minimum pressures less than specified but within Y psi of the permissible minimum. The value of Y is specified under the keyword LIMP. The output will list the optimal solution as well as the queue of Pareto Optimal solutions. Generation of the solution queue will require extra computer time. The program can avoid the generation of the queue (i.e. only select a single optimal solution) by assigning values of 0 (zero) to both X and Y. Pipe diameters of the optimal solution and the outputs of the pattern which generates the lowest pressure are assigned. Program control returns to the menu of the optimization routine. It is then possible to return to program control and simulation in order to balance the optimal system and to view the output.

28-30. Example 2. The network for this example is shown in Figure 28-6. The purpose of the example is to illustrate cost data entry and the entry of the optimization parameters.

a. System Data Input. First the input of the system data in the simulation routine is shown. Lines without a question mark are the prompts printed by the program. The user's input appears behind the question mark.

```
PROGRAM CONTROL :
          SIMULATION         : ENTER  1  PRESS RETURN
          OPTIMIZATION       :        2
          COST DATA          :        3
          TERMINATE PROGRAM  :        9

? 1

SIMULATION ROUTINE

SELECT PROGRAM OPTION :

          TO ENTER NEW JOB   : ENTER  1  PRESS RETURN
          TO RETRIEVE DATA   :        2

? 1
```

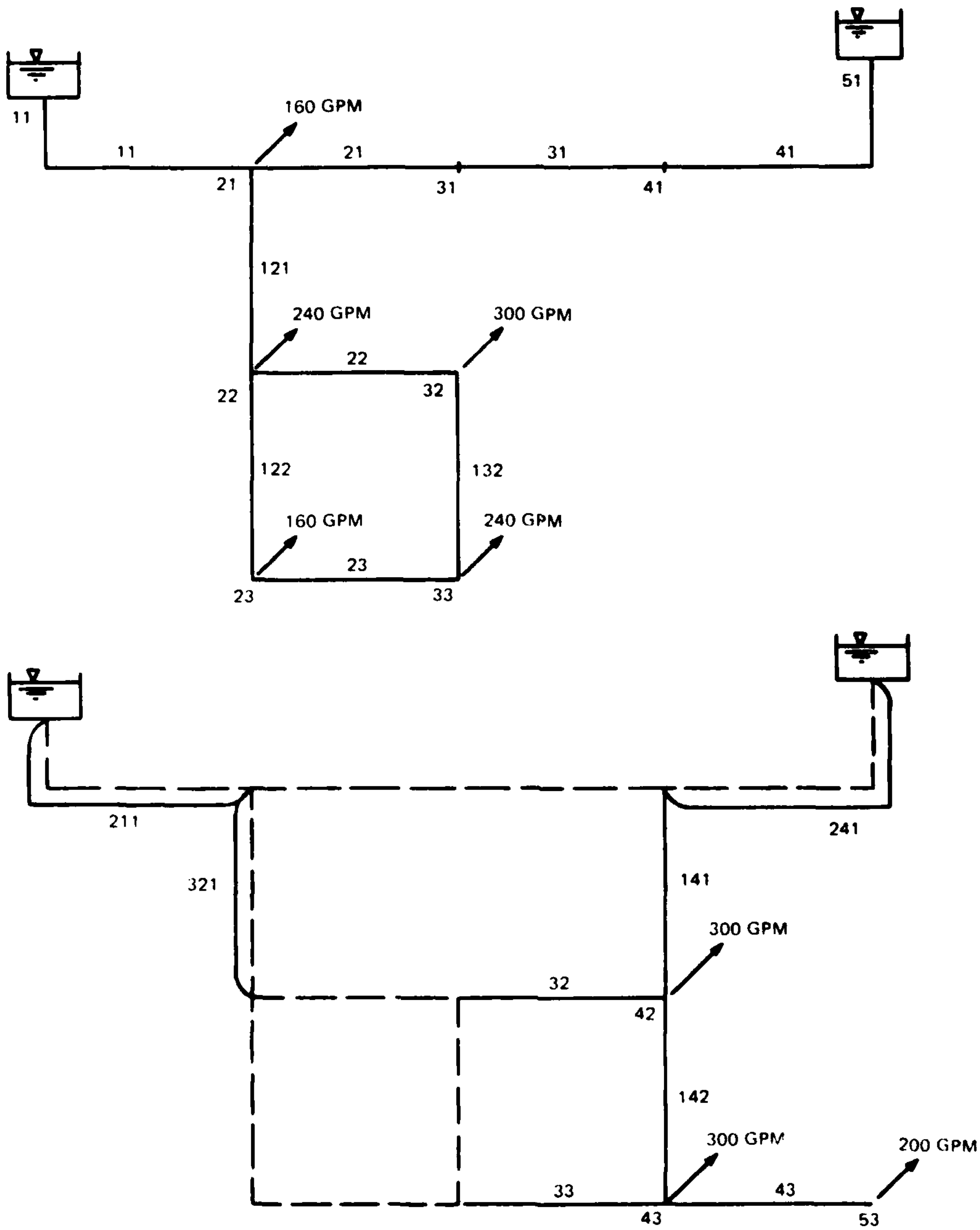


Figure 28-6. System Layout Example 2. Before and After Expansion

```
S. KEYWORD IS JOB ENTER (KEYWORD DATA LIST
? EXAMPLE 2
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 11 11 21 14 15840 75
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 21 21 31 10 5280 80
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 22 22 32 8 5280
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 23 23 33 8 5280
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 31 31 41 10 5280 80
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 41 41 51 10 21120 80
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 121 21 22 10 5280 80
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 122 22 23 10 5280 80
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 132 32 33 4 5280
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? NODE
FOR NODE 11 ENTER ELEVATION OUTPUT
? 1200
FOR NODE 21 ENTER ELEVATION OUTPUT
? 1050 160
FOR NODE 22 ENTER ELEVATION OUTPUT
? 980 240
FOR NODE 23 ENTER ELEVATION OUTPUT
? 950 160
FOR NODE 31 ENTER ELEVATION OUTPUT
? 1070 160
FOR NODE 32 ENTER ELEVATION OUTPUT
? 970 240
FOR NODE 33 ENTER ELEVATION OUTPUT
? 950 240
FOR NODE 41 ENTER ELEVATION OUTPUT
? 1090
FOR NODE 51 ENTER ELEVATION OUTPUT
? 1120
S. KEYWORD IS TANK ENTER (KEYWORD) DATA LIST
? 11 0
S. KEYWORD IS TANK ENTER (KEYWORD) DATA LIST
? 51 100
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? END
```

After the menu appears, select option 2, PRINT INPUT. The node and link table for the input data are shown in Table 28-9. After the data is printed the user takes option 1, MODIFY SYSTEM, in order to expand the system as shown in Figure 28-6. The dashed lines indicate the existing part of the system, the solid lines the expansion to be sized. The output on the existing system to be increased by 25%. The outputs on the expansion are shown in Figure 28-6. Note the line 241 is necessary even if the only options for this line are elimination of cleaning/lining of line 41. Entry of the data for system expansion and modification is now continued.

```
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? RATIO 1.23
S. KEYWORD IS RATIO ENTER (KEYWORD) DATA LIST
? PIPE 32 32 42 12 5280 120
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 33 33 43 12 5280 120
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 43 43 53 12 5280 120
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 141 41 42 43 12 5280 120
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 142 42 43 12 5280 120
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 211 11 21 12 15840 120
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 241 41 51 12 21120 120
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 321 21 22 12 5280 120
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? NODE
FOR NODE 42 ENTER ELEVATION OUTPUT
? 960 300
FOR NODE 43 ENTER ELEVATION OUTPUT
? 960 300
FOR NODE 53 ENTER ELEVATION OUTPUT
? 950 200
S. KEYWORD IS TANK ENTER (KEYWORD) DATA LIST
? END
```

In Table 28-10 the input data of the system to be optimized is shown. The optimization routine can only be executed if the system was balanced. So after printing the input data, option 0 (zero) (BALANCING) is selected. The output is shown in Table 28-11. Note that a diameter of 12 inches was used for all pipes to be sized. This value has no effect on the optimization routine and the final answer. Any value could have been used. Yet in order to get a better feeling for the performance of the system it is suggested to use 'reasonable' diameters. To terminate the simulation routine the user takes option 8 in the menu of the simulation routine.

b. Cost Data Input. The user is likely to have the cost data permanently stored in a cost data file under a user selected name. When this file is to be used the user must transfer the permanent file to local work space before running the program. From the program control menu:

Table 28-9. First Input for Example 2

PIPE NETWORK ANALYSIS AND OPTIMIZATION

JOB: EXAMPLE 2

NODE NO.	ELEV. FT.	OUTPUT GPM	
11	1200.0		RESERVOIR
21	1050.0	160.	
22	980.0	240.	
23	950.0	160.	
31	1070.0	160.	
32	970.0	240.	
33	950.0	240.	
41	1090.0	0.	
51	1120.0		TANK HEIGHT: 100.0

PIPE CONNECTIONS

PIPE NO	B NODE	E NODE	DIAM. IN.	LENGTH FT.	COEF
11	11	21	14.0	15840.0	75.
21	21	31	10.0	5280.0	80.
22	22	32	8.0	5280.0	100.*
23	23	33	8.0	5280.0	100.*
31	31	41	10.0	5280.0	80.
41	41	51	10.0	21120.0	80.
121	21	22	10.0	5280.0	80.
122	22	23	10.0	5280.0	80.
132	32	33	4.0	5280.0	100.*

```
     PROGRAM CONTROL :

          SIMULATION        : ENTER  1  PRESS RETURN
          OPTIMIZATION      :        2
          COST DATA         :        3
          TERMINATE PROGRAM :        4
```

the user now selects option 3. The next menu is:

```
     COST DATA ROUTINE
     SELECT PROGRAM OPTION :

     TO ENTER NEW COST DATA : ENTER  1  PRESS RETURN
     TO RETRIEVE COST DATA  :        2
```

Table 28-10. Input for Example 2 after Expansion

PIPE NETWORK ANALYSIS AND OPTIMIZATION

JOB: EXAMPLE 2

NODE NO.	ELEV. FT.	OUTPUT GPM	
11	1200.0		RESERVOIR
21	1050.0	200.	
22	980.0	300.	
23	950.0	200.	
31	1070.0	200.	
32	970.0	300.	
33	950.0	300.	
41	1090.0	0.	
42	960.0	300.	
43	960.0	300.	
51	1120.0		TANK HEIGHT: 100.0
53	950.0	200.	

PIPE CONNECTIONS

PIPE NO	B NODE	E NODE	DIAM. IN.	LENGTH FT.	COEF
11	11	21	14.0	15840.0	75.
21	21	31	10.0	5280.0	80.
22	22	32	8.0	5280.0	100.*
23	23	33	8.0	5280.0	100.*
31	31	41	10.0	5280.0	80.
32	32	42	12.0	5280.0	120.
33	33	43	12.0	5280.0	120.
41	41	51	10.0	21120.0	80.
43	43	53	12.0	5280.0	120.
121	21	22	10.0	5280.0	80.
122	22	23	10.0	5280.0	80.
132	32	33	4.0	5280.0	100.*
141	41	42	12.0	5280.0	120.
142	42	43	12.0	5280.0	120.
211	11	21	12.0	15840.0	120.
241	41	51	12.0	21120.0	120.
321	21	22	12.0	5280.0	120.

Table 28-11. Example 2 after First Output

PIPE NETWORK ANALYSIS AND OPTIMIZATION

JOB: EXAMPLE 2

NODE DATA

Page 1

NODE NO.	ELEV. FT.	OUTPUT GPM	E.G.L. FT.	PR.HEAD FT.	PRESSURE PSI	
11	1200.0	-1195.	1200.0			RESERVOIR
21	1050.0	200.	1180.8	130.8	56.7	
22	980.0	300.	1174.3	194.3	84.2	
23	950.0	200.	1162.5	212.5	92.1	
31	1070.0	200.	1179.4	109.4	47.4	
32	970.0	300.	1164.0	194.0	84.0	
33	950.0	300.	1157.5	207.5	89.9	
41	1090.0	75.	1180.3	90.3	39.1	
42	960.0	300.	1164.2	204.2	88.5	
43	960.0	300.	1157.8	197.8	85.7	
51	1120.0	-1105.	1220.0	100.0	43.3	SUPPLY
53	950.0	200.	1157.0	207.0	89.7	

PIPE DATA

PIPE NO.	NODES FROM	TO	DIAM. IN.	LENGTH FT.	COEF	FLOW GPM	VEL. FT/SEC	HEAD LOSS
11	11	21	14.0	15840.0	75	578.	1.2	19.2
21	21	31	10.0	5280.0	80	112.	.5	1.4
22	22	32	8.0	5280.0	100.*	229.	1.5	10.3
23	23	33	8.0	5280.0	100.*	154.	1.0	5.0
31	41	31	10.0	5280.0	80.	88.	.4	.9
32	42	32	12.0	5280.0	120.	100.	.3	.2
33	43	33	12.0	5280.0	120.	116.	.3	.3
41	51	41	10.0	21120.0	80.	323.	1.3	39.7
43	43	53	12.0	5280.0	120.	200.	.6	.8
121	21	22	10.0	5280.0	80.	258.	1.1	6.6
122	22	23	10.0	5280.0	80.	354.	1.4	11.8
132	32	33	4.0	5280.0	100.*	29.	.7	6.5
141	41	42	12.0	5280.0	120.	1016.	2.9	16.1
142	42	43	12.0	5280.0	120.	617.	1.7	6.4
211	11	21	12.0	15840.0	120.	617.	1.7	19.2
241	51	41	12.0	21120.0	120.	782.	2.2	39.7
321	21	22	12.0	5280.0	120.	625.	1.8	6.6

Note that this menu will be skipped if the user previously entered or retrieved cost data during this computer run. In this case control would go directly to the menu of the cost data routine. In this example option 1 is selected in order to show how cost data is entered. The data to be entered is sufficient only to run this example. The item by item input is shown below. Lines without a question mark are the prompts printed by the program. The user's response appears behind the question mark.

```
C. KEYWORD IS SIZE ENTER (KEYWORD) DATA LIST
? 6 8 10 12 14 16
C. KEYWORD IS SIZE ENTER (KEYWORD) DATA LIST
? PRICE 1

FOR PRICE FUNCTION 1 ENTER COST/FT FOR SIZES:

FOR SIZE 6.
? 15.1
FOR SIZE 8.
? 19.3
FOR SIZE 10.
? 28.9
FOR SIZE 12.
? 40.5
FOR SIZE 14.
? 52.1
FOR SIZE 16.
? 59.4

C. KEYWORD IS PRIC ENTER (KEYWORD) DATA LIST
? 2
FOR PRICE FUNCTION 2 ENTER COST/FT FOR SIZES:

FOR SIZE 6.
? 14.5
FOR SIZE 8.
? 15.7
FOR SIZE 10.
? 16.8
FOR SIZE 12.
? 17.7
FOR SIZE 14.
? 18.5
FOR SIZE 16.
? 19.2
C. KEYWORD IS PRIC ENTER (KEYWORD) DATA LIST
? ENERGY 0.075
C. KEYWORD IS ENER ENTER (KEYWORD) DATA LIST
? YEAR 10
C. KEYWORD IS YEAR ENTER (KEYWORD) DATA LIST
? INTEREST 10
C. KEYWORD IS INTE ENTER (KEYWORD) DATA LIST
? END
```

In the above routine price function 1 was entered, which is the default cost function for new pipes, and function 2 was entered, which is the default cost function for cleaning/lining existing pipes. After the menu appears, select option 2, PRINT COST DATA. The cost data table as printed appears in Table 28-12. The last three data items are used only when calculating the present worth of pumping cost. Since this system does not include pumps these items are not required in order to run the optimization. To terminate the cost data routine the user takes option 8 in the menu of the cost data routine.

c. Optimization Parameters. At this point the balanced system data and cost data are entered. From the program control menu the user now takes option 2, OPTIMIZATION. The program responds with the menu of the optimization routine. Selection of the optimization parameters in this example is based on the following considerations. The new demands require reinforcement of either line 11 or 41. Considering the low Hazen-Williams coefficients of these lines, cleaning and lining should be considered as an alternative to adding new parallel pipes. Because of the distance from node 11 to the new area line 321 is also added as part of the reinforcement in this part of the system. Lines 211 and 321 form group 1. Line 241 forms group 2. Lines 141 and 142 are to have the same diameter and form group 3. Lines 32 and 33 are put into group 4, while line 43 forms group 5. All new lines are assigned to price function 1 (default for new pipes) and pipes 11 and 41 are assigned to price function 2 (default for cleaning). To illustrate the assigning to price function the assignment will be done explicitly, even though it would not be necessary, since the pipes would automatically default to these functions. The Hazen-Williams coefficient for the cleaned pipes is entered as 120 (again in case of no assignment the program would default to this value). Input of data is shown below, starting at the point after option 1 was selected in the menu of the optimization routine.

```
0. KEYWORD IS GROU 1 ENTER (KEYWORD) DATA LIST
? 211 321
0. KEYWORD IS GROU 1 ENTER (KEYWORD) DATA LIST
? GROUP 2 241
0. KEYWORD IS GROU 2 ENTER (KEYWORD) DATA LIST
? GROUP 3 141 142
0. KEYWORD IS GROU 3 ENTER (KEYWORD) DATA LIST
? GROUP 4 32 33
0. KEYWORD IS GROU 4 ENTER (KEYWORD) DATA LIST
? GROUP 5 43
0. KEYWORD IS GROU 5 ENTER (KEYWORD) DATA LIST
? SIZE 1 E C 12 14 16
0. KEYWORD IS SIZE 1 ENTER (KEYWORD) DATA LIST
? SIZE 2 E C 12 14 16
0. KEYWORD IS SIZE 2 ENTER (KEYWORD) DATA LIST
? SIZE 3 8 10 12
0. KEYWORD IS SIZE 3 ENTER (KEYWORD) DATA LIST
? SIZE 4 6 8 10
0. KEYWORD IS SIZE 4 ENTER (KEYWORD) DATA LIST
? SIZE 5 6 8 10 12
0. KEYWORD IS SIZE 5 ENTER (KEYWORD) DATA LIST
```

Table 28-12. Cost Data

SIZE	PRICE FUNCTIONS 1	2
6.0	15.1	14.5
8.0	19.3	15.7
10.0	28.9	16.8
12.0	40.5	17.7
14.0	52.1	18.5
16.0	59.4	19.2

ENERGY COST .075 $/KWH

TIME PERIOD 10 YEARS

INTEREST 10.0%

```
? PRICE 1 32 33 43 141 142 211 241 321
O. KEYWORD IS PRIC 1 ENTER (KEYWORD) DATA LIST
? PRICE 2 11 41
O. KEYWORD IS PRIC 2 ENTER (KEYWORD) DATA LIST
? HWCC 120
O. KEYWORD IS HWCC  ENTER (KEYWORD) DATA LIST
?
```

As indicated above the last three entries are not necessary. The program would default to these values. The loading patterns will be specified next. Under the loads entered in the simulation routine the required pressure is 50 psi at all nodes, except nodes 21 and 41 where pressures of 40 psi and 25 psi, respectively, are acceptable. In a second loading pattern a fire load of 1000 gpm is to be added at node 32 for a total output of 1300 gpm. A minimum pressure of 20 psi is to be maintained throughout the system except at the location of the fire load, where 15 psi is acceptable. In the third loading pattern a fire load of 600 gpm is added at node 53 for a total output of 800 gpm. Again pressures should be larger than 20 psi, except at node 53 where 15 psi is acceptable. Data entry is now continued.

```
  LOAD 1 MINI 50

O. KEYWORD IS LOAD 1 ENTER (KEYWORD) DATA LIST
? MINI 21 40
O. KEYWORD IS LOAD 1 ENTER (KEYWORD) DATA LIST
? MINI 41 25
O. KEYWORD IS LOAD 1 ENTER (KEYWORD) DATA LIST
? LOAD 2 OUTPUT 32 1300
O. KEYWORD IS LOAD 2 ENTER (KEYWORD) DATA LIST
? MINI 20
```

```
O. KEYWORD IS LOAD 2 ENTER (KEYWORD) DATA LIST
? MINI 32 15
O. KEYWORD IS LOAD 2 ENTER (KEYWORD) DATA LIST
? LOAD 3 OUTPUT 53 800
O. KEYWORD IS LOAD 3 ENTER (KEYWORD) DATA LIST
? MINI 20
O. KEYWORD IS LOAD 3 ENTER (KEYWORD) DATA LIST
? MINI 53 15
O. KEYWORD IS LOAD 3 ENTER (KEYWORD) DATA LIST
? END
```

The program returns to the option menu. When taking option 2, PRINT OPT. DATA, the program prints all the data as entered (or the default values if data were not entered). The output is reproduced in Table 28-13. The optimization data as entered in this paragraph can be stored with option 3. And at a later time the data could be retrieved again under option 4 for editing to be used in another optimization run. Data stored here is limited to the optimization parameters only as printed under option 2. The system data and cost data are not part of the data stored here.

d. Executing the Optimization Routine. The user now can take option 0, OPTIMIZE. The program will respond with printing the following information.

```
IN GROUP 5:    SIZE 6.  ELIMINATED
IN GROUP 2:    SIZE 0.  ELIMINATED
IN GROUP 2:    CLEANING ELIMINATED

GROUP 1, # OF SIZES:  3
GROUP 2, # OF SIZES:  3
GROUP 3, # OF SIZES:  3
GROUP 4, # OF SIZES,  3
GROUP 5, # OF SIZES,  5

405 COMBINATIONS WILL BE TESTED.

OPTIMUM SOLUTION

GROUP      1      2      3     4     5
DIAM       E   14.0   12.0   8.0   8.0
AT COST OF       1833744.
MIN. PRESSURE           2.1

ALTERNATE SOLUTIONS
           E   16.0   12.0  10.0  12.0
MIN. PRESSURE 13.4 IN PATTERN       COST 2201232.

           E   16.0   12.0   8.0  12.0
MIN. PRESSURE 13.1 IN PATTERN       COST 2099856.

           E   16.0   10.0  10.0  12.0
MIN. PRESSURE 10.1 IN PATTERN       COST 2078736.
```

Table 28-13. Optimization Parameters

```
OPTIMIZATION PARAMETERS

GROUP ASSIGNMENTS

PIPES IN GROUP    1 :
211 321

PIPES IN GROUP    2 :
241

PIPES IN GROUP    3 :
141 142

PIPES IN GROUP    4 :
 32  33

PIPES IN GROUP    5 :
 43

PRICE FUNCTION ASSIGNMENTS

PIPES IN PRICE FCT.    1 :
 32  33  43 141 142 211 241 321

SIZE ASSIGNMENTS

GROUP #     SIZES ASSIGNED:
    1        E  12.0  14.0  16.0     C
    2        E  12.0  14.0  16.0     C
    3     8.0  10.0  12.0
    4     6.0   8.0  10.0
    5     6.0   8.0  10.0  12.0

LOADING PATTERNS

             LOADS IN GPM  AND  MIN. PRESSURE IN PSI
PATTERN #        1     *        2     *        3     *
NODE # *               *              *              *
  21    *   200.  40.0*   200.  20.0*   200.  20.0*
  22    *   300.  50.0*   300.  20.0*   300.  20.0*
  23    *   200.  50.0*   200.  20.0*   200.  20.0*
  31    *   200.  25.0*   200.  20.0*   200.  20.0*
  32    *   300.  50.0*  1300.  15.0*   300.  20.0*
  33    *   300.  50.0*   300.  20.0*   300.  20.0*
  41    *     0.  25.0*     0.  20.0*     0.  20.0*
  42    *   300.  50.0*   300.  20.0*   300.  20.0*
  43    *   300.  50.0*   300.  20.0*   300.  20.0*
  53    *   200.  50.0*   200.  20.0*   800.  15.0*

PRESSURE TOLERANCE -3. PSI
COST TOLERANCE     +3. %
```

```
            E    14.0    12.0    8.0    10.0
MIN. PRESSURE  2.1 IN PATTERN        COST 1884432.
```

The program first lists the sizes eliminated. With these sizes the pressure requirement cannot be met, even if all other sizes are kept at their maxima assigned. Then a list of all groups with the number of sizes to be tested in the group is printed. Then the total number of combinations to be considered is given. The program will not necessarily compute the flow and pressure distribution for all these combinations. Some combinations are eliminated because of their cost. Other ones can be eliminated because the pipe sizes are too small, as judged by earlier combinations which failed the pressure requirement. The program then lists the pipe sizes by group for the optimum solution, its cost, and the smallest pressure increment by which the allowable minimum pressure is exceeded at any node to be tested for pressure. The alternate solutions are Pareto Optimal, i.e. they offer better pressure at increased cost, or do not meet the pressure requirement at less cost. The program returns to the menu of the optimization routine. The user can now take option 8, PROGRAM CONTROL, followed by option 1, SIMULATION, in the program control menu. The user can balance the system once more. Note that the program automatically assigns the optimal diameters, and the most critical loading pattern. The resulting simulation output is reproduced in Table 28-14.

28-31. Example 3. The network for this example is shown in Figure 28-7. The purpose of this example is to illustrate inclusion of pumps into the optimization. In this case flow continuity in the network dictates the flow rate through the pump. During the optimization the program will ignore the characteristic curve of the pump. It will select the pump head in each loading pattern such that the lowest pressure on the downstream side of the pump is equal to the permissible minimum.

a. System Data. The system data is entered through the simulation routine. For the pump the default characteristic curve will be used with a rated discharge and head of 800 gpm and 300 ft, respectively. The line by line prompts and inputs are given below. Lines without a question mark are the prompts. The user's input appears behind the question mark.

```
PROGRAM CONTROL :

     SIMULATION         : ENTER   1   PRESS RETURN
     OPTIMIZATION       :         2
     COST DATA          :         3
     TERMINATE PROGRAM  :         9

? 1

SIMULATION ROUTINE

SELECT PROGRAM OPTION :

     TO ENTER NEW JOB   : ENTER   1   PRESS RETURN
     TO RETRIEVE DATA   :         2
```

```
? 1
S. KEYWORD IS JOB ENTER (KEYWORD) DATA LIST
? EXAMPLE 3
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 11 11 21 16 10560
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 21 21 31 14 5280
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 22 22 32 8 5280
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 31 31 41 14 5280
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 32 32 42 8 5280
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 51 51 61 8 5280
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 61 61 71 8 5280
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 121 21 22 8 5280
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 131 31 32 8 5280
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 141 41 42 8 5280
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? PUMP 41 41 51
POINT 1 ON CHARACTERISTIC CURVE:  ENTER DISCHARGE, HEAD
? 800 300
POINT 2 ON CHARACTERISTIC CURVE:  ENTER DISCHARGE, HEAD
? E
S. KEYWORD IS PUMP ENTER (KEYWORD) DATA LIST
? NODE
FOR NODE 11 ENTER ELEVATION OUTPUT
? 1000
FOR NODE 21 ENTER ELEVATION OUTPUT
? 800 100
FOR NODE 22 ENTER ELEVATION OUTPUT
? 800 200
FOR NODE 31 ENTER ELEVATION OUTPUT
? 800
FOR NODE 32 ENTER ELEVATION OUTPUT
? 780 300
FOR NODE 41 ENTER ELEVATION OUTPUT
? 800
FOR NODE 42 ENTER ELEVATION OUTPUT
? 780 1200
FOR NODE 51 ENTER ELEVATION OUTPUT
? 800
FOR NODE 61 ENTER ELEVATION OUTPUT
? 980 300
FOR NODE 71 ENTER ELEVATION OUTPUT
? 950 500
```

Table 28-14. Example 2 Final Output

PIPE NETWORK ANALYSIS AND OPTIMIZATION

JOB: EXAMPLE 2

NODE DATA

NODE NO.	ELEV. FT.	OUTPUT GPM	E.G.L. FT.	PR.HEAD FT.	PRESSURE PSI	
11	1200.0	-1123.	1200.0			RESERVOIR
21	1050.0	200.	1134.5	84.5	36.6	
22	980.0	300.	1059.5	79.5	34.5	
23	950.0	200.	1055.8	105.8	45.8	
31	1070.0	200.	1134.7	64.7	28.0	
32	970.0	1300.	1020.2	50.2	21.7	
33	950.0	300.	1155.8	105.8	45.9	
41	1090.0		1140.5	50.5	21.9	
42	960.0	300.	1087.2	127.2	55.1	
43	960.0	300.	1074.8	114.8	49.7	
51	1120.0	-2177.	1220.0	100.0	43.3	SUPPLY
53	950.0	200.	1069.1	119.1	51.6	

PIPE DATA

PIPE NO.	NODES FROM	TO	DIAM. IN.	LENGTH FT.	COEF	FLOW GPM	VEL. FT/SEC	HEAD LOSS
11	11	21	14.0	15840.0	75	1123.	2.3	65.5
21	21	31	10.0	5280.0	80	40.	.2	.2
22	22	32	8.0	5280.0	100.*	472.	3.0	39.4
23	23	33	8.0	5280.0	100.*	10.	.1	.0
31	41	31	10.0	5280.0	80.	240.	1.0	5.7
32	42	32	8.0	5280.0	120.	755.	4.8	67.0
33	43	33	8.0	5280.0	120.	382.	2.4	19.0
41	51	41	10.0	21120.0	80.	470.	1.9	79.5
43	43	53	8.0	5280.0	120.	200.	1.3	5.7
121	21	22	10.0	5280.0	80.	963.	3.9	75.0
122	22	23	10.0	5280.0	80.	190.	.8	3.7
132	32	33	4.0	5280.0	100.*	72.	1.8	35.7
141	41	42	12.0	5280.0	120.	1937.	5.5	53.2
142	42	43	12.0	5280.0	120.	882.	2.5	12.4
211	11	21	.0	15840.0	120.	0.	R	65.5
241	51	41	14.0	21120.0	120.	1707.	3.6	79.5
321	21	22	.0	5280.0	120.	0.	R	75.0

The input data is shown in Table 28-15.

The pipe diameters are arbitrary, but 'reasonable'. All pipes are to be sized, except pipe 131 which has a fixed diameter of 6 inches. The output at node 42 is 200 gpm plus a fire flow of 1000 gpm. After data entry the system is balanced. The corresponding output is shown in Table 28-16.

b. Cost Data. The input of the cost data follows the same format as used and illustrated in Example 2. After the system data is entered and the system is balanced once, the user returns to the PROGRAM CONTROL by taking option 8. From the program control menu

```
PROGRAM CONTROL:

     SIMULATION          : ENTER  1 PRESS RETURN
     OPTIMIZATION        :        2
     COST DATA           :        3
     TERMINATE PROGRAM   :        4
```

user selects option 3. The next menu is:

```
COST DATA ROUTINE
SELECT PROGRAM OPTION:

     TO ENTER NEW COST DATA    : ENTER  1 PRESS RETURN
     TO RETRIEVE COST DATA     :        2
```

Option 1 is selected. Only price function 1 will be entered, as well as energy cost, time period and interest rate.

```
C. KEYWORD IS SIZE ENTER (KEYWORD) DATA LIST
? 6 8 10 12 14 16 18 20 24
C. KEYWORD IS SIZE ENTER (KEYWORD) DATA LIST
? PRICE 1
FOR PRICE FUNCTION 1 ENTER COST/FT FOR SIZES:
FOR SIZE 6.
? 15.1
FOR SIZE 8.
? 19.3
FOR SIZE 10.
? 28.9
FOR SIZE 12.
? 40.5
FOR SIZE 14.
? 52.1
FOR SIZE 16.
? 59.4
FOR SIZE 18.
? 68.6
FOR SIZE 20.
? 80.1
```

```
FOR SIZE 24.
? 106
C. KEYWORD IS SIZE ENTER (KEYWORD) DATA LIST
? ENERGY 0.075
C. KEYWORD IS ENER ENTER (KEYWORD) DATA LIST
? YEAR 10
C. KEYWORD IS YEAR ENTER (KEYWORD) DATA LIST
? INTEREST 10
C. KEYWORD IS INTE ENTER (KEYWORD) DATA LIST
? END
```

The cost data can then be printed by taking the appropriate option in the option menu of the cost data routine. The table is printed in this routine is shown in Table 28-17.

c. Optimization Parameters. Pipe 11 is to form group 1. Diameters of 14, 16, and 18 inches are to be tried. Pipes 21 and 31 together form group 2. Diameters of 12, 14, and 16 inches are to be tried. Group 3 is to include the four pipes 121, 22, 32, and 141, with diameters including 6, 8, and 10 inches. Pipe 51 forms group 4, and pipe 61 forms group 5. Both groups are assigned pipe sizes 6, 8, and 10 inches. Three loading patterns are to be tested. In the first pattern no fire flow is to be included and a minimum pressure of 50 psi must be maintained. This pattern is typical of how the pump operates 50% of the time. In pattern 2 the water use is 70% of that in pattern 1. Again a pressure of 50 psi must be maintained at all times. This pattern is typical of how the pump is operated 50% of the time. In the third pattern the output at node 42 includes the fire load, for a total of 1200 gpm. Pressures to be maintained are at least 20 psi, except at node 42 where 15 psi is acceptable. Input of the optimization parameters follows the same format as illustrated in Example 2. The only new aspects are specification of the pump parameters. Below this input is shown, following the last prompt after specifying the minimum pressure for loading pattern 3.

```
O. KEYWORD IS LOAD 3 ENTER (KEYWORD) DATA LIST
? LOAD 1 PUMP 41 50 80
O. KEYWORD IS LOAD 1 ENTER (KEYWORD) DATA LIST
? LOAD 2 PUMP 41 50
O. KEYWORD IS LOAD 2 ENTER (KEYWC    DATA LIST
? END
```

Note that for loading pattern 3 no percentage for time running was specified for pump 41. The program defaults to zero percent, i.e. no pump cost will be included for this pattern since fire flow only occurs for a very small percentage of the time. IN determining the total cost, the program will include the pipe cost as well as the cumulative present worth of the pumping cost, according to the percentage of time running under each loading pattern. In Table 28-18 the table of the optimization parameters is shown as printed under the print option of the optimization routine. After taking option 0 (zero) in the menu of the optimization routine the program will print the following output.

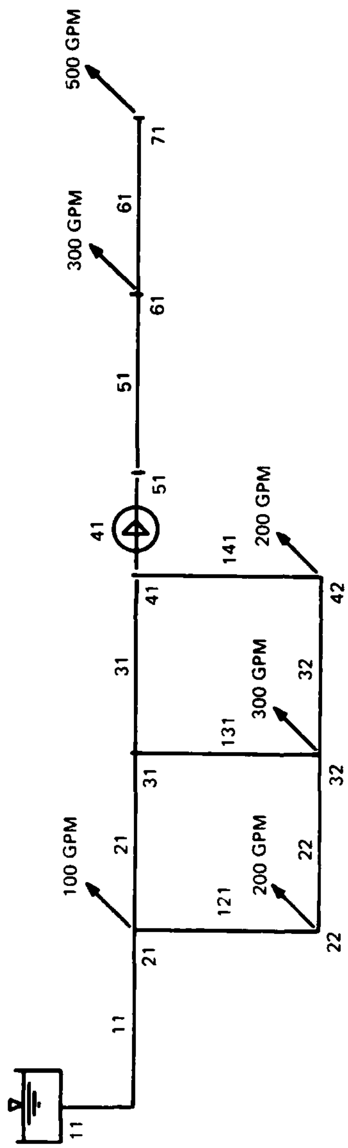


Figure 28-7. System Layout Example 3.

Table 28-15. Input Data for Example 3

PIPE NETWORK ANALYSIS AND OPTIMIZATION

JOB: EXAMPLE 3

NODE NO.	ELEV. FT.	OUTPUT GPM	
11	1000.0		RESERVOIR
21	800.0	100.	
22	800.0	200.	
31	800.0	0.	
32	780.0	300.	
41	800.0	0.	
42	780.0	1200.	
51	800.0	0.	
61	980.0	300.	
71	950.0	500.	

PIPE CONNECTIONS

PIPE NO	B NODE	E NODE	DIAM. IN.	LENGTH FT.	H-W-C	
11	11	21	16.0	10560.0	100.*	
21	21	31	14.0	5280.0	100.*	
22	22	32	8.0	5280.0	100.*	
31	31	41	14.0	5280.0	100.*	
32	32	42	8.0	5280.0	100.*	
41	41	51				PUMP
51	51	61	8.0	5280.0	100.*	
61	61	71	8.0	5280.0	100.*	
121	21	22	8.0	5280.0	100.*	
131	31	32	8.0	5280.0	100.*	
141	41	42	8.0	5280.0	100.*	

PUMP COEFFICIENTS FOR PUMP 110

Q*Q	Q	CONSTANT
-31.4761	-.0017	400.0

Table 28-16. First Output for Example 3

PIPE NETWORK ANALYSIS AND OPTIMIZATION

JOB: EXAMPLE 3

NODE DATA Page 1

NODE NO.	ELEV. FT.	OUTPUT GPM	E.G.L. FT.	PR.HEAD FT.	PRESSURE PSI	
11	1000.0	-2600.	1000.0			RESERVOIR
21	800.0	100.	936.6	136.6	59.2	
22	800.0	200.	865.5	65.5	28.4	
31	800.0		904.3	104.3	45.2	
32	780.0	300.	829.6	49.6	21.5	
41	800.0		881.4	81.4	35.2	
42	780.0	1200.	791.6	11.6	5.0	
51	800.0		1181.4	381.4	165.2	
61	980.0	300.	1076.9	96.9	42.0	
71	950.0	500.	1033.1	83.1	36.0	

PIPE DATA

PIPE NO.	NODES FROM	TO	DIAM. IN.	LENGTH FT.	COEF	FLOW GPM	VEL. FT/SEC	HEAD LOSS
11	11	21	16.0	10560.0	100.*	2600.	4.1	63.4
21	21	31	14.0	5280.0	100.*	1850.	3.9	32.3
22	22	32	8.0	5280.0	100.*	450.	2.9	36.0
31	31	41	14.0	5280.0	100.*	1537.	3.2	22.9
32	32	42	8.0	5280.0	100.*	463.	3.0	38.0
41	41	51	PUMP HEAD	300.0	FT	800.	POWER	61. HP
51	51	61	8.0	5280.0	100.*	800.	5.1	104.5
61	61	71	8.0	5280.0	100.*	500.	3.2	43.7
121	21	22	8.0	5280.0	100.*	650.	4.1	71.1
131	31	32	6.0	5280.0	100.*	313.	3.6	74.7
141	41	42	8.0	5280.0	100.*	737.	4.7	89.7

Table 28-17. Cost Data for Example 3

SIZE	PRICE FUNCTIONS 1
6.0	15.1
8.0	19.3
10.0	28.9
12.0	40.5
14.0	52.1
16.0	59.4
18.0	68.6
20.0	80.1
24.0	106.0
ENERGY COST	.075 $/KWH
TIME PERIOD	10 YEARS
INTEREST	10.0 %

```
IN GROUP 4:  SIZE 6.     ELIMINATED
IN GROUP 3:  SIZE 6.     ELIMINATED

GROUP 1, # OF SIZES:  3
GROUP 2, # OF SIZES:  3
GROUP 4, # OF SIZES:  2
GROUP 5, # OF SIZES:  3

108 COMBINATIONS WILL BE TESTED.

PUMPS WITH UNSPECIFIED CHARACTERISTIC CURVE:
PUMP #    41 FLOW  801. HEAD   294.9

OPTIMUM SOLUTION:

GROUP      1      2      3      4      5
DIAM.   16.0   12.0   10.0    8.0    8.0
AT COST OF        2020658.
MIN. PRESSURE           1.6
PRESENT WORTH OF PUMPING COST           151538.
CHARACTERISTIC CURVES MUST BE ASSIGNED TO PUMPS LISTED ABOVE
BEFORE RUNNING SIMULATION AGAIN.

ALTERNATIVE SOLUTIONS:
        18.0  14.0   8.0   10.0   10.0

MIN.PR.   2.2 IN PATTERN       3  COST  2087086.
         18.0  14.0  8.0    8.0    6.0
```

```
MIN.PR.    2.2 IN PATTERN         3  COST  2072198.
        18.0  14.0   8.0     8.0    8.0

MIN.PR.    2.2 IN PATTERN         3  COST  2026880.
        16.0  16.0   8.0     8.0    8.0

MIN.PR  -1.9 IN PATTERN          3  COST  2007309.
```

As indicated in the printout above it will be necessary to assign a characteristic curve to pump 41 since the curve entered in the simulation is no longer appropriate. The printout indicates the discharge and head required. From the menu of the optimization routine the user takes option 8 in order to return to the program control menu. Then option 1, SIMULATION, is selected. In the menu of the simulation routine option 1 is used to enter the characteristic curve (default curve for a rated discharge of 800 gpm and a head of 294.9 ft). The final output after balancing is shown in Table 28-19.

28-32. Example 4. The purpose of this last example is to show how cost of a pump with fixed characteristic curve can be included in the optimization. In Figure 28-8 the layout of the system is shown. It has three supply points, two tanks and a pump, pumping from a reservoir into the system. Unrestricted optimization, including the elimination of certain pipes as options, would certainly result in the elimination of the loop. Grouping and size ranges are used to prevent the optimization from reducing redundancies.

a. System Data. The data is entered through the simulation routine. In the program control menu option 1 (SIMULATION) is selected. In the first simulation routine menu again option 1 (TO ENTER NEW JOB) is selected. The prompt by prompt and line by line input follows.

```
S. KEYWORD IS JOB ENTER (KEYWORD) DATA LIST
? EXAMPLE 4
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? PUMP 11 11 21
POINT 1 ON CHARACTERISTIC CURVE:  ENTER DISCHARGE, HEAD
? 1500 350
POINT 1 ON CHARACTERISTIC CURVE:  ENTER DISCHARGE, HEAD
? E
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 21 21 31 16 10560
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 22 22 32 16 10560
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 31 31 41 16 10560
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 32 32 42 16 5280
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 42 42 52 16 5280
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? 121 21 22 16 5280
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
```

```
? 131 31 32 16 5280
S. KEYWORD IS PIPE ENTER (KEYWORD) DATA LIST
? NODE
FOR NODE 11 ENTER ELEVATION OUTPUT
? 100
FOR NODE 21 ENTER ELEVATION OUTPUT
? 100
FOR NODE 22 ENTER ELEVATION OUTPUT
? 350 500
FOR NODE 31 ENTER ELEVATION OUTPUT
? 350 500
FOR NODE 32 ENTER ELEVATION OUTPUT
? 350 2000
FOR NODE 41 ENTER ELEVATION OUTPUT
? 385
FOR NODE 42 ENTER ELEVATION OUTPUT
? 350 1000
FOR NODE 52 ENTER ELEVATION OUTPUT
? 400
S. KEYWORD IS TANK ENTER (KEYWORD) DATA LIST
? 11 0
S. KEYWORD IS TANK ENTER (KEYWORD) DATA LIST
? 41 80
S. KEYWORD IS TANK ENTER (KEYWORD) DATA LIST
? 52 80
S. KEYWORD IS TANK ENTER (KEYWORD) DATA LIST
? END
```

Arbitrarily all pipes were assigned a diameter of 16 inches. The pump was entered with a head of 350 ft at a discharge of 1500 gpm, using the default curve. Output of the balanced system is shown in Table 28-21.

b. Cost Data. The same cost data is used as in Example 3, see Table 28-17.

c. Optimization Parameters. Pipes 21, 31, and 131 each form one group: groups 1, 2, and 4 respectively. Pipes 22 and 121 form group 3. And pipes 32 and 42 form the fifth group. No price functions are specified, i.e. all pipes will default to function 1. Selection of size ranges is more difficult. it may not be immediately obvious that the main supply is to come through pipes 32 and 42, i.e. group 5. Experimentation in the simulation routine and/or some preliminary runs in the optimization routine can help to clarify what size ranges may be reasonable. Such experimentation shows that groups 1 through 4 can be kept small, while group 5 needs to be large. Two loading patterns are specified: the first one has loads as entered in the simulation routine, and the minimum pressure to be maintained is 40 psi. The second pattern has flow rates 50 % higher than pattern 1, and the minimum pressure must be a least 25 psi. Pattern 1 is to be used for 42 % of the time and pattern 2 for 18 %

Table 28-18. Optimization Parameters for Example 3.

```
OPTIMIZATION PARAMETERS

GROUP ASSIGNMENTS

PIPES IN GROUP    1 :
11
PIPES IN GROUP    2 :
 21  31
PIPES IN GROUP    3 :
 22  32 121 141
PIPES IN GROUP    4 :
 51
PIPES IN GROUP    4 :
 61

PRICE FUNCTION ASSIGNMENTS

PIPES IN PRICE FCT.    1 :
 11  21  22  31  32  51 121 141

SIZE ASSIGNMENTS

GROUP #    SIZES ASSIGNED:
    1   18.0  16.0  14.0
    2   16.0  14.0  12.0
    3   10.0   8.0   6.0
    4   10.0   8.0   6.0
    5   10.0   8.0   6.0

LOADING PATTERNS

             LOADS IN GPM  AND  MIN. PRESSURE IN PSI
PATTERN #       1      *       2      *       3      *
NODE # *               *              *              *
  21    *   100.  50.0*    70.  50.0*  100.  20.0*
  22    *   200.  50.0*   140.  50.0*  200.  20.0*
  31    *     0.  50.0*     0.  50.0*    0.  20.0*
  32    *   300.  50.0*   210.  50.0*  300.  20.0*
  41    *     0.  50.0*     0.  50.0*    0.  20.0*
  42    *   200.  50.0*   140.  50.0* 1200.  15.0*
  51    *     0.  50.0*     0.  50.0*    0.  20.0*
  61    *   300.  50.0*   210.  50.0*  300.  20.0*
  71    *   500.  50.0*   350.  50.0*  500.  20.0*

              PUMP EFFICIENCY %  AND  % TIME RUNNING
PATTERN #                    1 *        2 *         3 *
PUMP #  EFFIC.                 *          *           *
  41    * 80.0     *      50.0 *     50.0 *        .0 *
COEF. FOR CLEANING 120.
PRESSURE TOLERANCE -3. PSI
COST TOLERANCE     +3. %
```

Table 28-19. Final Output for Example 3, after Assigning Characteristic Curve

PIPE NETWORK ANALYSIS AND OPTIMIZATION

JOB: EXAMPLE 3

NODE DATA   Page 1

NODE NO.	ELEV. FT.	OUTPUT GPM	E.G.L. FT.	PR.HEAD FT.	PRESSURE PSI	
11	1000.0	-2600.	1000.0			RESERVOIR
21	800.0	100.	936.6	136.6	59.2	
22	800.0	200.	887.7	87.7	38.0	
31	800.0		887.6	87.6	37.9	
32	780.0	300.	856.0	76.0	32.9	
41	800.0		849.4	49.4	21.4	
42	780.0	1200.	831.9	51.9	22.5	
51	800.0		1144.3	344.3	149.2	
61	980.0	300.	1039.9	59.9	42.0	
71	950.0	500.	996.1	46.1	20.0	

PIPE DATA

PIPE NO.	NODES FROM	TO	DIAM. IN.	LENGTH FT.	COEF	FLOW GPM	VEL. FT/SEC	HEAD LOSS
11	11	21	16.0	10560.0	100.*	2600.	4.1	63.4
21	21	31	12.0	5280.0	100.*	1545.	4.4	49.1
22	22	32	10.0	5280.0	100.*	755.	3.1	31.7
31	31	41	14.0	5280.0	100.*	1348.	3.8	38.1
32	32	42	10.0	5280.0	100.*	652.	2.7	324.1
41	41	51	PUMP HEAD	294.9	FT	800.	POWER	60. HP
51	51	61	8.0	5280.0	100.*	800.	5.1	104.5
61	61	71	8.0	5280.0	100.*	500.	3.2	43.7
121	21	22	10.0	5280.0	100.*	955.	3.9	48.9
131	31	32	6.0	5280.0	100.*	197.	2.2	31.5
141	41	42	10.0	5280.0	100.*	548.	2.2	17.5

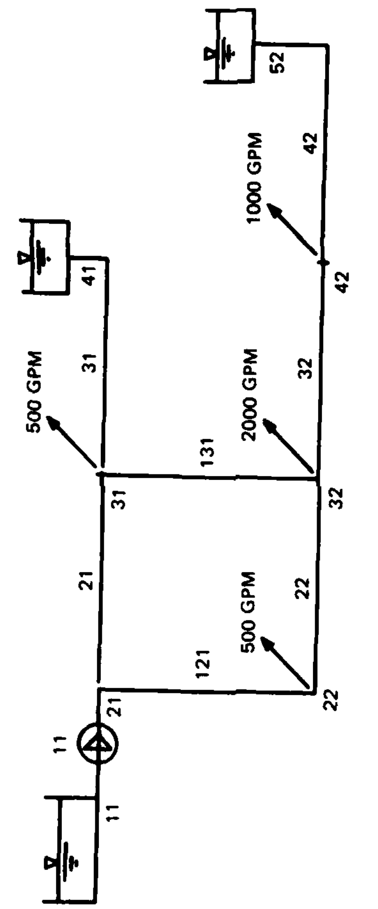


Figure 28-8. System Layout Example 4.

of the time. These percentages are specified with the keyword LOAD and PUMP. Pump efficiency is 75 %. The optimization parameters are listed in Table 28-22.

Upon selecting option 0, OPTIMIZATION, in the menu of the optimization routine the program will respond with the following output.

```
IN GROUP 3: SIZE 6.      ELIMINATED

GROUP 1, # OF SIZES:  3
GROUP 2, # OF SIZES:  3
GROUP 3, # OF SIZES:  2
GROUP 4, # OF SIZES:  3
GROUP 5, # OF SIZES:  3

162 COMBINATIONS WILL BE TESTED.

OPTIMUM SOLUTION:

GROUP       1       2       3       4       5
DIAM.     6.0     8.0     8.0     6.0    20.0
AT COST OF        2252146.
 MIN. PRESSURE            .7

ALTERNATIVE SOLUTIONS:
          6.0  10.0   8.0  10.0  20.0
MIN.PR.    5.1  IN PATTERN     1 COST   2426818.

          8.0   8.0   8.0  10.0  20.0
MIN.PR.    4.7  IN PATTERN     2 COST   2396494.

          8.0   8.0   8.0   8.0  20.0
MIN.PR.    4.6  IN PATTERN     1 COST   2346628.

          8.0   8.0   8.0   6.0  20.0
MIN.PR.    4.6  IN PATTERN     2 COST   2323994.

          8.0   6.0   8.0   8.0  20.0
MIN. PR.   3.2  IN PATTERN     2 COST   2302969.

          6.0   8.0   8.0   8.0  20.0
MIN.PR.    2.9  IN PATTERN     2 COST   2276147.
```

Since optimization was carried out with a fixed characteristic curve the user can access the simulation routine directly for a final rebalancing, before printing the output corresponding to the worst loading pattern. Note that this is pattern 2, even though some of the Pareto Optimal solutions correspond to pattern 1. The output is reproduced in Table 28-23.

Table 28-20. Input Data for Example 4

PIPE NETWORK ANALYSIS AND OPTIMIZATION

JOB: EXAMPLE 4

NODE NO.	ELEV. FT.	OUTPUT GPM		
11	100.0		RESERVOIR	
21	100.0	0.		
22	350.0	500.		
31	350.0	500.		
32	350.0	2000.		
41	385.0		TANK HEIGHT:	80.0
42	350.0	1000.		
52	400.0		TANK HEIGHT:	80.0

PIPE CONNECTIONS

PIPE NO	B NODE	E NODE	DIAM. IN.	LENGTH FT.	H-W-C	
11	11	21				PUMP
21	21	31	16.0	10560.0	100.*	
22	22	32	16.0	10560.0	100.*	
31	31	41	16.0	10560.0	100.*	
32	32	42	16.0	10560.0	100.*	
42	42	52	16.0	5280.0	100.*	
121	21	22	16.0	5280.0	100.*	
131	31	32	16.0	5280.0	100.*	

PUMP COEFFICIENTS FOR PUMP 11

Q*Q	Q	CONSTANT
-10.4454	-.0010	466.7

Table 28-21. First Output for Example 4

PIPE NETWORK ANALYSIS AND OPTIMIZATION

JOB: EXAMPLE 4

NODE DATA Page 1

NODE NO.	ELEV. FT.	OUTPUT GPM	E.G.L. FT.	PR.HEAD FT.	PRESSURE PSI	
11	100.0	-1421.	100.0			RESERVOIR
21	100.0		462.0	362.0	156.8	
22	350.0	500.	457.5	107.5	46.6	
31	350.0	500.	458.8	108.8	47.1	
32	350.0	2000.	455.5	105.5	45.7	
41	385.0	-741.	465.0	80.0	34.7	SUPPLY
42	350.0	1000.	463.3	113.3	49.1	
52	400.0	-1838.	480.0	80.0	34.7	SUPPLY

PIPE DATA

PIPE NO.	NODES FROM	TO	DIAM. IN.	LENGTH FT.	COEF	FLOW GPM	VEL. FT/SEC	HEAD LOSS	
11	11	21	PUMP HEAD	362.0	FT	1421.	POWER	130.	HP
21	21	31	16.0	10560.0	100.*	519.	.8	3.2	
22	22	32	16.0	10560.0	100.*	402.	.6	2.0	
31	41	31	16.0	10560.0	100.*	741.	1.2	6.2	
32	42	32	16.0	10560.0	100.*	838.	1.3	7.8	
42	52	42	16.0	5280.0	100.*	1838.	2.9	16.7	
121	21	22	16.0	5280.0	100.*	902.	1.4	4.5	
131	31	32	16.0	5280.0	100.*	760.	1.2	3.3	

Table 28-22. Optimization Parameters for Example 4.

```
OPTIMIZATION PARAMETERS

GROUP ASSIGNMENTS

PIPES IN GROUP    1 :
 21
PIPES IN GROUP    2 :
 31
PIPES IN GROUP    3 :
 22 121
PIPES IN GROUP    4 :
 131
PIPES IN GROUP    5 :
 32  42

PRICE FUNCTION ASSIGNMENTS

PIPES IN PRICE FCT.    1 :
 21  22  31  32  42 121 131

SIZE ASSIGNMENTS

GROUP #    SIZES ASSIGNED:
    1     6.0   8.0  10.0
    2     6.0   8.0  10.0
    3     6.0   8.0  10.0
    4     6.0   8.0  10.0
    5    18.0  20.0  24.0

LOADING PATTERNS

             LOADS IN GPM  AND  MIN. PRESSURE IN PSI
PATTERN #       1     *        2     *
NODE # *              *              *
  21   *      0.  40.0*     0.  25.0*
  22   *    500.  40.0*   750.  25.0*
  31   *    500.  40.0*   750.  25.0*
  32   *   2000.  40.0*  3000.  25.0*
  42   *   1000.  40.0*  1500.  25.0*

              PUMP EFFICIENCY %  AND  % TIME RUNNING
PATTERN #                   1 *        2 *
PUMP #  EFFIC.                *          *
  11   * 75.0    *       42.0 *      18.0 *

COEF. FOR CLEANING 120.
PRESSURE TOLERANCE -3. PSI
COST TOLERANCE     +3. %
```

Table 28-23. Final Output for Example 4

PIPE NETWORK ANALYSIS AND OPTIMIZATION

JOB: EXAMPLE 4

NODE DATA — Page 1

NODE NO.	ELEV. FT.	OUTPUT GPM	E.G.L. FT.	PR.HEAD FT.	PRESSURE PSI	
11	100.0	-1012.	100.0			RESERVOIR
21	100.0		513.6	413.6	179.2	
22	350.0	750.	419.7	69.7	30.2	
31	350.0	750.	410.0	60.0	26.0	
32	350.0	3000.	419.7	69.7	30.2	
41	385.0	-389.	465.0	80.0	34.7	SUPPLY
42	350.0	1500.	449.3	99.3	43.0	
52	400.0	-4599.	480.0	80.0	34.7	SUPPLY

PIPE DATA

PIPE NO.	NODES FROM	NODES TO	DIAM. IN.	LENGTH FT.	COEF	FLOW GPM	VEL. FT/SEC	HEAD LOSS	
11	11	21	PUMP HEAD	413.6	FT	1012.	POWER	106.	HP
21	21	31	6.0	10560.0	100.*	257.	2.9	103.6	
22	22	32	8.0	10560.0	100.*	5.	.0	.0	
31	41	31	8.0	10560.0	100.*	389.	2.5	55.2	
32	42	32	20.0	10560.0	100.*	3099.	3.2	29.6	
42	52	42	20.0	5280.0	100.*	4599.	4.7	30.7	
121	21	22	8.0	5280.0	100.*	755.	4.8	93.9	
131	31	32	6.0	5280.0	100.*	104.	1.2	9.7	

APPENDIX B: USING THE WADISO PROGRAM ON CDC CYBERNET

This appendix consists of Appendix B to the "Methodology for Areawide Planning Studies" (Engineer Manual 1110-2-502). It describes how to access the program on the CDC Cybernet Computer System, run the program, and use different files.

APPENDIX B

RUNNING THE WADISO PROGRAM ON CDC CYBERNET

B-1. Introduction. In order to run the WADISO program, the user must call the program from storage and start the program. This procedure varies from one computer to another, so it is not included in the user's guide. The procedure for the CDC Cybernet System is described below. Before the description of how to run the program on CDC, there is a short introduction on CDC computer file terminology and a description of the logon procedure.

B-2. Overview. After illustrating how to run the program for simple cases, subsequent paragraphs describe how to direct program output to a file, how to run the program in batch mode and how to list, edit, and recompile the source program. Those familiar with the CDC Cybernet system can skip the sections on File Terminology and Logon-Logoff procedure.

B-3. File Terminology. Before using the water distribution program, the user needs to understand the terminology for describing files. These terms are described below.

B-4. Program vs. Data. Files can either contain programs or data. Program files contain the program while data files contain data used to run the program, or, in some cases, output from previous runs.

B-5. Text vs. Binary. The information in the files can be stored as text or binary information. Binary files are written in machine language and cannot be listed or modified using the system editor. The WADISO program that is run by the user is a binary, program file. The data files created when pipe network data is stored using WADISO are binary, data files. Text files are created using the system editor and can be examined and modified using the editor. Most users do not need text files. However, the Fortran source listing of the program, which is called SWADISO, is a text, program file. Text, data files can also contain commands to submit runs as batch jobs and lines of output which the user did not wish to view as the program was running.

B-6. Permanent vs. Local. Files on the CDC Cybernet System can also be classified as permanent or local. Permanent files exist on disk at the site of the computer. In order to use these files, the user must make them local by issuing a GET command (e.g. GET,WADISO). Local files are lost when the user logs off the system. To save these files for future use, the user issues a SAVE or REPLACE command (e.g. REPLACE,MYFILE). The SAVE command can only be used if a permanent file with that name does not already exist.

B-7. Interactive Run. While the above sounds fairly complicated, for the simplest case, the user need only know that the binary program file is called WADISO and is a permanent file on account CECELB. To run the program, the user need only enter

/GET,WADISO/UN=CECELB
/WADISO

Of course the user must have already logged onto the system. That procedure is explained below. (In the following sections, entries typed by the user are underlined. The / at the start of each line represents the CDC System prompt. (User's responses are underlined.))

B-8. Logon/Logoff. The user must obtain a telephone number for access to the Cybernet system from a Cybernet sales representative for the user's area or the local Corps ADP coordinator. Once the user has dialed the appropriate Cybernet telephone number and the terminal is connected to the system, he receives the message

83/09/26/ 15.34.54.AA245IA
EASTERN CYBERNET CENTER SN487 NOS 1.4/531/.281/17AD
FAMILY: KOE

USER NAME:

to which he enters his assigned account number. For example, the user may enter

USER NAME: CEQQXX

He then receives the message

PASSWORD:

to which he enters his assigned password. For example, the user may enter

PASSWORD: PASSWD

He then receives the message

TERMINAL: 510, NAMIAF
RECOVER/CHARGE: CHARGE, ___________ , ___________

to which he enters his assigned charge number and project name. For example the user may enter

CHARGE,CHRGNO,ZZZZ

He then receives the message

$CHARGE,CHRGNO,ZZZZ/ /07.02.22./

The system responds with a slash mark (/) which indicates that the user is in the batch subsystem. Two question marks (??) indicate that the user is in the edit mode and a single question mark (?) indicates that the user is in the input mode. If the user should make a mistake while logging on and the system prompts APPLICATION: the user should enter "IAF" for interactive facility. To logoff the system, the user types BYE in response to a / prompt. The computer responds by printing out some accounting information for the session before dropping the phone line.

B-9. Interactive Runs-No Existing Data File. The simplest way to run the WADISO program consists of the user making WADISO a local file using the GET command and then starting the program using the command WADISO.

```
/GET,WADISO/UN=CECELB
/WADISO
```

The first question asked by the program is

```
PROGRAM CONTROL:
     SIMULATION           :    ENTER 1 PRESS RETURN
     OPTIMIZATION         :          2
     COST DATA            :          3
     TERMINATE PROGRAM    :          4
```

To enter a new system the user must enter the simulation routine by answering with "1". The next prompt is

```
SELECT PROGRAM OPTION:
     TO ENTER NEW SYSTEM:  ENTER 1 PRESS RETURN
     TO RETRIEVE DATA:  2
```

In this case, the user must answer "1." The "2" response can only be issued if the user has a local, binary, data file created during a previous run. To use the program as described above, the user must enter all the system data each time the program is run. This would quickly get tiring. The user can, however, store the data in a local, binary, data file by typing "3" in response to the simulation menu as described in the user's guide. The user is then asked to give a name to this file.

B-10. Saving File Created During Run. Suppose the user calls it "MYFILE." MYFILE is a local, binary, data file and because it is local it will be lost when the user logs off the system. To make the file permanent, the user must issue a SAVE or REPLACE command before logging off the computer. For example

```
/SAVE,MYFILE
```

If the file MYFILE is already permanent, the command must be REPLACE instead of SAVE. The user can also save MYFILE under a different file name (say DATA1) by entering

```
/SAVE,MYFILE=DATA1
```

Once the file is saved, the user can logoff or rerun the program. If the user wishes to rerun the program using the data just entered, he need only enter

/WADISO

In response to the "SELECT PROGRAM OPTION" question, he should answer "2." The program will then ask for the local, data file name, to which the user should respond

MYFILE

While only one file is required to store data for simulations, three files are needed to store all of the data for optimization. One file contains the simulation data needed to describe the system, the second contains cost data and the third contains information on which pipes are to be optimized. Suppose the user creates these three files called SIMDAT (Simulation Data), COSDAT (Cost Data) and OPTDAT (Optimization Data). These files can be made permanent after a run using the command

/SAVE,SIMDAT,COSDAT,OPTDAT

or

/SAVE,SIMDAT
/SAVE,COSDAT
/SAVE,OPTDAT

B-11. Interactive Runs-Existing Binary Data File. It is seldom possible to complete a pipe network analysis in one session at the computer. Eventually, the user must log off the computer. When the user logs on again, he would like to start up where he left off and not have to reenter all of his data again. This is possible, if before logging off the previous session, he made his binary, local, data file into a permanent file (call it MYFILE for this example). To run WADISO in this instance, the user must make the binary program file and binary data file local.

/GET,WADISO/UN=CECELB
/GET,MYFILE
/WADISO

If this is to be an optimization run and the user has three optimization files, he would enter

/GET,SIMDAT,COSDAT,OPTDAT
instead of /GET,MYFILE.

To the question, "SELECT PROGRAM OPTION," the user would answer "2" and would then supply the binary, data file name "MYFILE."

B-12. Replacing Existing Data Files. If the user wishes to save changes made to the data, during this run and subsequent runs, he must issue a STORE DATA (i.e. "3") in response to the main menu which makes changes to the local file, and must replace the local file using

/REPLACE,MYFILE

which makes the local, binary, data file permanent. If the user wishes to save the data in MYFILE as originally created and save any changes in another file (say MYFILE2), the user would enter

/REPLACE,MYFILE=MYFILE2

In this case, there will be two permanent, binary data files: MYFILE containing the original data and MYFILE2 containing the updated data.

B-13. Interactive Runs-Text Data File. Some users, especially those familiar with the CDC Cybernet Editor, may prefer to build data files using the Editor and not bother with binary data files. (The CDC Cybernet Editor is called "XEDIT.") This has some advantages in that the user can modify and list data without using the program, merge files to build large networks from small ones and use the data files for batch runs later. The primary disadvantage is that the user must learn how to use the editor. Suppose the user wants to build a text data file (called TDATA) using the editor to run example problem 1 in the user's guide. The file, listed below, contains all of the information the user would enter in response to prompts during an interactive run. (Another disadvantage to using text data files is that the user must be able to anticipate all of the menus and prompts provided by the program.)

```
1 For first menu (Program Centres).   Simulation Data
1                                     New Data
EXAMPLE 1                             Job Card
101 2 3 12 2000
102 3 6 10 1500
111 12 13 12 5000
112 12 15 8 1500
114 15 16 8 1500
123 34 35 8 1500                      Pipe Data
124 35 36 8 1500
11 3 13 8 1800
13 6 16 10 1000
31 13 33 8 1000
32 25 35 8 1000
33 26 36 8 1000
```

PRV 22 15 25 60 23 16 26 60 122 33 34 60	PRV Data
PUMP 110 11 12 600 143 1000 130 1400 111	Pump Data
NODE 950 910 905 50 950 970 920 890 80 890 75 890 890 870 50 870 870 75 850 1500 11 0 2 100 END	Node Data
0	Run Simulation
9	Stop Program

Values like 1, 0, and 9 are responses to various menus. When file TDATA is created it will be local. The user may want to make it permanent with a /SAVE,TDATA command. To run the program, the user need only GET, WADISO and start the program.

/GET,WADISO/UN=CECELB
/WADISO,TDATA

If TDATA was not already local, the user would first need to make it local using

/GET,TDATA

The printout will contain all of the prompts and menus issued by the program. If the user receives an "END-OF-FILE" error message when attempting to start WADISO, he should REWIND,TDATA and rerun the program. If data are entered out of order it is possible for the program to become stuck on a given menu. The user must correct the error before running the program.

B-14. Directing Output to a File. The user may not want to view all of the output from a run when a text data file is used, or he may wish to save output to a file (say TOUT). To do this the user enters

/GET,WADISO/UN=CECELB
/GET,TDATA
/WADISO,TDATA,TOUT

The program will respond with a message indicating how many CP seconds were used to run the program. The user can now make TOUT permanent if he wishes by entering

/SAVE,TOUT

He can list TOUT in its entirety by entering

/REWIND,TOUT
/LIST,F=TOUT

B-15. Examining Output with Editor. The user can use the editor to look at certain lines of output, or to skip all prompts and menus and print only the hydraulic output. To skip the menus the user enters

```
/XEDIT,TOUT
 EDIT MODE
 ??L/ACCUR/
 ACCURACY LIMITS  10 GPM; 2 PSI
 ??P  *
(Output will appear here)
```

B-16. Directing Output to RJE Printer. The output file can also be directed to a remote job entry (RJE) terminal printer by entering

/REWIND,TOUT
/ROUTE,TOUT,DC=PR,UN=account

where account is the user's account number.

B-17. Running Program Remote Batch-Existing Text Data File. When the user is learning to use the program, entering data for a study or analyzing a small system, the user can make the most out of the program by running it interactively. For large networks, however, once the data files have been debugged, the user can save a considerable amount of money by running the program batch. To run the program batch, the user sets up a batch job file and submits it to the computer. The speed with which the computer works on the batch job depends on the priority assigned to the job by the user and the computer's workload. If the job has a priority of 5, it will be processed almost immediately after it is submitted at a cost roughly one half of interactive processing. If it is submitted with a priority of 2, it will usually be processed overnight at one twentieth the cost of interactive processing. The savings using batch job processing can be quite significant. A typical batch job file (called BATCH) is shown below.

```
XEDIT,BATCH
Edit Mode
??(Hit Return)
Input
?/JOB
?EXAMPLE,P5.
?/USER
?/CHARGE
?GET,WADISO.        }    Getting Files
?GET,TDATA.         }

?WADISO,TDATA,TOUT. }    Running Program

?REPLACE,TOUT.      }
?DAYFILE,DAYF.      }    Saving Output and Dayfile
?REPLACE,DAYF.      }

?EXIT.              }
?DAYFILE,DAYF.      }    Saving Output and Dayfile if Error
?REPLACE,DAYF.      }
?REPLACE,TOUT.      }
?/EOR               }
?(Hit return)
??END,BATCH,SAVE
```

The JOB, USER and CHARGE statements indicate that the batch job is to be charged to the same account as the user logged onto the system. The 'EXAMPLE,P5' card assigns the job a name and a priority (5). If P2 was used, the job would have a priority of 2. The next several commands are similar to those for running WADISO from a text, data file. TDATA and TOUT are described earlier. The DAYFILE commands save some job accounting information and system error messages.

B-18. Submitting Batch Job. To submit the batch job, the user enters

/SUBMIT,BATCH

The batch job commands do not need to be in the file called BATCH. Any file name can be assigned to that file (e.g. SUBMIT,BFILE). When the user submits the job, the computer will respond with a job number (e.g. ACF2JGG). The user can check on the status of the job using the 'ENQUIRE' command and the last three digits of the job number. For example,

/ENQUIRE,JN=JGG

If the system responds 'JOB NOT FOUND,' the job is complete. The user can then GET the output file and, if needed, the dayfile by entering

/GET,TOUT,DAYF

The user can look at these files using the LIST command or the editor as described earlier.

B-19. Deleting Files. Since output files are fairly large, permanent files, and hence costly to store, they should be deleted after they have been listed. This can be done using the PURGE command as

/PURGE,TOUT

B-20. Listing Source Version. Occasionally, a user may want to obtain a listing of the text, source file of the program. This file is called SWADISO and is stored under another account number. The user generally does not have permission to access this file. To obtain READ ONLY access, the user should call the program developers (601-634-3931). They will give the user access to the program and tell the user the account number under which it is stored. The user can then make the file local by entering

/GET,SWADISO/UN=account

where account is the account number under which the program is stored. The user can then save PIPNET under his account by entering

/SAVE,SWADISO

The user can use the editor to examine or modify the program or list the entire program by entering

/LIST,F=SWADISO

B-21. Compiling the Program. Users are discouraged from modifying the program. However, if they need to modify the program, they must edit their own copy of the text, program file (SWADISO or some other name if they have changed the program name), recompile the program (i.e. make a new, binary program file) and save that file. To recompile the file, the user must make the text, program file local and invoke the Fortran V compiler.

/GET,PIPNET
/FTN5,I=PIPNET,SEQ,L=LIST,B=progname

This command creates a local binary program file called whatever name is used for 'progname' (say WADISO2). The user can then make this version permanent on his own account by entering

/SAVE,WADISO2

To use this version of the program, the user enters

/GET,WADISO2

instead of

/GET,WADISO/UN=CECELB

as described in earlier sections. The file LIST (see FTN5 command above) is a local, text file which contains a listing of the program plus compiler diagnostic messages. If the user only wants to see error messages, if any, he should substitute L=0 for L=LIST in the FTN5 statement. If there are errors in the compilation, and the user wishes to try again, he should rewind all files before reissuing the FTN5 command. For example,

/REWIND,PIPNET,LIST,WADISO2

B-22. Recovering a Lost Connection. During a run of the program, the terminal may be accidentally disconnected from the system, or a system malfunction may require that the login process be restarted, or the terminal may be logged off by the system after ten minutes of inactivity. The user then has twenty minutes to recover the connection by restarting the login process and following the sequence to the point where the system requests

RECOVER/CHARGE:

The user now enters

RECOVER/CHARGE: RECOVER,xxx

where xxx is the terminal number being used when the broken connection occurred. In the example logon shown earlier, the terminal number is 510. This number may be found in the initial login sequence immediately before the request for USER ID in the form TERMINAL: xxx, NAMIAF or by executing ENQUIRE. The system should then respond

RECOVERY COMPLETE
LAST COMMAND - command
NEXT OPERATION

The user should then hit a carriage return and proceed from the point where the broken connection occurred. If an error message is received, the user has either allowed the twenty-minute recovery period to elapse or has used an incorrect terminal number. He should then check the number and repeat the process. Sometimes recovery is not possible.

APPENDIX C: OBTAINING PROGRAM AND DOCUMENTATION

1. This appendix describes how the WADISO (Water Distribution Simulation and Optimization) program and documentation can be obtained. Different rules are required for Corps of Engineer and non-Corps users. Transferring the program to other computers is also discussed.

Obtaining Documentation

2. Detailed documentation of the WADISO program has been published as Chapter 28 of Part 2 of the MAPS (Methodology for Areawide Planning Studies) manual, which is Engineer Manual EM 1110-2-502. Copies of the entire MAPS manual can be obtained from:

USACE Publications Depot
2803 52nd St.
Hyattsville, MD 20781
301-436-2063

The WADISO program was issued as Change 5 to the MAPS manual (EM 1110-2-502), so be certain to obtain a version of the manual that includes Change 5.

3. The documentation of the program is difficult to follow without a listing of the program. A listing and a copy of the documentation only (i.e. without documentation for the rest of the MAPS manual) can be obtained from:

US Army Engineer Waterways Experiment Station
ATTN: Dr. Thomas Walski, WESEE-R
P.O. Box 631
Vicksburg, MS 39180-0631
601-634-3931
FTS 542-3931

Corps Users

4. The US Army Engineer Waterways Experiment Station (WES) will support an executable version of the WADISO program on the Corps-wide library on the the CDC Cybernet computer system under account CECELB. This is the only version that will be supported by WES. Instructions on how to access the program are given in Appendix B of this report. Corps users with technical questions about the program should contact Walski at the above address.

Non-Corps Users

5. Non-Corps users can obtain a copy of the source program by furnishing a blank magnetic tape to:

US Army Engineer Waterways Experiment Station
ATTN: Engineer Computer Program Library
P.O. Box 631
Vicksburg, MS 39180-0631
601-634-2581
FTS-542-2581

The Engineer Computer Program Library (ECPL) will make a copy of the program on the tape at no charge. WES does not however provide support for the program for non-Corps users. Technical assistance can be obtained from:

Dr. Johannes Gessler
Dept. of Civil Engineering
Colorado State University
Ft. Collins, CO 80523
303-428-8021

There will be a charge to cover the costs of providing the assistance.

Transferring Program to Other Computers

6. The WADISO program was developed in CDC Extended Fortran V in sequential format (i.e. line numbered files). With very few exceptions, the program is consistent with Fortran 77. The program occupies roughly 140K octal memory on a Cybernet 175. The program should therefore fit on most computers. Overlaying the program and reducing the size of dimensioned arrays can help the program fit on smaller machines.

7. The primary restrictions to converting the program to other computers are the anomalies in the Fortran compilers on various machines. Those converting the program are expected to be intimately familiar with the Fortran compiler on their computer. Long-range plans for WADISO include development of a microcomputer version.

APPENDIX D: THE NATURE OF PIPE SIZE SELECTION

Introduction

1. Selecting optimal pipe sizes initially appears to be the type of constrained optimization problem that is amenable to solution by one of the standard optimization techniques such as linear programming or dynamic programming. However, the problem is considerably more difficult than first imagined because: (a) evaluation of the hydraulic constraints requires solving complex systems of nonlinear equations; (b) the cost function is nonlinear and may have local minima; (c) pipes are only available in discrete diameters; (d) energy costs in the objective function can only be evaluated by solving the network hydraulics; and (e) the objective function is not one of merely minimizing costs with hydraulic constraints but minimizing costs subject to a requirement to provide redundancy, which may be difficult to describe mathematically.

2. In the following sections, some simple examples are presented to illustrate the problems involved in selecting optimal, discrete pipe sizes. First some formulas are developed for determining the optimal continuous pipe size for pipes in series. These formulas are reconciled with the discrete nature of pipe sizing decisions with an example with two pipes in series first with a single design flow rate, then secondly as the design flow varies spatially. Another problem with four pipes in series illustrates how selection of optimal pipe sizes changes in a somewhat unpredictable manner when only discrete pipe sizes are allowed.

3. Parallel pipes are usually considered when reliability is important. First, it is shown that parallel pipes are more expensive than a single pipe with equal capacity. Then, trade-offs between pipe sizes and required redundancy are illustrated using some examples involving two pipes.

Examples

Pipes in series (continuous diameters)

4. Given the flow that must be carried in a length of pipe and the allowable head loss, the optimal (least capital cost) pipe diameters can be determined using Lagrangian multipliers. The initial cost of n pipes in

series can be given by

$$T = \sum_{i=1}^{n} AL_iD_i^b \qquad \text{(D1)}$$

where

T = total cost of pipe, \$

n = number of pipes

A,b = coefficients in function relating cost per length of pipe to diameter

L_i = length of i-th pipe, L

D_i = diameter of i-th pipe, L

If h feet of head can be lost in the pipe, the head loss constraint can be given as

$$h \geq \sum_{i=1}^{n} KL_iQ_i^MD_i^{-m} = h_{act} \qquad \text{(D2)}$$

where

h = allowable head loss, L

K = units conversion factor

Q_i = flow in i-th pipe, L^3/T

M,m = exponent on flow and diameter in head loss equation

h_{act} = actual head loss, L

When Q is given in gallons per minute, D is given in inches, M and m are 1.85 and 4.87 (from Hazen-Williams equation), and h and L are in the same units, K is $10.4/C^{1.85}$ where C = Hazen Williams C-factor.

5. The lowest cost (smallest acceptable pipe diameter) will be obtained when Equation D2 is a strict equality. Letting $F_i = KQ_i^M$ gives

$$h = \sum_{i=1}^{n} F_iL_iD_i^{-m} \qquad \text{(D3)}$$

where

$$F_i = KQ_i^M$$
$$= [10.4\ (Q_i/C_i)^{1.85} \text{ for Hazen-Williams equation}]$$

The Lagrangian function can be given by

$$Y = \sum_{i=1}^{n} AL_i D_i^b + y \left(\sum_{i=1}^{n} F_i L_i D_i^{-m} - h \right) \qquad \text{(D4)}$$

where

Y = Lagrangian function, \$

y = Lagrangian multiplier, \$/L(head)

6. To find the optimal pipe diameters, differentiate Equation D4 by each D_i and y and set the results equal to 0. This gives a system of n + 1 equations with n + 1 unknowns (n D_i's and y). The first n equations are of the form

$$\frac{dY}{dD_i} = 0 = AbD_i^{b-1} - myF_i D_i^{-m-1} \qquad , i = 1, 2, \ldots n \qquad \text{(D5)}$$

and one equation of the form

$$\frac{dY}{dy} = 0 = \sum_{i=1}^{n} \left(F_i L_i D_i^{-m} \right) - h \qquad \text{(D6)}$$

which is equivalent to Equation D3. Since A, b, m, and y are constants for a given problem, Equation D5 can be rearranged to give a relationship between any two diameters D_i and D_j

$$D_i = \left(\frac{F_i}{F_j} \right)^{1/(b+m)} D_j \qquad \text{(D7)}$$

Equation D7 can be substituted into Equation D6 and solved for the diameter of a specific section of pipe (say j)

$$D_j = \left\{ \frac{\left[\sum_{i=1}^{n} F_i L_i (F_j/F_i)^{1/(1+b/m)} \right]}{h} \right\}^{1/m} \qquad \text{(D8)}$$

Once a single diameter D_j is determined using Equation D8, the remaining diameters can be determined using Equation D7.

7. Once one of the optimal pipe sizes have been determined, y can be calculated as

$$y = \frac{AbD_i^{(b+M)}}{mF_i} \tag{D9}$$

The Lagrangian multiplier y is the sensitivity of the cost of the optimal solution with respect to the value of the constraint (i.e. $\partial Y/\partial h$).

8. Use of Equations D7 and D8 is now illustrated by an example shown in Figure D1. Consider two 10,000-ft-long pipes in series with a Hazen-Williams C of 120. The allowable head loss is 100 ft and the flow in pipe 1 (2Q) is twice that of pipe 2 (Q). Use $A = 1.0$, $b = 1.4$, and $m = 4.87$.

9. From Equation D3

$$F_1 = \frac{10.4(2Q)^{1.85}}{120^{1.85}} = 0.00534Q^{1.85}$$

$$F_2 = \frac{10.4(Q)^{1.85}}{120^{1.85}} = 0.00148Q^{1.85}$$

$$L_1 = L_2 = 10{,}000$$

The diameter of pipe 1 can be given by Equation D8

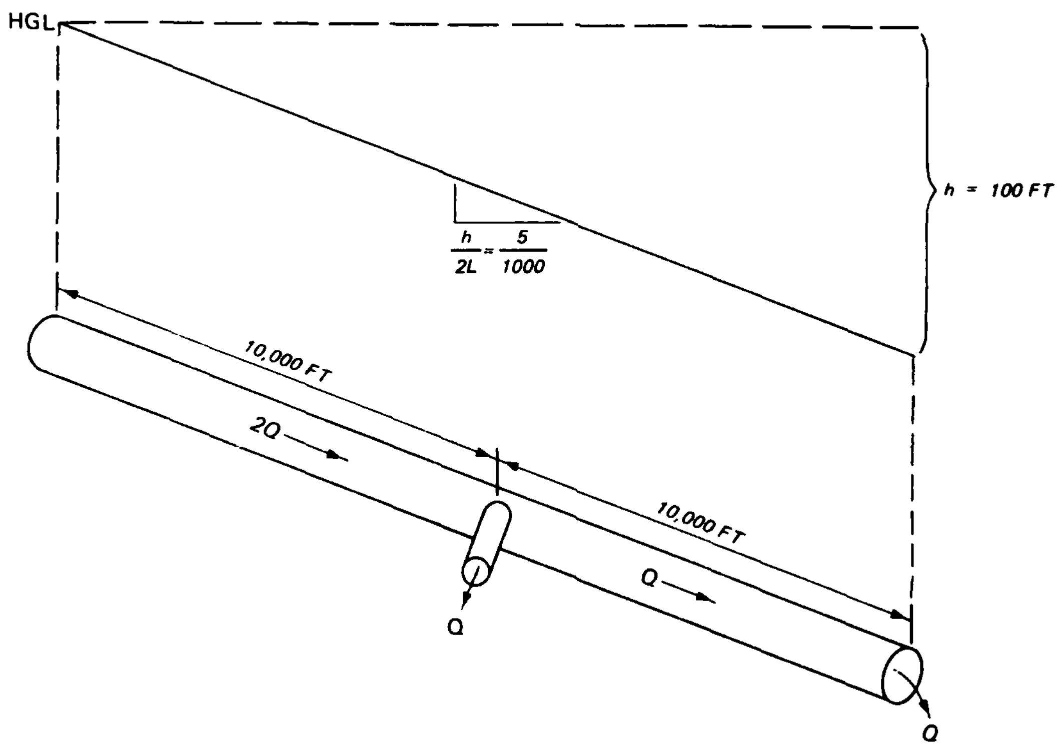


Figure D1. Example with two pipes in series

$$D_1 = \left[\frac{0.00534Q^{1.85}(10{,}000) + 0.00148Q^{1.85}(10{,}000)(0.00534/0.00148)^{\frac{1}{1+1.4/4.87}}}{100}\right]^{1/4.87}$$

$$= \left[\frac{(53.4 + 40.1)Q^{1.85}}{100}\right]^{0.205} = 0.986Q^{0.379}$$

For any flow Q , D_1 can be calculated as above and D_2 can be given by Equation D7

$$D_2 = \left(\frac{0.00148}{0.00534}\right)^{0.159} D_1 = 0.815\ D_1 = 0.804\ Q^{0.379}$$

Given the flow Q that is withdrawn from the end of the second pipe and the connection between pipes 1 and 2, the optimal pipe diameters are given in Table D1.

10. Suppose Q is 10,000 gpm. The pipe sizes would be 32.3 and 26.0 in., respectively, and the total cost would be

$$TC = 1.0(10{,}000)\ 32.3^{1.4} + 1.0(10{,}000)26.0^{1.4} = \$2{,}253{,}943$$

Table D1

Optimal Pipe Diameters for Example Problem

Q gpm	D_1 in.	D_2 in.	V_2 ft/sec	Cost 10^6\$
100	5.65	4.54	1.98	0.20
200	7.34	5.90	2.35	0.28
500	10.4	8.36	2.93	0.46
1,000	13.5	10.9	3.44	0.67
2,000	17.6	14.1	4.12	0.96
5,000	24.9	20.0	5.12	1.56
10,000	32.3	26.0	6.07	2.25
20,000	42.1	33.8	7.18	3.26
50,000	59.5	47.9	8.93	5.30
100,000	77.4	62.2	10.6	7.65

The sensitivity of the cost to change in the head loss requirement can be determined as

$$y = \frac{1.0(1.4)(32.3)^{(4.87+1.4)}}{(4.87)(0.00534)(10,000)^{1.85}} = \$6,219/\text{ft}$$

The above means that there will be a savings of $6,219 for every foot by which the head loss constraint is relaxed.

11. Column 4 of the table shows the velocities in pipe 2 corresponding to the optimal diameter. This column illustrates two important points: (a) in systems in which allowable head loss is fixed, the velocity corresponding to optimal pipe size is not a constant (i.e. rules of thumb such as velocity = 5 ft/sec at peak flow are invalid for selecting least costly piping), and (b) the optimal diameter as determined by the approach described in this section may result in very high velocities (in such cases the cost of surge control as a function of diameter should be considered).

12. In summary, if pipe diameter can be treated as a continuous variable, it is possible to select optimal pipe sizes for pipes in series given design flow and allowable head loss at one point in the system.

Pipes in series (discrete diameters)

13. Pipes are commercially available only in certain discrete pipe sizes, so it is unlikely that the pipe sizes determined in the previous section can be purchased. Rounding off continuous pipe diameters is not as easy as it may seem at first since one will not obtain an optimal solution if all of the diameters are rounded up, yet one cannot be sure of meeting the head loss constraints if diameters are simply rounded to the nearest diameter.

14. The problem of selecting optimal discrete pipe sizes can be illustrated by showing the solution of the previous example in the discrete domain (Figure D2). Solution to the problem only exists at the dots. The value above a point is the cost in tens of thousands of dollars while the value below is the flow in thousands of gallons per minute. The straight line in the graph corresponds to the continuous solution (i.e. $D_2 = 0.815 D_1$). (Note that to keep the graph from becoming too cluttered some sizes (e.g. 14, 10, 8) were omitted.)

15. As the required flow increases, the optimal solutions in the discrete domain change as indicated by the arrows. Note that discrete optimal

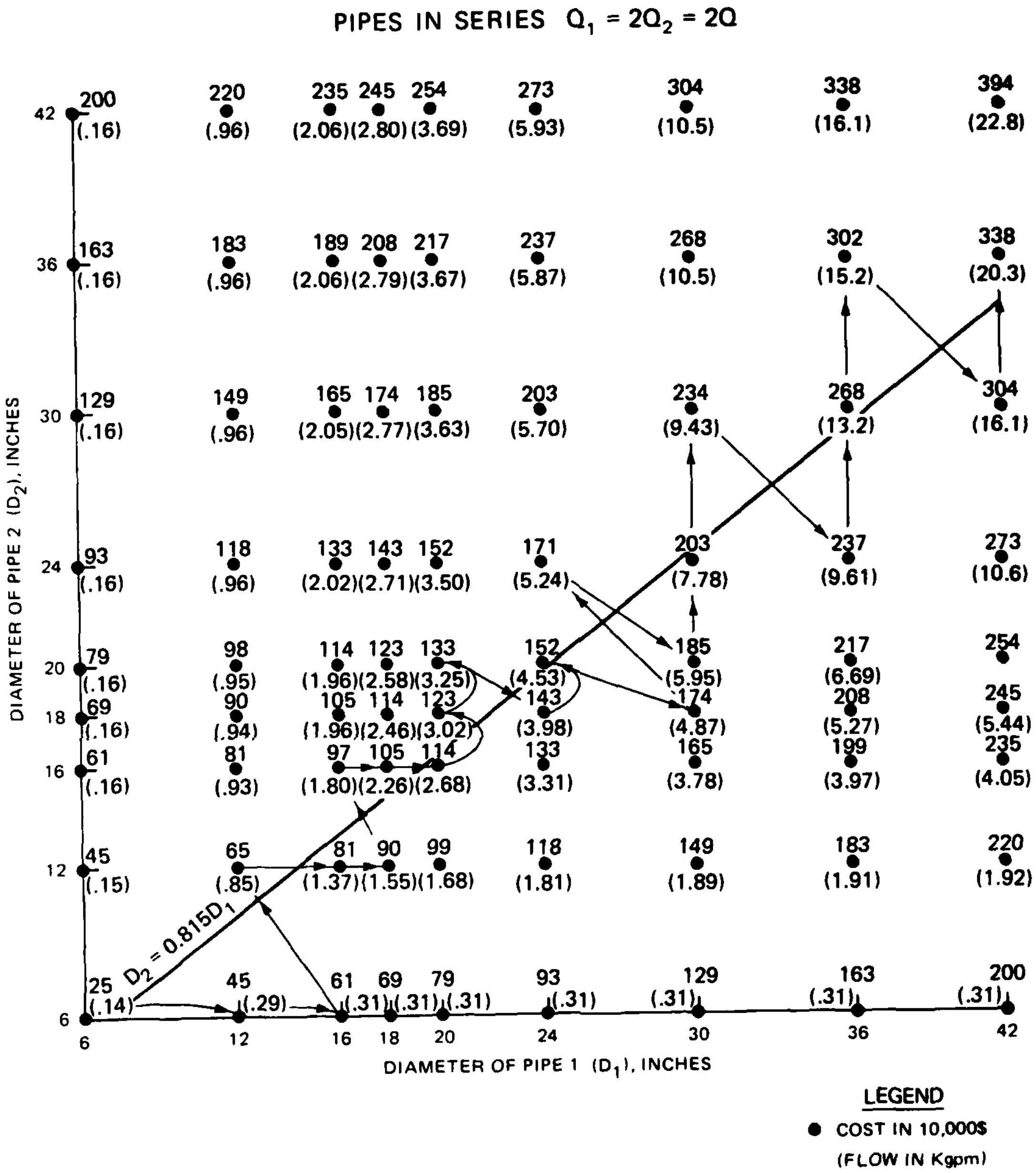


Figure D2. Graphical solution for two pipes in series

solutions lie close to the line corresponding to the continuous solution. For example, when the flow is between 3,020 and 3,250 gpm, the optimal solution is (D_1 = 20 in., D_2 = 20 in.), but when the flow increases to 3,260, the optimal solution is (D_1 = 24 in. and D_2 = 18 in.). The optimal continuous solution for Q = 3,260 gpm is (D_1 = 21.1 in. and D_2 = 17.2 in.). The rounding off of the continuous solutions is not intuitively obvious. Discrete optimal solutions at flows corresponding to some of the flows in Table D1 are presented in Table D2.

Table D2

Discrete Optimal Solutions

Q gpm	D_1 in.	D_2 in.
1,000	16	12
2,000	18	16
5,000	24	24
10,000	36	30
20,000	42	36

16. For a problem involving two pipes, a graphical solution is feasible. With three pipes, the optimal continuous solution becomes a plane in space. For n pipes the optimal solution is a hyperplane in hyperspace. When the number of pipes is reasonable, it is possible to enumerate all logical combinations of pipe sizes to determine the cost and performance of each alternative. (In the previous example the performance was indicated by the flow at a given head loss; performance could have also been characterized by the head loss or pressure at a given flow.)

17. Selecting the optimal discrete pipe size is usually a fairly complicated process requiring trial and error. Figure D3 shows a simple system involving four pipes in series. The candidate diameters for each pipe are shown below each pipe. The cost of the system and discharge from each pipe Q are shown for each combination of pipes in Figure D4. Ideally the engineer would select pipe combinations that are near the bottom of the band of points in the figure since these points represent the combinations that will deliver the flow at the least cost. The continuous optimal solution is shown as the solid line in Figure D4. The ratio of diameters of the segments of pipe in the continuous solution is 1.0:0.919:0.818:0.655. Good solutions to the discrete problem lie close to the continuous optimal.

18. Figure D5 is a section of Figure D4 for the flows between 12,000

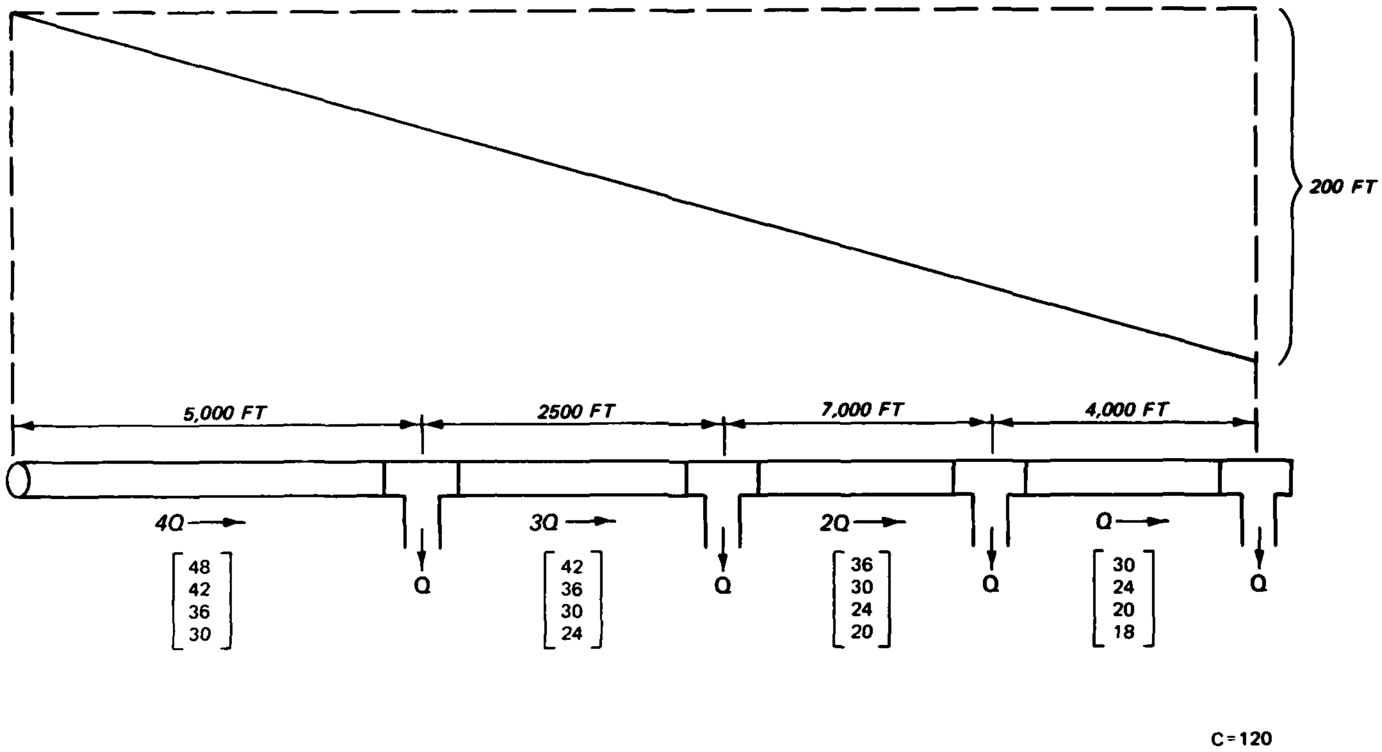


Figure D3. Example with four pipes in series

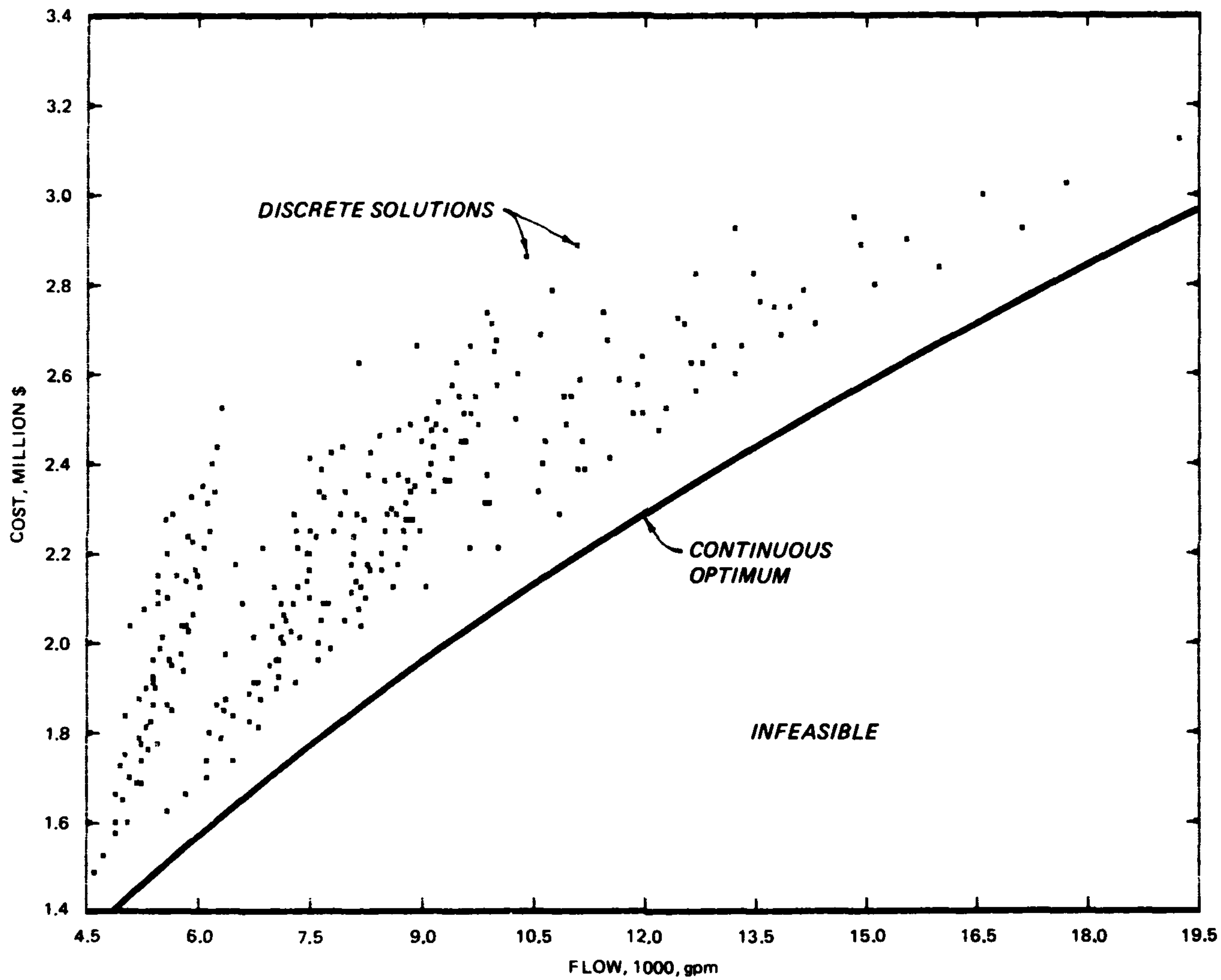


Figure D4. Solution with four pipes in series

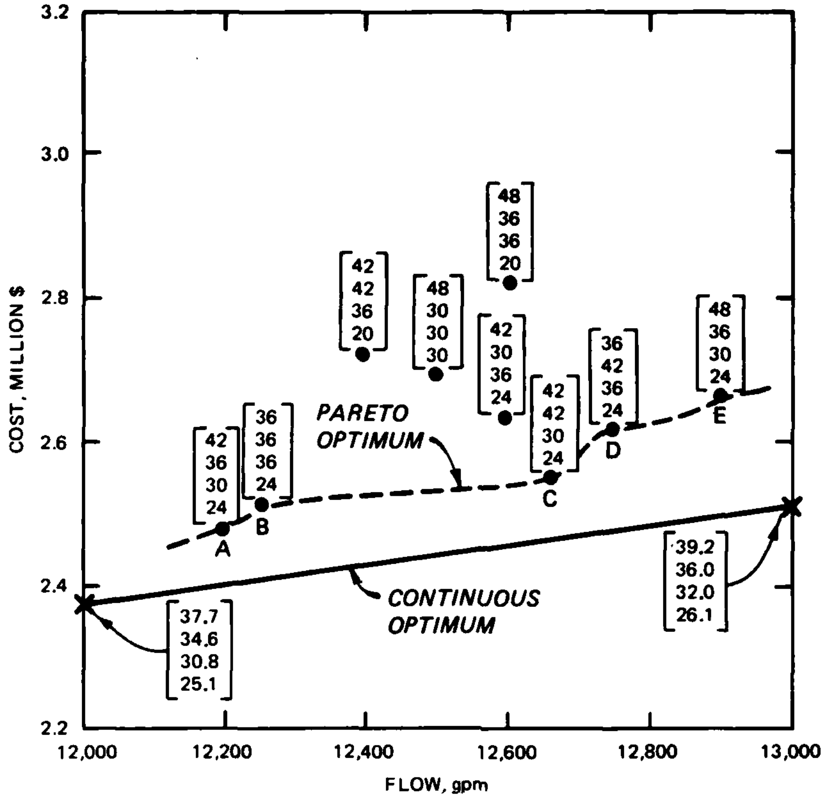


Figure D5. Portion of solution with four pipes in series

and 13,000 gpm. In this figure, the pipe sizes that make up each combination are given. The diameters for the continuous solutions are given by the x's at the end of the line segment corresponding to the continuous solution. Some of the discrete solutions are fairly close to the continuous solution, which is the theoretical lower limit.

19. Five of the nine solutions (designated A through E) have the special property that there is no solution which can produce greater flow at a lower cost (at least in this range of flows); i.e., they are Pareto Optimal or noninferior. The other combinations are inferior. It would take an engineer a good deal of trial and error to identify the noninferior solutions.

20. Figure D6 shows the percent difference between the optimal continuous solution and the discrete solution. It shows that a savings of 12 percent (15-3 percent) can be realized by moving from some inferior solutions to a nearby noninferior solution. An engineer using a traditional trial and error

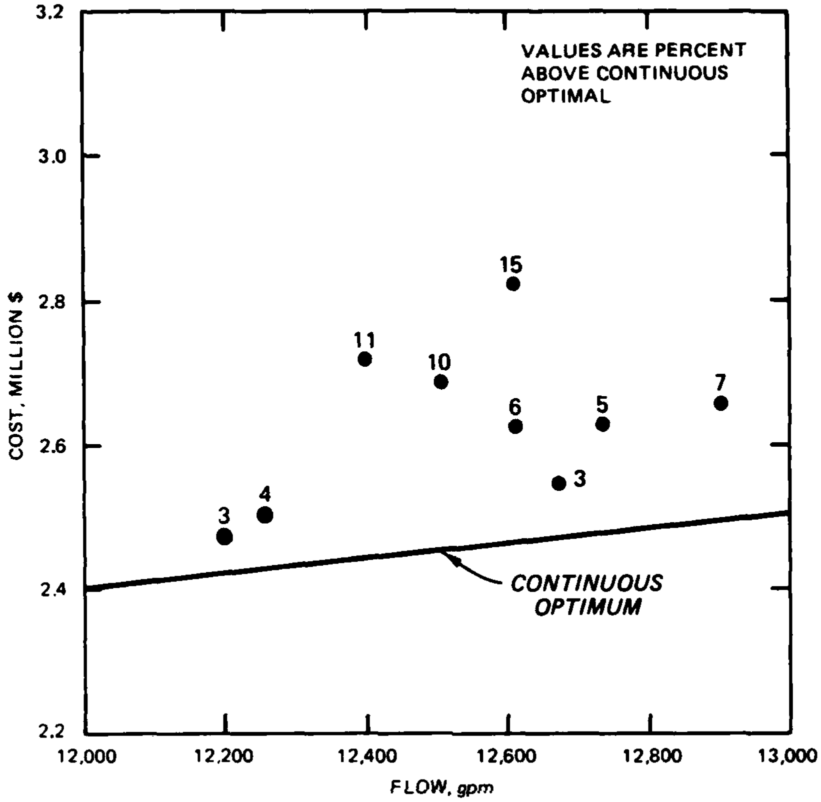


Figure D6. Difference between solutions to a four-pipe example for discrete and continuous solutions

approach might not be able to select pipes to realize these savings.

21. In summary, sizing pipes in series is fairly easy if costs are not important. However, when costs become critical, a considerable number of trial and error solutions are required to achieve a least-cost solution.

Pipes in parallel (continuous diameters)

22. Installation of parallel pipes provides additional reliability to a system since water has more than one path to take between the source and the demand. An analysis using Lagrangian multipliers, as was done for series pipes, would indicate a critical point when all of the pipes in parallel are of the same diameter. This critical point corresponds to a maximum. That is, the costs are a maximum when all of the diameters are equal.

23. The least-cost solution corresponds to the case in which the diameters of all but one of the parallel pipes are zero. This can be proven by comparing the cost of a single equivalent pipe D* with the cost of N equal

size pipes with the same equivalent carrying capacity. The cost can be given by Equation D1 and it is proposed that

$$aD^{*b} < \sum aD_i^b = NaD_i^b \tag{D10}$$

(cost of one pipe) < (cost of parallel pipes)

The diameter of a single pipe with the same carrying capacity as the set of pipes can be given according to the Hazen-Williams equation by

$$D^* = (ND_i^{2.63})^{0.38} = N^{0.38}D_i \tag{D11}$$

Substituting gives

$$(N^{0.38}D_i)^b < ND_i^b \tag{D12}$$

For $D_i > 0$, the equation becomes

$$N^{0.38b} < N \tag{D13}$$

which for $N > 1$, becomes

$$b < 2.63 \tag{D14}$$

Since b is virtually always less than 2.63, inequality (D14) is true and a single pipe is virtually always cheaper. The above equation agrees with a previous observation by Deb (1976).* The cases in which $b > 2.63$ occur when one moves from standard sizes to nonstandard sizes. This is the reason that large irrigation or stormwater lift lines are sometimes made up of a set of parallel pipes.

Pipes in parallel (discrete diameters)

24. The problem of selecting optimal pipes in parallel with discrete diameters for the case shown in Figure D7 can be examined graphically in

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* Deb, A. K. 1976 (Aug). "Optimization of Water Distribution Network Systems," Journal of the American Society of Civil Engineers, Environmental Engineering Division, Vol 102, No. EE4, p 837.

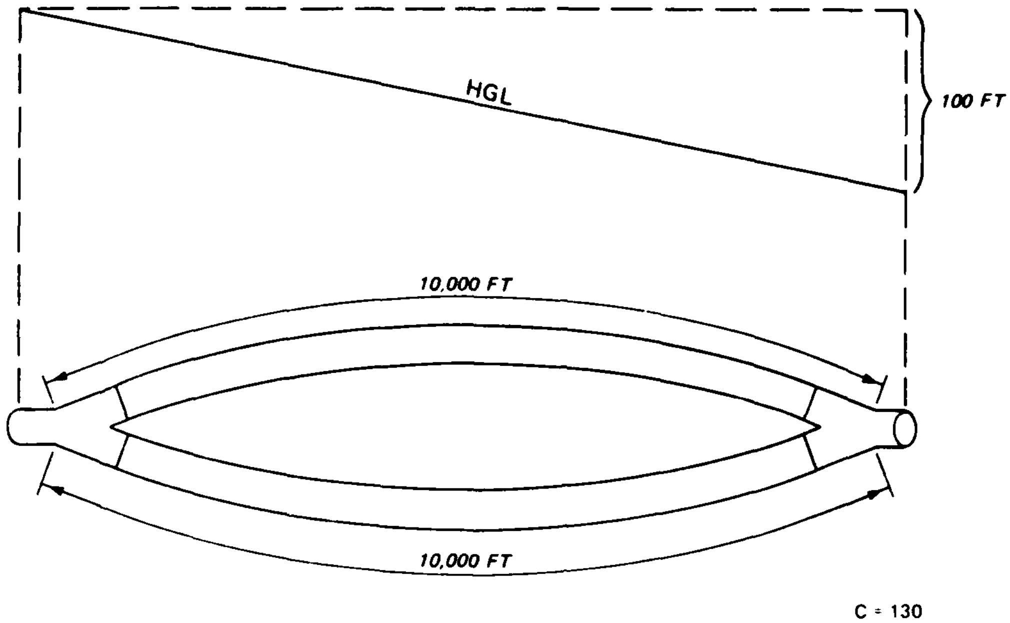

Figure D7. Parallel pipe example

Figure D8 which is similar to Figure D2 for pipes in series. It shows that, when the capacity of a single pipe is slightly less than the required flow, the extra flow can be economically provided by a small pipe in parallel. This is somewhat unrealistic however since in most cases an engineer would simply select the next larger size or install part of the pipe with the larger diameter. As is the case with continuous diameters, a single pipe is economical.

25. To provide reliability in a system, one generally specifies that a parallel pipe of minimum diameter be installed. Figure D9 shows such a problem for the case when a minimum diameter of 16 in. is specified for pipe 2. As the required flow increases, in general it is less expensive to increase the size of the larger pipe. This can be demonstrated by examining the rate of change of cost with respect to change in flow for large (flow = Q_1) and small (flow = Q_2) pipe. Flow can be related to diameter by

$$Q = GD^{2.63} \tag{D15}$$

where G = constant in head loss equation, and cost per unit length can be related to diameter by

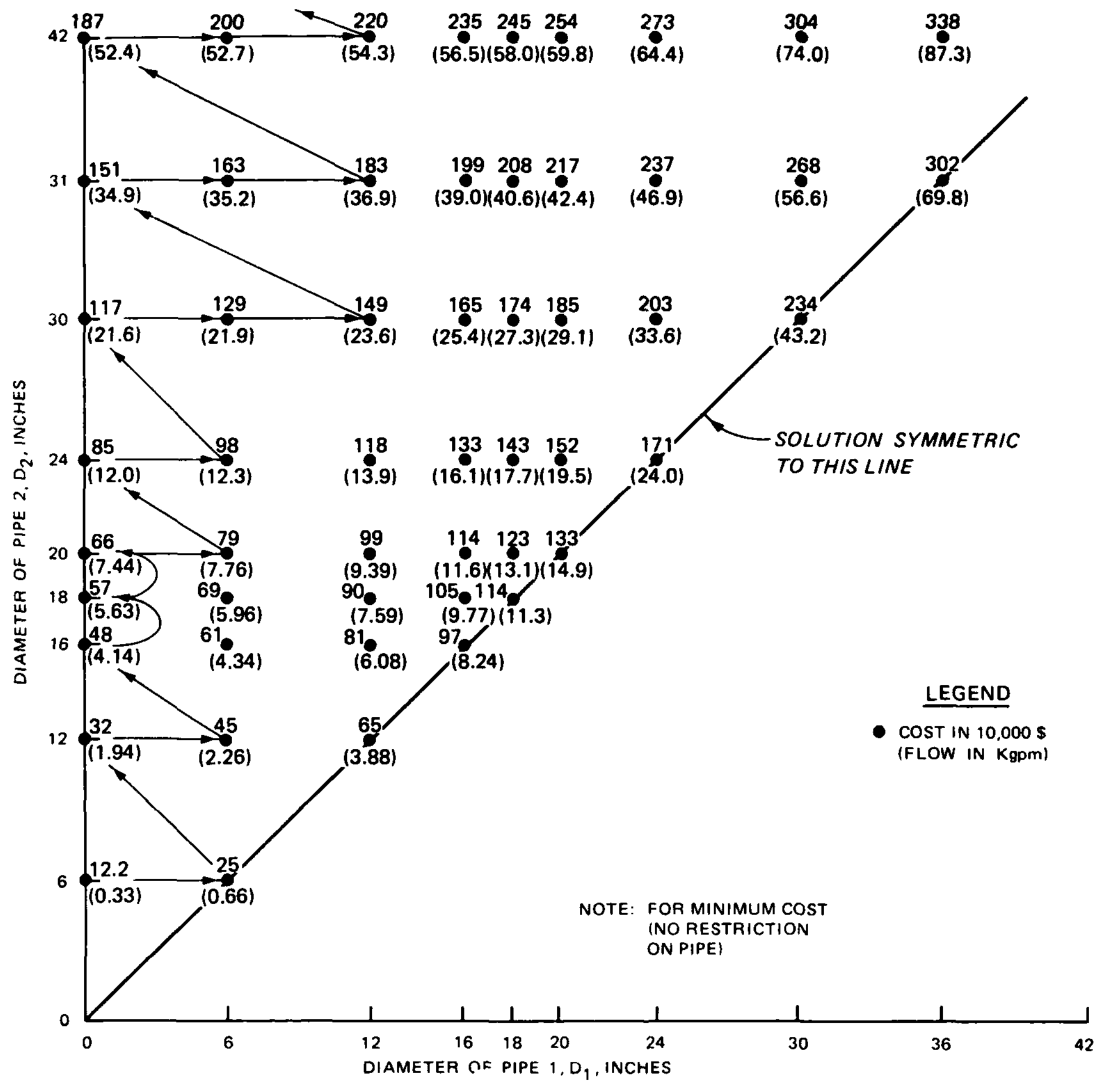

Figure D8. Graphical solution to two parallel pipe example

$$U = aD^b \tag{D16}$$

where U = unit cost of pipe, \$/L. Combining Equations D15 and D16 and differentiating with respect to Q (assuming D is continuous) gives

$$U = a(G^{-1}Q)^{0.38b} \tag{D17}$$

and

$$\frac{dU}{dQ} = aG^{-038b}\ (0.38b)Q^{0.38b-1} \tag{D18}$$

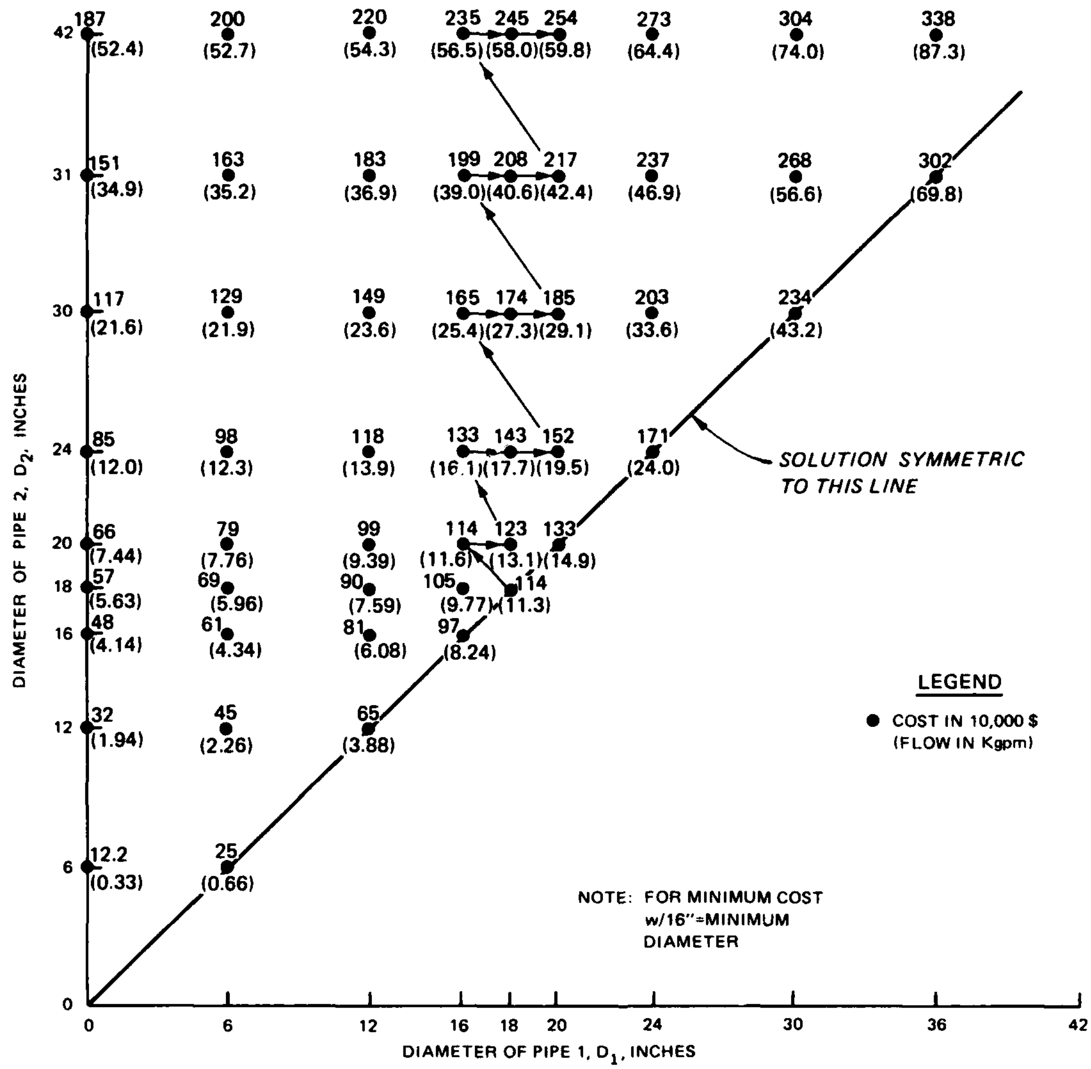

Figure D9. Solution to the two parallel pipe example with minimum diameter specified

Since b is usually less than 2.63, costs will increase less for the pipe which has the highest existing flow, that is $\frac{dU}{dQ}(Q_1) < \frac{dU}{dQ}(Q_2)$ where $Q_1 > Q_2$. When working with discrete diameters, there are some exceptions to this (i.e. those cases in Figure D9 in which the 18-in. pipe is used), but in general the diameter of the small pipe remains near the minimum.

26. For parallel pipes, the objective of cost minimization is directly in conflict with the objective of reliability. While specifying a minimum diameter of parallel pipes is a possible approach to solving the problem, it

will result in other than a least-cost solution.

Summary

27. While it is possible to develop fairly simple rules for pipe sizing for pipes in series when diameters can be treated as continuous variables, selecting the optimal diameter when only discrete sizes are available is considerably more difficult. For problems with any complexity, rounding the continuous optimum to the discrete solution is not a simple procedure and can easily produce inferior solutions.

APPENDIX E: LITERATURE REVIEW OF PIPE NETWORK OPTIMIZATION MODELS

Introduction

1. This appendix is based on a paper presented at the American Society of Civil Engineers (ASCE) Conference on Computers in Water Resources in Buffalo, N.Y., in June 1985. It summarizes previous work in pipe network optimization.

2. People have been building water distribution systems for several hundred years. Customers in most parts of the world can be fairly certain that when they open their taps, water, under adequate pressure, will flow. No one, however, can say with certainty that any water distribution system is the least costly system that could have carried the water.

3. With the development of the high-speed digital computer and powerful optimization techniques in the 1950s, it appeared to be only a matter of time before engineers could supply some simple data to a computer and the computer would determine the optimal pipe network. (Optimal in this paper will refer to least costly in terms of life cycle cost, although much of what is said also pertains to optimality in terms of reliability or minimizing only capital costs.) To date, the problem of optimally sizing pipes in networks remains largely unsolved. It is not as if researchers have not been working on the problem; dozens of papers containing "solutions" to pipe network optimization problems have been prepared. However, one would indeed have to diligently search to find practicing engineers who actually use these optimization techniques to solve pipe network problems. Rules of thumb and trial and error remain the primary tools of choice for practicing engineers faced with the problem of selecting water distribution system components.

4. In the early 1980s, pipe network optimization programs are in a position similar to that of network steady-state simulation programs in the late 1960s. The mathematics of the problem have been addressed in theoretical papers and some programs have been written and, in a few instances, applied to real problems. However, pipe network optimization is not considered a standard engineering tool and user-friendly programs are just becoming available.

5. The purpose of this appendix is to summarize the state of the art in pipe network optimization. This is done by first presenting a classification of problems followed by a brief description of published approaches. Finally,

the problems in developing a practical, general program for pipe network optimization are discussed.

Classification

6. Pipe network optimization problems can be classified in numerous ways. The two most meaningful classifications concern whether the flow distribution is initially fixed (fixed versus variable flow pattern), and whether the system's energy is provided by gravity or pumping (gravity versus pumped systems).

7. Systems in which the flow distribution is initially fixed and only one constant head node (e.g. tank, pump) exists are fairly easy to handle because the flow pattern does not change when the diameter changes. Branched systems and long pipelines with occasional withdrawals (e.g. closed conduit irrigation systems and rural water systems) fall into this category.

8. Most water distribution systems, however, contain loops and multiple sources of supply, some of which may be constant head nodes while others are pumps. As a result, the flow in any pipe is determined by the diameter in that pipe and the diameter of all other pipes in the network. Solving this type of problem is much more difficult because of interactions among pipe sizing decisions.

9. The approaches used also differ between gravity and pumped systems. In gravity systems, the least costly piping system will dissipate all excessive head thus keeping pipe size, and hence cost, to a minimum. In pumped systems, the available head is not fixed but can be altered by changing pump head with the associated changes in energy and pumping equipment costs.

Work to Date

Traditional approach

10. The approach traditionally used by design engineers to size pipes for fairly complicated systems is to first construct and calibrate a mathematical model of the system. Future demands and emergency situations are then simulated using the model. This enables the engineer to identify problem areas in the system. To identify workable solutions, alternative pipes, pumps, tanks, and valves are tested using the model. The costs for some of

the more promising alternatives are then calculated to arrive at a recommended solution.

11. In this process the design engineer is generally armed with a few rules of thumb to arrive at a practicable solution. These include:

- a. Velocities less than 8 ft/sec at peak flow.
- b. Velocities on the order of 2 ft/sec at average flow.
- c. Pressures between 60 and 80 psi under normal conditions.
- d. Pressure at least 20 psi during fire conditions.
- e. Diameters at least 6 in. for systems providing fire protection.
- f. Diameters at least 2 in. for systems without fire protection.
- g. Adequate pumps such that design flow can be delivered with one pump out of service.
- h. No dead-end mains.

12. Armed with a good model and the above rules, engineers have been able to design workable distribution systems at an acceptable cost.

Field pattern--gravity

13. The first work on optimizing gravity systems dates back to Camp (1939).* Cowan (1971); Swamee, Kumar, and Khanna (1973); Deb (1973); Chiplunkar and Khanna (1983); and Walski (1984) present methods that rely essentially on classical, constrained optimization techniques--in particular Lagrangian Multipliers. Canales-Ruiz (1980) proposes a method which relies on Pontryagin's Maximum Principle. The MAPS (Methodology for Areawide Planning Studies) (Headquarters, Corps of Engineers 1980) and MAINS (Koh and Maidment 1984) computer programs use trial-and-error techniques.

14. When the problem becomes sufficiently complicated, as is the case for highly branched systems, classical optimization techniques and brute force trial and error become unworkable. In those cases, linear programming (LP) can be used to select optimal pipe sizes. Actually, since costs are a linear function only of length, it is the length of pipe of a given diameter that is determined by the program. Karmeli, Gadish, and Meyers (1968); Lai and Schaake (1969); Gupta, Hussan, and Cook (1969); Calhoun (1971); Robinson and Austin (1976); and Bhave (1979) developed LP solutions for systems with known flow patterns.

15. Oron and Karmeli (1979) developed a method that combines

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* See References at the end of this appendix.

generalized geometric programming with a branch-and-bound technique to solve the problem. Buras and Schweig (1969), Liang (1971), Sathaye and Hall (1976), and Kareliotis (1984) used dynamic programming to optimize branched systems. Kettler and Goulter (1983) offer a method that accounts for reliability of looped systems, but is based on a fixed initial flow pattern. Mandl (1981) summarized available techniques for optimizing branched systems.

Fixed flow pattern--pumped

16. When pumping is allowed or required in the system, optimization of pipe sizes can be viewed as a trade-off between capital and energy costs subject to head constraints. Babbitt and Doland (1931), Camp (1939), Osborne and James (1973), ASCE Committee on Pipeline Planning (1975), Dancs (1977), Deb (1978, 1981), and Walski (1984) have developed manual methods for finding optimal pipe sizes. The PIPEOPT (Ainsworth 1979), MAPS (Headquarters, Corps of Engineers 1980), and MAINS (Koh and Maidment 1984) programs use trial-and-error solutions to arrive at optimal pipe size. Walski (1984) also gives nomograms from which it is possible to directly read pipe diameter given peak and average flow, energy cost, and construction cost index.

17. Pernold (1974) presents a method for sizing pumped irrigation systems with varying demands based on heuristic rules. The approach of Chiplunkar and Khanna (1983) includes pumping cost in a Lagrangian formulation. Nolte (1979) described several pipe optimization techniques used in the chemical process industry.

18. In general, methods that rely solely on trade-offs between capital and energy cost tend to predict smaller pipe sizes than customarily used. It is important that pipe sizes selected by such methods be checked to ensure they are hydraulically feasible without requiring excessive initial heads.

Variable flow pattern

19. In most real systems, the flows in the pipes are not fixed beforehand but vary with the pipe sizes selected. Shamir (1974, 1979) summarized the approaches developed through the 1970s and Stephenson (1976) gave procedures for applying some methods. de Neufville, Schaake, and Stafford (1971) discussed pipe optimization in a broader framework than simply minimizing cost.

20. Most of the methods used for solving problems with variable flow patterns involve first fixing the flow pattern and finding the optimal solution, then adjusting the flow pattern using a gradient search approach.

Kally (1971); Shamir (1974); Alperovits and Shamir (1977); Shamir (1979); Quindry, Brill, and Liebman (1979, 1981); and Mays (1984) suggest variations in this type of approach. Smith (1966) combined random sampling and linear programming. Bhave (1983) and Kikacheishvilli (1984) also developed methods incorporating linear programming.

21. Other researchers have used a combination of nonlinear programming techniques and heuristic algorithms. Pitchai (1966) used a random sampling technique. Jacoby (1968) used a gradient, random experience approach. Cembrowicz and Harrington (1973) suggested using a combination of graph theory and heuristic rules while Lam (1973) proposed what he called a "discrete gradient optimization."

22. Deb and Sarkar (1971) proposed a method for determining pipe sizes based on equivalent pipes. Swamee and Khanna (1974) point out that this method essentially fixes the hydraulic gradient. Deb (1976) extended the equivalent pipe approach to determination of inlet heads. Watanatada (1973) used a sequential, nonlinear programming technique. Rasmusen (1976) used a gradient search based on critical node(s) in the system.

23. Bhave (1978) proposed an iterative manual approach which is based on breaking the system into a system with fixed flows by fixing flow or diameter in "nonprimary" links. Cenendese and Mele (1978) used a heuristic procedure to determine optimal pipe sizes. Kher, Agarwal, and Khanna (1979) proposed an iterative method that uses the Univariate method to adjust diameters. Ormsbee and Contractor (1981) used a modified Box-Complex optimization.

24. Gessler (1982) used an enumeration technique to identify not only optimal but several nearly optimal systems as well as taking into account pipe rehabilitation. Featherstone and El-Jumaily (1983) fixed a constant hydraulic gradient to optimize a network. Conbere and Jeppson (1984) used a line search among discrete variables. Stoner Associates added a heuristic pipe selection technique to an existing network simulation model.

25. Rowell (1979) and Rowell and Barnes (1982) presented a two-step procedure for determining pipe layout as well as pipe sizes. Morgan and Goulter (1982, 1985) used linear programming to determine optimal layout while Bhave and Lam (1983) used "Steiner trees" to identify optimal layout for branched systems.

Critique

26. The most common trait of the models mentioned above is that they are not available for engineers. For example, Jeppson's program (1982) can be used to size pipes and pumps but it does not contain formal optimization. Why has much of the sophisticated technology described above not been transferred to practicing engineers?

27. A major problem is that optimizing water distribution systems is a difficult, if not impossible, problem to solve. None of the programs developed can solve real world optimization problems. In a discussion of the paper by Cenendese and Mele (1978), Lischer (1979) stated:

> In this writer's opinion, based on a lifetime of experience in the water supply field, that the optimum design for most new systems, and for improvement of old systems, cannot be achieved by mathematical or computer exercise alone. Experienced judgement will be necessary to select the options and system operational methodology before computer techniques and network analysis are applied.
>
> To emphasize the complexity of the problem and not to misguide the naive into oversimplification, it is appropriate here to list some, and hopefully most, of the parameters entering into public water supply system design:
>
> 1. Water usage and demand: (a) Pattern of water use for various types of customers; (b) location of customer demand; (c) fire flow requirements; and future trends.
>
> 2. Storage considerations: (a) Reserve; (b) peaking; (c) elevated storage; (d) ground storage; with pumping; and (e) site determination to best obtain optimum design of whole system.
>
> 3. Minimum pressure requirements: (a) Residential areas; (b) high value districts; and (c) industrial areas.
>
> 4. Population distribution: (a) Future trends.
>
> 5. Topographic: (a) Need for separate pressure districts; (b) need for pressure reducing controls; and (c) available sites for storage.
>
> 6. Reliability considerations: (a) Looping; (b) standby power for pumping operations; (c) limitations and cost of attended operations; (d) system size;

(e) practicality, maintainability, and reliability of automatic controls; and (f) cost of storage.

7. Pumping options: (a) Outdoor or housed; (b) vertical; (c) horizontal split case; (d) submersible; and (e) booster pumping.

8. Pipe options: (a) Material, as affecting cost life and depreciation; (b) carrying capacity; (c) structural properties; (d) reliability; (e) means and ease of repair as affecting maintenance cost; and (f) cost.

9. Economic consideration: (a) Value of money; (b) depreciation; (c) capital recovery; and (d) inflation or deflation effects.

10. Energy options: (a) Electric; and (b) other power.

28. Other factors not mentioned by Lischer contribute to the complexity of the problem. For example, pipes are only available in specific discrete sizes. Most optimization methods assume the existence of continuously variable pipe sizes which are later rounded off.

29. Most of the models are oriented toward optimal pipe size selection, but pipe size selection is only one facet (albeit a complicated one) of the overall water system design problem. Engineers must also select pumps and decide how to operate them, choose locations and settings for pressure reducing valves, and determine tank heights and volumes. These decisions are tied closely with pipe sizing decisions.

30. Systems are not static, but rather grow over many years. None of the methods allow for staging of construction. The carrying capacity of existing systems can be increased by cleaning with or without cement mortar lining. Few of the programs allow for realistic cost functions (i.e. costs expressed as a function of more than merely diameter).

31. Most of the methods proposed handle one or only a handful of loadings. Yet most systems must be able to operate over a fairly wide range of conditions. Fires may occur at many locations in the system; valves and pumps may malfunction; pipes may break. The number of conditions that must be considered for a thorough analysis can be staggering.

32. This does not mean that practicing engineers are doing any better than models in adequately addressing the problem today. However, in standard practice, overdesign and redundancy are commonly used to minimize the impact

of uncertainty. Optimization methods result in cost savings by reducing redundancy and overdesign.

33. The engineer trying to optimize water systems is also faced with ambiguous design and performance criteria for the system. This problem is described in Appendix F.

Summary

34. Because of the complexity of real systems, models which appear to be attractive in journal articles tend to cough and sputter when fueled with real data. The challenge before the engineering profession is to develop tools that can be used by practicing engineers to design real systems.

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APPENDIX F: SENSITIVITY OF MODEL RESULTS TO DESIGN ASSUMPTIONS

Introduction

1. Given accurate data, mathematical models of water distribution systems can accurately predict pressure and flows and even select optimal pipe sizes. The key to the preceding sentence is the phrase "given accurate data." The quality of the data entered into a model is often the weakest link in using these models. Overall, there are three categories of "errors" that can result in a model resulting in a poor design of improvements to a system: (a) clerical errors, (b) inaccurate representation of the system by the model, and (c) poor design assumptions.

2. There are numerous sources of clerical errors in entering data. The most obvious are simple typographical errors. The maps from which system data are extracted may contain errors or may be read incorrectly. Elevations must sometimes be read from maps with poor resolution.

3. The second type of error occurs when the model does not behave like the real system because of the way the real system is considered by the model. While pipe length and diameter data are usually accurate, most systems must be skeletonized to make modeling practicable. The errors introduced in developing skeletal systems have been studied by Eggener and Polkowski (1976).* Other errors can occur due to the way in which pumps and valves are represented by the model, or lumping water users at nodes in the model.

4. The third type of error is not an error in modeling but rather uncertainty with regard to the conditions which need to be modeled. The engineer must tell the program such things as tank water levels, pipe roughness, and water use, which the engineer cannot know with certainty. This is not a problem with the modeling process but with the way in which performance standards to be met are specified at present.

5. Water use fluctuates with time, so that any model provides only a "snapshot" of the system at a single point (or series of points) in time. In using a model for design, the engineer must anticipate future water use and fire flow requirements, and other deviations from average water use.

6. The user must also select boundary heads for the model. These

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* See References at the end of this appendix.

include water levels in tanks, settings on pressure reducing valves, status of existing pumps (on/off), and characteristic curves for new pumps. The user must also project values of pipe roughness which vary spatially throughout the system and temporally with age of pipes depending on pipe material and water quality. In the case of optimization models which select pipe sizes, the engineer must also specify accurate pressure requirements and cost functions.

7. One would think that there are some fairly standardized methods available for setting parameters such as Hazen-Williams C-factors, tank levels, and pump operations to meet the required pressures. Instead, there is virtually no published guidance and these decisions are fairly arbitrary. In this appendix they will be referred to as "design assumptions."

8. The purpose of this appendix is to show the ambiguity of existing performance standards and to analyze the sensitivity of model calculations to the design assumptions that must be made. Some existing design and performance standards are reviewed. The sensitivity of design assumptions is then analyzed for the models used, first to evaluate an existing system, and secondly to select optimal pipe sizes.

Existing Performance Standards

9. In the area of water distribution hydraulics, existing standards are performance standards rather than design standards. (Design standards say how something should be built (e.g. American Water Works Association (AWWA) standards); performance standards only specify performance and leave the methods to the discretion of the engineer (e.g. typical state standards).) With a few exceptions (e.g. minimum pipe size), the hydraulic standards do not state how a system should be built but rather how it should perform once it is built. These standards are usually established by the respective state health department, board of health, or other water supply regulating agency. These standards are influenced by rating systems and standards used in the fire protection and insurance industries. In this section a sampling of the wording in existing standards and guidelines on system performance is presented. In the subsequent section areas in which the existing standards leave a great deal of room for assumptions are pointed out.

10. The Great Lakes--Upper Mississippi River Board of State Sanitary Engineers standards (also called "Ten State Standards") (1982) state:

> All water mains, including those not designed to provide fire protection, shall be sized after a hydraulic analysis based on flow demands and pressure requirements. The system shall be designed to maintain a minimum pressure of 20 psi at ground level at all points in the distribution system under all conditions of flow. The normal working pressure in the distribution system should be approximately 60 psi and not less than 35 psi.

11. Most other states have similar standards. For example, Virginia's <u>Waterworks Regulations</u> (Virginia State Board of Health 1982) state: "The system shall be designed to maintain a minimum pressure of 20 psi at all points in the distribution system under all conditions of flow."

12. Tennessee's draft design criteria (Tennessee Department of Public Health, No Date) state: "The system shall be designed to maintain a minimum pressure of 20 pounds per square inch at all points in the distribution system under all conditions of flow."

13. Alabama's design criteria (Alabama State Board of Health 1978) specify the instantaneous water use corresponding to the pressure required and that the required pressure is to be provided at the customer's meter, as follows:

> The distribution system shall be so designed that the minimum residual pressure at the meter of the consumer shall be no less than 20 psi under all conditions of flow: however it is strongly recommended that a minimum of 35 psi be available at the meter for domestic purposes. The Instantaneous Flow Curve shall be the minimum design criteria. Fire flow criteria shall comply with that of the Insurance Services Office.

14. Other government entities have their own standards. The Army Fire Prevention Manual (Headquarters, Department of the Army 1977) states:

> This section presents requirements concerning water supplies for fire protection purposes. These supplies are that quantity of water required to meet estimated flow rates through sprinklers and hose line systems for the duration of a fire. The fire protection water supply is in addition to that required for industrial and domestic usage during the fire demand period. Overall water supply system design at any particular installation will be based upon meeting the predominating largest demand under variable conditions for the maximum prevailing fire-flow requirements.

Subsequently, it gives the minimum pressure: "The hose stream demand for unsprinklered facilities shall be available at a flowing pressure of not less than 10 lb per sq in at the hydrant discharge."

15. The AWWA does not set performance standards for water distribution systems. However, the AWWA (1962) has produced a water distribution training course manual which discusses why 20 psi is usually set as the minimum pressure:

> The principal reason for a minimum residual-pressure requirement of 20 psi is that this pressure is sufficient to overcome the friction loss in the hydrant branch, hydrant, and suction hose and furnish the supply to the fire pumper under pressure. The 20-psi residual pressure has been more or less accepted by the water industry as the minimum acceptable pressure for furnishing domestic service to a residential customer. If 20 psi (46 ft of head) is available in the street and the customer has a two-story house located somewhat above street level, after allowance for friction losses in the customer's service branch, meter, and house piping there remains about enough pressure to provide a minimum flow at the second-story level. A pressure of 30 psi is a more desirable minimum for normal residential requirements.

16. The National Fire Protection Association (NFPA) is the standard setting organization of the fire protection industry. While the NFPA does not set standards for municipal water distribution systems, it does specify how hydrants are to be rated according to the results of hydrant tests (NFPA 1983):

> For the purpose of uniform marking of fire hydrants, the ratings should be based on a residual pressure of 20 psi for all hydrants having a static pressure in excess of 40 psi. Hydrants having a static pressure of less than 40 psi should be rated in one-half of the static pressure.

More importantly the NFPA addresses the condition under which the hydrant test is to be run, "Tests should be made during a period of ordinary demand." However, they do not indicate what "ordinary demand" means.

17. The Alliance of American Insurers (1982) provides some guidance on when tests should be conducted:

> What time of day is best for a flow test? Ideally a test should take place when the domestic demand is the greatest, and as a result, the hydraulic conditions are usually the poorest. Whenever possible, the test should take place sometime between 9 AM and 5 PM, the period of normal water demand. Occasionally, however, the water department will not allow testing at this time because water supplies are weak or barely adequate and flow testing might unduly strain the public supply.

Knowing when a system will be tested can help the design engineer select the domestic and industrial use that must be met by the system in addition to fire flows.

18. The Insurance Services Office (ISO) is the organization that actually evaluates and rates municipal fire protection systems. The ISO Fire Suppression Rating Schedule (ISO 1980) rates water distribution systems depending on the system discharge at 20 psi compared with what they refer to as "Needed Fire Flow." They do not indicate in any of their publications what the tank water levels, pump operation, etc., should be while the system is being tested. However, ISO's unpublished, internal guidance states that "(a) pumps can be on, (b) tanks should be at their normal daily minimum level, and (c) the nonfire water use should be at the average consumption rate on the peak day."* The ISO also records normal and maximum daily consumption to be sure that the supply facility can serve both domestic consumption and fire flows simultaneously. Sometimes instantaneous large fire flows are limited to a lesser volume because hourly duration is also a part of needed Fire Flow; the water supply for a duration of several hours may be a limiting factor.

Required Design Assumptions

19. The design engineer faced with the problem of sizing pipes, pumps, and tanks usually uses a computer model of the system to simulate alternative designs or to select optimal sizes. Computer programs require precise input but the engineer cannot obtain such precise information from the standards and guidelines described in the previous section. The engineer must, therefore, make assumptions to aid in design. Some of the questions left unanswered in the preceding section are described below. (The comments below also apply even if a computer is not used.)

20. What is meant by "under all conditions" in the various standards? For any water system, it is possible to conjure some set of conditions for which the system will fail to meet the performance standard. For example, suppose the main leading out of the treatment plant ruptures the same day that the largest tank is out of service for painting and the backup well is out of service due to a toxic chemical spill. No system can meet performance

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* Personal communication with Mr. Dick Hughey, Insurance Services Office, Commercial Risk Services, October 1984.

standards "under all conditions." Thus, all design engineers must make value judgments on what is an acceptable risk for a water system.

21. Where should the fire flows be simulated? Should they be simulated at locations spaced uniformly throughout the system or at locations that will most likely produce the worst results? Most engineers would argue that the system must provide fire flows at all locations so a conscious effort must be made to identify and focus on "worst" situations.

22. At what elevation should the pressure be measured to compare with the 20-psi minimum requirement? It is not uncommon in hilly areas for elevation to change by 20 to 40 ft in a short distance. The elevation at which the 20-psi criterion is applied can greatly affect pipe sizing decisions in some cases. Should it be 20 psi at the main, or the street level, or the first story of homes?

23. What tank water levels should be used as input to the computer model? Water tanks will probably not be full when a major fire occurs; similarly, they will not be empty or nearly empty. Is half full a representative condition? In most cases the engineer would most likely use a reasonable worst case. But is this the low water level on a normal use or peak use day, during the current year or ultimate design year?

24. Certainly, a system must supply water to other users in addition to fighting fires. Should the water use rate and spatial distribution of use correspond to instantaneous peak, peak hour, or peak day, and should this day occur in the current year, 10 years into the future, or 20 years into the future? This question is especially important for communities undergoing growth.

25. Which pumps should be considered running during critical fires? A utility may turn on all of its pumps during a fire. Should the engineer assume all of the pumps are available or should one pump per station be assumed to be out-of-service? If a fire should occur during a power outage, only the pumps with auxiliary power can be used. On the other hand some in-line booster pumps may be pumping water from the fire location to higher pressure zones. Will these be running during a fire? Similar questions can be posed concerning settings on pressure reducing valves.

26. Internal pipe roughness varies with pipe age, water quality, pipe material, and installation practices. Which values for pipe roughness or C-factor should be used? For new pipes, published or slightly conservative

values for C-factors may be sufficiently accurate. Typical literature values are available for old pipes, but it is likely that field-measured values for a given system will be significantly different from typical values. Field measurements and careful model calibration should be performed to ensure that correct C-factors are used. These is no requirement to verify system C-factors before conducting a design study.

27. While water mains are quite reliable, they are occasionally taken out of service for repairs. Should systems be expected to meet pressure requirements at fire flows during these events, and if so, how many pipes should be considered out of service at any one time?

28. Given that there is some uncertainty in all design assumptions, should additional safety factors be included? Most engineers would argue that the minimum pressure requirement of 20 psi has enough of a safety factor built in. Similarly, decisions as to fire location, tank level, pipe roughness, etc., should be made conservatively so that any uncertainty will result in excess capacity.

29. From the above discussion, it is clear that distribution system sizing to meet performance standards involves a lot of assumptions that usually are not explicitly stated by the engineer and for which there is little published guidance. There is little reason to believe that all engineers use the same design assumptions, or that a given engineer uses the same assumptions on consecutive days. It appears that some standardization would be helpful.

Sensitivity Analysis

30. An obvious question that can be raised after reading the preceding section is, "So what? What difference do these design assumptions make?" In the following two sections, the sensitivity of pressure in an existing system and the sensitivity of cost of a new system will be determined for some simple examples. It will be shown that design assumptions can make a dramatic difference in system evaluation and design.

31. Because of the potentially large amounts of computer time that may be required to analyze real systems, this sensitivity analysis will be performed for fairly simple pipe networks. However, these simple systems have been set up to behave like real water distribution systems, so that the

results should be relevant for real systems.

32. In the example systems that follow, the diameters, pipe lengths, water use, elevations, and pump characteristic curves are considered to be known exactly. There are no pressure reducing valves. Demands are lumped at nodes, and the effects of eliminating pipes to form a skeletal system are negligible.

33. Pipe roughness, tank water level, and pump operation are the parameters that will be allowed to vary. Pipe roughness, as represented by the Hazen-Williams C-factor, will be varied even though it is a parameter that can be known precisely for individual pipes. However, it is usually estimated and used as a calibration parameter. The pump operation and tank levels will be varied since, for many problems, the settings for these parameters are fairly arbitrary decisions by the design engineer.

Evaluating existing system

34. In this section, an engineer must determine if the pressure at nodes 8 and 9 in Figure F1 is at least 40 psi at normal water use and 20 psi during fire events at nodes 8 and 9 while maintaining normal water use at other nodes.

35. Water use is 500 gpm at nodes 4, 5, 6, 8, 9, and 10. All of the nodes are at the same elevation except for nodes 2 and 9 which are 100 ft and 50 ft, respectively, above the others. The water level in the elevated tank at node 2 can fluctuate between 120 ft and 80 ft above the ground elevation of 100 ft. The pump at node 1 can be represented using the following pump head curve.

$$H = 320 - (1.1 \times 10^{-6})Q - (2.0 \times 10^{-5})Q^2 \qquad \text{(F1)}$$

where

H = pump head above datum, ft

Q = pump discharge, gpm

36. Now, suppose the engineer analyzing the system is unsure of what boundary heads to use to evaluate whether or not the pressure criteria are met. Furthermore, suppose that all the engineer knows about pipe roughness is that the Hazen-Williams C-factor lies somewhere between 80 and 120.

37. Some engineers might assume a C-factor, tank level, and whether the pump is operating or not; determine the pressure using the model; and include

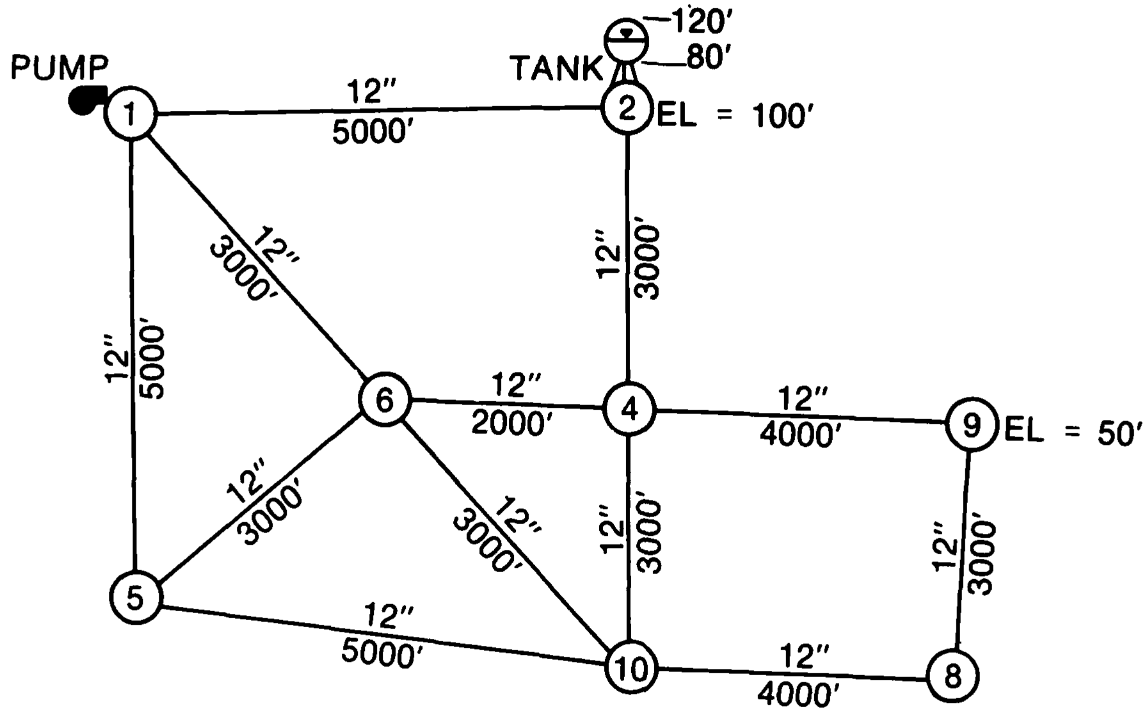

Figure F1. Network for example 1

that value in a report to two decimal places. Suppose, however, that a more skeptical engineer makes a series of runs using the model for a range of C-factors and water levels, assuming the pump is both on and off. The pressures calculated at nodes 8 and 9 are listed in Table F1 for normal water use. The most striking thing about Table F1 is the range of values for pressure at both nodes. The largest variation depending on design assumptions is at node 9 where the pressure varies from 68 to 29 psi. Remembering that the minimum allowable pressure is 40 psi, the engineer can conclude almost nothing about the adequacy of the system without more precisely determining boundary heads and C-factors.

38. Similar runs were made with a fire flow of 1,500 gpm at node 8 and then for a fire flow of 1,000 gpm at node 9. Even when the fire flows were required at node 8, the lowest pressure in the system was at node 9 because of that node's elevation. The pressures at node 9 are shown in Table F2 for fire flows at nodes 8 and 9.

39. Again, it is possible to conclude that the system is either completely capable or woefully inadequate to provide the desired flows, depending

Table F1

Pressure (in psi) at Nodes 8/9 Under Normal Use

C-factor	Tank Level, ft 120	100	80
Pump On			
120	89/68	81/59	73/51
80	83/61	75/53	67/45
Pump Off			
120	82/61	74/52	65/43
80	68/46	59/38	51/29

Table F2

Pressure (in psi) at Node 9 for Fire Flow at Nodes 8/9

C-factor	Tank Level, ft 120	100	80
Pump On			
120	55/59	47/51	39/42
80	35/43	27/35	19/27
Pump Off			
120	42/48	34/40	25/31
80	7/20	-1/12	-10/3

on the boundary heads used. At the higher flow rates, the results become much more sensitive to C-factors since the velocities are greater. This highlights the need for accurate model calibration based on careful data collection (Walski 1984).

Capacity expansion costs

40. In this second example, the pipe network optimization program described in the body of this technical report was used to optimally size a

pipe network. The network is shown in Figure F2. The system was optimally sized for pipe C-factors of 120 and 80, and tank water levels of 140 ft and 100 ft. This resulted in four different "optimal" pipe networks with costs ranging from $934,900 to $692,100 as shown in Table F3. (A minimum diameter of 8 in. was specified to prevent any pipe from being eliminated from the system, and a minimum pressure of 20 psi was specified at all nodes.)

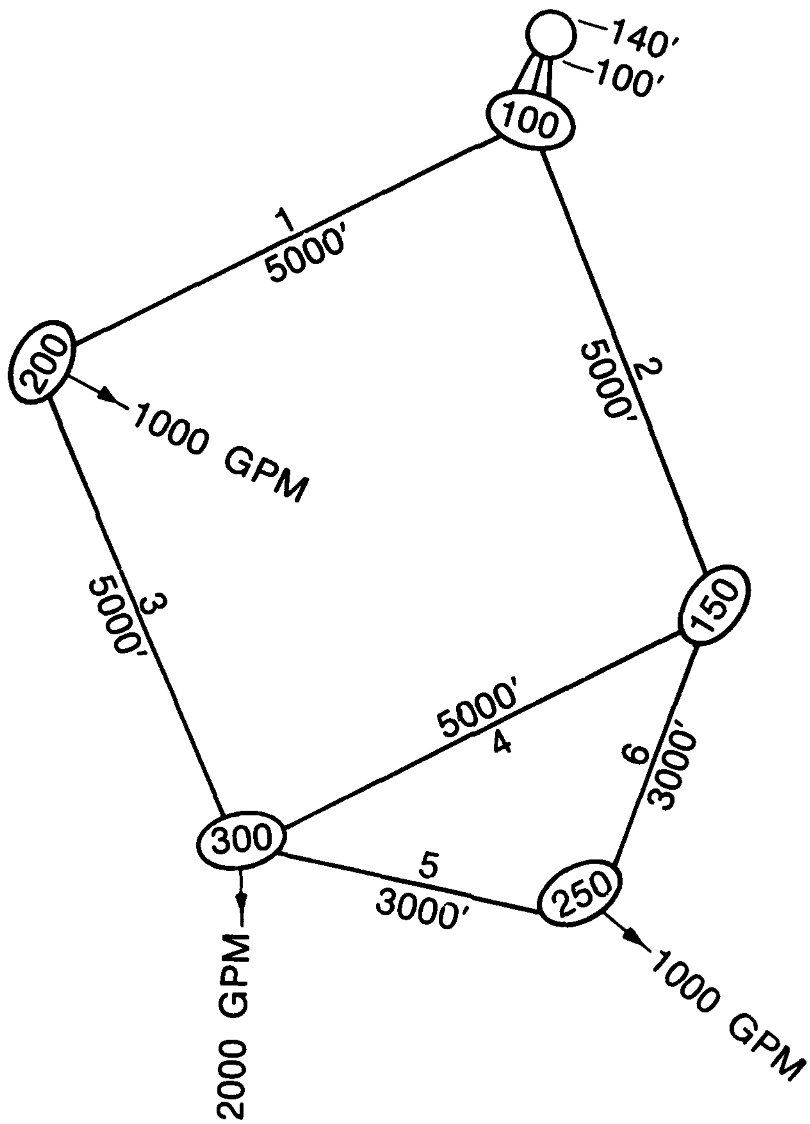

Figure F2. Network for example 2

Table F3

Sensitivity of Optimal Pipe Sizes to Alternative Design Assumptions

Tank Level ft	C-Factor	Cost 1000$	Optimal Diameters, in. 1	2	3	4	5	6
140	120	692	12	12	10	8	10	10
140	80	831	12	16	8	12	10	12
100	120	774	10	16	8	12	8	12
100	80	935	12	18	8	16	8	12

41. The interesting point about the solution is not only that the total costs increase as the design assumptions become more conservative (e.g. tank empty, rough pipe), but that the nature of the solutions changes. For example, in the case of a full tank and C = 120, only 30 percent (602/2000) of the flow to node 300 passes through pipe 4 (optimal size = 8 in.) while when the tank is empty and C = 80, 83 percent (1758/2000) of the flow to node 300 would pass through pipe 4 (optimal size = 16 in.). The design assumptions in that situation made a difference not merely in total cost but in the flow pattern of the system.

42. Another type of design assumption concerns the minimum pressure criterion, which is usually expressed as "must meet 20 psi under all conditions." First, this "20 psi" is rather arbitrary. If the pressure should drop to 19 psi, the distribution system will not completely fail. Similarly, if the elevation at which the pressure criteria was to be met increased (or decreased) by as little as 10 ft, the pressure criteria at the original elevation would really be changed to 24.3 psi (or 15.7 psi).

43. Table F4 gives a list of noninferior solutions to the previous problem when the tank is nearly empty and the C-factor is 120. (Noninferior solutions are solutions for which it is impossible to increase pressure without increasing cost.) The solutions are plotted on Figure F3 which shows how the cost varies with the minimum pressure required. Point C is the minimum cost ($774,400) solution when the minimum pressure required is 20 psi. If the minimum pressure required were 18 psi, the cost could be reduced to $752,500 (point A), a savings of 2.8 percent.

Table F4

Noninferior Solutions for C = 120, Tank Level = 100 ft with Pumps Off

Solution	Cost 1000$	Minimum Pressure psi	Diameters, in. 1	2	3	4	5	6
A	752.5	18.3	10	16	8	12	8	10
B	772.6	18.6	10	16	8	12	10	10
C	774.4	20.3	10	16	8	12	8	12
D	789.0	21.8	12	16	8	12	8	10
E	810.9	24.3	12	16	8	12	8	12
F	817.9	24.3	10	18	8	12	8	12
G	831.2	24.4	12	16	8	8	12	16
H	838.2	24.7	10	18	8	8	12	16
I	857.3	25.3	12	16	8	8	12	18
J	864.3	25.9	10	18	8	8	12	18
K	869.1	26.0	10	16	8	8	16	18
L	890.8	26.7	12	16	8	10	12	18

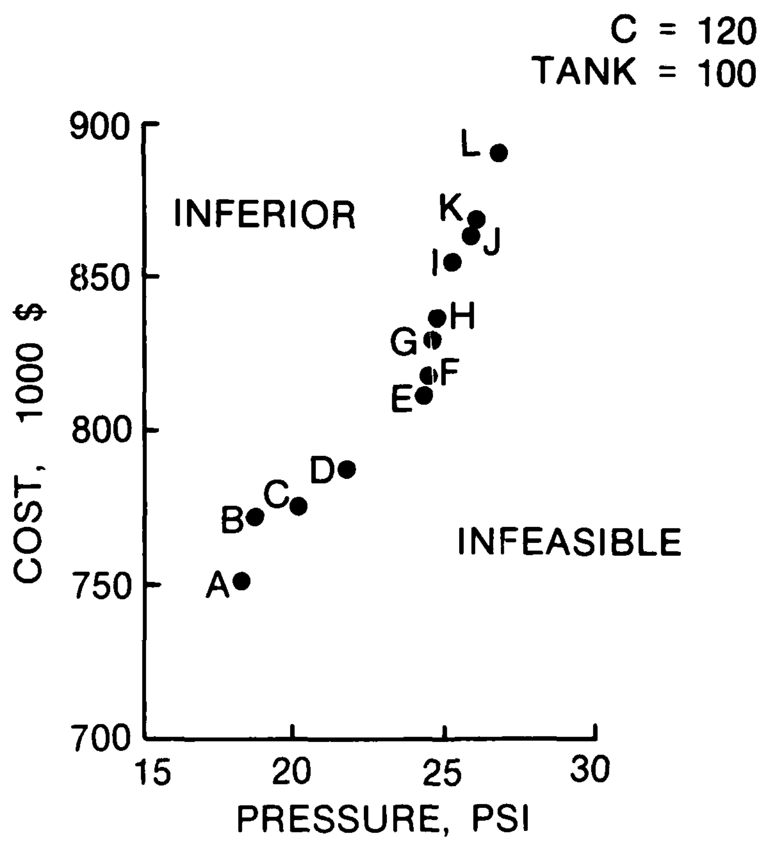

Figure F3. Noninferior solutions for example 2

44. Figure F3 shows that large savings can be realized by making small changes in either the pressure required or the elevation at which the required pressure must be met. A straight line fit through the points in Figure F3 has a slope of $14,600/psi or $6,320/ft.

45. The above example was for the case in which an entire system was to be built. The savings can be even more dramatic in cases when the capacity of an existing system is being increased. A small change in C-factor, tank levels, or required pressures can eliminate the need for improvements or show that drastic improvements are required.

Summary and Conclusions

46. Existing published guidelines for water distribution system performance leave a great deal of room for engineers to make design assumptions. Depending on how engineers make these design assumptions, distribution systems can either be overdesigned with the associated excessive costs, or have very little capacity to handle extreme situations. Examples presented in this appendix showed that a given system can be demonstrated to be either woefully inadequate or totally capable depending upon the design assumptions made, and that costs of capacity expansion can vary based on design assumptions.

47. Water consumers could possibly be better served if these design assumptions were more consistent throughout the country. An organization such as AWWA could formulate and publish a set of standard design assumptions which could be implemented by the respective state regulatory agencies. At a minimum, engineers should explicitly state the design assumptions made when they present the findings of studies on water distribution systems improvements.

48. Development of a set of standard design assumptions should help engineers design systems that will provide excellent service at the lowest cost.

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