DESIGN OF WATER SUPPLY PIPE NETWORKS

Prabhata K. Swamee
Ashok K. Sharma

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PREFACE

A large amount of money is invested around the world to provide or upgrade piped water supply facilities. Even then, a vast population of the world is without safe piped water facilities. Nearly 80% to 85% of the cost of a total water supply system is contributed toward water transmission and the water distribution network. Water distribution system design has attracted many researchers due to the enormous cost.

The aim of this book is to provide the reader with an understanding of the analysis and design aspects of water distribution system. The book covers the topics related to the analysis and design of water supply systems with application to sediment-transporting pipelines. It includes the pipe flow principles and their application in analysis of water supply systems. The general principles of water distribution system design have been covered to highlight the cost aspects and the parameters required for design of a water distribution system. The other topics covered in the book relate to optimal sizing of water-supply gravity and pumping systems, reorganization and decomposition of water supply systems, and transportation of solids as sediments through pipelines. Computer programs with development details and line by line explanations have been included to help readers to develop skills in writing programs for water distribution network analysis. The application of linear and geometric programming techniques in water distribution network optimization have also been described.

Most of the designs are provided in a closed form that can be directly adopted by design engineers. A large part of the book covers numerical examples. In these examples, computations are laborious and time consuming. Experience has shown that the complete mastery of the project cannot be attained without familiarizing oneself thoroughly with numerical procedures. For this reason, it is better not to consider numerical examples as mere illustration but rather as an integral part of the general presentation.

The book is structured in such a way to enable an engineer to design functionally efficient and least-cost systems. It is also intended to aid students, professional engineers, and researchers. Any suggestions for improvement of the book will be gratefully received.

PRABHATA K. SWAMEE
ASHOK K. SHARMA

NOTATIONS

The following notations and symbols are used in this book.

A	annual recurring cost, annuity
A_e	annual cost of electricity
A_r	annual installment
a	capsule length factor
B	width of a strip zone
C	cost coefficient
C_0	initial cost of components
C_A	capitalized cost
C_c	overall or total capitalized cost
C_D	drag coefficient of particles
C_e	capitalized cost of energy
C_m	cost of pipe
C_{ma}	capitalized maintenance cost
C_N	net cost
C_P	cost of pump
C_R	cost of service reservoir, replacement cost
C_T	cost of pumps and pumping
C_v	volumetric concentration of particles
c_i	cost per meter of pipe i
D	pipe link diameter
D_e	equivalent pipe link diameter
D_{min}	minimum pipe diameter
D_n	new pipe link diameter
D_o	existing pipe link diameter
D_s	diameter of service connection pipe
D^*	optimal pipe diameter
d	confusor outlet diameter, spherical particle diameter, polynomial dual

d^*	optimal polynomial dual
E	establishment cost
F	cost function
F_A	annual averaging factor
F_D	daily averaging factor
F_g	cost of gravity main
F_P	cost of pumping main
F_s	cost of service connections
F_P^*	optimal cost of pumping main
F^*	optimal cost
f	coefficient of surface resistance
f_b	friction factor for intercapsule distance
f_c	friction factor for capsule
f_e	effective friction factor for capsule transportation
f_p	friction factor for pipe annulus
g	gravitational acceleration
H	minimum prescribed terminal head
h	pressure head
h_a	allowable pressure head in pipes
h_b	length parameter for pipe cost
h_c	extra pumping head to account for establishment cost
h_f	head loss due to surface resistance
h_j	nodal head
h_L	total head loss
h_m	minor head losses due to form resistance
h_{mi}	minor head losses due to form resistance in pipe i
h_{min}	minimum nodal pressure head in network
h_0	pumping head; height of water column in reservoir
h_0^*	optimal pumping head
h_s	staging height of service reservoir
I_k	pipe links in a loop
I_n	input source supplying to a demand node
I_p	pipe links meeting at a node
I_R	compound interest, pipes in a route connecting two input sources
I_t	flow path pipe
I_s	input source number for a pipe
i	pipe index
i_L	total number of pipe links

J_1, J_2	pipe link node
J_s	input source node of a flow path for pipe i
J_t	originating node of a flow path for pipe i
j	node index
j_L	total number of pipe nodes
k	cost coefficient, loop pipe index, capsule diameter factor
K_1, K_2	loops of pipe
k_f	form-loss coefficient for pipe fittings
k_{fp}	form-loss coefficient for fittings in pth pipe
k_L	total number of loops
k_m	pipe cost coefficient
k_n	modified pipe cost coefficient
k_p	pump cost coefficient
k_R	reservoir cost coefficient
k_s	service pipe cost coefficient
k_T	pump and pumping cost coefficient
kW	power in kilowatts
k'	capitalized cost coefficient
L	pipe link length
ℓ	index
M_1	first input point of route r
M_2	second input point of route r
MC	cut-sets in a pipe network system
m	pipe cost exponent
m_P	pump cost exponent
N_R	total pipes in route r
N_n	number of input sources supplying to a demand node
N_p	number of pipe links meeting at a node
N_t	number of pipe links in flow path of pipe i
n	input point index, number of pumping stages
n^*	optimal number of pumping stages
n_L	total number of input points
n_s	number of connections per unit length of main
P	power; population
P_i	probability of failure of pipe i
P_{NC}	net present capital cost
P_{NS}	net present salvage cost
P_{NA}	net present annual operation and maintenance cost

P_N	net present value
P_s	probability of failure of the system
p	number of pipe breaks/m/yr
Q	discharge
Q_c	critical discharge
Q_e	effective fluid discharge
Q_i	pipe link discharge
Q_s	sediment discharge, cargo transport rate
Q_T	total discharge at source (s)
Q_{Tn}	discharge at *n*th source
q	nodal withdrawal
q_s	service connection discharge
$\mathbf{R}$	Reynolds number
$\mathbf{R_s}$	Reynolds number for sediment particles, system reliability
R	pipe bends radius
R_E	cost of electricity per kilowatt hour
r	rate of interest; discount rate
s	ratio of mass densities of solid particles and fluid
s_b	standby fraction
s_s	ratio of mass densities of cargo and fluid
T	fluid temperature, design period of water supply main
T_u	life of component
t_c	characteristic time
V	velocity of flow
V_a	average fluid velocity in annular space
V_b	average fluid velocity between two solid transporting capsules
V_c	average capsule velocity
$V_{\max}$	maximum flow velocity
V_R	service reservoir volume
V_s	volume of material contained in capsule
w	sediment particles fall velocity, weights in geometric programming
w^*	optimal weights in geometric programming
x_{i1}, x_{i2}	sectional pipe link lengths
z	nodal elevation
z_o	nodal elevation at input point
z_L	nodal elevation at supply point
z_n	nodal elevation at *n*th node
z_x	nodal elevation at point *x*

α	valve closer angle, pipe bend angle, salvage factor of goods
β	annual maintenance factor; distance factor between two capsules
β_i	expected number of failure per year for pipe i
λ	Lagrange multiplier, ratio of friction factors between pipe annulus and capsule
ν	kinematic viscosity of fluid
ε	roughness height of pipe wall
ρ	mass density of water
σ	peak water demand per unit area
ξ	length ratio
η	efficiency
θ	capsule wall thickness factor
θ_p	peak discharge factor
ω	rate of water supply
ΔQ_k	discharge correction in loop k

Superscript

*	optimal

Subscripts

e	effective, spindle depth obstructing flow in pipe
i	pipe index
$i1$	first section of pipe link
$i2$	second section of pipe link
L	terminating point or starting point
o	entry point
p	pipe
s	starting node
t	track

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INTRODUCTION

1.1. BACKGROUND

Water and air are essential elements for human life. Even then, a large population of the world does not have access to a reliable, uncontaminated, piped water supply. Drinking water has been described as a physical, cultural, social, political, and economic resource (Salzman, 2006). The history of transporting water through pipes for human

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consumption begins around 3500 years ago, when for the first time pipes were used on the island of Crete. A historical perspective by James on the development of urban water systems reaches back four millennia when bathrooms and drains were common in the Indus Valley (James, 2006). Jesperson (2001) has provided a brief history of public water systems tracking back to 700 BC when sloped hillside tunnels (*qantas*) were built to transport water to Persia. Walski et al. (2001) also have published a brief history of water distribution technology beginning in 1500 BC. Ramalingam et al. (2002) refer to the early pipes made by drilling stones, wood, clay, and lead. Cast iron pipes replaced the early pipes in the 18th century, and significant developments in making pipe joints were witnessed in the 19th century. Use of different materials for pipe manufacturing increased in the 20th century.

Fluid flow through pipelines has a variety of applications. These include transport of water over long distances for urban water supply, water distribution system for a group of rural towns, water distribution network of a city, and so forth. Solids are also transported through pipelines; for example, coal and metallic ores carried in water suspension and pneumatic conveyance of grains and solid wastes. Pipeline transport of solids containerized in capsules is ideally suited for transport of seeds, chemicals that react with a carrier fluid, and toxic or hazardous substances. Compared with slurry transport, the cargo is not wetted or contaminated by the carrier fluid; no mechanism is required to separate the transported material from the fluid; and foremost it requires less power for maintaining the flow. For bulk carriage, pipeline transport can be economic in comparison with rail and road transport. Pipeline transport is free from traffic holdups and road accidents, is aesthetic because pipelines are usually buried underground, and is also free from chemical, biochemical, thermal, and noise pollution.

A safe supply of potable water is the basic necessity of mankind in the industrialized society, therefore water supply systems are the most important public utility. A colossal amount of money is spent every year around the world for providing or upgrading drinking water facilities. The major share of capital investment in a water supply system goes to the water conveyance and water distribution network. Nearly 80% to 85% of the cost of a water supply project is used in the distribution system; therefore, using rational methods for designing a water distribution system will result in considerable savings.

The water supply infrastructure varies in its complexity from a simple, rural town gravity system to a computerized, remote-controlled, multisource system of a large city; however, the aim and objective of all the water systems are to supply safe water for the cheapest cost. These systems are designed based on least-cost and enhanced reliability considerations.

1.2. SYSTEM CONFIGURATION

In general, water distribution systems can be divided into four main components: (1) water sources and intake works, (2) treatment works and storage, (3) transmission mains, and (4) distribution network. The common sources for the untreated or raw water are surface water sources such as rivers, lakes, springs, and man-made reservoirs and groundwater sources such as bores and wells. The intake structures and pumping stations are constructed to extract water from these sources. The raw water is transported to the treatment plants for processing through transmission mains and is stored in clear water reservoirs after treatment. The degree of treatment depends upon the raw water quality and finished water quality requirements. Sometimes, groundwater quality is so good that only disinfection is required before supplying to consumers. The clear water reservoir provides a buffer for water demand variation as treatment plants are generally designed for average daily demand.

Water is carried over long distances through transmission mains. If the flow of water in a transmission main is maintained by creating a pressure head by pumping, it is called a pumping main. On the other hand, if the flow in a transmission main is maintained by gravitational potential available on account of elevation difference, it is called a gravity main. There are no intermediate withdrawals in a water transmission main. Similar to transmission mains, the flow in water distribution networks is maintained either by pumping or by gravitational potential. Generally, in a flat terrain, the water pressure in a large water distribution network is maintained by pumping; however, in steep terrain, gravitational potential maintains a pressure head in the water distribution system.

A distribution network delivers water to consumers through service connections. Such a distribution network may have different configurations depending upon the layout of the area. Generally, water distribution networks have a looped and branched configuration of pipelines, but sometimes either looped or branched configurations are also provided depending upon the general layout plan of the city roads and streets. Urban water networks have mostly looped configurations, whereas rural water networks have branched configurations. On account of the high-reliability requirement of water services, looped configurations are preferred over branched configurations.

The cost of a water distribution network depends upon proper selection of the geometry of the network. The selection of street layout adopted in the planning of a city is important to provide a minimum-cost water supply system. The two most common water supply configurations of looped water supply systems are the gridiron pattern and the ring and radial pattern; however, it is not possible to find an optimal geometric pattern that minimizes the cost.

1.3. FLOW HYDRAULICS AND NETWORK ANALYSIS

The flow hydraulics covers the basic principles of flow such as continuity equation, equations of motion, and Bernoulli's equation for close conduit. Another important area of pipe flows is to understand and calculate resistance losses and form losses due to pipe fittings (i.e., bends, elbows, valves, enlargers and reducers), which are the essential parts of a pipe network. Suitable equations for form-losses calculations are required for total head-loss computation as fittings can contribute significant head loss to the system. This area of flow hydraulics is covered in Chapter 2.

The flow hydraulics of fluid transporting sediments in suspension and of capsule transport through a pipeline is complex in nature and needs specific consideration in head-loss computation. Such an area of fluid flow is of special interest to industrial engineers/designers engaged in such fluid transportation projects. Chapter 2 also covers the basics of sediment and capsule transport through pipes.

Analysis of a pipe network is essential to understand or evaluate a physical system, thus making it an integral part of the synthesis process of a network. In case of a single-input system, the input discharge is equal to the sum of withdrawals. The known parameters in a system are the pipe sizes and the nodal withdrawals. The system has to be analyzed to obtain input point discharges, pipe discharges, and nodal pressure heads. In case of a branched system, starting from a dead-end node and successively applying the node flow continuity relationship, all pipe discharges can be easily estimated. Once the pipe discharges are known, the nodal pressure heads can be calculated by applying the pipe head-loss relationship starting from an input source node with known input head. In a looped network, the pipe discharges are derived using loop head-loss relationship for known pipe sizes and nodal continuity equations for known nodal withdrawals.

Ramalingam et al. (2002) published a brief history of water distribution network analysis over 100 years and also included the chronology of pipe network analysis methods. A number of methods have been used to compute the flow in pipe networks ranging from graphical methods to the use of physical analogies and finally the use of mathematical/numerical methods.

Darcy–Weisbach and Hazen–Williams provided the equations for the head-loss computation through pipes. Liou (1998) pointed out the limitations of the Hazen–Williams equation, and in conclusion he strongly discouraged the use of the Hazen–Williams equation. He also recommended the use of the Darcy–Weisbach equation with the Colebrook–White equation. Swamee (2000) also indicated that the Hazen–Williams equation was not only inaccurate but also was conceptually incorrect. Brown (2002) examined the historical development of the Darcy–Weisbach equation for pipe flow resistance and stated that the most notable advance in the application of this equation was the publication of an explicit equation for friction factor by Swamee and Jain (1976). He concluded that due to the general accuracy and complete range of application, the Darcy–Weisbach equation should be considered the standard and the others should be left for the historians. Considering the above investigations, only the Darcy–Weisbach equation for pipe flow has been covered in this book for pipe network analysis.

Based on the application of an analysis method for water distribution system analysis, the information about pipes forming primary loops can be an essential part of the data. The loop data do not constitute information independent of the link-node information, and theoretically it is possible to generate loop data from this information. The information about the loop-forming pipes can be developed by combining flow paths. These pipe flow paths, which are the set of pipes connecting a demand (withdrawals) node to the supply (input) node, can be identified by moving opposite to the direction of flow in pipes (Sharma and Swamee, 2005). Unlike branched systems, the flow directions in looped networks are not unique and depend upon a number of factors, mainly topography, nodal demand, layout, and location and number of input (supply) points. The pipe flow patterns will vary based on these factors. Hence, combining flow paths, the flow pattern map of a water distribution network can also be generated, which is important information for an operator/manager of a water system for its efficient operation and maintenance.

The analysis of a network is also important to make decisions about the network augmentation requirements due to increase in water demand or expansion of a water servicing area. The understanding of pipe network flows and pressures is important for making such decisions for a water supply system.

Generally, the water service connections (withdrawals) are made at an arbitrary spacing from a pipeline of a water supply network. Such a network is difficult to analyze until simplified assumptions are made regarding the withdrawal spacing. The current practice is to lump the withdrawals at the nodal points; however, a distributed approach for withdrawals can also be considered. A methodology is required to calculate flow and head losses in the pipeline due to lumped and distributed withdrawals. These pipe network analysis methods are covered in Chapter 3.

1.4. COST CONSIDERATIONS

To carry out the synthesis of a water supply system, one cannot overlook cost considerations that are absent during the analysis of an existing system. Sizing of the water distribution network to satisfy the functional requirements is not enough as the solution should also be based on the least-cost considerations. Pumping systems have a large number of feasible solutions due to the trade-off between pumping head and pipe sizes. Thus, it is important to consider the cost parameters in order to synthesize a pumping system. In a water distribution system, the components sharing capital costs are pumps and pumping stations; pipes of various commercially available sizes and materials; storage reservoir; residential connections and recurring costs such as energy usage; and operation and maintenance of the system components. The development of cost functions of various components of water distribution systems is described in Chapter 4.

As the capital and recurring costs cannot be simply added to find the overall cost (life-cycle cost) of the system over its life span, a number of methods are available to combine these two costs. The capitalized cost, net present value, and annuity methods for life-cycle cost estimation are also covered in Chapter 4. Fixed costs associated with source development and treatment works for water demand are not included in the optimal design of the water supply system.

1.5. DESIGN CONSIDERATIONS

The design considerations involve topographic features of terrain, economic parameters, and fluid properties. The essential parameters for network sizing are the projection of residential, commercial, and industrial water demand; per capita water consumption; peak flow factors; minimum and maximum pipe sizes; pipe material; and reliability considerations.

Another important design parameter is the selection of an optimal design period of a water distribution system. The water systems are designed for a predecided time horizon generally called design period. For a static population, the system can be designed either for a design period equal to the life of the pipes sharing the maximum cost of the system or for the perpetual existence of the water supply system. On the other hand, for a growing population or water demand, it is always economic to design the system in stages and restrengthen the system after the end of every staging period. The design period should be based on the useful life of the component sharing maximum cost, pattern of the population growth or increase in water demand, and discount rate. The reliability considerations are also important for the design of a water distribution system as there is a trade-off between cost of the system and system reliability. The essential parameters for network design are covered in Chapter 5.

1.6. CHOICE BETWEEN PUMPING AND GRAVITY SYSTEMS

The choice between a pumping or a gravity system on a topography having mild to medium slope is difficult without an analytical methodology. The pumping system can be designed for any topographic configuration. On the other hand, a gravity system is feasible if the input point is at a higher elevation than all the withdrawal points. Large pipe diameters will be required if the elevation difference between input point and withdrawals is very small, and the design may not be economic in comparison with a pumping system. Thus, it is essential to calculate the critical elevation difference at which both pumping and gravity systems will have the same cost. The method for the selection of a gravity or pumping system for a given terrain and economic conditions are described in Chapter 6.

1.7. NETWORK SYNTHESIS

With the advent of fast digital computers, conventional methods of water distribution network design have been discarded. The conventional design practice in vogue is to analyze the water distribution system assuming the pipe diameters and the input heads and obtain the nodal pressure heads and the pipe link discharges and average velocities. The nodal pressure heads are checked against the maximum and minimum allowable pressure heads. The average pipe link velocities are checked against maximum allowable average velocity. The pipe diameters and the input heads are revised several times to ensure that the nodal pressure heads and the average pipe velocities do not cross the allowable limits. Such a design is a feasible design satisfying the functional and safety requirements. Providing a solution merely satisfying the functional and safety requirements is not enough. The cost has to be reduced to a minimum consistent with functional and safety requirements and also reliability considerations.

The main objective of the synthesis of a pipe network is to estimate design variables like pipe diameters and pumping heads by minimizing total system cost subject to a number of constraints. These constraints can be divided into *safety* and *system* constraints. The safety constraints include criteria about minimum pipe size, minimum and maximum terminal pressure heads, and maximum allowable velocity. The system constraints include criteria for nodal discharge summation and loop headloss summation in the entire distribution system. The formulation of safety and system constraints is covered in Chapter 5.

In a water distribution network synthesis problem, the cost function is the objective function of the system. The objective function and the constraints constitute a nonlinear programming problem. Such a problem can only be solved numerically and not mathematically. A number of numerical methods are available to solve such problems. Successive application of liner programming (LP) and geometric programming (GP) methods for network synthesis are covered in this book.

Broadly speaking, following are the aspects of the design of pipe network systems.

1.7.1. Designing a Piecemeal Subsystem

A subsystem can be designed piecemeal if it has a weak interaction with the remaining system. Being simplest, there is alertness in this aspect. Choosing an economic type (material) of pipes, adopting an economic size of gravity or pumping mains, adopting a minimum storage capacity of service reservoirs, and adopting the least-cost alternative of various available sources of supply are some examples that can be quoted to highlight this aspect. The design of water transmission mains and water distribution mains can be covered in this category. The water transmission main transports water from one location to another without any intermediate withdrawals. On the other hand, water distribution mains have a supply (input) point at one end and withdrawals at intermediate and end points. Chapters 6 and 7 describe the design of these systems.

1.7.2. Designing the System as a Whole

Most of the research work has been aimed at the optimization of a water supply system as a whole. The majority of the components of a water supply system have strong interaction. It is therefore not possible to consider them piecemeal. The design problem of looped network is one of the difficult problems of optimization, and a satisfactory solution methodology is in an evolving phase. The design of single-supply (input) source, branched system is covered in Chapter 8 and multi-input source, branched system in Chapter 9. Similarly, the designs of single-input source, looped system and multi-input source, looped system are discussed in Chapters 10 and 11, respectively.

1.7.3. Dividing the Area into a Number of Optimal Zones for Design

For this aspect, convenience alone has been the criterion to decompose a large network into subsystems. Of the practical considerations, certain guidelines exist to divide the network into a number of subnetworks. These guidelines are not based on any comprehensive analysis. The current practice of designing such systems is by decomposing or splitting a system into a number of subsystems. Each subsystem is separately designed and finally interconnected at the ends for reliability considerations. The decision regarding the area to be covered by each such system depends upon the designer's intuition. On the other hand, to design a large water distribution system as a single entity may have computational difficulty in terms of computer time and storage. Such a system can also be efficiently designed if it is optimally split into small subsystems (Swamee and Sharma, 1990a). The decomposition of a large water distribution system into subsubsystems and then the design of each subsystem is described in Chapter 12.

1.8. REORGANIZATION OR RESTRENGTHENING OF EXISTING WATER SUPPLY SYSTEMS

Another important aspect of water distribution system design is strengthening or reorganization of existing systems once the water demand exceeds the design capacity. Water distribution systems are designed initially for a predecided design period, and at the end of the design period, the water demand exceeds the design capacity of the existing system on account of increase in population density or extension of services to new growth areas. To handle the increase in demand, it is required either to design an entirely new system or to reorganize the existing system. As it is expensive to replace the existing system with a new system after its design life is over, the attempt should be made to improve the carrying capacity of the existing system. Moreover, if the increase in demand is marginal, then merely increasing the pumping capacity and pumping head may suffice. The method for the reorganization of existing systems (Swamee and Sharma, 1990b) is covered in Chapter 13.

1.9. TRANSPORTATION OF SOLIDS THROUGH PIPELINES

The transportation of solids apart from roads and railways is also carried out through pipelines. It is difficult to transport solids through pipelines as solids. Thus, the solids are either suspended in a carrier fluid or containerized in capsules. If suspended in a carrier fluid, the solids are separated at destination. These systems can either be gravity-sustained systems or pumping systems based on the local conditions. The design of such systems includes the estimation of carrier fluid flow, pipe size, and power requirement in case of pumping system for a given sediment flow rate. The design of such a pipe system is highlighted in Chapter 14.

1.10. SCOPE OF THE BOOK

The book is structured in such a way that it not only enables engineers to fully understand water supply systems but also enables them to design functionally efficient and least-cost systems. It is intended that students, professional engineers, and researchers will benefit from the pipe network analysis and design topics covered in this book. Hopefully, it will turn out to be a reference book to water supply engineers as some of the fine aspects of pipe network optimization are covered herein.

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