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Systems Analysis for Urban Water Supply and Distribution

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ABSTRACT

The use of systems analysis, computer-aided planning and engineering and a multidisciplinary team of specialists in urban planning, hydraulics engineering, systems analysis and financial analysis represents a comprehensive approach to the development of water supply and distribution systems. Each technical discipline must interact efficiently with the others at various phases of the project and few major decisions can be made without input from several disciplines. Systems analysis methodology in planning, operations research and hydraulics has advanced sufficiently in recent years so that solution techniques as well as computer programs are available for a wide variety of water resource problems. The optimization of water supply and distribution networks to meet future demands will depend on the use of comprehensive and systematic analyses of the type described here.

Introduction

The proper planning of an efficient urban water supply and distribution system may be accomplished only through an interdisciplinary effort that recognizes the importance of each of the technical disciplines related to water resources. Planners, hydraulic engineers, systems analysts, financial analysts, and economists are all essential to the task of developing a comprehensive plan for creating a new supply and distribution system or for the expansion of an existing system to meet future demands. It has traditionally been the role of the hydraulic engineer to assume responsibility for all of the decisions related to water supply and distribution. It may now be argued that the

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availability of new technology, especially in the fields of computer-aided land use planning and systems optimization, should lead to a redefinition of the role of the hydraulics engineer. If it is desired to develop a water system that represents the most efficient use of physical and financial resources, it is necessary that the new available technology play an important role in system development. This can be done only if the planner and the systems analyst are an integral and important part of the team. The hydraulic engineer must continue to play an important and perhaps dominant role in planning projects, but it should be recognized that team leadership must be aware of, and sensitive to, new technologies.

This paper will describe a comprehensive approach to the problem of optimizing a water supply and distribution system for a large urban region. The contribution of the disciplines necessary to solve the problems will be investigated and specific planning and engineering techniques will be described. In addition, the interaction between disciplines will be examined in terms of decision priorities and the overlap of solution techniques.

The Problem

Given a politically defined region, the problem is to develop a water supply and distribution system that will meet all probable demands for water over some planning period. The total cost of such a system should be minimized. This is the problem stated in a general way. The precise definition of a specific project problem must include a number of explanatory and qualifying statements that help to reduce the large number of alternative solutions to a tractable subset with which the team can work. This definition process is composed of a series of decisions to be made by the study team in coordination with their client. Some decisions are obvious; others are complex and difficult to make.

The total planning process takes place in four large steps—determination of demand; conceptual development of alternative systems; optimization of the selected system; and development of a design, construction, and financial plan for the selected optimum system. The final result of the process is a comprehensive report which details the process itself, the proposed system, the design and construction schedule, and the financial implementation plan. This report may now be used for future decisions concerning final implementation towards the future system.

Determination of Demand

The first step in the planning process is the determination of the demand for water over the selected planning period. The water demand will be a function of the land use patterns during the planning period and the principal task of the group performing the demand analysis will be to predict these patterns as a function of time and space. This is a traditional task in urban planning, implying the necessity of including urban planners on the study team.

The specific tasks include:

- the assembly and consolidation of available planning studies for the region,
- analysis of existing studies to determine relevance to the requirements of supplying water service,
- projection of probable future activity patterns,
- derivation of water demand for various types of land uses and future activity patterns,
- analysis of the probable effects of new water systems on future land use patterns.

The prediction of the type and distribution of future land use is amenable to systems analysis and the use of computers. The first step in the systematic analysis of a region is to define land use categories. These may include heavy and light industry, dense and sparse residential development, commercial development, institutional uses and passive uses including parks, open space, vacant land, cemeteries, and other open land uses.

These categories may be defined in several ways. Heavy industry, for example, may be defined as labor intensive or capital intensive industry with a certain employment density or investment figure. For the purposes of developing future water demand, it is reasonable to define land uses with respect to water use. Using such a definition, heavy industries would include pulp and paper manufacturing, petroleum refining, or metal manufacturing because of their intensive use of water. Light industries would include leather manufacturing, electrical equipment manufacturing, or lumber and wood production because of their relatively low water usage.

The next step is to define a series of zonal characteristics. The region is subdivided into zones of uniform size, by political jurisdiction, by geographic boundaries, or by any other parameter that is reasonable for the specific region under study. For each zone, the socio-economic and physical characteristics are graded. These characteristics may include crime rates, community prestige, travel times to centers, past land uses, presence of sewer or water systems, existence of lakes, existence of transit, proximity to major road interchanges, distance from airport, or any other specific characteristic that would have an affect on the location of the land use categories previously defined. The grading may be performed on a binary basis or on a scalar basis. That is, the presence or absence of a specific characteristic may be noted by a simple "yes"-"no" or "0"-"1," or, alternatively, the existence of a specific characteristic may be rated on a scale from 0 (absence) to 10 (or any other number greater than 1) depending upon the degree to which that characteristic is present in the specific zone. This grading will create a matrix of zonal characteristics.

The third step in defining future land use patterns is to determine the relationship between the land use categories and the zonal characteristics. This relationship may have a binary character or a scalar character. For example, it may be decided that heavy industry is not favorably located on swampy land. This may be signified by a "0" in a matrix relating zonal characteristics to land use categories. Alternatively, the degree by which a specific zonal characteristic is favorable to the location of a specific land use category may be rated on some arbitrary scale. In either case, a second matrix is generated.

Now, the demand for specific land uses must be determined. This demand is arrived at through a careful analysis of existing land use, population, employment, planning patterns, and other socio-economic and political information relating to the region. The principal product of this analysis is a forecast of population, employment, and the expected density of each of these two parameters. This forecast is then used to predict the gross future land use. Note that the forecast is for the region as a whole and no distribution is determined at this point. In addition to this forecast, a comprehensive list is made of the possible public policies that might influence land use distribution. These policies would include the location of major highways, rail lines, airports, recreational facilities, and water and sewer lines.

At this point, systems analysis and the computer are applied. The problem is to distribute the gross future land use to the zones in such a way as to minimize the conflicts between land use categories and zonal characteristics. This distribution is most efficiently performed using systems analysis techniques and digital computers. For even a small region, the problem is intractable without these tools. The writer and his colleagues have worked with a model of this type, called DYLAM (*Dy*namic *La*nd Use *M*odel), developed at Columbia University.[1]

After the land uses have been distributed to the zones, they are translated into a zonal water demand matrix which relates the demand for water to the specific zones. This task requires both the planner and the engineer; and it is at this point that they begin to interact. The project now moves into the principal engineering phase.

Conceptual Development of Alternative Systems

The planning process has created an understanding of the demand for water and has distributed that demand to the regional zones. The engineering team must now develop alternative systems that will serve to meet that demand. The first step in this process is to examine the sources of water to be tapped. In some areas the source is obvious and entirely dictated by economics or political jurisdiction. For example, those cities lying directly on the great lakes (Buffalo, Erie, Cleveland, Chicago, Detroit, etc.) would probably not look beyond these enormous bodies of water for alternative supplies. A city such as Akron, which lies close to Lake Erie cannot, however, use the lake as a water source because the city lies in a different watershed and water may not be transferred across the watershed boundary under current federal law.

In other areas, there may be many alternative supplies including lakes, ground water, rivers, or surface water diversion. Either one or a combination of these sources would be an element in the water supply system. The specific choice of supply is based on a multitude of factors including economics, engineering, politics, and law. For each alternative supply the hardware necessary to develop that supply must be designed (in sufficient detail to determine rough cost estimates), costs must be computed, and the political and legal ramifications of diverting water from that source must be studied. For example, existing water rights belonging to others may preclude further development of that supply by a specific municipality.

An important decision point occurs here. It is possible to optimize the water supply system and choose the least expensive source without regard to its effect on the distribution system. This should be done only if the supply and distribution systems are uncoupled, or if the combined supply and distribution systems are too complex to allow efficient solution of the optimization problem. If possible, optimization should be applied to the entire supply and distribution system including source structures, supply pipelines or tunnels, treatment plants, pumps, valves, pipes, and the other elements of a total system. It is possible under certain circumstances that the distribution system is highly dependent on the type of source to be used. In this case, optimization must be performed on the combined systems. An excellent discussion of the problem of water supply and alternative sources is given in Hirshleifer, De Haven, and Milliman.[2]

Either after the supply sources have been chosen or concurrent with their choice, it is necessary to develop alternative distribution systems. This job is best performed by small, independent teams of engineers, each working towards the same goal but from different viewpoints. Consider, for example, the development of a water supply and distribution system for a city which already has a complex network but wishes to expand its system to meet future demands. One team might examine alternative methods for adding to the existing system without changing the basic nature of the network. Concurrently, a second, and independent, team would examine the demand pattern and study new alternative types of distribution systems that would meet that demand.

It is infeasible to ignore an existing system because of the high sunk cost, but the mode of operation of the system may be changed radically while retaining the physical structure. As an example, a city located on a lake with existing intake structures and a distribution system may operate that system in several ways. The water can be treated at the intake pump stations and held in low reservoirs for demand pumping. Alternatively, the water can be pumped to high storage areas such as tanks or upland reservoirs and gravity fed through the same distribution system. Valves would have to be changed, but most of the system could probably be retained in many cases. The savings in electric power achieved by pumping during off-peak hours must be weighed against the cost of changing system elements and providing upland or high storage. A combination of several systems may also be explored. In the example cited here, a combination of intake site storage and upland storage with gravity feed might be accomplished through the use of a large diameter pipe encircling the demand region and creating "ring" storage. Demands would be met with a combination of pumping and gravity feed.

When a group of alternative distribution systems have been sketched, a preliminary cost estimate is made of each system. Although none of the systems has been optimized, the cost difference would, in most cases, be large enough to allow for the selection of one alternative. The systems analyst now becomes the dominant team member and proceeds to optimize the chosen alternative.

Optimization of the Selected System

The systems analysis portion of the problem may be defined as follows:

> By varying certain physical parameters (structures, pipe sizes, etc.) find a system (the total supply and distribution system) composed of these parameters that satisfies all operative constraints (physical laws of hydraulics and demand for water) such that the functional objective (total system costs) is optimized (made a minimum).

A problem so described can then be treated as a mathematical program. Available solution techniques developed in the fields of systems analysis and utilizing the mathematical tools of operations research are applicable. Most efforts in the recent development of systems analysis as related to the design of water distribution systems have been dedicated to the determination of steady-state flows and head losses in hydraulic networks.[3] The Hardy-Cross analysis is a prominent example. Shamir and Howard developed a procedure for solving networks that appears to be an improvement over Hardy-Cross.[4] Only recently have the applications of optimization techniques appeared feasible for the design of hydraulic networks.

Pitchai utilized nonlinear integer programming in attempting to minimize the cost of pipes and the present value of the annual cost of pumping.[5] His solution required a heuristic, sequential random sampling scheme, and is computationally complex and expensive. Jacoby discusses the formulation of a more general nonlinear constrained integer programming problem.[6] Methods of finding solutions to the comprehensive problem defined by Jacoby are still subject to further refinement and research. No reference has been found to actual field applications of either of the two methods mentioned above. Schaake and Lai describe the application of linear programming to a water distribution network for the City of New York. An essentially nonlinear problem was linearized through the use of variable transformations.[7]

Simulation has been used by Parsons, Brinckerhoff in developing a water transfer plan for Molokai, Hawaii,[8] and is now being used by the City of Denver in planning the future of their water supply system which depends principally on reservoirs fed by Rocky Mountain surface diversions. In this case, the variability of stream flow, and the necessity of respecting senior water rights makes simulation a powerful method for the analysis of reservoir operations. Simulation is most appropriate in those cases where supply and demand are stochastic and storage must be regulated. If the time variation of demand is seasonal and the month-to-month storage problem is not encountered, the operational characteristics of the line reservoirs which regulate day-to-day delivery of water may be analyzed independently and need not be the concern of the optimization process. Under these circumstances direct simulation does not yield information pertinent to the optimal design of water supply systems.

The mathematical programming optimization process requires the development of four major programming elements—*decision variables, cost coefficients, objective function,* and *constraint equations.* In a water distribution network the decision variables are those parameters that will determine the cost of the system such as pipe diameters, treatment plant capacities, or pump sizes. Each decision variable has an associated cost coefficient by which it is multiplied in the objective equation. This equation states that the sum of all costs must be a minimum. The constraint equations are of two types—*demand* and *hydraulic* laws. These equations are also written in terms of the decision variables, and express the requirements that the demand for water be met and that no physical laws of hydraulics be violated.

The principal problems that arise in the development of the mathematical program are concerned with nonlinearities in either the objective function, the constraint equations, or both. Nonlinearities in the objective function arise because the relation between cost and decision parameters is often nonlinear. For example, the cost of a water pipe is a nonlinear function of pipe diameter. The constraint equations in water system problems is invariably nonlinear because the physical laws governing the behavior of these systems are nonlinear with respect to the decision parameters such as pipe diameter. Assuming that the constraint equations are convex, these problems are usually surmountable.

The operations research literature describes the solution of nonlinear problems in a variety of forms.[9] For water networks, the use of separable linear programming is one solution. A second is that proposed and used by Schaake and Lai in which the decision variables are linearized through a simple transformation which creates linear constraint equations.[7] This forces the objective function into a nonlinear form which can be easily treated by stepwise programming or linear approximation.

The result of the mathematical programming is a series of decision variables which, taken together, represent the minimum cost system that satisfies the constraints. In addition, the final value of the objective function will be the cost of that system.

It should be noted that the typical water resource system mathematical program is not a simple linear program that may be prepared by a hydraulic engineer and submitted for a computer run to a data center. Considerable thought must be given to the careful choice of decision variables, the form of the constraint equations and the objective function, and to the problems that arise due to the nonlinearity of the mathematical forms. Success in the useful solution of the problems of actual water resource systems should not be expected without the continued efforts of a water resource systems analyst trained in the techniques of operations research. It is also true that the successful modeling of a water resource system cannot be achieved by an operations research expert or a systems analyst working without the help of a hydraulics engineer familiar with the operational characteristics of water resource networks. It cannot be emphasized too strongly that the solution of problems in complex systems such as water distribution networks cannot be successfully attained without the cooperation of team members from a variety of complementary disciplines.

Development Plan for the Selected System

The selected and optimized system is now ready for financial analysis. This work is best performed by economists or financial experts with an understanding of municipal financing, debt structure, bond markets, rate structures, and political feasibility. This phase of the work is also interdisciplinary because project financing depends both on availability of funding as a function of time and on construction scheduling. The former is best determined by financial experts; the latter by hydraulic design engineers. These two must work together to arrive at a schedule of construction over the planning period and a schedule of cash flow over the financial period.

In producing a financial framework for developing the new or extended water supply and distribution system several important factors must be investigated. The applicable local, state and Federal legislation should be examined to determine the permissible modes and extent of financing, and the constraints. Existing intergovernmental arrangements should be investigated in the light of authorizations and constraints and the possible institutional relationships for financing development or expansion of the system. The characteristics of the existing debt structure of the involved political jurisdictions must be examined, again, as possible sources of constraints on financing. The characteristics that should be considered include amount and type of debt, terms, and methods of debt service, all related to sources of revenue and financial viability. The public and private sources of funding the proposed system should be explored. Applicable Federal and state grant and loan programs should be examined. Other sources and types of financing that can be examined include entrepreneurial investment such as public or mixed corporations, general government through taxation or bonds, special levies, or revenue bonds serviced through user charges.

With the completion of the financial plan, the project is ready to move into design and construction phases. If the kind of comprehensive and systematic study outlined in this paper has been performed, the design and construction of the project should proceed at minimum cost and in a minimum time. The study phase lays the groundwork for efficient completion of the job and will serve to create a plan which can be followed with the assurance that the project represents an optimal approach to the development of new facilities.

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