The History of Water Distribution Network Analysis: The Computer Age

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Abstract

Computation of flows and pressures in networks of pipes has been of great value and interest for those involved with the design, construction and maintenance of public water distribution systems. Many methods have been used in the past to compute flows in networks of pipes. Such methods range from graphical methods to the use of physical analogies and finally to the use of mathematical models. This paper will attempt to catalog and review those methods that have been developed and applied since the dawn of the "computer age" in 1957 when the original Hardy Cross method was first adapted for solution using a computer in analyzing the water distribution system of the city of Palo Alto, California. Subsequent methods have included the "simultaneous node: method, the "simultaneous loop" method, the "simultaneous pipe" method, and the "simultaneous network" method. A brief review of the theoretical framework of each method will be presented along with a critique of the relative advantages and/or limitations of each method.

With the advent of computer models of water distributions systems, it has now become possible to analyze more complex network components (e.g. pumps, tanks, PRVs, etc) of the water distribution system as well as to investigate more complex issues associated with their design and operation. Such additional applications have included 1) extend period simulations, 2) transient analysis, 3) water quality analysis, 4) optimal model calibration and design, 5) optimal operations, 6) optimal sampling plans, etc. The utility and feasibility of these additional types of applications can be demonstrated to be largely dependent upon the underlying simulation methods that were first developed beginning in the early 1960s.

Keywords
Water distribution models, history, mathematical algorithms

1. INTRODCTION

Computation of flows and pressures in network of pipes has been of great value and interest for those involved with design, construction and maintenance of public water distribution systems. In a recent article, Jesperson (2001) provides a brief historical overview of public water systems. According to Jesperson, the idea of public water supply systems can be traced back to as early as 700 BC when "qanats" (slightly sloped hillside tunnels) that brought water to Persia were built. Romans started constructing aqueducts from 312 BC. Recently discovered spring-water collection systems at Machu Pichu in Peru shed light on the elaborate engineering designs of ancient water supply systems. The Machu Pichu water supply systems dates bask to 1450AD. The first public water system in the United States dates back to 1652 AD when the City of Boston incorporated its water works formed to provide water for fire-fighting and domestic use. Since then many public water supply systems came into existence. In the earlier periods channels were made from cut stone, brick, or rubble. Pipes were made mostly from drilled stone, wood, clay and lead. In 18^{th} century, cast iron pipes replaced the wooden pipes. The 19^{th} century witnessed significant improvements in making pipe joints that withstood high pressures. Water supply pipelines made of steel, ductile-iron, asbestos cement and reinforced concrete came into increasing usage during the early 20^{th} century. Increasing complexities associated with distribution systems necessitated precise estimation of flows and pressures in various parts of the distribution system. Solution of single-pipe flow problem was no longer adequate. Quest for methods that analyze (solve for flows and pressures) entire water distribution network gave birth to the topic "water distribution network analysis" or "pipe network analysis."

2. NETWORK ANALYSIS METHODS

Many methods have been used in the past to compute flows in network of pipes. Such methods range from graphical methods to the use of physical analogies and finally to the use of mathematical models. This paper will review those methods of network analysis that have been developed and/or implemented on the computer over the last fifty years. A summary of some of the more important methods include:

- Hardy Cross Method (s)
- The Simultaneous Node Method
- The Simultaneous Loop Method
- The Linear Method (Simultaneous Pipe Method)
- The Gradient Method (Simultaneous Network Method)

The suitability, reliability, computational efficiency and accuracy of each of the above methods has been documented in the past and reported in the literature. The more recent computer methods such as the simultaneous node method, simultaneous loop method, the linear method, and the gradient method all use matrix formulations of the network problem in order to take advantage of the full power of modern day computers. The history of computer based models for use in network analysis can basically be divided into three periods: 1) The pre-computer period, 2) The Dawn of the Computer Age, and 3) The age of the advanced methods. Each of these periods is briefly reviewed in the following sections.

2.1 The Pre Computer Age

In 1936, Hardy Cross, a structural engineering professor at the University of Illinois at Urbana Champaign, developed a mathematical method for performing moment distribution analyses for statically determinate structures. Cross subsequently realized that the developed method could also be used to solve for pressures or flows in closed loop water distribution systems and published a paper outlining the application of the method for that purpose. In that paper, Cross actually presented two different methods: one which solved for the flows in each pipe by the iterative application of a flow adjustment factor for each loop in the network, and one which solved for the hydraulic grades at each node in the system by iterative application of a grade adjustment factor for each node in the system. In the former case, the associated nodal grades were then obtained by starting from a given reference point (e.g. a tank or reservoir) and then adding or subtracting the associated pipe headloss between adjacent nodes as determined by application of the Hazen-Williams equation. In the latter case, the flows in each pipe where then determined by solving the Hazen-Williams equation directly for discharge by using the differences in the resulting adjacent nodal grades as a measure of the headloss for the pipe. In applying the "loop" method, initial estimates of pipe flow had to be specified for each pipe which initially satisfied flow continuity at each junction node. In applying the "node" method, initial estimates of nodal hydraulic grade had to be specified for each junction node.

In comparing the two methods, Cross noted that "convergence was slow and not very satisfactory" when employing the node adjustment method. This was attributed to the difficulty in obtained good initial estimates for the hydraulic grades. As a result, the loop adjustment method gained greater acceptance in the engineering community and quickly became known exclusively as the "Hardy Cross Method". While the Hardy Cross method was originally developed for use with a non-computer based solution methodology, the overall structure of the method was clearly a candidate for such an application, however, the method would have to wait for several decades for the arrival of the computing hardware and software necessary for its full implementation.

2.2 The Dawn of the Computer Age

In 1957, Hoag and Weinberg adapted the Hardy Cross method for solving the network flow problem to the digital computer and applied the method to the water distribution system of the city of Palo Alto, California. In presenting their application the authors discussed issues of speed, accuracy, and the economic viability of applying the method for a large class of network problems. Subsequently, two consulting engineering firms, Rader & Associates, Miami, and Brown & Caldwell, San Francisco, quickly emerged as early pioneers in the use of the computer to analyze water distribution systems for their associate clients. In that same year, an electronic computing firm, Datics Corporation of Fort Worth, Texas became one of the first companies to sell a pipe network analysis computer program to one of its customers. The era of commercial software for network analysis had finally arrived (Engg. News-Records, 1957).

2.3 Advanced Computer Methods

With the advent of increasingly sophisticated computers, more engineers began exploring the use of the Hardy Cross method to analyze flows and pressures in water distribution systems. However, with applications to larger systems, came a growing realization of some major limitations of the method: 1) depending upon the size and complexity of the system, the Hardy Cross method could sometimes take long periods to converge to a solution and in some instances fail to converge at all, and 2) the original method was restricted to closed loop systems and did not explicitly simulate the behavior of network components such as valves, pumps, etc. In response to such limitations, several researchers began investigating new mathematical formulations of the network analysis problem which could more fully take advantage of the opportunities afforded by high speed computations. Among the methods subsequently developed were 1) the simultaneous node method, 2) the simultaneously loop method, 3) the simultaneous pipe method, and 4) the composite method. A brief overview of each of these methods is provided below.

Martin and Peters (1963) were the first researchers to publish a computer algorithm that could be used to simultaneously solve for the hydraulic grades at each junction node in the distribution system. In essence, the method represented a simultaneous solution methodology for the original "node" method of Cross (1936). In applying the algorithm, the headloss equations for each pipe (e.g. Hazen Williams Equation) are written in terms of the flows in each pipe as expressed as a function of the hydraulic grades at the upstream and downstream ends of the pipe. Substitution of these equations into the associated conservation of mass equation for each junction yields a set of N (where N is the total number of junction nodes) nonlinear equations written in terms of the nodal grades. The resulting equations are then linearized using a standard Taylor Series expansion and solved iteratively using the Newton Raphson method. Uri Shamir of Israel and Chuck Howard of Canada (1968) demonstrated that the method could also be used to accommodate systems with pumps and valves and also showed how the method could be used to solve for other unknowns.

In 1969, Alvin Flower and a graduate student named Robert Epp developed a new approach to network analysis at the University of British Columbia that applied the Newton-Raphson method to simultaneously solve for the flow adjustment factors associated with the original "loop" method of Cross (1936). This had the net benefit of significantly improving the convergence characteristics of the original algorithm.

In 1972, Wood and Charles introduced yet another formulation of the network problem ("the linear method") in which the nodal conservation of mass and the conservation of energy equations for each loop or path are solved simultaneously to directly yield the flowrate in each pipe. As with the "simultaneous loop" method, determination of the associated nodal grades requires the application of a secondary headloss routine. However, by virtue of the combination of conservation of mass and conservation of energy equations, an initial flow balance of the nodes is no longer required. This method has the added advantage of being able to readily determine other unknown parameters besides flowrate. In some sense, the characterization of the method as the "linear method" is archaic and arose from the original way in which Wood and Charles proposed for minimizing the iterative convergence error associated with the solution of the nonlinear energy equations. Subsequent developments of the algorithm into commercial programs (i.e. WOODNET, KYPIPE, PIPE2000) actually employed a standard Newton Raphson solution methodology (Wood, 1980).

Subsequent researchers like Roland Jeppson at Utah State University worked with CH2M Hill to develop a commercial program for network analysis based on the "simultaneous loop" method (Jeppson 1976). In using this approach, the nonlinear energy equations for each loop or path in the system are written in terms of flow adjustment factors. As with the "node" methods, the equations are linearized using a standard Taylor Series expansion and then solved iteratively using the Newton Raphson method. Once the final adjustment factors are obtained, the individual pipe flows can be determined by multiplication of the original pipe flow estimates by the resulting factors. As with the original Hardy Cross method, the algorithm requires initial flow estimates for all pipes that satisfy flow continuity. In addition, like the original Hardy Cross method, determination of the associated nodal grades requires the subsequent application of the Hazen Williams equation for each pipe.

A final method for discussion is the Gradient Method, which was proposed by Todini and Pilati (1987). In this formulation, individual energy equations for each pipe are combined with the individual nodal equations for each junction node to provide for a simultaneous solution for both nodal heads and individual pipe flows. Similar to the "simultaneous loop" and the "linear method", the nonlinear energy equations are first linearized using a Taylor Series expansion. However, in this case, the equations are solved using an efficient recursive scheme that employs an inversion of the original coefficient matrix. This method has been adopted for use by the EPA in the development of the program EPANET (Rossman, 1993).

3. COMMERICAL SOFTWARE

The late 1960s and early 1970s were a fertile period for the development of many network analysis algorithms at various universities around the country and even internationally. In the 1980s, many of these "research" programs (e.g. Fowler, Wood, Jeppson, Sharmir and Howard, Sarikelle) were converted into commercial software that were either marketed through universities or through small firms and/or large corporations. Among some of the more prominent industry entries into the market were WATSIM, by Boeing Computer Services and FASST, by MCAUTO. Domestic firms like Stoner Associates, and international firms like Expert Development Corporation (WATSYS), WRC (WATNET), Charles Howard and Associates (SPP8), and SAFEGE Consulting Engineers (Piccolo) also emerged to provide full service modeling to various utilities around the world. As we continued to move into the 1990s, additional firms like Haestad Methods (Cybernet) and WHM Soft Inc, began to develop nitch markets with both smaller and larger utilities respectively. The release by EPA of EPANET which was developed by Lewis Rossman in 1993, provided users with a comprehensive, free, and open architecture water distribution model that has been subsequently used and adapted by both the research and applications communities alike.

In April 1992, the first Network Analysis Forum was held in Nashville Tennessee as part of the American Water Works Association Computer Conference. This forum brought together 12 different vendors who appeared on stage together to briefly promote their products as well as to discuss the current state and future opportunities of network modeling. Among those in attendance were representatives of the following software packages: CYBERNET, RINCAD, STONER, AQUA, KYPIPE, Camp Dresser & McKee, CalcFlow, Piccolo, WaterWorks, TDHNET, Pipes for Windows, and WATSYS. Just two months later at the AWWA Annual Conference in Vancouver, BC, the list of vendors in attendance had grown to 22. Although many of these packages have since dropped out of the picture or developed a reduced market share of the modeling industry, network models as a whole continue to play a pivotal and integral role in the analysis and management of water distribution systems today, as they will undoubtedly continued to do so into the future

4. TEXTBOOKS AND HANDBOOKS

In addition to computer models, several excellent textbooks and handbooks on water distribution modeling have also been developed over the last several decades. One of the first textbooks of the "modern period" was written by Roland Jeppson – *Analysis of Flow in Pipe Networks* (1976) which provided one of the first complete descriptions of different solutions algorithms. This was followed by another classic – *Analysis of Water Distribution Systems* by Thomas Walski (1984). This book represented a compilation of several technical reports that Tom had produced while working for the Army Corps of Engineers in Vicksburg, and provided several practical guidelines on the development and application of network models. This was followed in 1990 by *Water Distribution Systems: Simulation and Sizing* by Walksi, Gessler, and Sjostrom. In 1995, Lee Cesario produced *Modeling, Analysis, and Design of Water Distribution Systems*, which among other contributions provides an excellent summary of the history of network modeling up through the mid 1990s. In 2000, Larry Mays served as editor of the AWWA *Water Distribution Systems Handbook* which covered a full range of topics dealing with water distribution systems and mathematical models. In 2001, Haestad Press published *Water Distribution Modeling*, which was authored by Thomas Walski, Donald Chase, and Dragan Savic. This was followed in 2003 by *Advanced Water Distribution Modeling and Management.* In 2005, after many years of revisions, AWWA issued the second edition of *M32-Manual of Water Supply Practices: Computer Modeling of Water Distribution Systems.* This report was the extended labor of the AWWA Engineering Computer Applications Committee which was originally formed in 1982. This library of textbooks and manuals has provided the water distribution modeler of the 21st century a rich resource of experience and guidance on the development and application of water distribution models for use in addressing the continuing challenges associated with delivery of potable water to the citizens of the world in a safe, reliable, and cost effective manner.

5. SUMMARY

This article has presented a brief historical review of various methods for computing flows and pressures in water distribution networks from the middle of the 19th century through the dawn of 21st century. This era has witnessed the development of several innovative methods for network analysis, including such methods as the Hardy Cross method, and the application of the Newton Raphson method to various formulations of the conservation of mass and conservation of energy equations associated with water distribution networks. In addition to continuing to play a vital role in the design, operation, and management of water distribution system today, such methods provide yet another example of the legacy of civil engineers and ASCE in impacting the quality of life in both the United States as well as the international community. With the advent of greater knowledge about the physical, chemical, and biological characteristics of water distribution systems, as well as the advent of new computer algorithms and associated computer technologies, the future opportunities for even greater impacts remain bright.

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