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ORIGINAL ARTICLE

Integrated approach for the optimal design of pipeline networks

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Abstract This paper presents the development of a GIS-based model for water pipeline network data integration and analysis named Integrated Water Distribution network design and Calibration Utility (IWDCU). IWDCU tackles two main applications in the field of Water Distribution Network (WDN). The first application (ELGTnet) addresses hydraulic analysis for both looped and branched networks. Also, based on Evolutionary Algorithms (EAs), EAnet is a computer-based technique for the optimal hydraulic design of WDN that satisfies both design demands and pressures at all network nodes with lowest possible cost. For the abovementioned two computer applications, mathematical modeling was combined with Geographic Information System (GIS) application for better data visualization and for best performance. The application of this integrated approach was subsequently further tested in Kostol Irrigational area to evaluate its applicability to real applications and its performances in finding best commercial design of network.

1. IWDCU architecture

The architecture of the IWDCU tool is lightweight and open. It integrates three software components, as shown in the data flow diagram in Fig. 1.

Data from water utility are gathered and then exported to Microsoft Excel™ workbooks, accompanied by metadata. WDN hydraulic Modeling is performed with ELGTnet model based on ‘‘Extended Linear Graph Theory Model'' presented by Gupta and Prasad 2000 and modified by Ayman 2010. Information is consolidated and then an application was made to find the optimal design of the network that satisfies all demands and pressures by means of EAnet. With this application, the ability to identify various types of Evolutionary algorithms options is available. Data are then extracted and converted into GIS format for visualization in the GIS data viewer ArcGIS 9.2 (ESRI, Redlands, CA). Results are then extracted and converted into GIS format for visualization and further querying.

2. ELGTNET

Water Distribution Network (WDN) represents a major portion of the investment in urban infrastructure and is consid-

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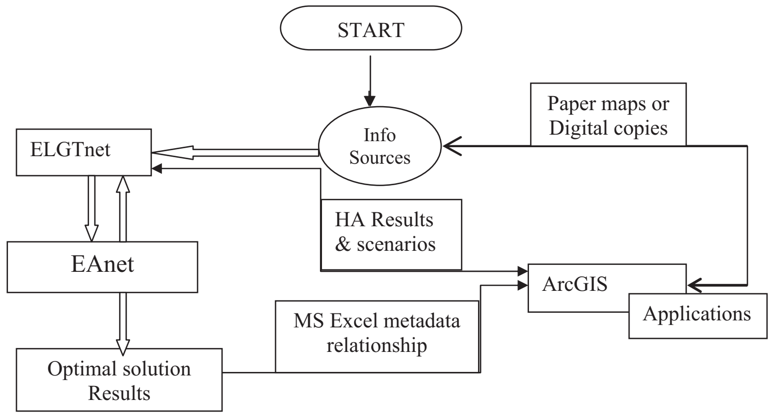

Figure 1 Data flow diagram for IWDCU GIS-based integrated tool for WDN.

ered a critical component of public works. The goal is to design water distribution systems to deliver drinking water for all areas satisfying design demands and pressure.

Pipe network analysis involves the process seeking the determination of discharge and associated pressure at every node. The analysis of a pipe network can be one of the more complex mathematical problems that engineers are called upon to solve. The proposed method uses (ELGT) presented by Gupta and Prasad [1] to formulate the model. This technique is modified to: (i) include new network components such as flow control valves, tanks, and for extended period simulation (EPS), and (ii) improve the convergence rate by introducing a modified method for the calculation of updated flows (Ayad [3]).

The proposed method is applicable if flow rates, heads, or a combination of both is specified at nodes in the network.

The method is applicable to hydraulic components that are commonly found in most distribution networks, such as pumps, valves, and junctions. An additional branch in the linear graph simulates pump and pressure reducing valve (PRV), respectively and the components and their graph models are given in Table 1. The head loss in a valve, fitting, or junction is approximated by its equivalent length, or by writing the head Loss equation in linear form and adding it to the head loss expressions that correspond to the pipes or branches connected to it. The method can be used for pipe failure analysis where the heads at nodes are not limited to specified values. To perform this analysis, entries corresponding to the pipe in question are set to zero in the matrix **S**.

2.1. Solution steps

1. Assume any initial flow rate $q0$ in the pipes (same in all pipes).
2. Calculate a stiffness factor($k = 1/r|q_0^{\alpha-1}|$) for each pipe. (1)
3. Obtain the matrix **K** using $[\mathbf{K}] = [S]^T[k][S]$ (2)
4. Compute the unknowns(nodal heads and/or nodal flows)
   $$[K]_{n\times n} = [S]^T[k][S] \quad (3)$$
5. Compute pipe head losses using $[K]_{n\times n}[h_t] = -[I][q_t]$ (4)
6. Compute pipe flows using $[h_c] = [-S] \times [h_t]$ (5)
7. Compute the weighted flow rates in pipes using Eq. (6) with $b = 0.45$.
   $$q_i = \lambda h_i^{\alpha}, \text{ and } h_i = \left(\frac{q_i}{\lambda}\right)^{\frac{1}{\alpha}} \quad (6)$$
   where
   q_i = flow through pipe i.
8. Repeat steps 2–8, with the weighted flow rates calculated in Step 7, until the desired accuracy is achieved.

The solution algorithm incorporates an exact mass balance at each node. A negligible change in pipe flows after a succession of iterations indicates that the mass balance requirements have been met, and the solution has converged. The relative error, defined below, is considered to be a convergence:

$$\text{Criterion} \left(\frac{\sum_{i=1}^{P}|q_{cij} - q_{cij-1}|}{\sum_{i=1}^{P}|q_{cij}|}\right) < 0.1\% \quad (7)$$

where q_{cij} flow through pipe i in iteration j; q_{cij-1} flow through pipe i in iteration $(j-1)$.

2.2. EPAnet program

EPAnet is a public-domain, water-distribution-system modeling package developed by the U.S. Environmental Protection Agency's Water Supply and Water Resources Division. EPAnet performs extended period simulation of hydraulic and water quality behavior within pressurized pipe networks. A network consists of pipes, nodes (pipe junctions), pumps, valves and storage tanks or reservoirs. EPAnet tracks the flow of water in each pipe, the pressure at each node, the height of water in each tank, and the concentration of a chemical species throughout the network during a simulation period comprised of multiple time steps.

EPAnet first appeared in 1993 (Rossman [4]). The program can be downloaded from the World Wide Web. EPAnet is used as calibrating software to compare the performance of presented model named (ELGTnet). Also, the result of each model is being checked to ensure model accuracy.

2.3. ELGTNET applications

The model is used for the hydraulic simulation of a water distribution network. The presented model has been coded in