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APPLICATION OF PRESSURE-DEPENDENT EPANET EXTENSION

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Abstract

Several hydraulic modelling approaches have been proposed previously to simulate pressure deficient operating conditions in water distribution systems more realistically including the pressure dependent EPANET extension model EPANET-PDX that has an embedded logistic nodal head-flow function. The model has been extensively tested previously on benchmark as well as real life networks. In this article, we demonstrate an alternative implementation of the line search and backtracking procedure to enhance EPANET-PDX further. This has increased the robustness by enhancing greatly the computational properties for low flow conditions and increasing the algorithm's consistency over a wider range of operating conditions. We present results for extended period simulations of a real life network considering pipe closures and variations in the heads at the supply nodes.

Keywords: Logistic pressure-dependent nodal head-flow function, pressure deficient water distribution system, line minimization, line search and backtracking, EPANET-PDX, penalty-free constrained evolutionary multiobjective optimization

INTRODUCTION

Hydraulic models are used extensively in the design and operation of water distribution systems to help predict potential changes under a wide range of operating conditions. In abnormal operating conditions, water distribution systems may be pressure deficient and thus unable to satisfy demands in full (Gupta and Bhave [1]; Tanyimboh and Templeman [9]). In such circumstances, pressure dependent analysis models are suitable, to quantify the shortfall in flow and pressure accurately for crucial decision-making. Such scenarios cannot be simulated satisfactorily with the conventional demand driven analysis models as they do not consider the relationship between nodal flows and the available pressure. A review of nodal head-flow functions can be found in Tanyimboh and Templeman [9].

Recently, Siew and Tanyimboh [6] developed a pressure dependent extension of the EPANET hydraulic simulator to enable modelling of pressure deficient networks. The model has an integrated continuous nodal head-flow function (Tanyimboh and Templeman [9]) coupled with a line search and backtracking procedure to facilitate convergence. Extensive testing conducted on the model with benchmark and real life networks revealed good modelling performance. Also, the model was combined with a penalty-free multi-objective genetic algorithm for optimization of water distribution systems that generated superior results for benchmark as well as real life networks in terms of cost, hydraulic performance and computational efficiency compared to previous solutions (Siew and Tanyimboh [7], Siew *et al*. [8]). It has also been utilised for water quality modelling of real life networks (Seyoum and Tanyimboh [4]). Overall, the model has not experienced convergence problems while executing millions of simulations.

Having demonstrated the robustness and benefits of the model previously, including seamless integration in genetic algorithms, it seems beneficial to investigate ways of improving the algorithm further. In this article, the line search and backtracking procedure of the algorithm has been improved. This has increased the robustness further by enhancing greatly the computational properties for low flow conditions and increasing the algorithm's consistency over a wider range of operating conditions. Extended period simulations were executed, for a real life network that comprises multiple supply sources and various demand categories considering a range of normal and pressure-deficient operating conditions. Details of the results and computational efficiency of the improved algorithm are included herein.

PRESSURE DEPENDENT EPANET EXTENSION

The pressure-dependent extension EPANET-PDX integrates the continuous nodal head-flow function that Tanyimboh and Templeman [9] proposed in the global gradient algorithm (Todini and Pilati [10]) that is the hydraulic analysis model of EPANET 2.

$$Qn_i(Hn_i) = Qn_i^{req} \frac{\exp(\alpha_i + \beta_i Hn_i)}{1 + \exp(\alpha_i + \beta_i Hn_i)} \qquad (1)$$

where, for node i, Qn_i and Hn_i are the flow and head respectively; Qn_i^{req} is the demand; α_i and β_i are parameters determined using relevant field data. The ratio Qn_i/Qn_i^{req} is the fraction of the demand satisfied and is called the demand satisfaction ratio, with values from 0 to 1. Preserving the full functionality of EPANET 2, the pressure-dependent extension model can perform hydraulic and water quality modelling under normal and low-pressure conditions entirely seamlessly including extended period simulations (Siew and Tanyimboh [5, 6]; Seyoum and Tanyimboh [4]).

To integrate the nodal head-flow functions in the global gradient algorithm, the line search and backtracking procedure (Press *et al*. [2]) was utilized in EPANET-PDX to help ensure global convergence. In each iteration of the global gradient algorithm, the line search procedure checks the full Newton step first. If the Newton step does not make progress towards convergence that is acceptable, backtracking along the Newton direction is carried out to obtain an acceptable step. The application of the line search and backtracking procedure in the previous implementation in Siew and Tanyimboh [6] was somewhat limited, in an attempt to preserve the excellent computational properties of EPANET 2. We have developed an improved implementation herein that allows more iterations of the line search procedure. A significant improvement has been achieved particularly for operating conditions that have extremely small flows in comparison to the demands. For simplicity the improved algorithm is named hereinafter as EPANET-PDX (0.2) while the original version is named EPANET-PDX (0.1).

EXAMPLE, RESULTS AND DISCUSSION

The real life network indicated in Figure 1 is used here to demonstrate the accuracy, computational efficiency and robustness of the enhanced pressure dependent model. The network consists of 251 pipes of various lengths, 228 demand nodes, 29 fire hydrants and 5 supply nodes. The network is supplied in full from the neighbouring water supply zones via the supply nodes R1 to R5 in Figure 1 that have a level of 155 m. The network comprises multiple demand categories that include domestic demand, commercial demand, unaccounted for water and fire demands. We used the Darcy-Weisbach pipe friction head loss formula (Rossman [3]). Further details of the network can be found in Seyoum and Tanyimboh [4]. The required residual head at all demand nodes is 20 m.

For all three models considered here namely EPANET 2 and both versions of EPANET-PDX, extended period simulations were carried out by varying the supply node heads from 75 m to 130 m in equal steps of 1 m. Also, 10 additional extended period simulations were performed by closing various combinations of the supply pipes from the sources with the three EPANET hydraulic simulator variants. Each extended period simulation covered a period of 31 hours, based on a 1-hour hydraulic time step. All simulations were carried out on an Intel Xeon workstation (2 processors of CPU 2.4 GHz and RAM of 16 GB).

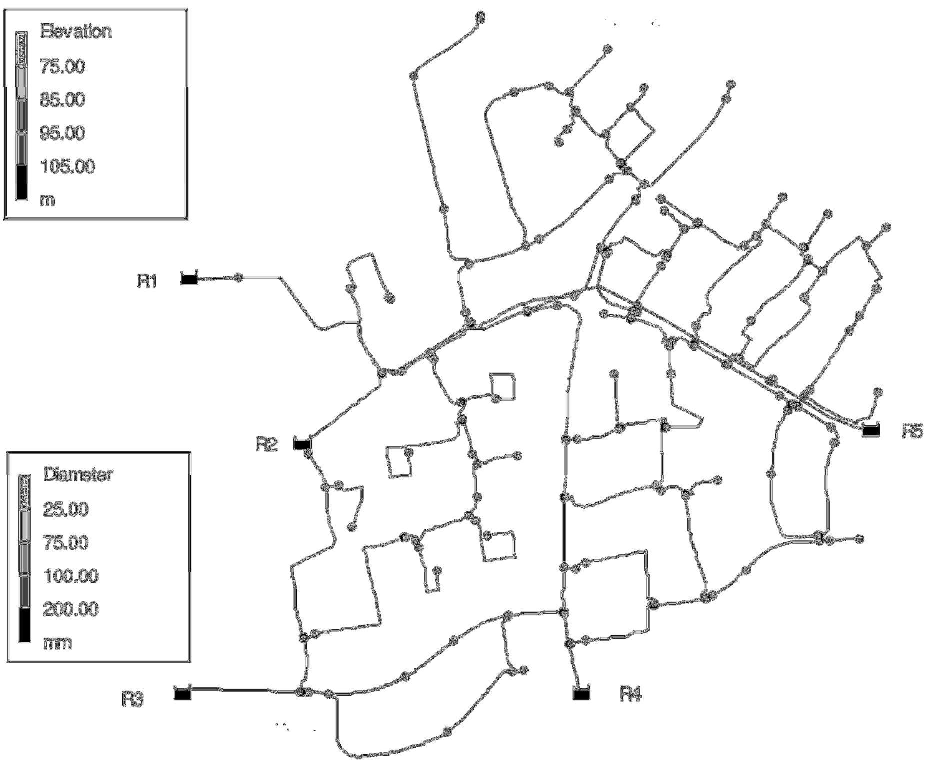

Figure 1. Network layout

Figure 2 shows a comparison of EPANET-PDX (0.1) and (0.2), for the average hourly network demand satisfaction ratios. All the simulations reported in this article were extended period simulations as mentioned earlier. Identical results were obtained for the hydraulic simulations, for the entire range of demand satisfaction ratios.

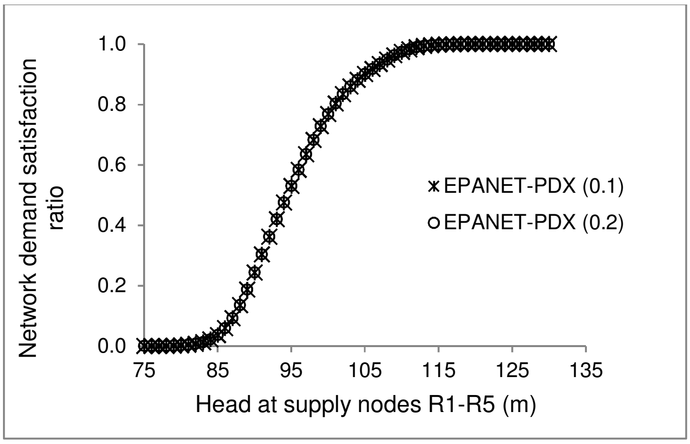

Figure 2. Influence of variations in supply node heads on the flow delivered

Figure 3 shows the number of iterations needed to solve the system of hydraulic equations as a function of the pressure in the network. The average numbers of iterations required per simulation were 6.96, 4.80 and 5.16 for EPANET-PDX (0.1), EPANET-PDX (0.2) and EPANET 2 respectively. EPANET-PDX (0.2) achieved a significant improvement for very low supply node heads and, overall, required the smallest numbers of iterations. Figure 4 compares the CPU times. It was noted that with the exception of extremely low flow conditions, EPANET-PDX (0.1) performs consistently well on the whole. However, it is quite variable in performance when the supply node heads are very low. This inconsistency has been addressed here in EPANET-PDX (0.2) without a significant reduction in the computational efficiency for other flow conditions. However, EPANET 2 in general is more efficient and consistent.

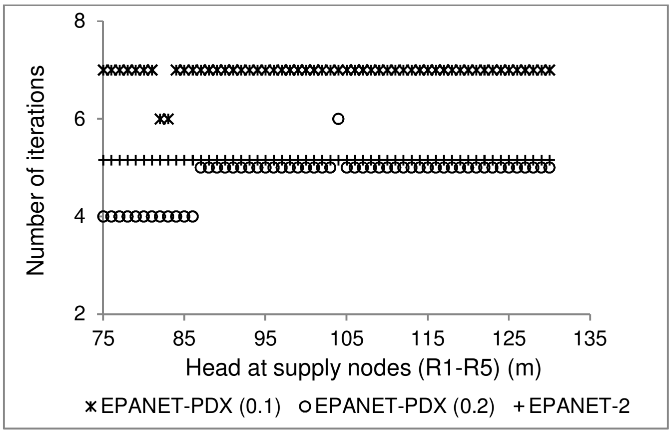

Figure 3. Number of iterations required as a function of the available pressure in the network

On average EPANET-PDX (0.1) and (0.2) that use line minimization required about 0.30 seconds and 0.29 seconds, respectively, per extended period simulation compared to 0.16 seconds for EPANET 2. It is worth re-stating, however, that EPANET 2 is not entirely suitable for pressure-deficient operating conditions. Also, EPANET 2 and EPANET-PDX apply convergence criteria that are not identical (Siew and Tanyimboh [6]). Therefore, it is worth emphasizing that the EPANET 2 results here provide a rough guide rather than an absolute direct comparison.

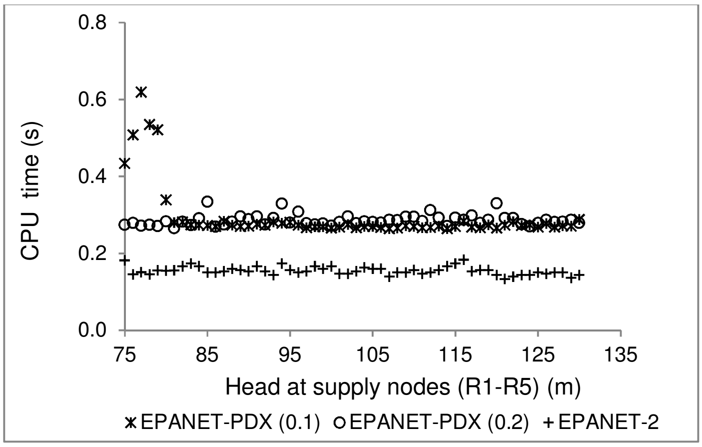

Figure 4. Comparison of CPU times for EPANET 2 and EPANET-PDX

EPANET-PDX (0.2) was assessed also, in the context of simulated major supply mains failures by closing simultaneously the supply pipes from three supply nodes out of five. A total of 10 such 'supply failures' resulting from multiple simultaneous supply mains failures were simulated. In these simulations the network was supplied by only two supply nodes out of five and the nodal demands were fully satisfied in each case (i.e. all the network demand satisfaction ratios were 1.0). The average numbers of iterations required per extended period simulation were 6.77, 5.22 and 4.90 for EPANET-PDX (0.1), EPANET-PDX (0.2) and EPANET 2, respectively. The corresponding CPU times were 0.20 seconds, 0.21 seconds and 0.14 seconds, respectively, for EPANET-PDX (0.1), EPANET-PDX (0.2) and EPANET 2. Even with network demand satisfaction ratios of 1.0 for each pipe closure simulation, the CPU times for the EPANET-PDX (0.1) and EPANET-PDX (0.2) models were about the same. Hence, the alternative implementation of EPANET-PDX would appear to be successful.

CONCLUSIONS

An alternative implementation of the line search and backtracking procedure for integrating the logistic nodal head-flow function into the system of hydraulic equations in the global gradient algorithm has been demonstrated on a real life water distribution network considering 66 extended period simulations. A significant improvement in the computational properties has been achieved for extremely low flow conditions.

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