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# Pressure-Dependent Demand and Leakage Modelling With an EPANET Extension - WaterNetGen

J. Muranho[a,b,c,*], A. Ferreira[d], J. Sousa[c,e], A. Gomes[a,b], A. Sá Marques[c,f]

[a]*Departamento de Informática, Universidade da Beira Interior, Rua Marquês d'Ávila e Bolama, 6201-001 Covilhã, Portugal*
[b]*Instituto de Telecomunicações, Universidade da Beira Interior, Rua Marquês d'Ávila e Bolama, 6201-001 Covilhã, Portugal*
[c]*IMAR - Instituto do Mar,Dep. Ciências da Vida, Universidade de Coimbra,3004-517 Coimbra, Portugal*
[d]*U.T.C. Eng. Civil,Instituto Politécnico de Castelo Branco,Av. do Empresário,6000-767 Castelo Branco, Portugal*
[e]*Dep.Engenharia Civil, Instituto Politécnico de Coimbra, Rua Pedro Nunes, 3030-199 Coimbra, Portugal*
[f]*Dep. Engenharia Civil, Universidade de Coimbra, Rua Luís Reis Santos - Pólo II, 3030-788 Coimbra, Portugal*

**Abstract**

This paper presents the approach followed by WaterNetGen – an EPANET extension – to simulate water distribution systems considering both normal pressure and pressure-deficient scenarios. WaterNetGen models pressure-deficient scenarios by incorporating a pressure-demand relationship, which computes the available demand as a function of the current pressure, and considering leakage at pipe level (background and bursts). This new capability is fully integrated into the original EPANET interface, so the same network model can be used to perform demand-driven and pressure-driven analysis, leading to a faster a more accurate modelling of water distribution systems.



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*Keywords:* EPANET; WaterNetGen; Demand-driven analysis; Pressure-driven analysis; Leakage.

## 1. Introduction

Water distribution system (WDS) models are built based on the link-node formulation, in which links are interconnected at nodes. Water consumption that occurs along links is transferred to their end nodes, and defined as nodal demand. This nodal demand aggregates water consumption that can be pressure-independent (volume based) or

* Corresponding author. Tel.: +351 275 242081; fax: +351 275 319899.
*E-mail address:* jmuranho@ubi.pt


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pressure-dependent (the flow provided to consumers depends on the available hydraulic pressure). However, to attain more realistic results, WDS models must also include leakage (background and bursts).

WDS models are able to compute node heads and link flows for a fixed set of reservoir/tank levels, and this is accomplished by solving simultaneously the mass conservation equation for each node and the head loss relationship for each link in the network. In demand-driven models the nodal outflows are assumed constant irrespective of the network pressures. But, if the model assumes that the nodal outflows depend on the available pressure, then it is classified as pressure-driven. Both simulation approaches have an unquestionable value for planning, design, diagnosis and operation of WDS. However, the demand-driven approach is quite accurate when the system operates under "normal" conditions (adequate positive pressures), while pressure-driven approach is more suitable for scenarios that take into consideration the impact of pressure change on the flow supplied.

EPANET [1] is one of the most widespread software used for WDS simulation. EPANET is composed by two pieces of software: the solver component (epanet2.dll), which deals with the hydraulic computations, and the graphical user-interface component (Epanet2w.exe), which handles user input/output and also communicates with the solver. EPANET uses a demand-driven simulation model to predict the "dynamic" hydraulic and the water quality behavior of pressurized pipe networks over an extended period of time. However, there are some pressure-driven EPANET extensions that modified the solver functionality to compute the pressure-dependent demand. This paper presents the approach followed by WaterNetGen [2] and the changes made to the interface (mainly with the definition of new properties for the pipe object) and solver components (to deal with the pressure-dependent demand and leakage – background and bursts).

Besides the introduction, the paper includes a section of background work that includes a short literature review and the definition of the pressure-driven model. Then, the WaterNetGen pressure-driven approach is described and afterwards WaterNetGen is used to exemplify the new EPANET capabilities. The paper includes a final conclusion section that summarizes and draws some conclusions.

## 2. Background work

### *2.1. Brief literature review*

Demand-driven simulation as implemented in EPANET has its origin in the global-gradient algorithm (GGA) of Todini and Pilati [3], and can be used to determine the nodal heads, considering that the water demand assumes fixed and known values that are assigned to nodes. Pressure-driven simulation considers nodal outflows as variables that depend on the available pressure, and several methods have been proposed over the years to formulate this dependency. Some authors (Ozger and Mayer [4]; Todini [5, 6]; Ang and Jowitt [7]) proposed modelling approaches based on the Demand-Driven-Analysis (DDA) and iteratively add artificial reservoirs. Others (Germanopoulos [8]; Wagner *et al*. [9]; Wu and Walski [10]; Wu *et al*. [11, 12]) proposed approaches based on a pressure-demand relationship (see [13] for a comparison of methods based on nodal head and nodal flow). The approaches based on artificial reservoirs have the advantage of avoiding the introduction of extra parameters in the model, but changes the network topology, which may increase the computation time for large networks. The approaches based on the pressure-demand relationship introduce new parameters in the model, this meaning extra calibration effort, but are simple to compute.

The original EPANET [1] can associate an emitter to each node. Emitters are devices that model the flow through a nozzle or orifice that discharges to the atmosphere. The flow rate through the emitter is defined as a power function of the nodal pressure using an emitter coefficient and an exponent. EPANET emitters can simulate hydrants, but they can also be used to model the pressure-dependent demands. However, they produce wrong results when the nodal pressure becomes negative, and also there is no upper limit for the emitter flow (Todini [5, 6]; Wu *et al*. [11, 12]). Todini [6] suggested a modification in the emitter device in order to avoid such behavior. In order to circumvent this limitation, Rossman [14] proposed a technique that attaches a status variable to the emitter devices.

Cheung *et al*. [15] proposed an EPANET extension for Pressure-Driven-Analysis (PDA) using a pressure-demand relationship, by changing the EPANET solver to include the pressure dependent demands directly in the hydraulic model. The EPANET user-interface was not modified and new parameters were included in the EPANET input file to accommodate the PDA. Hayuti *et al*. [16] proposed an iterative procedure to implement the head-dependent analysis, in which the nodal demand is adjusted according to the EPANET results (demand and pressure) and to the demand satisfaction ratio (chosen as the pressure-outflow relationship for each category of demand). Leakage was implemented using the EPANET emitter devices. Pathirana [17] used emitters to include PDA support at the EPANET solver level. The original solver functions were replaced by wrapping functions that carry out the replacement of demands by emitters, invoking then the original functions. The pressure-based demand was then computed by an iterative demand-driven process, avoiding negative pressures during the iterative process by introducing a state variable associated to the emitters.

Todini [5] proposed an extended global-gradient algorithm to simultaneously solve for nodal heads and demands, considering head driven demand (or leakage). Giustolisi *et al*. [18] extended the Todini simulation model in order to account for pressure-driven leakage at the pipe level.

## 2.2. Pressure-driven model

Two types of pressure-dependent demands are considered: consumptions and leakage (background and bursts). For pressure-dependent consumption it is assumed that the available demand ($q_i^{avl}$) is computed based on the following pressure-demand relationship [9]:

$$q_i^{avl}\left(P_i\right) = q_i^{req} \times \begin{cases} 1 & P_i \geq P_i^{ref} \\ \left(\dfrac{P_i - P_i^{min}}{P_i^{ref} - P_i^{min}}\right)^{\alpha} & P_i^{min} < P_i < P_i^{ref} \\ 0 & P_i \leq P_i^{min} \end{cases} \tag{1}$$

where $P_i^{ref}$ is the reference (or service) pressure necessary to fully satisfy the required demand $q_i^{req}$, $P_i^{min}$ is the pressure below which no water can be supplied, $\alpha$ (typically $\alpha = 0.5$) is the exponent of the pressure-demand relationship, $P_i$ is the current pressure at node $i$.

It is assumed that leakage continuously increases with pressure and can be expressed as the sum of the background leakage and the bursts leakage. So, the pressure-leakage relationship for a pipe $k$ can be stated as follows [8, 18]:

$$q_k^{leak}\left(P_k\right) = \begin{cases} \beta_k l_k (P_k)^{\alpha_k} + C_k (P_k)^{\delta_k} & P_k > 0 \\ 0 & P_k \leq 0 \end{cases} \tag{2}$$

where $q_k^{leak}$ is the total leakage along pipe $k$; $l_k$ is the length of pipe $k$; $\alpha_k$ and $\beta_k$ are parameters of the background leakage model; $C_k$ and $\delta_k$ are are parameters of the bursts leakage model (classical orifice flow formulas); and $P_k$ is the average pressure in pipe $k$ computed as the mean of the pressure values of its end nodes. According to Lambert [19] the $\alpha_k$ parameter can take values between 0.5 and 2.5, depending on the leak type. The $\beta_k$ parameter is related to the pipe material deterioration and its value but must be set by calibration (initial values can be set around $10^{-7}$).

For each pipe, the total leakage is assigned to its end nodes, half to each node. So, the nodal leakage flow $q_i^{leak}$ for a node $i$ can be computed as follows:

$$q_i^{leak} = \frac{1}{2}\sum_k q_k^{leak} \tag{3}$$

where $k$ iterates over all pipes connected to node $i$.

The steady state flow in a WDS is described by the mass and energy conservation laws. Todini's formulation [5] for the pressure-driven model of a hydraulic network composed of $np$ pipes with unknown flow rates, $nn$ nodes with unknown heads and $n0$ nodes with known heads is stated as follows:

$$\begin{bmatrix} A_{pp} & A_{pn} \\ A_{np} & A_{nn} \end{bmatrix} \begin{bmatrix} Q \\ H \end{bmatrix} = \begin{bmatrix} -A_{p0}H_0 \\ -q \end{bmatrix} \tag{4}$$

where $Q=[Q_1, Q_2, ..., Q_{np}]^T$ is a column vector of unknown pipe flow rates; $H=[H_1, H_2, ..., H_{nn}]^T$ is the column vector of unknown nodal heads; $H_0=[H_{01}, H_{02}, ..., H_{0n0}]^T$ is the column vector of known nodal heads; $q=[q_1, q_2, ..., q_{nn}]^T$ is the vector of known pressure-independent demands.

In equation (4), $A_{pp}$ is a $np \times np$ diagonal matrix whose elements correspond to the pipe head losses; $A_{pn} = A_{np}^T$ and $A_{p0} = A_{0p}^T$ are topological incidence sub-matrices of size $np \times nn$ and $np \times n0$, respectively, obtained from the global topological incidence matrix $\overline{A}_{pn} = \begin{bmatrix} A_{pn} & A_{p0} \end{bmatrix}$ of size $np \times (nn+n0)$. $A_{nn}$ is a $nn \times nn$ diagonal matrix whose generic element is the pressure-dependent demand.

Giustolisi *et al*. [18] extended the Todini's formulation in order to account for leakage flow rates, through the redefinition of the diagonal matrix $A_{nn}$: the elements are the scalar product $(q^{avl}+q^{leak})H^{-1}$, where $q^{avl}$ is the vector of pressure-dependent nodal demands and $q^{leak} = (q_1^{leak}, q_2^{leak},...,q_{nn}^{leak})$ is the vector of nodal leakages.

The solution of (4) with pressure-dependent demands defined by (1) and considering pipe leakage is given by Todini [5] and Giustolisi *et al*. [18]:

$$DDL_{nn}^{iter} = D_{nn}^{iter} + DL_{nn}^{iter} \tag{5}$$

$$A^{iter} = A_{np}\left(D_{pp}^{iter}\right)^{-1} A_{pn} - DDL_{nn}^{iter} \tag{6}$$

$$F^{iter} = \left[A_{np}Q^{iter} - \left(q_{avl}^{iter} - q_{leak}^{iter}\right)\right] - A_{np}\left(D_{pp}^{iter}\right)^{-1}\left(A_{p0}H_0 + A_{pp}^{iter}Q^{iter}\right) - DDL_{nn}^{iter}H^{iter} \tag{7}$$

$$H^{iter+1} = \left(A^{iter}\right)^{-1} F^{iter} \tag{8}$$

$$Q^{iter+1} = Q^{iter} - \left(D_{pp}^{iter}\right)^{-1}\left(A_{pp}^{iter}Q^{iter} + A_{pn}H^{iter+1} + A_{p0}H_0\right) \tag{9}$$

$$H^{iter+1} = \varphi^{iter}\left(H^{iter+1} - H^{iter}\right) + H^{iter} \tag{10}$$

$$Q^{iter+1} = \varphi^{iter}\left(Q^{iter+1} - Q^{iter}\right) + Q^{iter} \tag{11}$$

where $D_{pp}$ is the derivative of $A_{pp}$ with respect to pipe flow, $DL_{nn}$ and $D_{nn}$ are the derivatives of $q^{leak}$ and $q^{avl}$ elements with respect to pipe pressure and nodal pressure, respectively. The iterative process starts with $\varphi^{iter=0} = 1$; each element $H^{iter=0}$ is set equal to the corresponding node elevation plus the maximum reference pressure of its pressure-dependent demands; and each element of $Q^{iter=0}$ is set to the inverse of the head loss coefficient of the respective pipe. The relaxation coefficient $\varphi^{iter}$ ($\in [0,1]$) is used to improve convergence when updating the nodal head and flow estimates [16, 18].

## 3. Pressure-driven – the WaterNetGen approach

The pressure-demand relationship in (1) requires the definition of three parameters, $P^{ref}$, $P^{min}$ and α, for each node. Among these, the trickiest is the definition of the reference pressure because that reference can differ from node to node to take into account the height of the surrounding buildings represented by the nodes. In WaterNetGen the reference pressure of each node is set as a user-defined function of the number of storeys above ground ($N$) – the default function is $P(N) = 100 + 40N$, with $P$ in KPa (requirement of the Portuguese regulation).

The EPANET properties of junction nodes are modified to permit the specification of the number of storeys (and the function to compute the reference pressure). The EPANET Demand Editor was also modified to allow the specification of the required parameters to support the pressure-driven simulation. For each demand category, besides the base demand and time pattern, it is possible to specify a different $P^{min}$ and α. To handle leakage as specified in (2), default parameters for the background leakage (the coefficient $\beta_k$ and the exponent $\alpha_k$) and for the bursts leakage (the coefficient $C_k$ and the exponent $\delta_k$) are set at the EPANET project defaults, but these default values can be reset for each pipe with customized values. At run-time the pressure-driven parameters are exported and embedded in an ".inp" file and read by the EPANET hydraulic solver. The new parameters are converted inside the solver to the internal system of units.

Inside the EPANET solver two new functions are declared in "funcs.h" and implemented in the "hydraulic.c" file: *void PDdemands(void)* and *void PDleakages(void)*. The function *PDdemands* uses the current pattern multiplier to compute the current demand value (using the pressure-demand relationship) and the derivative term for each node. The function *PDleakages* computes the leakage flow for each pipe and also the derivative terms. The solver function *void newcoeffs(void)* was changed in order to account for the new derivative terms computed in the new functions. The function *int netsolve(int *, double *)*, which solves the network nodal equations for heads and flows using Todini's Gradient algorithm, was changed to the new formulation of the algorithm. The pseudo-code of Fig. 1 illustrates the iterative process used to solve the system of equations.

```
REPEAT
    PDdemands();   // compute pressure-dependent demand + derivative terms
    PDleakages();  // compute pressure-dependent leakages + derivative terms
    newcoeffs();   // compute coefficients of linearized network equations
    netsolve(...); // compute linear system solution (new heads)
    newflows();    // computes new flows
    update heads;  // update heads using relaxation
    update flows;  // update flows using relaxation
    update relaxation; // update relaxation coefficient
UNTIL convergence;
```

Fig. 1 - EPANET code adaptation for pressure-driven demands and pipe leakage

The embedding of the pressure-demand relationship into the hydraulic solver creates some difficulties to the convergence of the network solver. Details about the measures taken to circumvent these difficulties, including the use of relaxation coefficients and sparse matrix solver modifications, are beyond the scope of the present paper. Also beyond the scope of the paper is the comparison of the convergence rate of the original solver and the new solver.

The computation of the total leakages (both for each pipe and for the network as a whole) is done inside the solver and the results are written to the EPANET hydraulic output file at each time step (frequently it is considered a value of one hour). The total water lost in each time step is computed taking into account all hydraulic events that occur during the time step. These events can occur due to changes in the state of the network elements (for example, the change of a pump status or of a tank status). Leakage from pipes connected to tanks (or reservoirs) is fully assigned to the other end node.

The solver is also changed to report the occurrence of pressure-deficient events (and the respective node or nodes and the time of occurrence) and the amount of pressure violations. This information can be used by a skilled user to take suitable measures to remedy or avoid fault conditions.

## 4. Exploring WaterNetGen

To illustrate the pressure-driven behavior of WaterNetGen the C-Town network model was chosen. This model is used in the Battle of Background Leakage Assessment for Water Networks – BBLAWN, a competition that is going to take place at the 16th Water Distribution Systems Analysis conference. The C-Town network requires a minimum pressure of 20 m to fully satisfy the required demand (or nonnegative in nodes without demand). Fig. 2 shows the C-Town network layout. Some nodes are highlighted [20] to easily identify zones with insufficient pressure (that is, nodes with pressure below the minimum required).

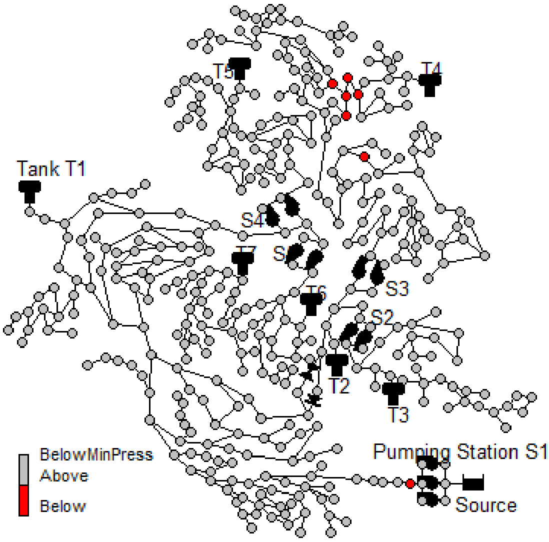


Fig. 2 – C-Town network layout with pressure-deficient nodes highlighted.

The aim of the BBLAWN competition is to propose a design methodology for reducing water losses due to background leakage. The "competitors" must propose a strategy to minimize the operational costs (energy consumption and water losses) and the capital costs (if used). Fig. 3 shows the nodal pressures and the pipe leakages computed with (2). The background leakage graph allows an easily identification of the pipes (and areas) that most contribute to the water losses.

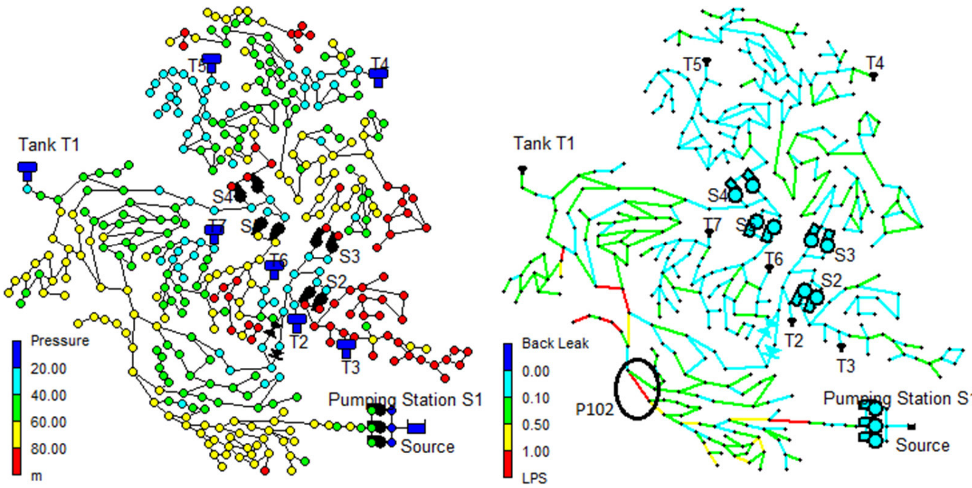


Fig. 3 – C-Town network: nodal pressure and background leakage.

The background leakage is assigned to pipe end nodes following (3). Fig. 4 shows the relationship between the pipe background leakage and the pressure at its end nodes for pipe *P102* (marked in Fig. 3). Pipe *P102* is a lengthy pipe (1,280 m) and its end nodes (*J109* and *J408*) always show high pressure, leading to high background leakage values.

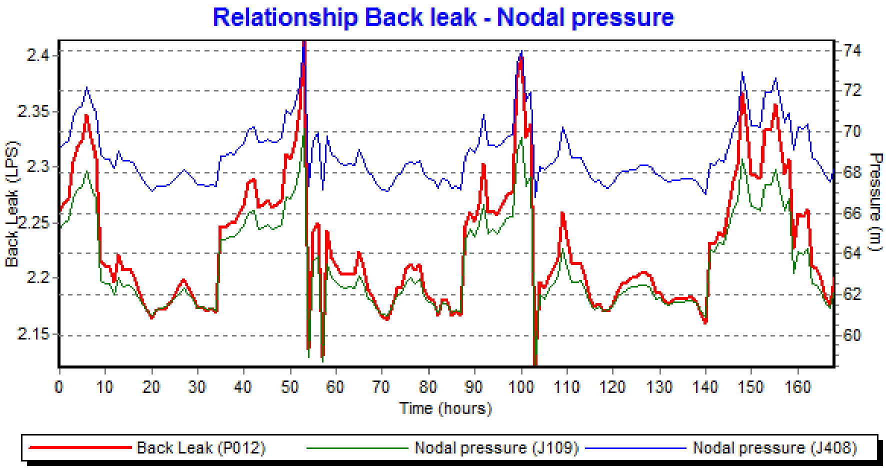


Fig. 4 – Relationship between pipe end nodes pressure (and pipe length) and the background leakage.

Fig. 4 shows the instantaneous background leakage computed based on the average pressure of the pipe end nodes. The total water losses, for a single pipe or for the network as a whole, can be computed by multiplying the instantaneous leakage values by the time step. However, there can be a small difference between the value obtained in this way and the value computed using the sum of the leakage over all “small” sub-time steps that occur in a time step (due to the hydraulic events referred in the above section). For example, over the first time step (one hour), the total water losses computed using instantaneous leakage value is 431,352 litres while it is 431,038 litres using the sum over all the sub-time steps.

EPANET (interface component) only reports the network state at some specific instants, namely at the report time step or at the hydraulic time step. Hydraulic events that occur between these report time marks are hidden from the user, unless negative pressures are verified in the network. This reporting mode is satisfactory for most analysis scenarios. Nevertheless, in pressure-deficient scenarios this reporting mode can hide unacceptable network states. Therefore, the EPANET hydraulic solver was adapted to report all pressure-deficient events, identifying the target node, the time of the occurrence and the amount of pressure violation. This data was used in [21] to obtain solutions for the BBLAWN competition that fulfil the minimum pressure constraint on every node and at every time (not only on the report time).

## 5. Conclusions

The analysis of WDS under pressure-deficient conditions must be supported by tools that can compute the available demand as a function of the pressure conditions. This requirement has led to the development of pressure-demand and pressure-leakage relationships to model the available nodal demand and pipe leakage. This paper shows how these relationships are implemented in WaterNetGen – an EPANET extension – and how these new capabilities can be used. It is focused on the behavior of the pressure-driven simulation and addresses the need to report more data about the internal state of the system, mainly when the pressure is positive but insufficient to fully satisfy the required demand. A special attention has been dedicated to the computation of water losses through pipe leakages.

One great advantage of joining in the same tool – WaterNetGen – the demand-driven and the pressure-driven approaches is that the same network model (with minor and automatic modifications) can be used for both types of simulation, which can save time and effort.

## Availability

WaterNetGen can be downloaded from http://www.dec.uc.pt/~WaterNetGen.

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