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Extending EPANET capabilities with Add-In Tools

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Abstract

EPANET is probably the most widespread model for water distribution network (WDN). More than twenty years after its appearance, it has become a global reference both for hydraulic and quality analysis of water networks. In 2000, EPANET 2 appears, which includes as most important computational feature a new Toolkit. This toolkit was a library of functions allowing the modification of network data and reading results without access to the appropriate files. Over time, the use of this library has been the communication protocol for every application developers who use the method propose by Todini and Pilati to analyze the behavior of WDN. This library also provides interface tools that allow the execution of a simulation from an external application, as long as the network characteristics had been previously defined.

This paper presents a change in the original EPANET model, including a new menu in the graphical user interface (GUI). This menu allows users to set up a personal collection of Add-In tools, which use both project data and simulation results. These tools can be customized and allows to extend the analysis capability of EPANET. All of them can access EPANET functions through the Toolkit and were developed by the authors during the Spanish translation of EPANET, taking into account the homologous Add-in tools developed for SWMM model. As an example of the operation and capabilities of this new menu, several applications integrated as EPANET add-in tools are presented. These tools perform tasks such as importing data network from both CAD and GIS systems, the design of WDNs using genetic algorithms, automatic assignment of initial water quality to network nodes; the skeletonization of a network or optimization of pumping schedule in the network in order to achieve a minimum energy cost.

Keywords: EPANET; Toolkit; Add-In Tools

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1. Introduction

Nowadays, the technical management of water distribution networks (WDN) requires a fundamental tool: an accurate model representing the behavior of the system. Constructing a mathematical model is complex, but its core is the model used to solve the hydraulic equations. EPANET is the hydraulic model for analyzing WDN developed by the US EPA, and today is the main reference in this field. The model uses the method proposed by Todini and Pilati [1] and performs extended period simulations of the hydraulic response of the system. In this sense, it allows knowing flow and velocities evolutions inside the pipes, pressure variations in demand points, levels in the tanks. Besides it provides the concentration of any substance in any point of the network over the time. In addition, the model also allows determining the residence time of water in the network and its origin from the different supply points.

The first EPANET model dates back to around 1994 [2]. It integrated gradient method to solve the hydraulic equations; all this under a very simple Graphical User Interface (GUI) running on MS-DOS operating system. At the end of the twentieth century began the development of the embryo of what would be the new version of EPANET [3]. The key to success of this version is based on two key elements: on one hand, the use of a dynamic link library (DLL) which is also known as EPANET Programmer's Toolkit [4] and secondly, the use of a more friendly and sophisticated GUI. The final result is what today is known as the EPANET 2. The model's success is evidenced by the huge number of citations its main reference [5] has and the number of different languages (Spanish [6], French [7], Portuguese [8], in Brazilian Portuguese [9] and Russian [10] among others) it has been translated into.

Although EPANET is universally accepted as a reference model in the analysis of WDN, its editing capabilities, information processing and post-processing features have been shown clearly insufficient. Since the publication of the latest version of EPANET, there have been many applications, modifications and changes that different authors have made over the original model. Undoubtedly, the fact that both the calculation engine and the application are open source, has led to the generation of such third party applications. Some of the simplest applications have sought to improve or expand the calculation capabilities of the original EPANET. One of the first extensions was made by the USEPA itself, developing the EPANET-MSX, which can represent complex reactions in the case of several pollutants may interact between each other [11]. Other models consider jointly both the analysis of water quality and the representation of the behavior of consumptions [12]. Other applications on the same line have focused on the hydraulics aspects. Maintaining the original GUI, several improvements of EPANET's engine it has been developed. These have allowed correcting or even adding capabilities to the model. Among these, there are improvements in the representation of pressure dependent consumptions [13]; adaptations to represent leakage behavior [14]; corrections to improve the calculation efficiency of pumping units when they rotate at speeds different from its nominal [15], or inclusion of certain transient calculations [16].

More complex variations in EPANET's engine have allowed the development of an entire set of libraries or functions that expand access and management options during the calculation process. Some involve slight modifications of the original EPANET Toolkit, for example to allow changing rule based controls and thus expediting optimization processes [17]. Other involve a complete restructuring of the library, based on an object-oriented programming and generally based on open source approach. Thus, OOTEN [18] includes all the capabilities of the original library and includes some additional features such as methods for handling curves. CSWNET [19] presents among other features the ability to run different simulations of the same network or different networks in parallel; a Demand-Driven Global Gradient Algorithm solver and a Toolkit structure in three different layers: the network topology, the hydraulic behavior and a mathematical layer. Meanwhile, Porteau [20] is a complete restoration of the representation of the network by using classes and super-classes. It is an experience of designing a new hydraulic toolkit with object- oriented coded in the context of an open-source project.

Other libraries have been specifically developed to be used in real-time connections between a SCADA databases and the hydraulic simulator, such as EPANET-RTX [21]. Even though some libraries have been adapted for use in

programming environments like Matlab [22]. This type of libraries which relates EPANET with other mathematical models has been used among other applications to improve efficiency calculation for large networks [23], the implementations of pressure-dependent demands [24], the development of a new solver [25], the optimization of certain operation modes of WDN [26], etc.

But not all extensions and applications have focused on the engine of EPANET. A significant number of applications have developed new features modifying the original structure of EPANET's GUI and enabling new menus and forms for the specific edition of required parameters. Thus, there are different tools related with WDN calibration. Some of them such as CALIBRATOR [27] include a simple parameter calibration procedure based on de definition of groups of elements. Other cases such as LENHS-Calibra [28] include a more generic treatment of calibration, considering many variables and even including potential errors of the initial data model. Other problems solved by modifying the original GUI are: optimal design of WDN [29], pressure driven demand modeling [30] or the managment of a background and the definition of the reference coordinates [31]. Therefore, each tool has its own GUI, so it is necessary to have as many versions of EPANET as different solutions are desired.

A philosophy that avoids the continuous modifications of the EPANET's GUI is the development of third party applications using as starting point the INP file. Thus, there are tools using EPANET under a spreadsheet interface [32] or applications using the engine in specific applications like the analysis and design of irrigation networks [33]. Other utilities have a more external behavior with respect to EPANET itself, such as calculating the maximum fire flows in a network [34] or simply read and present adequately the results of a hydraulic simulation [35].

Definitely, each extension has its own way to use and manage either the INP file, either the toolkit library. With the idea of trying to unify the EPANET-related improvements and expand its capabilities for use in different languages and platforms, some code adaptations in different programming languages (C# [36], Java [37] or Phyton [38]) have been already made. Moreover, the project of an Open EPANET is more than an open debate [39] and it even has already defined some programming styles [40].

This work is based on the idea of integrating as many Add-In Tools as possible into EPANET, with maximum respect to the original GUI. For this, a new interconnection gateway for information exchanging between EPANET and third parties programs have been developed. The works take as reference a similar applications that EPANET's author developed in the latest versions of the EPASWMM model [41]. Thus, through the work the structure and management of this link is developed, and also are exposed the capabilities offered to improve the performance of the current version.

2. Integrating Add-In tools in EPANET

The operation mode of the EPANET model, based on its stand-alone application is collected in Fig. 1. A configuration file defines the basic management options of EPANET. Subsequently, any calculation requires the communication with the DLL through three files: one containing the model data (INP), another with the calculation results in binary format (BIN) and a third one with the results report in text format (RPT). On the contrary, the use of the DLL library can be performed from an external application by means of Toolkit functions. This operation mode is also shown in Fig. 1. In both cases information exchange is carried out through the INP file.
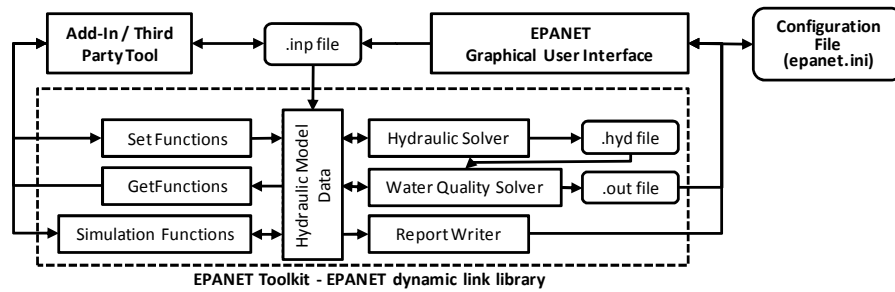
Fig. 1. Operating diagram of stand-alone EPANET and third party tools using Toolkit.

All in all, the Add-In Tools are additional extensions that third parties can add to the menu of EPANET. These are applications that will run at the same time that EPANET does and improve the capabilities of the model. The development of these applications is based on the generation of several files and paths which allow some interaction between EPANET and the external programs. Examples of interesting tools that can be included are:

- A statistical analysis tool of flows, velocities and pressures in the network.
- Using an external spreadsheet that makes easier the data editing.
- A program that performs an automatic assignment of flow consumption at nodes from the data volumes contained in a certain database.
- A post processing program using hydraulic EPANET results to calculate areas where water quality deterioration is bigger or places where the appearance of cracks in pipes are more feasible.
- A program that performs successively water quality analysis considering different contaminants.

In the last versions of SWMM [41], there is a new feature allowing third-party tools. The main idea of this paper is modifying the EPANET's GUI to develop an extensions system that connect EPANET to external applications, following the same steps as in the case of SWMM. This change involves the appearance of a new menu where it is possible to add, edit or modify the different Add-in tools. The operating diagram of this EPANET adaptation and its relationship with the Toolkit is shown in Fig. 2. As can be seen, there remains a swap file, although it is temporary and the end-user of the application can skip editing and working with it. In addition, different options for setting up each extension are stores in the configuration file, so that this new features added become available as new options in EPANET. Each link with the Add-In tools should be collected in the *Epanet2Tools.ini* file, which must be in the same folder as the *epanet.ini* file.
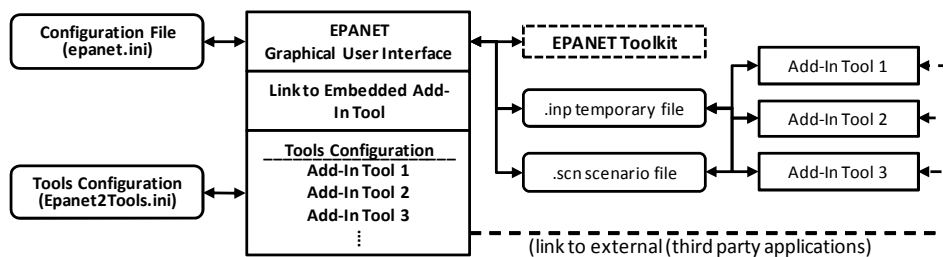

Fig. 2. Operating diagram of the Add-In Tools in EPANET.

In fact, the capabilities of this kind of tool that would connect EPANET GUI with other programs are limitless. Thus, by way of illustration, some developed applications are detailed in the next section. These applications range from simple ones, that connect EPANET's GUI with existing programs, to more complex that require the use of multiple applications and different transfer files.

3. Applications based on Add-In Tools

With the Add-In tools system, defined in the previous section, it is possible integrating into EPANET both own applications and existing ones, whether commercial or free. So, existing applications that can be easily integrated are text editors and spreadsheets, either for data editing either for the analysis of the model results. The Table 1 collects configuration details of some conventional applications to be directly connected as extensions of EPANET.

Moreover, related with this work other specific tools have been integrated into EPANET expanding its capabilities. This applications fall into two different groups: information and initial data management applications, and tools to enhance the features of analysis and optimization of WDN. In the following sections every group is explained.

Table 1. Configuration of standard applications as EPANET extensions.

Application description	ExeName	Params	Disabled[a]	Update[b]
Text editors to modify the inp file	notepad.exe	$INPFILE	1[c]	1[d]
	notepad++.exe			
Editor to review the results	notepad.exe	$RPTFILE	0	0
	notepad++.exe			
	winword.exe			
Advances editing data with a spreadsheet	excel.exe	$INPFILE	1	0 [e]

[a] Disables or not EPANET while the third-party tool is running. Its options are *0* (enabled) or *1* (disabled).

[b] Updates INP file once the add-in tool has finished. Its options are *0* (not update) or *1* (update).

[c] Recommended if you do not want to edit two versions of the same file at the same time

[d] Recommended if you want to update the changes made within the tool when you return to EPANET

[e] Microsoft Excel does not properly return the data to EPANET. You need a macro specific programs for it.

A first group of applications are those related to the management and the edition of the data model. An important part during the model building involves obtaining data from information that requires some treatment and processing. Some simple applications already developed it is interesting to take into consideration are:

- Import from CAD programs or Geographical Information Systems (GIS): tools that generate the topological definition of the network taking as initial point standard files such as DXF, SHP, etc. If CAD or GIS files are used and the information is organized additional information such as pipe diameter or conduits roughness can be added at the same time is imported the topological information.
- Importing georeferenced images as backdrop files. During the development of this work a change in EPANET's GUI was made to allow the use of JPG format as background file. Therefore, another tool built allows not only the selection of the jpg file as background image, but also the coordinates of EPANET are modified from a georeference image file.
- Generation of node elevations from Digital Elevation Models (DEM). This assumes that network layout is available, but not the elevations of the different points. A new tool was made which uses list of points with three coordinates (x, y, z) as input data. Using a DEM and a Delaunay triangulation every node elevation is obtained.
- Node base demand calculation from consumptions databases. Average flows allocated as demands at nodes are obtained from total volumes consumed by consumers over a period of time. This application uses a direct mapping between each consumer and a node in the model. Thus, demand at each node can be assigned from the data of the monthly consumption of consumers connected to that node.
- Definition of initial quality at nodes. Any water quality analysis requires defining initial concentrations of pollutants in each node. A fairly simple technique to fix these concentrations is to set zero concentration in all

nodes and let the model repeat calculations until it reaches a steady state value. With this application, this process is done automatically and the establishment of the initial concentrations is quite easy.

More complex applications connected as Add-in tools in EPANET are related with the optimization, skeletonization and sectorization of WDN. In optimization-based applications the Pseudo Genetic Algorithm [42] has primarily been used. Thus, in the case of the design of WDN the objective function F is given by the expression:

$$F = \sum_{i=1}^{N_P} C_{B,i} + \sum_{i=1}^{N_D} C_{P,i} + \lambda_1 \sum_{i=1}^{N} \delta_i \left(P_{\min,i} - P_i \right) + \lambda_2 \sum_{i=1}^{N} \delta_i \left(V_{\min,i} - V_i \right) + \lambda_3 \sum_{i=1}^{N} \delta_i \left(V_i - V_{\max,i} \right) \tag{1}$$

In (1), $C_{B,i}$ if the energy cost related with each of the N_P pumping stations, $C_{P,i}$ is the cost of installing each of the N_D lines that are potentially resizable; and λ_1, λ_2 y λ_3 are penalties for non-compliance of the design restrictions. These constraints are: the pressure P_i at each node must be above the minimum pressure $P_{\min,i}$; and the velocity of every line should be between the minimum $V_{\min,i}$ and the maximum $V_{\max,i}$ value. In addition, each limitation has associated a Heaviside step function, which takes the null value if the constraint is satisfied and 1 value otherwise. The result of this process are the diameters in pipes and the pumping head at the header nodes of the network.

An application that is used recursively is one that allows the simplification and skeletonization of WDNs. Using the setting curve concept large areas of the networks are simplified, mainly branched subareas and those which have only an input node. During this simplification process, demands, pressure requirements [43] and highest quality allowed [44] are transposed to the header node of the subarea. This rearrangement is performed in such a way that pressure and quality requirements in terminal nodes are guaranteed.

Other cases developed are based on the application of heuristic optimization techniques to determine the most economical of WDN. In n some cases [45], economic and energy optimization network operation is intended. In others [46], the main objective is to minimize the background leakage assessment of a WDN. In these cases, applications specifically developed for solving problems such as the one described in [47] are integrated as extensions of EPANET. In them, dimensioning of pipes previously selected network, operation of the pumping stations (start and stop levels) and networks pipes that should be closed are optimized.

A more direct application is the heuristic optimization of a WDN operation scheme. Thus, given a WDN with tanks, pumps and control valves the goal is to design a working mode that minimizes operation costs. In this case, the function F is focused on the energy cost of every pump $C_{B,i}$ and in compliance with the constrains of the problem. These restrictions are: the pressure at each node j in each instan i ($P_{i,j}$) must be greater than the node minimum pressure ($P_{\min,j}$), and the final level in each tank i ($z_{fin,i}$) should be the same or above the starting one ($z_{ini,i}$). These restrictions are activated through two Heaviside step functions as happened in equation (1). Mathematically function F can be expressed as:

$$F = \sum_{i=1}^{N_P} C_{B,i} + \lambda_1 \sum_{i=1}^{T} \sum_{i=1}^{N} \delta_{i,j} \left(P_{\min,j} - P_{i,j} \right) + \lambda_2 \sum_{i=1}^{N_T} \delta_i \left(z_{ini,i} - z_{fin,i} \right) \tag{2}$$

In the optimization based on the above equation the decision variables are the ON/OFF levels of the pumps, its initial state, determining states (open or closed) in certain pipelines through the day, and the setting of pressure reducing valves. The method has been integrated into an Add-In called HOLORED [48], which was applied to a network in Murcia (Spain). The scheme of the network is shown if Fig. 3. Before applying the optimization method, a tool that simplifies the network was used. This simplification tool accumulates flows in nodes and defines pressure and quality set-point curves in each node. In the same figure, the level of simplification achieved in the network and the reduction in the computation time can be appreciated. Also in the figure the initial network operation cost (515 €) is collected. With the optimization tool a reduction in this cost is obtained. The first reduction is bases on improving the operation scheme of the elements. The second one is obtained by applying pressure-driven demand and adjusting the pressure reducing valve settings at the entrance of each district metering area.
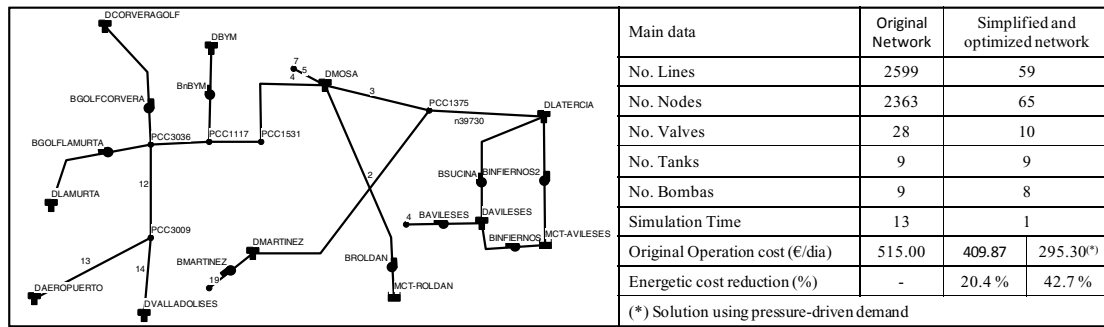
Main data	Original Network	Simplified and optimized network	
No. Lines	2599	59	
No. Nodes	2363	65	
No. Valves	28	10	
No. Tanks	9	9	
No. Bombas	9	8	
Simulation Time	13	1	
Original Operation cost (€/dia)	515.00	409.87	295.30(*)
Energetic cost reduction (%)	-	20.4 %	42.7 %
(*) Solution using pressure-driven demand			

Fig 3. Optimizing the performance of a network i Murcia (Spain).

Finally, a sectorization model for WDN has also been developed as Add-In tool. This tool implements the METIS algorithm [49], based on the multilevel k-way partitioning scheme. This model performs a weighted partition so that all DMA have a similar base demand while the diameter of the pipes to be closed are also minimized. The result has been used to solve the Battle of Water Networks District Meter Areas (BWNDMA), which is the the sixth Battle Competition since the beginning of the Water Distribution Systems Analysis Conference [50].

4. Conclusions

Although EPANET is universally accepted as a reference model in the analysis of water distribution networks, its editing capabilities, information processing and post-processing features have been shown clearly insufficient. For this, in this work a new platform for information exchanging between EPANET and third parties programs have been developed. This new link allows using EPANET's GUI and simultaneously extend its editing capabilities, its computing resources and its processing capabilities.

The application presented in this paper is developed only in the Spanish translation of EPANET [6]. However, with the new project Open - EPANET [39], this application should remain as open source.

References

[1] E. Todini and S. Pilati, "A gradient algorithm for the analysis of pipe networks," in *Computer Applications for Water Supply and Distribution*, 1988, pp. 1–20.

[2] L. A. Rossman, *EPANET User's Manual. Version 1.1*. Cincinnati, OH 45268: Risk Reduction Engineering Laboratory. Office of Research and Development. Environmental Protection Agency, 1994.

[3] US Envinronmental Protection Agency, "EPANET. Software that models the hydraulic and water quality behavior of water distribution piping systems," 2000. [Online]. Available: https://www.epa.gov/water-research/epanet#downloads.

[4] L. A. Rossman, "The EPANET Programmer's Toolkit for Analysis of Water Distribution Systems," in *Water Resources Planning and Management Conference*, 1999, pp. 1–10.

[5] L. A. Rossman, *EPANET 2. User's manual*. Cincinnati, OH: Water Supply and Water Resources Division National Risk Management Research Laboratory - Environmental Protection Agency, 2000.

[6] Universidad Politécnica de Valencia, "EPANET 2.0 vE. Página de EPANET en castellano. Análisis y simulación de redes hidráulicas a presión," 2012. [Online]. Available: http://www.epanet.upv.es.

[7] Systèmes d'information Géographique pour l'Enseignement Agricole, "EPANET: simulation hydraulique," 2015. [Online]. Available: http://sigea.educagri.fr/applications/supports-thematiques/gestion-de-leau.html.

[8] Laboratório Nacional de Engenharia Civil, "Epanet 2.0 em português. Simulaçao hidraulica e de parametros de qualidades em sistemas de transporte e distribuçao de água," 2011. .

[9] Laboratório de Eficiência Energética e Hidráulica em Saneamento, "Manual do EPANET 2.0 Brasil," 2009. [Online]. Available: http://www.lenhs.ct.ufpb.br/?page_id=32.

[10] D. Tsarenko, "EPANET 2. Russian version," 2016. [Online]. Available: http://www.epanet.com.ua/home.

[11] F. Shang, J. G. Uber, L. A. Rossman, and R. Janke, *EPANET Multi-Species Extension. User's Manual*. Cincinnati, OH 45268: US Environmental Protection Agency, 2008.

[12] A. G. Seyoum, T. T. Tanyimboh, and C. Siew, "Assessment of water quality modelling capabilities of EPANET multiple species and pressure-dependent extension models," *Water Sci. Technol. Water Supply*, vol. 13, no. 4, p. 1161, Aug. 2013.

[13] C. Siew and T. T. Tanyimboh, "Pressure-Dependent EPANET Extension," *Water Resour. Manag.*, vol. 26, no. 6, pp. 1477–1498, 2012.

[14] J. Muranho, A. Ferreira, J. Sousa, A. Gomes, and A. Sa-Marques, "Pressure-dependent demand and leakage modelling with an EPANET extension - WaterNetGen," *Procedia Eng.*, vol. 89, pp. 632–639, 2014.

[15] A. Marchi and A. R. Simpson, "Correction of the EPANET Inaccuracy in Computing the Efficiency of Variable Speed Pumps," *J. Water Resour. Plan. Manag.*, vol. 139, no. 4, pp. 456–459, 2013.

[16] D. Avesani, M. Righetti, D. Righetti, and P. Bertola, "The extension of EPANET source code to simulate unsteady flow in water distribution networks with variable head tanks," *J. Hydroinformatics*, vol. 14, no. 4, p. 960, 2012.

[17] A. Marchi, A. R. Simpson, and M. F. Lambert, "Optimization of Pump Operation Using Rule-Based Controls in EPANET2: New ETTAR Toolkit and Correction of Energy Computation," *J. Water Resour. Plan. Manag.*, p. 04016012, 2016.

[18] J. E. Van Zyl, J. Borthwick, and A. Hardy, "Ooten: An object-oriented programmers toolkit for epanet," in *Advances in Water Supply Management (CCWI 2003)*, 2003, pp. 1–8.

[19] M. Guidolin, P. Burovsky, Z. Kapelan, and D. Savić, "CWSNET: An Object-Oriented Toolkit for Water Distribution System Simulations," in *Water Distribution Systems Analysis*, 2010, pp. 1–13.

[20] O. Piller, D. Gilbert, K. Haddane, and S. S., "Porteau: An Object-Oriented programming hydraulic toolkit for water distribution system analysis," in *Computing and Control for the Water Industry (CCWI)*, 2011, pp. 1–6.

[21] S. Hatchett, J. Uber, D. Boccelli, T. Haxton, R. Janke, A. Kramer, A. Matracia, and S. Panguluri, "Real-Time distribution system modeling: development, application and insights," in *International Conference on Computing and Control for Water Industry (CCWI)*, 2011, pp. 1–6.

[22] D. Kyriakou, M; Eliades, "A Matlab class for EPANET water distribution simulation libraries," 2016. [Online]. Available: http://epanet.de/developer/matlab.html.en.

[23] O. Giustolisi, D. Laucelli, L. Berardi, and D. A. Savi, "Computationally Efficient Modeling Method for Large Water Network Analysis," *J. Hydraul. Eng.*, vol. 138, no. 4, pp. 313–326, 2012.

[24] N. B. Gorev and I. F. Kodzhespirova, "Noniterative Implementation of Pressure-Dependent Demands Using the Hydraulic Analysis Engine of EPANET 2," *Water Resour. Manag.*, vol. 27, no. 10, pp. 3623–3630, 2013.

[25] G. Burger, R. Sitzenfrei, M. Kleidorfer, and W. Rauch, "Quest for a New Solver for EPANET 2," *J. Water Resour. Plan. Manag.*, vol. 142, no. 3, p. 04015065, Nov. 2015.

[26] X. Xie, M. Nachabe, and B. Zeng, "Optimal Scheduling of Automatic Flushing Devices in Water Distribution System," *J. Water Resour. Plan. Manag.*, vol. 141, no. 6, p. 4014081, 2014.

[27] P. Cheung, "Epanet Calibrator – An integrated computational tool to calibrate hydraulic models," in *Proceedings of the tenth international conference on computing and control for the water industry, CCWI 2009*, 2009, pp. 129–133.

[28] M. M. Salvino, P. S. O. de Carvalho, and H. P. Gomes, "Multivariate calibration of water supply networks using multiobjective genetic algorithm," *Eng. Sanit. e Ambient.*, vol. 20, no. 3, pp. 503–512, 2015.

[29] H. Gomes, S. de T. M. Bezerra, P. de Carvalho, and M. Salvino, "Optimal dimensioning model of water distribution systems," *Water SA*, vol. 35, no. 4. Water Research Commission (WRC), 2009.

[30] A. Pathirana, "EPANET2 Desktop Application for Pressure Driven Demand Modeling," in *Water Distribution System Analysis*, 2010, pp. 65–74.

[31] Zonum Solutions, "EPANET Z v0.5," 2009. [Online]. Available: http://www.zonums.com/epanetz.html.

[32] D. A. Savic, J. Bicik, and M. S. Morley, "A DSS generator for multiobjective optimisation of spreadsheet-based models," *Environ. Model. Softw.*, vol. 26, no. 5, pp. 551–561, May 2011.

[33] R. Aliod and C. González, "A computer model for pipe flow irrigation problems," in *International Workshop on Numerical Modelling of Hydrodynamics for Water Resources: Proceedings of the Conference on Numerical Modelling of Hydrodynamic Systems*, 2007, pp. 293–316.

[34] E. Salomons, "Fire Flow Calculations Software," 2010. [Online]. Available: http://www.optiwater.com/fireflow/.

[35] B. Jeck, "Read text files in Epanet's .inp and .rpt formats into R," 2015. [Online]. Available: https://github.com/bradleyjeck/epanetReader.

[36] E. Salomons, "EPANET class for C#," 2014. [Online]. Available: http://www.water-simulation.com/wsp/2014/02/25/epanet-class-for-c-sharp/.

[37] S. Macke, "Epanet.js - EPANET in JavaScript," 2014. [Online]. Available: http://epanet.de/developer/epanetjs.html.

[38] D. Steffelbauer and D. Fuchs-Hanusch, "OOPNET: An object-oriented EPANET in Python," *Procedia Eng.*, vol. 119, no. 1, pp. 710–718, 2015.

[39] L. A. Rossman and J. E. Van Zyl, "The Open Sourcing of EPANET," in *Water Distribution Systems Analysis 2010*, 2011, vol. 41203, no. May, pp. 19–28.

[40] J. E. Van Zyl and Y. Chang, "Programming Styles for an Open Source EPANET Project (ASCE)," in *Water Distribution Systems Analysis*, 2010, pp. 29–36.

[41] L. A. Rossman, *Storm Water Management Model User's Manual Version 5 . 1*, no. September. Cincinnati, OH 45268: Environmental Protection Agency, 2015.

[42] D. Mora-Melia, P. L. Iglesias-Rey, F. J. Martinez-Solano, and V. S. Fuertes-Miquel, "Design of Water Distribution Networks using a Pseudo-Genetic Algorithm and Sensitivity of Genetic Operators," *Water Resour. Manag.*, vol. 27, no. 12, pp. 4149–4162, Jul. 2013.

[43] P. L. Iglesias-Rey, F. J. Martínez-Solano, D. Mora-Meliá, and J. V. Ribelles-Aguilar, "The Battle of Water Networks II: Combination of meta-heuristic techniques with the concept of setpoint function in water network optimization algorithms," in *WDSA 2012: 14th Water Distribution Systems Analysis Conference*, 2012, no. 2002, pp. 510–523.

[44] F. J. Martínez-Solano, P. L. Iglesias-Rey, D. Mora-Meliá, and V. S. Fuertes-Miquel, "Using the set point concept to allow water distribution system skeletonization preserving water quality constraints," *Procedia Eng.*, vol. 89, pp. 213–219, 2014.

[45] P. L. Iglesias-Rey, F. J. Martínez-Solano, D. M. Meliá, and P. D. Martínez-Solano, "BBLAWN: A Combined Use of Best Management Practices and an Optimization Model Based on a Pseudo-Genetic Algorithm," *Procedia Eng.*, vol. 89, pp. 29–36, 2014.

[46] P. L. Iglesias-Rey, F. J. Martínez-Solano, D. Mora Meliá, and P. D. Martínez-Solano, "Combining Engineering Judgment and an Optimization Model to Increase Hydraulic and Energy Efficiency in Water Distribution Networks," *J. Water Resour. Plan. Manag.*, vol. 142, no. 5, p. C4015012, May 2016.

[47] O. Giustolisi, L. Berardi, D. Laucelli, D. Savic, and Z. Kapelan, "Operational and Tactical Management of Water and Energy Resources in Pressurized Systems: the competition at WDSA 2014," *J. water Resour. Plan. Manag.*, vol. Submitted, no. Germanopoulos 1985, 2015.

[48] P. L. Iglesias-Rey, S. A. Oyarzún Constable, F. J. Martínez-Solano, and P. D. Martínez-Solano, "Energy optimization of tha water distribution network of 'El Camp de Murcia' (Spain)," in *SEREA 2012 - Seminário Ibero-Americano sobre Sistemas de Abastecimento e Drenagem*, 2012, pp. 1–12.

[49] G. Karypis and V. Kumar, "A Fast and High Quality Multilevel Scheme for Partitioning Irregular Graphs," *SIAM J. Sci. Comput.*, vol. 20, no. 1, pp. 359–392, 1998.

[50] F. J. Martínez-Solano, P. L. Iglesias-Rey, D. Mora-Meliá, and J. V. Ribelles-Aguilar, "Combining skeletonization, setpoint curves and heuristic algorithms to define DMAs in the BWNDMA," in *16th Water Distribution Systems Analysis Conference (WDSA 2016)*, 2016.