Parameterization of Offline and Online Hydraulic Simulation Models

J. Deuerlein, Olivier Piller, I. M. Arango, M. Braun

Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 119 (2015) 545 – 553

Procedia Engineering

www.elsevier.com/locate/procedia

13th Computer Control for Water Industry Conference, CCWI 2015

Parameterization of offline and online hydraulic simulation models

Jochen Deuerlein[a,*], Olivier Piller[b], Idel Montalvo Arango[a], Mathias Braun[c]

[a]3S Consult GmbH, Albtalstrasse 13, 76137 Karlsruhe, Germany
[b]Irstea, Water Department, Bordeaux regional centre, Cestas F-33612, France
[c]Fraunhofer Institute of Optronics, System Technologies and Image Exploitation (IOSB), Fraunhoferstrasse 1, 76131 Karlsruhe, Germany

Abstract

The proper estimation and regular update of model parameters is crucial for the actuality of a mathematical simulation model representing the hydraulics and water quality of a real physical water distribution system. Especially, when the model is running online, uncertainties in model parameters can result in large discrepancies between model predictions and behavior of the real system. Therefore, adequate techniques for data acquisition, maintenance and update of model parameters have to be developed. In what follows the "parameterization" of a hydraulic online simulation model is described including the classification of parameters regarding data source, update cycles and function in the model. The parameterization framework was developed to benefit the modeling of water critical infrastructure systems.

Peer-review under responsibility of the Scientific Committee of CCWI 2015

Keywords: Hydraulic online simulation, parameterization, calibration, SCADA-System, GIS, data acquisition, model update

1. Introduction

Driving online hydraulic simulations of water distribution systems in real-time or in replay mode requires within the simulator the integration of measurements and operational data that are continuously collected in the real physical system and transferred to a central SCADA (Supervisory Control And Data Acquisition) system [1]. Hydraulic simulation is especially important in the context of monitoring and modeling of critical infrastructure systems [2]. In the following document real-time measurements and operational data are denoted by "online data". In addition, the term "model parameters" refers to values of the hydraulic simulation model that are assumed to be known for the calculation and serve as boundary conditions for the system of differential algebraic equations or

*Corresponding author: Tel.: +49-721-33503-360; fax: +49-721-33503-130,
E-mail address: deuerlein@3sconsult.de

Peer-review under responsibility of the Scientific Committee of CCWI 2015
doi:10.1016/j.proeng.2015.08.907

describe the (constant) physical properties of the components of the model. Consequently, the model parameters can be subdivided into "physical parameters" such as pipe diameter, roughness and elevation of nodes and "operational parameters", for instance valve states, pump speeds and, of course, the water demand representing the timely changing load of the system. The following table shows the different classes of parameters and the associated rate of change:

Table 1. Classification of model parameters

Parameter class	Change rate	Description	Examples
Physical network parameters	Slow (month to years)	Describe the physical properties of the network elements such as pipes, pumps, valves and control devices. These properties normally change slowly in time. Some of them cannot be directly identified and need to be calibrated. For example, dependent on the pipe material and water quality, deterioration of pipes results in increased roughness values and reduced inner diameters caused by growing incrustations. However, these changes develop over years. In the online use case it is assumed that the model has been calibrated in advance and that slowly changing parameters have been properly identified and remain constant during the entire simulation period.	network topology, diameter, roughness and length of pipes, elevations, physical properties of valves and control devices
Remote controlled operational state parameters	Fast (multiple changes per day)	Operational parameters, like the previously described physical parameters, are assumed to be known in the hydraulic network calculations (boundary conditions). However, they are not constant but continuously updated. Their states are continuously monitored in the SCADA system.	operational states of valves, pump status (on/off) and speed, set values and state of remote controlled control devices, tank water level as initial conditions
Not remote controlled operational state parameters	Medium (weeks to month)	The values of non-remote controlled operational state parameters are more difficult to estimate since their current state is not transferred to the SCADA system and must be sometimes updated in the model by hand. Often this information is not available.	state of gate valves that are closed for rehabilitation works
Load parameters	Continuous	In general, the actual demand distribution is not known. The nodal demands in the model are based on meter readings that are carried out from time to time (months to year). The proper estimation of nodal demands is crucial for the results of the online simulations. For the hydraulic calculations the demand is normally assumed to be known. However, in dependency of the kind of modelling the demand can be used as fixed parameter (DDM: Demand Driven Modelling) or as an upper threshold (PDM: Pressure-Dependent Modelling).	Domestic demands, Industrial demands

In what follows the process of choosing the parameters of the mathematical model is called "parameterization". This consists of two steps. In the first (offline) step the components that are important for drawing a reliable picture of the real system are identified including: pipes and their characteristics, network topology, elevations, control devices and pumps with their corresponding physical properties and operational modes, valves and hydrants location and the customer repartition and behavior including average consumption. Measurement data of the past are typically used for a first offline calibration of model parameters. In the second (online) step the model is confronted with "online" data from the SCADA system (SCADA: Supervisory Control and Data Acquisition). In this context, the measurements and operational data of devices are subdivided into three groups. The first group includes operational states of devices (valves states, rotational speed of pumps) that can be directly transferred to the corresponding parameter of the model. The second group concerns measurements that are used as boundary conditions in the model like tank inflows and water levels. Group one and two are the driving parameters of the model (actuators). The third group consists of measurements that can be used only indirectly for the online calibration of the model or for comparison of measurements and calculation results (sensors). Examples are pressure heads at nodes and zone inflows that are used for adjusting the parameters that cannot be observed directly and are subject to uncertainty like demand values. As a refinement, water quality sensors are distinguished from hydraulic measurements.

Before the mathematical model of water supply systems is discussed in more detail in the following section, the relationship between online data and the hydraulic model is shown in Fig. 1. On the top is the hydraulic model that in the first level below is subdivided into state variables and model parameters. The state variables include amongst others link flows and nodal pressures. As described before, the model parameters can be further subdivided into physical properties that describe the topology and asset characteristics of the system, operational data (remote controlled and not remote controlled operations) and the system load. The connection of the hydraulic model with the online data consists of remote controlled operations (pumps on/off, valve closure, …) and measurements.

The data that control the hydraulic model (used as parameters) are called actuators, and the data that are used for comparison between calculation results and measurements are called sensors (see Fig. 1 from bottom). Both are continuously updated by the SCADA system and available normally on an OPC Server. It is important to note that only actuators can be directly triggered in the model. The sensor data are redundant with the calculation results. They serve as estimates for the quality of the online calculation model and cannot be triggered directly. The difference between measurements and calculation results can be used for adjustment of other model parameters (model calibration). In the online case this is only foreseen for a special class of parameters – the nodal demands (see arrow from sensors to demands in Fig. 2).

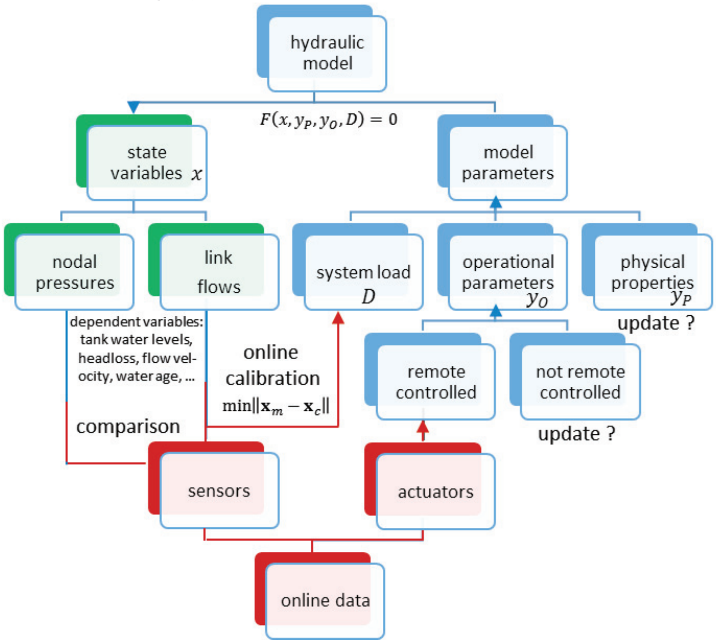

Fig. 1. Overview of model parameters, state variables and online data including their dependencies.

2. Mathematical Model

2.1. Overview

With the previously described grouping of parameters the calculation of the network hydraulics can be described by a functional relationship as a mapping of load and operational parameters on state variables. In a general formulation, the dynamic hydraulic calculation can be described as an Initial-Boundary Value Problem (IBVP) of a system of Differential Algebraic Equations (DAEs). Different simplification levels of the original formulation result in different modelling levels ranging from water hammer to steady-state calculation. For online simulations of large distribution systems an appropriate modelling techniques are the Rigid Water Column Model (RWCM or slow transient model) and the Extended Period Simulation (EPS or quasi steady-state formulation). For the latter, instead of solving the original IBVP a series of steady-state problems is solved neglecting the inertia terms in the more general system of equations of the RWCM. The only remaining time dependent differential equation in EPS is used for updating the water level in tanks. As shown in the introduction the terms of the mathematical model (independently from the actual modelling level) can be subdivided into parameters and state variables. For a water supply system model the most important parameters are:

Constant model parameters:

- Network topology;
- Pipe and valve characteristics;
- Elevations;
- Base demand.

Boundary conditions varying over time:

- Water level in reservoirs;
- Nodal demands;
- Fixed input flows.

Initial values (for t = 0):

- Water level in tanks;
- Water quality.

Operational data (varying over time, including integer values)

- Pump states;
- Pump speeds;
- Valve states;
- Rules and set values of local automation;
- Set values and state of control devices such as flow and pressure control valves.

The following Table 2 and Table 3 give an overview of model parameters that are part of common SCADA systems and how they are considered in the mathematical model.

Table 2. Measurements used as model parameters (received from SCADA)

Measurements	**Type**	**Remark**
nodal pressure	sensor	quality of results of online model, calibration
link flow rate	sensor	quality of results of online model, calibration
	actuator	lumped demand factor of supply zone
tank water level	actuator	initial condition for transient model
	sensor	control value during subsequent time steps. Cumulative nature singles out discrepancies between model and reality
reservoir or resource head	actuator	boundary condition for head
water quality indicator	sensor	quality of results of online model, calibration
dosage	actuator	input of substance

Table 3. Operations and control information used as model parameters (received from SCADA)

Type of information	**Type**	**Remark**
valve state	actuator	separation of pressure zones
pump state	actuator	pumps should operate during low electricity demand times
pump speed	actuator	adjustment of pump curve to demand
control device set values	*actuator*	*some modern control devices don't have fixed set points but can be adjusted to current conditions*

The mathematical problem of simulating the hydraulic behavior of water supply systems can be modelled as an initial boundary value problem for a system of differential algebraic equations. With the (not correct) assumptions of incompressibility of water and an infinite Young's modulus for the pipe material the DAE system includes only ordinary differential equations (water hammer theory is excluded in this case -> RWCM).

Initial values have to be defined for the water level in tanks and concentration of water quality parameters at nodes. The boundary conditions describe the given timely changing values for a certain set of nodes such as pressure heads at reservoirs, withdrawal at demand nodes and concentration at water quality sources.

2.2. Slow transient or rigid water column model

The rigid water column model for water supply models consists of the following system of differential algebraic equations (for the notation please see the Appendix):

$$\begin{aligned} \mathbf{L}\mathbf{q}'(\mathrm{t}) - \mathbf{A}_\mathrm{D}\mathbf{H}_\mathrm{D}(\mathrm{t}) - \mathbf{A}_\mathrm{T}\mathbf{H}_\mathrm{T}(\mathrm{t}) + \mathbf{h}\big(\mathbf{q}(\mathrm{t})\big) &= \mathbf{A}_\mathrm{R}\mathbf{H}_\mathrm{R}(\mathrm{t}) \\ \mathbf{S}\mathbf{H}_\mathrm{T}'(\mathrm{t}) + \mathbf{A}_\mathrm{T}^\mathrm{T}\mathbf{q}(\mathrm{t}) &= \mathbf{0} \\ \mathbf{A}_\mathrm{D}^\mathrm{T}\mathbf{q}(\mathrm{t}) &= \mathbf{D}(\mathrm{t}) \\ \mathbf{H}_\mathrm{T}(0) &= \mathbf{H_0} \end{aligned} \quad (1)$$

The static or only slowly changing parameters (blue) include pipe properties like length, diameter and roughness ($\mathbf{L}$ and also head loss function h(q) which includes the diameter and the roughness of the pipe), network topology ($\mathbf{A}_\mathrm{D}$,$\mathbf{A}_\mathrm{T}\mathbf{A}_\mathrm{R}$) and the geometry of storage tanks ($\mathbf{S}$). The head loss function is violet (composition of red and blue parameters) since it includes, in addition to the slowly changing pipe properties, also roughness and minor losses of valves that can result from maintenance work in the field. The remaining parameters refer to the boundary conditions (red) reservoir heads ($\mathbf{H}_\mathrm{R}(\mathrm{t})$), the nodal demands ($\mathbf{D}(\mathrm{t})$) and the initial value for the tank water levels ($\mathbf{H_0}$), which is needed only at the beginning of the simulation time. The decision variables (hydraulic state variables) are marked in green color.

It must be noted that the above system is a strong simplification of real water distribution networks that include also a number of pumps, remote controlled valves and other control devices. Control devices and pumps impact the head loss (or head gain) of a link. Therefore the equation in the first line of equation (1) could be extended to:

$$\mathbf{L}\mathbf{q}'(\mathrm{t}) - \mathbf{A}_\mathrm{D}\mathbf{H}_\mathrm{D}(\mathrm{t}) - \mathbf{A}_\mathrm{T}\mathbf{H}_\mathrm{T}(\mathrm{t}) + \mathbf{I}_\mathrm{P}\mathbf{h}_\mathrm{P}\big(\mathbf{q}(\mathrm{t})\big) + \mathbf{I}_\mathrm{CD}\mathbf{h}_\mathrm{CD}\big(\mathbf{r}(\mathrm{t}), \mathbf{q}(\mathrm{t})\big) = \mathbf{A}_\mathrm{R}\mathbf{H_R}(\mathrm{t}) \quad (2)$$

Here, the head loss function is subdivided into one part for pipes (index P) including manually operated gate valves and one part for other control devices and pumps (index CD) that are remote controlled from a SCADA system. Consequently, the first part remains violet as explained above and the second is red referring to the control devices ability to change their operational states by remote control on a regular base. For more advanced applications of the RWCM see for example [3] and [4].

3. Model parameters

3.1. Identification of model parameters

For the parameterization of the online model the availability of data must be considered. Measurements commonly include hydraulic state variables such as flow rates, pressure heads, and water level in tanks. In addition, operational state variables for remote controlled devices can be received from SCADA system: valve states, pump states (on/off), pump speed, set points of control devices (set pressures for pressure control devices and set flows for flow control devices). Nowadays, more and more water quality sensors that measure standard water quality parameters such as conductivity, pH, temperature, etc. are installed in the field and integrated within the SCADA system.

The comparison of SCADA variables with the system of equations shows that operational states can be directly used as boundary conditions or for modification of the nonlinear head loss (head gain) equation (defined as actuators). In contrast, only few of the measurements can be used as actuators: only tank water levels as initial condition and reservoir water levels as pressure boundary condition. In general, measurement data for nodal pressures and flows are sensors in the sense of the online simulation because they refer to state variables of the hydraulic simulation model. That means that they are not fixed parameters of the model rather than being calculation results. Yet, sensor data are very important for monitoring the quality of the online calculation results. If there are too large discrepancies there must be something wrong with the model assumptions expressed by the model parameters.

A special class of model parameters are the nodal demands. In general, the current actual demands are not available as real time measurements. However, demand meter readings are carried out by most of the utilities on a regular time scheme, say for example every half year or every year or using a rolling time schedule. In this case, as measurements only average values are available. In order to adjust the demand parameters to current conditions demand factors are applied. In offline planning models daily factors referring to the time of the year and the week day are distinguished from hourly factors representing the daily peak demand times and low demand times during night hours. The situation distinguishes if an online model is used. In this case, normally real time measurements of the total inflow into the system are available. If the system is subdivided into pressure zones sometimes more detailed measurements that reflect the actual demand of the particular supply zones can be used. Therefore, a common supply factor can be calculated for the smallest units and be applied to all the nodes in this sub network.

Using this technique flow measurements are not only sensors but in some way also actuators (for the zone demand). They are still sensors since having more than one inflow into the zone the calculated flows can still differ from the measurements. Possibly reasons are manifold in this case. Wrong assumptions about pipe properties such as diameter and roughness and state of gate valves are only few of them.

Static parameters:

The identification of static and slowly changing network parameters is strongly related to the creation of the water supply network model from reference data systems and model calibration for both water quality and hydraulic parameters [5]. The process of setting up the model starts with the adaption of the data describing the pipes and system layout that are mostly available from Geographic Information Systems (GIS). Efficient data interfaces are needed to allow the transfer of information from one system to the other without loss. Due to different requirements also adaption of network topology and automatized failure handling may be required. For example, often house connection pipes end at distribution pipes in the GIS and are not topologically connected.

Dynamically changing parameters:

Dynamically changing parameters include system operations and load. The latter will be treated separately in the following paragraph. Operational parameters refer to decisions on the state of control devices, pumps and valves that are often made by individuals in the control room and based on their experience. The online model can deal only with remote controlled operations since other data, such as gate valve states that are changed by technical staff in the field, are not transferred in real-time to the operating system. This, actually, can cause severe problems for the accuracy of the online simulation model.

Load or special dynamically changing parameters:

Special kind of time-varying parameters are network demands. In general, there exist two different kind of modelling: demand driven modelling where the withdrawals are assumed to be fixed and pressure driven modelling where the actual withdrawals are a nonlinear function of the current pressure. In the latter case the user demands serve as upper threshold for the withdrawal.

State variables

The state variables are calculated by the model for a given set of model parameters. Once the operational decisions are made by the system operator and the load is applied to the model, then the state variables can be calculated from the model equations. Dependent on the kind of the mathematical model the results (state variables) are uniquely determined by the model equations or there might by multiple solutions that describe the current operational state. Assuming a strictly convex problem with non-empty feasible sets for the state variables there exists always a unique solution. In some special cases, the operational conditions can be selected in such a way that a unique (stable) solution does not exist. As result the system might be in an unstable state that should be imperatively avoided.

3.2. Update of dynamically changing parameters

The update cycles of model data depend on the IT-equipment and the workflow of the utility. Usually, the update intervals increase with increasing effort (see Fig. 2). This is especially true for data that are not monitored in the SCADA systems and subject to manipulations by network operators. As an example the state of gate valves that are closed during rehabilitation works can be mentioned.

The actuality of SCADA data is dependent on the kind of data transmission. Whereas operational data and measurements of important operational stations (pump stations, storage tank, water treatment plans) are normally connected via data cables the measurements that are gathered in the field are often transferred by mobile phone networks (GPRS technology). In this case, the lifetime of the battery and the cost are strongly dependent on the frequency for data transmission. Therefore common time intervals range from minutes to one day.

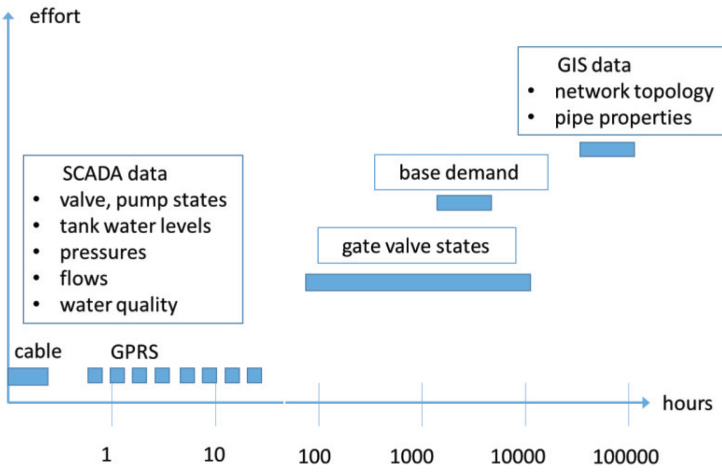

Fig. 2. Typical update cycles of model data originating from different sources (logarithmic scale)

The data update for non-remote controlled control devices and valve states poses particular difficulties for the online model. Often, the information is reported on paper sheets and not communicated to a central data management system. The risk of losing the information is high. Wrong assumptions of valve states highly impact the accuracy of online simulation results. In addition, closed valves that are assumed to be open can also lead to severe consequences for example in case of a fire. The performance of fire hydrants is reduced in such a case and can prevent efficient firefighting measures. Therefore, care and attention should be given to an adequate management on the information about valve states. The technical base already exits. For example modern GIS systems come with mobile phone integration. Using this technique the operator can pass the information about valve state changes on side to a central GIS database. From there the information could be transferred to the online model.

However, in reality most of the GIS systems in use are not connected to an online system. The creation and update of a hydraulic simulation model is still costly in terms of labor and time. Therefore, the update frequency of GIS data in the hydraulic simulation models is pretty large (models are normally updated on an annual base or even longer). There are different reasons causing this situation:

- GIS data often do not have the quality that is needed for the simulation model. Therefore more or less time-consuming repair mechanisms have to be applied.
- The size of the GIS-models is too big for the simulation model. Aggregation and skeletonization, however, result in losing the one to one relationship between GIS data and model data. As a consequence the differential update of single features is almost impossible and often a completely new creation of the simulation model from the source data is required.

4. Summary and Conclusions

Online simulation, either in real time or in replay mode, of the hydraulics and water quality of drinking water networks requires the availability of measurement data and operational data of the real physical system. There exist different ways of dealing with information gathered in the field and every utility has developed its own approach.

No general existing approach for implementation and parameterization of online simulation model including data acquisition for development of the offline hydraulic simulation model and its connection to live data for measurements and operational data can be identified. The different underlying IT-infrastructures of the water supply utilities have to be taken into account as well as number and quality of available offline and online data. Additionally, a proper work plan for the creation of hydraulic online simulation should take into account the individual requirements of the utility as well as technical, financial and human resources.

The quality of both online and offline model parameters is crucial for the validity and significance of the calculation results. Due to improved sensors and methods for data transmission the real-time data are often less critical than the data that is typically treated as offline information. The long update cycles of GIS data sets and less reliable documentation and availability of operational states of non-remote controlled valves and control devices highly affect the quality of the results. More work has to be done on improving data update techniques from reference data systems such as GIS and CMS (Content Management Systems). The absence of standards in offline data models complicates the development of general interfaces. In contrast, for the exchange of live data the OPC standard has been established allowing a fast connection between the hydraulic online simulation models and the SCADA system of the utility by using an OPC client integrated within the software for hydraulic calculations.

Acknowledgements

The work presented in the paper is part of the French-German collaborative research project SMaRT-Online^{WDN} that is funded by the French National Research Agency (ANR; project: ANR-11-SECU-006) and the German Federal Ministry of Education and Research (BMBF; project: 13N12178).

Appendix A. Notation

$\mathbf{L}$	: $(m \times m)$ −diagonal matrix, $L_{ii} = \frac{L_i}{A_i}$. L_i and A_i are the length and the diameter of pipe i.
$\mathbf{q}, \mathbf{q}'$	: m-vector of flows, vector of time derivatives of flows
$\mathbf{A}_D$	: $(m \times n)$ −link - node incidence matrix reduced to junction nodes
$\mathbf{A}_T$	: $(m \times t)$ −link - node incidence matrix reduced to tank nodes
$\mathbf{A}_R$	: $(m \times t)$ −link - node incidence matrix reduced to reservoir nodes
$\mathbf{H}_D$	: n-vector of unknown nodal heads
$\mathbf{h}(\mathbf{q})$	: m-vector of head losses of links as a (nonlinear) function of link flows
$\mathbf{H}'_T$	: t-vector of water level changes in tanks (time derivatives of tank node heads)
$\mathbf{S}$	: $(t \times t)$ −diagonal matrix with $S_{ii} = AS_i$. AS_i is the cross section of tank i.
$\mathbf{Q}_D$	: n-vector of flows leaving or entering the system at junction nodes
$\mathbf{D}$	: d-vector of demands or fixed input flows
$\mathbf{H}_R$	: r-sub vector of $\mathbf{H}$ where entries refer to nodes with pressure boundary condition
$\mathbf{R}$	: r-vector of given pressure heads
$\mathbf{H}_0$	: t-vector of initial water level in tanks
m	: total number of links
n	: total number of junction nodes
r	: number of reservoirs
d	: total number of demand and fixed input flow nodes
t	: number of tanks

References

[1] Montalvo Arango, Idel; Deuerlein, J. (2013): “Driving online simulations in water distribution systems“, Computing and Control for the Water Industry 2013 (CCWI 2013), Perugia, 02.09-04.09.2013.

[2] Bernard T., Braun M., Piller O., Gilbert D., Deuerlein J., Korth A., Nitsche R., Maurel M., Sandraz A.C., Sedehizade F., Weber J.M. and Werey C. (2013), “SMaRT-Online^{WDN}: Online Security Management and Reliability Toolkit for Water Distribution Networks.”, Proceedings of the 10th International ISCRAM Conference Baden-Baden, Germany, May 2013, T. Comes, F. Fiedrich, S. Fortier, J. Geldermann and T. Müller, eds., 5 pages.

[3] Jaumouillé, E., Piller, O., and van Zyl, J. E. (2007). "A hydraulic model for water distribution systems incorporating both inertia and leakage." Water Management Challenges in Global Change (CCWI2007 and SUWM2007 Conference), Leicester, GBR, 3-5 September 2007, 8.

[4] Piller, O., and Propato, M. (2006). "Slow Transient Pressure Driven Modeling in Water Distribution Networks." 8th annual Water Distribution System Analysis Symposium, University of Cincinnatti, Cincinnati, Ohio USA, August 27-30 2006, printed by ASCE, 13.

[5] Piller, O., Gilbert, D., and van Zyl, J. E. (2011). "Dual Calibration for Coupled Flow and Transport Models of Water Distribution Systems." Water Distribution Systems Analysis 2010, E. L. Kevin, Y. C. Christopher, O. Avi, and L. P. Ian, eds., ASCE, 722-731.