A Water Distribution System Model to Simulate Critical Scenarios by Considering Both Leakage and Pressure Dependent Demands

Article *in* Procedia Engineering · May 2017

DOI: 10.1016/j.proeng.2017.03.234

3 authors:

Pilar Conejos
Aguas de Valencia

Fernando Martínez Alzamora
Universitat Politècnica de València

Joan Carles Alonso Campos
Universitat Politècnica de València

Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 186 (2017) 380 – 387

Procedia Engineering

www.elsevier.com/locate/procedia

XVIII International Conference on Water Distribution Systems Analysis, WDSA2016

A water distribution system model to simulate critical scenarios by considering both leakage and pressure dependent demands

María Pilar Conejos[a] , Fernando Martínez Alzamora[b], Joan Carles Alonso[b]*

[a]*Grupo Aguas de Valencia, C/Pedrapiquers N 4-46014, Valencia (Spain)*
[b]*Research Institute of Water&Env.Eng (IIAMA), Universitat Politècnica de València (Spain)*

Abstract

To simulate the behavior of water distribution networks under any supply pressure conditions it is necessary to use head driven models, considering both the leakage and pressure dependent demands. Up to the present, many authors [1], [2], [3] and [4] have proposed different methods to simulate the network behavior considering user's demand and/or leaks depending on pressure, but few of them are ready to be implemented from the practical point of view.

With this aim, firstly the authors have analyzed the behavior of demand as a function of pressure (PDD), simulating the response of plumbing systems in different types of buildings in urban areas. Next, a new mathematical function has been proposed that fits the simulated dependence of demands with pressure. This function has the necessary mathematical properties to be integrated within a hydraulic model and its parameters have been adjusted in a specific sector of the Valencia water distribution network, using the field data taken during a four month test. Field data included the sector inflow, pressures at service connections and automated meter readings. On the other hand the authors have developed a procedure to find the leakage coefficients at each node that fit best for the total leakage volume in the sector, usually available in sectored water supply system.

Finally the new PDD function and the leakage coefficients have been integrated in a realistic model to consider the dependence of leakage and demands with pressure so that, for any scenario simulation, the integrated model is able to provide in every node the value of pressure and the total consumed flow differentiating its two components, leakage and demand.

Using this model, more realistic simulations can be carried out for new scenarios such as pressure reduction for leakage control, failure of critical components (water treatment plant, pumping station, pipe breaks, etc) or restrictions to be applied during an extended drought, in order to analyze in each case the demand satisfaction and leakage level.

* Grupo Aguas de Valencia, C/ Pedrapiquers 4 - 46014. Valencia (Spain) Tel.: +34963860600;
E-mail address: pconejos@aguasdevalencia.es

doi:10.1016/j.proeng.2017.03.234

Keywords: Pressure dependent demands; head driven models; leakage models; hydraulic simulation, critical scenarios

1. Introduction

In urban water distribution networks, leakage and demands depend on the available pressure. So, when due to different circumstances (pipe breaks, pumps detention...) a pressure reduction occurs in the network, the real consumed flow may decrease considerably. In this case it is said the network is working under insufficient pressure conditions. Otherwise, in normal conditions, when demands are fully satisfied, if pressure increases in the service connection, user's consumption and leakage will slightly increase.

Traditional simulation models do not take into account this circumstance and demand is considered constant and independent on pressure, which represents an important limitation. Due to this fact, it is vital to have more realistic hydraulic models to simulate the behavior of the network under any service pressure conditions.

Up to the present, many authors have proposed different methods to simulate the water distribution network considering user's demand and/or leaks depending on pressure, such as Giustolisi et al (2008) [2], Siew and Tanymboh (2011) [3], Jun and Guoping (2013) [5], Murano et al (2014) [4]. In most of them a function that correlates the leakage flow with pressure is needed and, additionally, another function that correlates user's demand with the available pressure in the user's node (PDD curve). Several approaches and real assays have been carried out in order to establish the relation for leakages, being the potential law based on fixed and variable discharge area concept (FAVAD), the most used and proven up to now. However, there are few studies that correlate the user's demand with pressure, especially from a practical point of view, in urban water distribution networks

Since the 80s some researchers have focused their efforts on obtaining a curve that correlate node's demand with pressure, so currently we can find several proposals in literature, Germanopoulos (1988), Wagner et al. (1988), Chandapillai (1991), Fujiwara and Ganesharajah (1993), Tucciarelli (1999), Tanymboh Templeman (2004, 2010) . However, there are no field tests to justify which of them fits better the reality.

In this work the authors have analyzed the behavior of demand as a function of pressure, simulating the response of plumbing system for different types of buildings in urban areas. As a consequence a new PDD function has been proposed that fits the analyzed behavior and at the same time has the necessary mathematical properties to be integrated within a model. This function has been adjusted in a specific sector of the Valencia water distribution network using the field data taken over a four months period.

Additionally, a practical methodology to implement an integrated model considering both distributed leakage and pressure-dependent demands from practical data available in any water supply has been proposed. This model is able to provide, in every node at each time and under any operating condition, the value of the pressure and the consumed flow. Moreover, the last one is breakdown differentiating leakage from demand. In addition the model provides in each junction the deficit or surplus demand.

So, more realistic simulations can be carried out for any scenario such us pressure reduction for leakage control, planning critical maintenance operations, failure of critical components of the network (water treatment plant, pumping station, pipe breaks, etc) or planning restrictions during an extended drought, in order to analyze in every case the effects on the demand satisfaction and leakage level. These simulations can not be carried out by a traditional model driven by fixed demands.

2. Variation of demand with pressure on urban water supply networks

2.1. Realistic analysis of variation of demand with pressure

There are two kinds of domestic demands: variable and fixed. The variable demands are those produced by the voluntary opening of a tap until the desired flow is obtained during a certain time. In this case flow depends on the tap opening degree and the plumbing system. From a hydraulic point of view, the outgoing flow of a single opened tap is determined by the equilibrium equation:

$$\frac{p_s}{\gamma}(q_{vd}) = \Delta z + \Delta h_t(q_{vd}) + \Delta h_v(q_{vd}) + \frac{p_{res}}{\gamma}(q_{vd}) = \Delta z + k_t(q_{vd})^2 + k_v(q_{vd})^2 + k_{res}(q_{vd})^2 \qquad (1)$$

where

q_{vd} is the demanded flow or outgoing flow of the tap (variable),
p_s is the pressure in the hydraulic connection,
Δz or p_{min} is the difference of elevations between the tap and the hydraulic connection,
Δh_t is the head losses in plumbing system that supply the tap,
Δh_v is the additional head losses caused by the regulation valve of the tap,
p_{res} is the minimum required pressure by the device to deliver the demanded flow and
represents the head losses in the fully opened tap, and the dynamic head of the flow (between 5 and 10 m)

The service pressure p_s in the hydraulic connection can vary with the network operation and so the outgoing outflow q_{vd}.

On the other hand, the demands called fixed are those caused by the automatic devices that take a determined volume of water from the network each time they are turned on, like cisterns, washing machines, dishwashers, volume automated irrigation, etc. In this case we can considerer that average flow demand is constant, except when the pressure is so low that the time taken to fill the desired volume is higher than the hydraulic simulation step, generally an hour. In this case the equation would be the same as for variable demand but eliminating the losses causes for the regulation valve of the tap.

If we superpose both curves, for fixed and variable demands, we will obtain the theoretical PDD function that can be approximated with a potential function (Fig. 1)

$$p = p_{\min} + k\, q^n \qquad n > 2 \qquad (2)$$

However, in the case of a multi-storey building we would have a different curve for each height and the global PDD function would be the result of the parallel combination of all. As a consequence the potential curve does not adjust so well to this condition.

Also we have to consider that when pressure varies users react by adjusting tap position so as to obtain the desired flow while there is enough pressure. If the pressure falls to a certain value, called p_{ref}, users would completely open the taps and the minimum resistance curve would be achieved, thus limiting and ending user's control. Again, the potential curve do not adjust to this behavior.

Therefore a more realistic PDD function that the potential one would be a function with S-shape, that would limit the increase of the demand q_d for high pressures being asymptotically bounded by a limit value q_{lim}, and with a softer curvature when $p > p_{ref}$, and more pronounced when $p < p_{ref}$. Also, it would be desirable to be able to control the curvature with the introduction of one or more parameters. (Fig. 2)

On the other hand demand flows and user's needs vary with time. So in each instant we will have a different PDD function, due to different number of open taps.

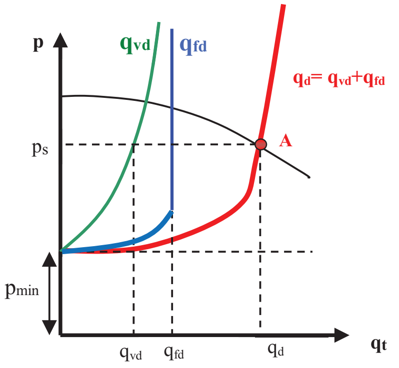


Fig. 1. Theoretical PDD curve for several taps in the same floor

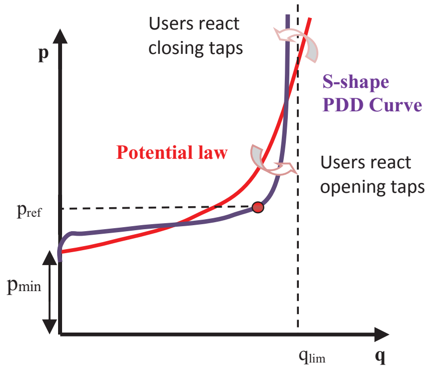


Fig. 2. More realistic PDD curve taking into account user's reaction

2.2. New PDD function to represent variation with pressure in an urban network

Pressure - demand relationship in an urban network has been analyzed. So, indoor domestic plumbing systems in urban areas supplied by a single node in the model have been simulated using EPANET.

The fixed and variable demand have been modeled separately on each storey using a valve that emulates the position of the taps and an emitter that discharges the desired flow when pressure is equal to the required one . Two types of valves have been considered, TCV and FCV, the first to simulate when consumers do not react and the second to simulate an optimum user intervention to obtain the desirable flow. The real and precise situation lies between both models. (Fig. 3)

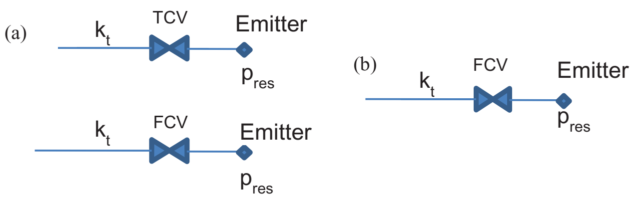


Fig. 3. (a) Variable demands model, (b) Fixed demands model.

For each building topology (single storey and multi- storey building with different percentage of variable demand) pressure in the service connection has been modified in order to observe how flow demands vary. Fig. 4 shows the hydraulic layout for two-storey building and Fig 5 and 6 the results for two-storey building and for a multi - storey building

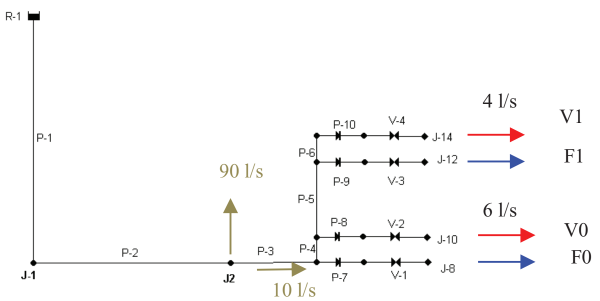


Fig. 4. Two- storey building model

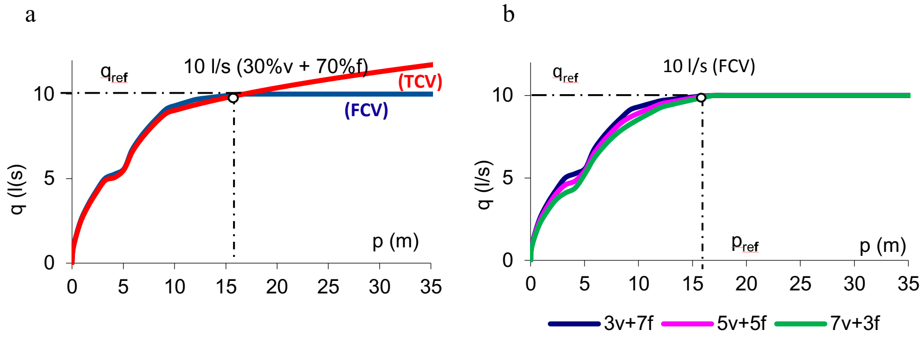


Fig. 5. (a) PDD curve for two- storey building with 30% of variable demand considering TCV and FCV, (b) PDD curve for two- storey buildings with different percentages of variable demand, considering FCV.

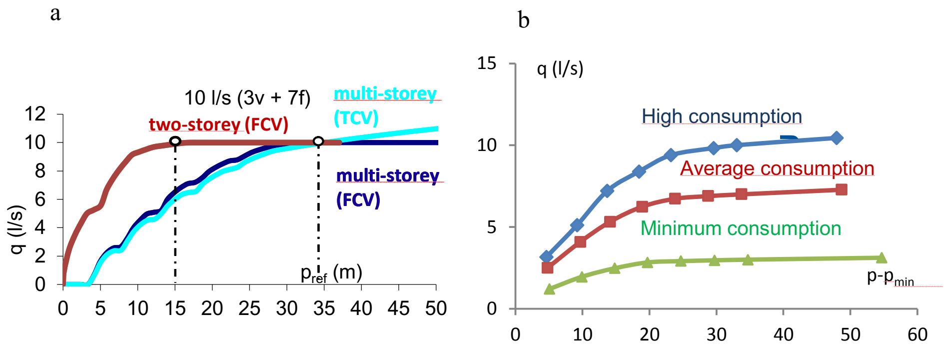


Fig. 6. (a) PDD curve for two-storey buildings and multi-storey buildings, (b) PDD curve for a multi-storey building and for several times.

As results shown (Fig. 5), there is a minimum pressure below which the demand is zero, and a reference pressure above which demand grows slightly. Furthermore PDD curve depends on the topology building, the number of stories and percentage of variable demand (Fig. 6).

Pressure - demand relationship for a multi - storey building has been analyzed over 24 hour period, considering that at each hour the demand flow desirable is different according to a demand pattern. The emitter coefficient in EPANET is constant for the simulation period, so, in order to set a different desirable flow at each instant the emitter has been replaced by a TCV valve connected to a reservoir. The TCV loss coefficient has been calculated at each instant so that the valve delivers the desirable flow when pressure is equal to residual pressure. The figure 6 show the DDP curves obtained from low to high consumption. They are different because as the number of open taps varies in time.

After a mathematical analysis the authors have proposed a new complete rational function of degree 2 which adjusts to the analyzed behavior. This function has the necessary mathematical properties to be integrated within a model in order to avoid convergence problems because it is continuous in the firts order derivatives for the full rank of pressure values. Also it has some parameters that can be adjusted to fit with different types of urban networks (Fig. 7 a)

$$q = \frac{A(p - p_{\min})^2}{(p - p_{\min})^2 + B(p - p_{\min}) + C} \tag{3}$$

Fig. 7 b shows how the new PDD function can represent the relationship between pressure and demand for a two-storey building, by comparing the results obtained simulating the inner plumbing system and the proposed function adjusted for this case. The new PDD function fits much better to the PDD behavior than the potential law.

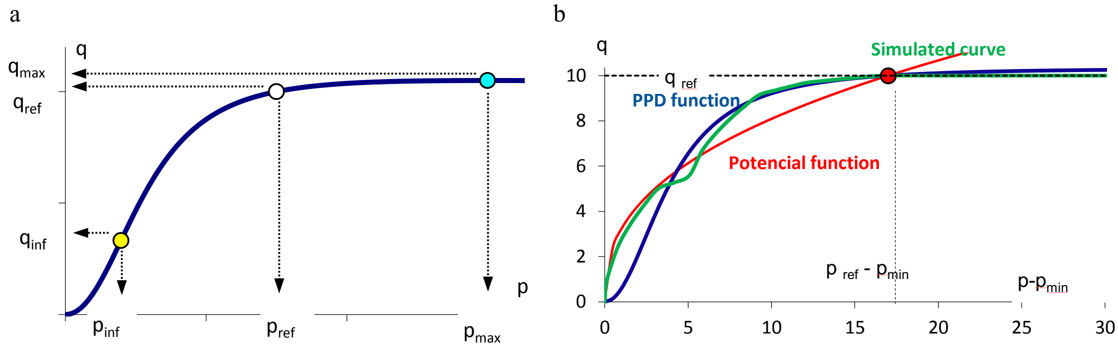


Fig.7. (a) New PDD Function proposed, (b) Simulated PDD Curve, potential function and new PDD function.

2.3. Developing an integrated model for water distributions systems considering both distributed leakage and pressure dependent demands

Taking into account the usually available information in a water supply, the new PDD function for demands and applying a potential law for leakage, the authors have proposed a pressure driven model that integrates leakage and pressure dependent demands [1]. This model is able to provide in every node and at each time the value of pressure, leakage and demand. Additionally the surplus or deficits demand can be also determined for each time and node.

Water companies are well aware that there is a deficit between the total water produced from sources in a period of time and those registered in the same period by the consumer water meters. This difference, known as unaccounted water, is due to different facts, such as pipe and connections leakage, under-measurements in water meters, non registered public consumption or illegal connections. The ratio between registered and produced water is known as the hydraulic efficiency.

Traditionally, when building a hydraulic network model, non-controlled consumption at junctions has been considered proportional to demands, in order to guarantee the balance between the total inflow and the total outflow. However, in order to achieve a reliable dynamic model, such hypotheses should not be sustained. In effect, in a water distribution network, pressures vary during the day and leakage depends on pressures. So the hydraulic efficiency can not be the same in diurnal periods, with the highest demands and the lowest pressure, as in nocturnal periods, with the lowest demands and the highest pressure. As a result, reality is clearly different from the conventional hypothesis. Furthermore, demands depends on pressures as well, and this fact is also omitted by the conventional dynamic models.

In the literature some leakage models have been proposed, and most of them assume some particular coefficients to fix the dependence of leakage on pressure at each junction. However, few of them establish a complete formulation to determine such coefficients using the overall efficiency values observed over long time periods, which really constitute the only available data from water utilities. Moreover, the dependence of demands on pressures must be considered .

The authors propose evaluating the leakage coefficients for each junction taking into account: the total leakage volume estimated in the network, the part of the network modeled, the physical characteristics of the modeled pipes, and a potencial law for relating pressures with leakage. The leakage volumen can be obtained from the analysis of night minimun flows or balances made in the sector. The leakage coefficients are determined by matching the leakage volume estimated with the leakage volume obtained from the expression that correlates the leaks wih pressure (a iterative method is need because pressures depend on flows assigned to nodes)

Once the leakage coefficients at each node are determined, the global hourly demand (user's consumption) can be obtained by differentating, at each hour, the total leakage flow from the injected flow. Then the demand is distributed proportionally to the average demand registered to each node.

As a result, each node has assigned a consumption which is composed by a demand and a leakage flow. Thus, if two of the three parameters of the proposed PDD function are knwon, the third parameter can be calculated from the demand flow assigned and the pressure obtained by the simulation.

Once, the laws that correlate leakage and demand with pressure are characterized, we can simulate the behavior of the network under any operating condition considering that both leakage and demands vary with pressure. As a result, we obtain for each node, the value of the pressure and the consumed flow, brokendown in its components (leakages, registered demand and non-registered demand in case that automated meter reading are available).

3. Case Study: Variation of demand with pressure in Valencia city

The water distribution network in Valencia is 1,200 Km in length and supplies water to 1,500,000 inhabitants. It is controlled and operated in real time from a control center with 100 remote stations distributed in the metropolitan area. The network has a looped configuration and recently it has been sectored for pressure and flow control. Most water meter readings are automated so user consumption is available on an hourly, daily and weekly basis.

Taking advantage of all the installed instrumentation, a sector located in the south of the city has been selected to analyze the influence of pressure on user demand . The selected area has a single point of injection where flow and pressure are measured. A pressure reducing valve allows to modify the pressure in the sector network. The counter meters, 1,414 in total, are automated and so, user consumption is knwon every hour. The area has a varied typology of buildings, where multi-storey buildings may have or not an integrated booster pumps. Obviously the consumption of users supplied by pumping is not influenced by pressure network. In the study sector there are 598 users supplied directly by the network and 650 users supplied by pumping.

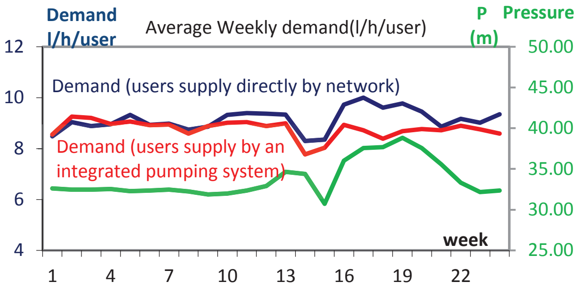
Over a three month period the pressure was modified and a data collection program was carried out. The pressure was increased from an initial value of 32 m to 40 m and later reduced to its original value. The monitoring program allowed us to analyze the effect of pressure variation in the user water consumption.

Figure 8 illustrates the results obtained. The pressure variation affected the daily consumption of users supplied directly by the network while, water consumption of users supplied by an integrated pumping system remained invariable because pressure for these users was kept.

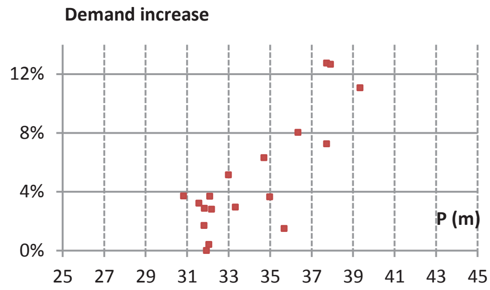
When pressure was increased from a value of 32 m to 38 m, user water consumption supplied directly by network increased 7%. When pressure was increased to 39 m water consumption increased to 11%.

This field test has been useful to demonstrate that even under normal conditions, water demand is affected by pressure. On other hand, the parameters of the new PDD function proposed by the authors has been adjusted for the specific case of Valencia, taking into account the data collection pro|gram and the results obtained after simulating the behaviour of the inner plumbing system of the most common building in the area. As a result, the values obtained for the PDD parameters for the average demand and for all users were:

$$A = 9.78,\ B = -0.55;\ C = 99.34$$



(a)



(b)

Fig.8. (a) Variation of demand with pressure in a sector, (b) Demand increase with pressure.

4. Conclusions

To simulate the behavior of water distribution networks under any supply pressure condition it is necessary to use head driven models, considering both leakage and pressure dependent demands. With this aim, the authors have proposed a new function that correlates the demand flow with pressure. The function has the suitable mathematical properties to be integrated in a model and fits the real behaviour of demands as a function of pressure, taking into account the user reaction and the building typology. A real test campaign carried out in a sector of the Valencia network has allowed us to demonstrate that, even under normal operating conditions, the demand is afeccted by pressure. The collection data program has been useful to adjust the parameters of the PDD function for this case.

The new function can be used in an integrated model for simulating both leakage and pressure-dependent demands proposed by the authors. The model can be implemented from the usual information available in any water supply and it is useful to simulate critical scenarios, such us pressure reduction for leakage control, failure of critical components (water treatment plant, pumping station, pipe breaks, etc.) or restrictions to be applied during an extended drought, in order to analyze in each case the demand satisfaction and leakage level.

References

[1] Martínez F., Conejos P. & Vercher J. (1999). "Developing an Integrated Model for Water Distribution Systems Considering Both Distributed Leakage and Pressure Dependent Demand" in Proc. of the 26th annual ASCE Water Resources Planning and Management Conf. Tempe, Arizona, June 1999, pp 1-14

[2] Giustolisi, O., Savic, D. and Kapelan, Z. (2008). ”Pressure-Driven Demand and Leakage Simulation for Water Distribution Networks.” in J. Hydraul. Eng., 134(5), 626–635.

[3] Siew, C and Tanyimboh, T. (2011). "Pressure. Dependen EPANET Extension: Pressure Dependent Demand". 12th annual Conf. on Water Distribution Systems Analysis 2010. pp 75-84. doi: 10.1061/41203(425)9

[4] Murano J., Ferreira A., Sousa J., Comes A., Sa Marques A. (2014). "Pressure- Dependent Demand and Leakage with an EPANET extension EPANET - WaterNetGen". 16th annual Conf, on Water Distribution System Analysis 2014. doi. 10.1016/j.preng. 2014.11.488

[5] Jun, L. and Guoping, Y. (2013). "Iterative Methodology of Pressure-Dependent Demand Based on EPANET for Pressure-Deficient Water Distribution Analysis" en J. Water Resour. Plann. Manage., 139(1), 34–44.

[6] Germanopoulos G. (1985), “A Technical Note on the Inclusion of Pressure Dependent Demand and Leakage Terms in Water Supply Network Models”en Civ., Engrg. Sys., 2(3), 171-179

[7] Wagner, J.M, Shamir, U, Marks, D.H .(1988). "Water Distribution Reliability: Simulation Methods" in Jour. Water Resource Planning & Management, 114(3) 276-294

[8] Chandadapillai, J. (1991). ”Realistic Simulation of Water Distribution System” in J. Transp. Eng., 117(2), 258–263

[9] Fujiwara, O., and T. Ganesharajah. (1993). "Reliability assessment of water supply systems with storage and distribution networks" en Water Resources Research., 29(8), 2917-2924

[10] Tucciarelly, T., & Termini, D. (1998). "Optimal valves regulation for calibration of pipe networks models" in Hydroinformatics (Vol. 98, pp. 1029-1036).

[11] T. T. Tanyimboh, A. B. Templeman.(2010). "Seamless pressure-deficient water distribution system model" in Proceedings of the ICE - Water Management, Volume 163, Issue 8 389-396