Proceedings of the Sixth IASTED International Conference
Environment and Water Resource Management (AfricaEWRM 2016)
September 5 - 7, 2016 Gaborone, Botswana

REAL-TIME DYNAMIC HYDRAULIC MODEL FOR WATER DISTRIBUTION NETWORKS: STEADY STATE MODELLING

Muhammad S. Osman[a], Sonwabiso Yoyo[a], Philip R. Page[a], Adnan M. Abu-Mahfouz[a,b]
[a]Council for Scientific and Industrial Research (CSIR), [b]Tshwane University of Technology (TUT)
[a]Built Environment, Building Science and Technology (BST), P.O.Box 395, Pretoria 0001, South Africa
[b]Department of Electrical Engineering, Tshwane University of Technology, Private Bag X680, Pretoria 0001, South Africa
mosman@csir.co.za

ABSTRACT

It is known that South Africa is a water scarce country which has been recently been experiencing erratic weather conditions resulting in a constrained water supply. Renewed focus has been placed on water conservation. This study seeks to develop a steady state hydraulic model that will be used within a real-time dynamic hydraulic model (DHM). The Council for Scientific and Industrial Research (CSIR) water distribution network (WDN) is used as a pilot study for this purpose. A hydraulic analysis was performed for the WDN. Model parameter data were obtained through as-built drawings and site visits. The data were verified, and critical unknown parameters (those whose absence results in model uncertainty) were measured and thereafter imported into a developed computer model in the EPANET program. The model is presented in this paper. The pilot WDN was analysed for a 24 hour period. Network results have revealed that the system is functional and that water is transported in the system at a very high rate and boosted by a high pressure at the abstraction point. Flow velocities are within the range of 0.6 m/s to 2 m/s as recommended by the CSIR internal guidelines, and therefore no stagnation is expected. The steady state hydraulic model will form part of the real-time DHM and the time and cost efficiency of the entire DHM process will be accessed. This assessment will be in view of a desire to replicate a similar procedure to numerous areas in municipalities across South Africa.

KEY WORDS

Hydraulic modelling, real time monitoring, steady state model, water distribution network.

1. Introduction

Changes in weather conditions, an increase in population growth, adverse water incidents, poor water management, departmental inefficiencies and deteriorating water infrastructure are some of the key contributing factors that have put a strain on South Africa's water supply [1]. The country currently suffers an annual financial loss of 7 billion Rand (Rand is the South African currency) due to NRW which is estimated at 36.8% (1 580 million m^3/annum) [2].

Attempts to resolve water loss problems using well-known techniques have not had the envisaged impact [3,4] and it is for this reason the CSIR has embarked on an initiative to develop a novel real-time dynamic hydraulic model (DHM) [1] that can be used to address water leakages and incidents.

The proposed DHM (see Figure 1) can be used for planning purposes and can also be retrofitted to improve existing water networks. The model will use the real-time sensed data from in-house developed sensor technology [5,6,7] to evaluate the current conditions of the network, and automatically send control signals to various network components. This will adjust the water distribution network (WDN) performance and make it more efficient. The DHM will be used to minimise water leakages and enable pressure management, by employing newly developed control algorithms [8]. Similar initiatives are been considered in other municipalities [9].

The DHM consists of a number of components and sub-components as seen in Figure 1. This paper focuses on the development of a steady state hydraulic model which forms the basis for the real time DHM. The CSIR WDN, together with its auxiliary equipment (pipes, reservoirs, pumps, valves, etc.) was used as a pilot WDN. Further information of the various other DHM components has been published [1].

The steady-state hydraulic model calculates the network hydraulic variables at a particular instant of time and gives the snapshot of a network [10]. A steady-state assessment will provide insight and understanding of the pipe network and its associated components to address potential adverse incidents. Several methods have been proposed to model the steady state hydraulic model, for example [11,12,13].

This approach employed in the paper is considered more cost-effective in addressing any possible water incidents and in providing an understanding into the analysis of an existing pipe network [14]. It also provides the ability to explore alternative conditions before deployment to a larger more complex municipal network. The method is expected to contribute positively towards understanding

DOI: 10.2316/P.2016.836-021

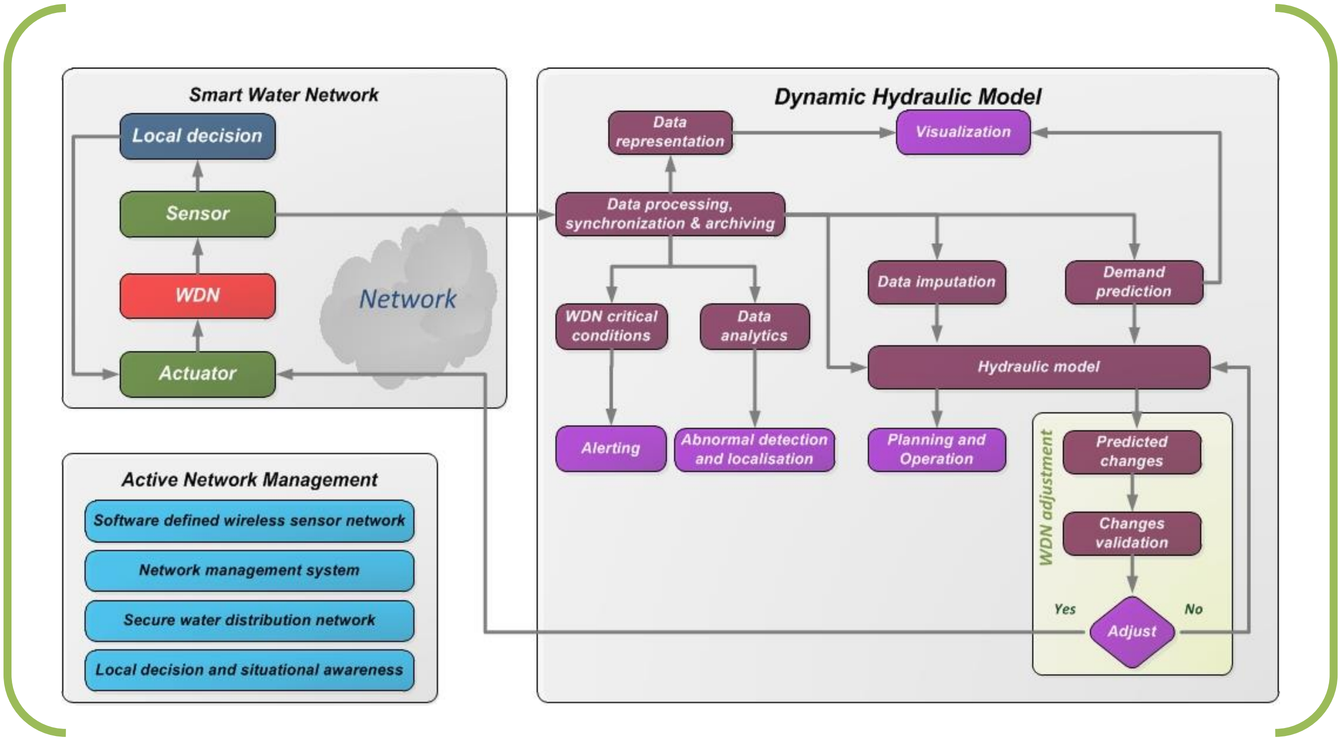

Figure 1. Schematic depiction of the real time dynamic hydraulic model [1]

the challenges likely to be faced by water authorities in their respective pipe networks.

2. An Overview of the Selected Pilot WDN

The identified pilot WDN (CSIR Pretoria campus WDN) receives its water from the Tshwane City Council's main water header. The water is routed, under gravity, through a 6" PVC pipe with an effective length of 900 m from the abstraction point to the two low-level concrete reservoirs. On this pipeline there is a 2" tie-off to an alternate consumer as well as another 2" tie-off (5 m length) to the pump station sump. Water from the pump station is pumped to two concrete storage reservoirs using 4" galvanised carbon steel pipes. Each of the four reservoirs has a storage capacity of approximately 2454 m^3. The water from these reservoirs gravitates to the network supplying the CSIR campus via 6" PVC pipes. On the water network, smart water meters [5] are positioned at systematic positions to monitor water consumption at the CSIR campus.

Model data was acquired from 'As Built' drawings and from site visits. The data is tabulated in Table 1, Table 2 and Table 3.

Table 1
Model data

Pipe No	Origin	Destination	Flow Type
1	Abstraction point	Pump station	Gravity
2	Pump station sump	Reservoir 1	Gravity
3	Pump station	Reservoir 2	Pumped
4	Pump station	Reservoir 3	Pumped
5	Reservoir 1	Supply node 3	Gravity
6	Reservoir 2	Supply node 2	Gravity
7	Reservoir 3	Supply node 1	Gravity

Table 2
Pipe data for steady state model

Pipe No	Pipe size (inch)	Eff pipe length (m)	Pipe material
1	6	1188	PVC
2	6	382	Carbon Steel
3	4	712	Carbon Steel
4	4	1056	Galvanised Steel
5	6	527	Carbon Steel
6	6	422	Carbon Steel
7	6	363	Ceramic Asbestos

Table 3
Model elevation data

Pipe No	Origin	Destination	Elevation diff (m)
1	Abstraction point	Pump station	9
2	Pump station sump	Reservoir 1	35.8
3	Pump station	Reservoir 2	65.5
4	Pump station	Reservoir 3	67.8
5	Reservoir 1	Supply node 3	-36.1*
6	Reservoir 2	Supply node 2	-16.9*
7	Reservoir 3	Supply node 1	-22.7*

* Destination is at a higher level than the origin

3. Hydraulic Model Development for the Pilot WDN

Two methods were considered to model the steady state hydraulic model for the WDN: 1) Mathematical calculations using Bernoulli's principle for pipe flow. 2) Hydraulic modelling software EPANET. Only the results for the EPANET model are further discussed in this paper.

3.1. Bernoulli's Principle for Incompressible Flow

For flowing fluids, Bernoulli's principle (also termed Bernoulli's equation) is a mathematically formulated equation that describes the conservation of energy in a system. It is derived from the continuity, momentum and energy equations [15].

Bernoulli's equation can be transformed into different forms and can be applied to various types of fluid flow. A simple form of Bernoulli's equation (in terms of pressure) to describe the flow of an incompressible liquid (such as water) is given in equation (1):

$$\Delta P_A = \Delta P_{EP} + \Delta P_{EL} + \Delta P_{KE} + \Delta P_f \quad (1)$$

ΔP_A is the pump head, *kPa*

ΔP_{EP} is the end point pressure, *kPa*

ΔP_{EL} is the pressure due to elevation, *kPa*

ΔP_{KE} is the pressure due to Kinetic energy, *kPa*

ΔP_f is the pressure due to friction, *kPa*

The pump head (ΔP_A) is pump specific and is obtained from the pump curve. The pressure due to endpoint differences, elevation, kinetic energy and friction (ΔP_{EP}, ΔP_{EL}, ΔP_{KE}) can be calculated from equations (2-4) respectively:

$$\Delta P_{EP} = P_2 - P_1 \quad (2)$$

P_1 is the pressure at endpoint 1, *kPa*

P_2 is the pressure at endpoint 1, *kPa*

$$\Delta P_{EL} = \frac{\rho g \Delta z}{1000} \quad (3)$$

ρ is the density, *kg/m*^{3}

g is the acceleration due to gravity, *m/s*^{2}

Δz is the height difference, *m*

$$\Delta P_{KE} = \frac{\rho \alpha_{KE} \Delta u^2}{2000} \quad (4)$$

α_{KE} is the dimensionless kinetic energy correction factor

Δu is the velocity difference, *m/s*

The pressure loss due to friction (ΔP_f) is made up of three terms (ΔP_{fP}, ΔP_{CV}, ΔP_{EQ}). ΔP_{CV} and ΔP_{EQ} are pressure losses due to control valves and equipment in the system. They are determined by means of specially developed methods which have been published and hence are not further discussed. ΔP_{fP} is the pressure loss due to pipe friction and determined from Darcy-Weisbach equation (5):

$$\Delta P_{fP} = \frac{f' \rho L u^2}{(D)2000} \quad (5)$$

f' is the friction factor

L is the pipe length, *m*

D' is the inner pipe diameter, *m*

The friction factor (f') is dependent on flow regime i.e. laminar flow or turbulent flow. The flow regime is determine from the Reynolds (Re) number (equation 6). For laminar flow, Re < 2000 where for turbulent flow Re > 4000. The critical zone (2000 < Re < 4000) is avoided in design due to uncertainties and flow instability. The friction factor for laminar and turbulent flow can be calculated from equations (7 and 8) respectively. Equation (8) is known as the Colebrook equation [16,17] and needs to be solved implicitly:

$$\mathrm{Re} = \frac{\rho u^2 D}{\mu} \qquad (6)$$

$$f' = \frac{64}{\mathrm{Re}} \qquad (7)$$

$$\frac{1}{\sqrt{f'}} = -2\log\left(\frac{\varepsilon}{(D)3.7} + \frac{2.51}{\mathrm{Re}\sqrt{f'}}\right) \qquad (8)$$

μ is the dynamic viscosity, *Pa.s*

ε is the absolute pipe roughness

3.2. EPANET

The steady state hydraulic model for the WDN was modelled in EPANET. EPANET is one of the most commonly used modelling software and it provides an effective way to analyse and diagnose hydraulic operations in WDNs [18]. Smart meter data using in-house developed technology was obtained to calibrate demands.

4. Results and Findings

The simulation model for the CSIR WDN was set up and analysed for a 24 hour period. Figure 2 shows an EPANET depiction of the water network, with pressure and flow predictions. The simulated results reveals that sufficient water discharge flows in the system and that pressure at the nodes of interest are within the acceptable range for most of the network. The specific velocities are tabulated in Table 4.

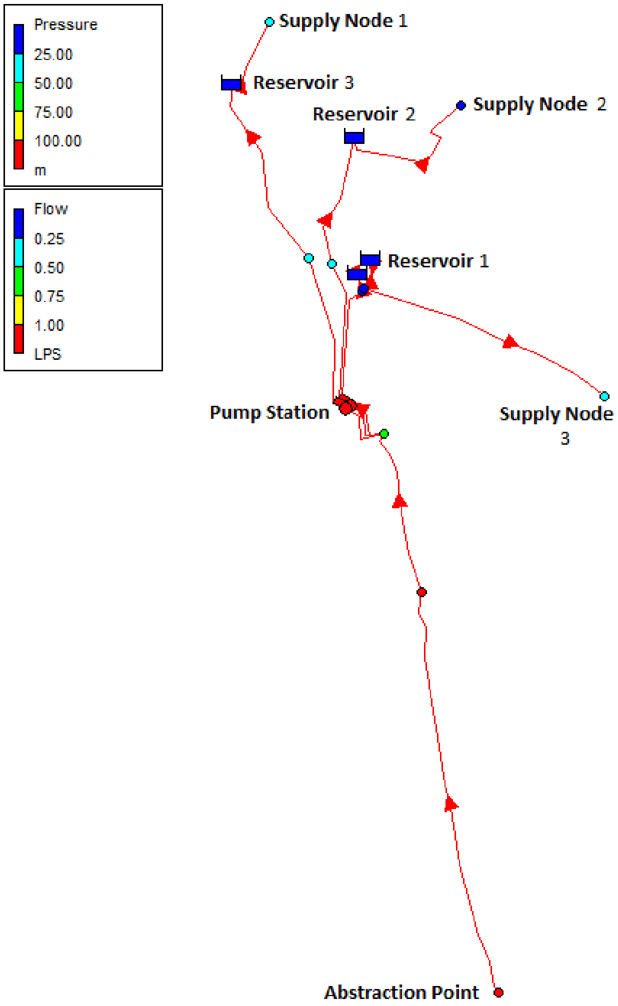

Figure 2. Pressure and flow depiction of the CSIR water network

Table 4
Model velocity results

Pipe No	Origin	Destination	Velocity (m/s)
1	Abstraction point	Pump station	5.97
2	Pump station sump	Reservoir 1	2.54
3	Pump station	Reservoir 2	3.39
4	Pump station	Reservoir 3	1.38
5	Reservoir 1	Supply node 3	1.10
6	Reservoir 2	Supply node 2	0.58
7	Reservoir 3	Supply node 1	0.73

Figure 3 shows the relationship between pressure and velocity. The flow velocities in the pipes of the distribution network are within the acceptable range according to CSIR's internal guidelines. Flow velocities are reasonable such that stagnation of water in pipes is avoided; however the water abstraction pipe needs to be anchored due to high water pressure and the high volume of water transported in the pipe. The specific flow rates are tabulated in Table 5.

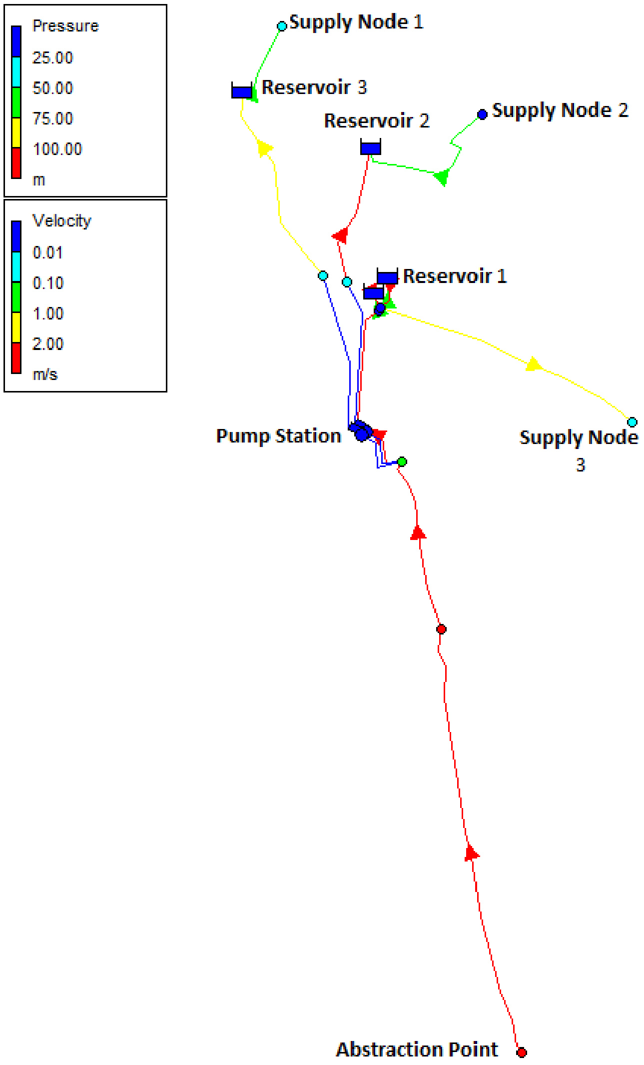

Figure 3. Pressure and velocity depiction of the CSIR water network

Table 5
Model flowrate results

Pipe No	Origin	Destination	Flowrate (LPS)
1	Abstraction point	Pump station	120.00
2	Pump station sump	Reservoir 1	24.16
3	Pump station	Reservoir 2	68.06
4	Pump station	Reservoir 3	27.72
5	Reservoir 1	Supply node 3	22.03
6	Reservoir 2	Supply node 2	11.75
7	Reservoir 3	Supply node 1	14.69

5. Conclusion

In this paper the development of a pilot WDN hydraulic model which forms an integral part of the real time DHM is proposed. The pilot WDN was analysed for a 24 hour period. Network results have revealed that the system is functional and that water is transported in the system at a very high rate and boosted by a high pressure at the abstraction point. Flow velocities are within the range of 0.6 m/s to 2 m/s as recommended by the CSIR internal guidelines, and therefore no stagnation is expected. However special pipe fittings need to be used on the main water supply pipeline due to high velocity of 6.0 m/s which might lead to pipe joint dislocation leading to more leaks in the network system.

As a future work, the CSIR plans on installing more smart meters and pressure sensors to continuously measure the water flow and pressure across the entire CSIR water network. The collected data will be used to update the parameters of the developed steady state model to improve the accuracy of the model. The authors of [19] clearly indicate the need to develop techniques to enable the update of the model parameters to reduce the discrepancies between model predictions and behaviour of the real water distribution network.

References

[1] A.M. Abu-Mahfouz, Y. Hamam, P.R. Page, K. Djouani & A. Kurien, Real-time dynamic hydraulic model for potable water loss reduction, *Proc. 12th International Conference on Hydroinformatics (HIC2016)*, Incheon, South Korea, 2016.

[2] R. Mckenzie, Z.N. Siqalaba, & W.A. Wegelin, *The state of non-revenue water in South Africa*, Water Research Commission, 2012.

[3] O. Bello, A.M. Abu-Mahfouz, O. Piller & Y. Hamam, Management Problems and Their Approaches in Water Distribution Networks, submitted for publication, 2016

[4] K. Adedeji, Y. Hamam, B. Abe & A.M. Abu-Mahfouz, Towards Achieving a Reliable Leakage Detection and Localisation Technique for Real-Time Application in Pipelines: An Overview, submitted for publication, 2016

[5] M.J. Mudumbe, & A.M. Abu-Mahfouz, Smart water meter system for user-centric consumption measurement. *Proc. 2015 IEEE 13th International Conference on Industrial Informatics (INDIN)*, Cambridge, UK, 2015, 993-998.

[6] C.P. Kruger, A.M. Abu-Mahfouz & G.P. Hancke, Rapid prototyping of a wireless sensor network gateway for the internet of things using off-the-shelf components, *Proc. the IEEE International Conference on Industrial Technology (ICIT)*, Seville, Spain, 2015, 1926–1931.

[7] C.P. Kruger, A.M. Abu-Mahfouz & S.J. Isaac, Modulo: A modular sensor network node optimised for research and product development, *Proc. the IST-Africa 2013 Conference and Exhibition*, Nairobi, Kenya, 2013, 1-9.

[8] P.R. Page, A.M. Abu-Mahfouz, & S. Yoyo, Real-time adjustment of pressure to demand in water distribution systems: Parameter-less P-controller algorithm. *Proc. 12th International Conference on Hydroinformatics (HIC2016)*, Incheon, South Korea, 2016, 21-26.

[9] L. Berardi, D. Laucelli, R. Ugarrelli & O. Giustolisi, Leakage management:planning remote real time controlled pressure reduction in Oppergard municipality, *Procedia Engineering, 118*(2015), 2015, 72-81.

[10] O. Bello, O. Piller, A.M. Abu-Mahfouz & Y. Hamam, Simulation models for management problems in water distribution networks: A review, Submitted for publication, 2016

[11] J.E. Van Zyl, D.A. Savic, & G.A. Walter, Extended period modeling of water pipe networks-a new approach, *Journal of Hydraulic Research, 43*(6), 2005, 678-688.

[13] A. Tavakoli & M. Rahimpour, Gröbner bases for solving ΔQ-equations in water distribution networks, *Applied Mathematical Modelling, 38*(2), 2014, 562-575.
[13] I. Sarbu, Nodal analysis of urban water distribution networks, *Journal of Water Resources Management, 28(10)*, 2014, 3143–3159.

[14] S. Yoyo, P.R. Page, S. Zulu & F. A'Bear, Adressing water incidents by using pipe network models. *Proc. WISA Biennial 2016 Conference and Exhibition*, Durban, KZN, 2016, 130.

[15] R.P. Benedict, *Fundamentals of pipe flow* (John Wiley & Sons, 1980).

[16] Z. Cojbasic & D. Brkic, Very accurate explicit approximations for calculation of the Colebrook friction factor, *International Journal of Mechanical Sciences, 67*(2013), 2013, 10-13.

[17] D. Taler, Determining velocity and friction factor for turbulent flow in smooth tubes, *International Journal of Thermal Sciences, 105*(2016), 2016, 109-122.

[18] L.A. Rossman, *EPANET 2 users manual* (United States Environmental Protection Agency, 2000).

[19] J. Deuerlein, O. Piller, I.M. Arango & M. Braun, Parameterization of offline and online hydraulic simulation models, *Procedia Engineering 119(2015)*, 2015, 545–553