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Real-time dynamic hydraulic model for potable water loss reduction

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Abstract

South Africa is a water scarce country with limited water resources and steadily growing water demand. Unacceptably high water losses and non-revenue water threaten our water resource security as well as the financial viability of municipal water service provision. Traditional approaches of solving water loss problems are not enough to make a significant improvement; for this, new approaches involving increased automation and monitoring are needed. Furthermore, the sensory and automation ICT-overlay required for the WDN can itself be a cause of technical problems that also need to be solved before water utilities will implement these techniques. This paper propose a real-time dynamic hydraulic model (DHM) based control system connected to near real-time sensing and actuation capability on the WDN as an effective approach to implementing an efficient, reliable and adaptive WDN. This is in contrast to current design and operation of most WDNs that rely on steady-state hydraulic models which have inherent limitations with respect to reliability and efficiency.

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Keywords: Active network management; data imputation; demand prediction; dynamic hydraulic model; leakage detection; non-revenue water; pressure management; smart water network; water loss; wireless sensor network;

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1. Introduction

The need for efficient and effective operational management of water distribution has never been greater [1]; South Africa is a water scarce country with limited water resources and steadily growing water demand. Unacceptably high water losses and non-revenue water (NRW) threaten our water resource security as well as the financial viability of municipal water service provision. Recent failures of key water services infrastructure have raised some concern amongst the general public, municipal officials and national sector departments. The current level of NRW estimated for South Africa as a whole is 36.8% (1 580 million m^3/annum). The estimated financial value of this loss is more than 7 billion Rand annually [2].

Water quality and reliability are major concerns in the design and operation of a potable water distribution network (WDN). Reliability assessment of WDNs requires a prediction of the network performance not only in normal operation but also under exceptional conditions or partial failure, for example; water-flow requirements for fire flow, pipe breaks, valve breaks, pump failures, high demand loadings etc.

The pressure on the pipes has a major impact on the water loss, where lower pressure leads to a lower water loss. In conventional pressurised systems, the pumps work hard to maintain a constant high pressure so the people at the far end of the pipe receive enough water during peak hours. This traditional system is associated with several disadvantages including:

- The pump is set for the peak hour demand so it consumes much more electricity during non-peak hours than is required. As a result, during the night - when the water demand is low - the water pressure in the pipes is much higher than required.
- When the pressure is high the pipe lifespan decreases; cracks are formed and water starts to leak through these cracks and exacerbates the leakage problem. The higher the pressure the more water is lost through the cracks.
- Pressure reduction valves must be installed in various locations on the distributed network to reduce the pressure to prevent damage. The system starts with high water pressure which needs to be reduced somewhere down the pipeline, this is a clear waste of energy.

Potable WDN hydraulic modelling is an effective way to analyse and diagnose network operation conditions [3]. However, most of the existing hydraulic models are steady-state models [4], which are primarily used for planning and water quality purposes. EPANET is one of the most commonly used modelling programs for WDN operation [5]. The steady-state nature of such a model limits the reliability and efficiency of a water network especially on partially failed conditions because it does not enable the automatic adjustment of parameters (e.g. pump curves, pressure reduction valves and flow valves) which would enhance the performance of the WDN.

Future WDN models should consider real-time applications in order to ensure that the implementation of measurement and logging technologies are used to provide higher credibility and simplify the modelling process [1]. In this paper we propose a framework for a real-time dynamic hydraulic model The proposed system consists of three major components; 1) Smart water network that enables the real-time monitoring and controlling of the WDN components (Section 2.1), 2) Dynamic hydraulic model to evaluate the current conditions of the WDN, determine and locate the inefficiencies in the WDN, predict the future demand and automatically send control signals to various WDN components (Section 2.2) and 3) Active network management to monitor, control, reconfigure the network components and ensure the security and efficient operation of the network (Section 2.3).

Nomenclature

DHM	dynamic hydraulic model
NRW	non-revenue water
Rand	the currency of South Africa
SDN	Software-Defined Networking
SDWSN	Software-Defined Wireless sensor network
WDN	water distribution network
WSN	Wireless sensor network

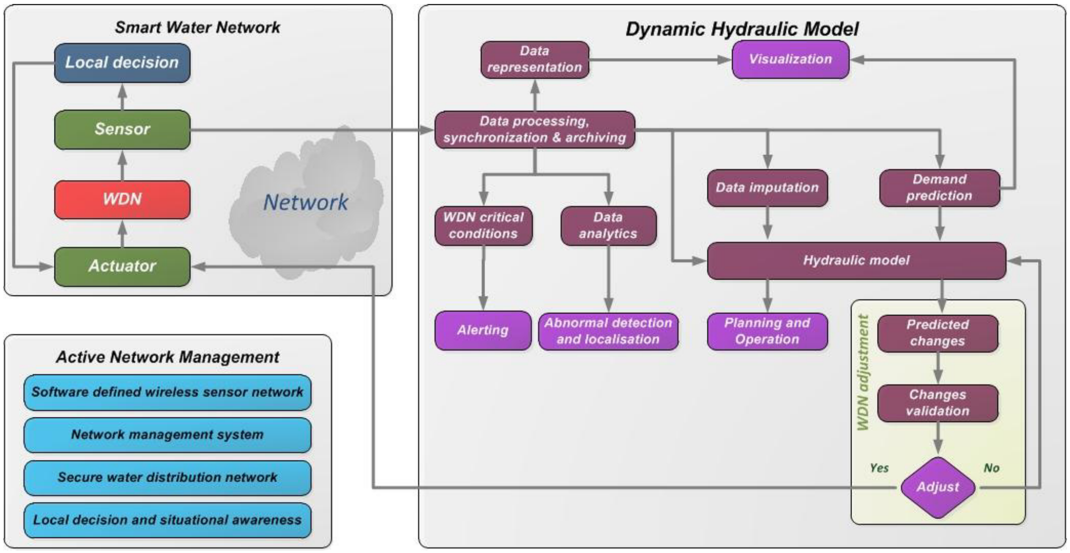

Fig. 1 System architecture

2. System architecture

We introduce a real-time dynamic hydraulic model (DHM) that not only can be used for planning purposes but also can be retrofitted onto the existing network. Several network parameters need to be sensed and directly fed into the model. The dynamic model will use real-time sensed data to evaluate the current conditions of the network and automatically send control signals to various network components. This would adjust the network performance and make it more efficient. Fig. 1 shows the system architecture of the proposed system, which consists of three main components: dynamic hydraulic model, smart water network and active network management.

2.1. Smart water network

This component is concerned with the development of various sensor and actuator interface nodes and other network devices that are required in the proposed system. As shown in Fig. 2, the purpose of this infrastructure is to provide a real-time monitoring and control of various WDN components (for example, water meters, pressure sensors, flow valves, pumps and pressure reduction valves). Initially, a water meter interface node [6] has been developed, based on Modulo sensor node [7], to collect the water meter reading and send it through a gateway device [8] to the back end system. Thereafter, a low cost general interface platform, called WaterGrid-Sense, has been developed. WaterGrid-Sense enables the real-time monitoring and controlling of several types of WDN components and can be attached to more than one device at the same time. WaterGrid-Sense provides a great flexibility to add new data processing and control algorithms to the firmware which makes it suitable to be used by various types of applications. Unlike most of the existing platforms that use the cellular network (e.g. GSM), WaterGrid-Sense can easily be integrated into the existing IP networking infrastructure. Two models of WaterGrid-Sense have been developed based on two communication technologies. The first is based on the IEEE 802.15.4 standard that uses 2.4 GHz to enable short range communication. The second is based on the LoRa standard that uses 868 MHz to enable medium range communication. It is not within the scope of this paper to give technical details about the WaterGrid-Sense platform.

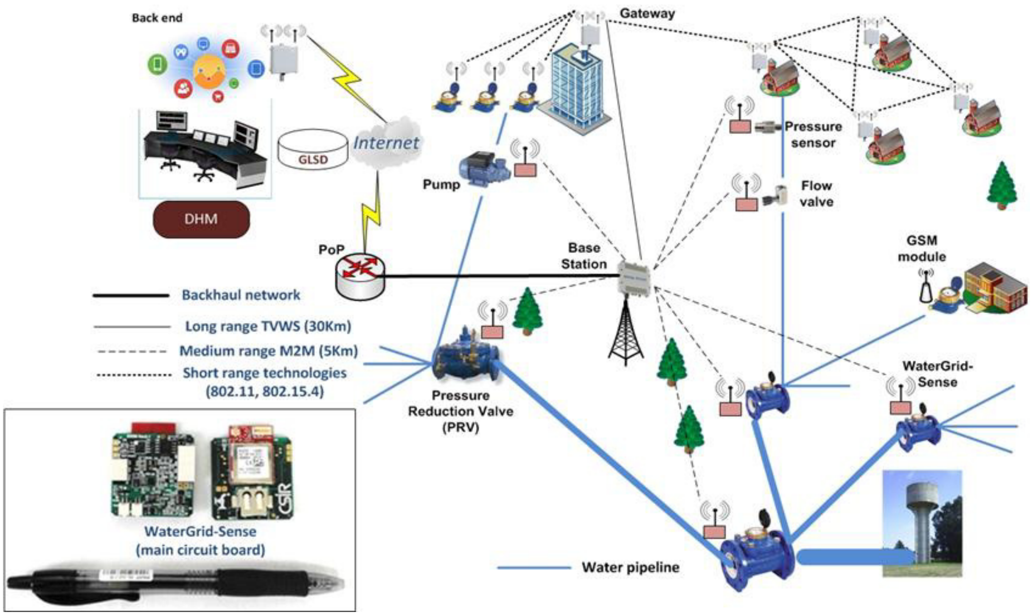

Fig. 2 Smart water network

2.2. Dynamic hydraulic model

The steady-state nature of all off-line hydraulic models limits the reliability and efficiency of water networks. These models approximate thousands of unknown parameters using a short-term sample of a sub-set of hydraulic data. Therefore, the calibration results are not expected to accurately represent the system conditions for the full range of operational conditions that can occur. A real-time dynamic hydraulic model that continuously considers the on-line hydraulic measurements will provide more realistic predictions. To build this model the following major components are required.

2.2.1. On-line data synchronisation and integration

Uncertainties in online hydraulic model parameters can result in large discrepancies between model predictions and the actual behaviour of the water distribution system. Therefore, there is a clear need for regular update of the WDN parameters to achieve accurate model predictions. [9] developed a parameterization framework for a hydraulic online model that classifies the WDN parameters, update cycles and function in the hydraulic model. The DHM expects input data from the sensors installed on the WDN to be provided continuously at specific rate, for example every one hour [10]. This bulk data need to be synchronised and integrated with the model in a real-time system.

2.2.2. Data imputation

Increasing the number of sensors is one way of increasing the known input into the hydraulic model. However, this option is expensive and increases the operational and maintenance effort. On the other hand, a reliable real-time monitoring system requires a throughput of 99.99% [11], where the throughput refers to the percentage of measured data that is correctly received at the control center (back-end system). However, sensor outages, radio malfunction or corrupted data make it a serious challenge to achieve this percentage. Data imputation (which is the process of replacing missing data with substituted values) can be used to overcome these challenges following these two approaches:

- Temporary sensors that can be deployed only for short period (e.g. one week). The collected data of these sensors will be correlated with a data from a subset of permanent sensors to predict data even after removing these temporary sensors. [12] uses the temporary sensors concept to propose a new approach for monitoring WDN. The authors use a non-parametric, machine learning technique called Gaussian Process Regression to impute data based on time history and spatial correlations between the temporary and permanent sensors.
- If the data from the permanent sensors are missing or corrupted this technique can be used to predict this data.

2.2.3. Demand prediction

Water demands (consumption) have dynamic/stochastic pattern variations which fluctuate with time-changing economic, demographic characteristics and local climatic conditions [13]. Therefore, estimating this demand based on historical or census data may not be appropriate for efficient operational analysis because it does not reflect the actual WDN conditions. Having accurate demand estimation, based on continuous data, is critical for the DHM especially for the real-time WDN adjustment component. Therefore, the prediction system will be consist of two models:

- Predictor model: to predict the future demand.
- Corrector/calibrator model: that will calibrate the predictor model based on the measured on-line hydraulic data.

To continuously predict the hydraulic state of the WDN, [14] use the M5 Model-Trees algorithm to forecast future water demand and Genetic Algorithm to correct the predicted values in real-time. Thereafter, the corrected outputs are used as inputs for the next iteration of the prediction model to facilitate a quick convergence toward an accurate prediction. Several machine learning techniques, for example [15, 16], have been used to forecast water demands due to their ability to model nonlinear processes accurately without using complex mathematical expressions.

2.2.4. Calibrated offline hydraulic model

Calibrating the existing off-line hydraulic model is an important activity to have a better representation of the real WDN. Therefore, instead of relying only on known model parameters, additional unknown parameters will need to be determined from records or by inspection of the site. To improve the accuracy of the model it should be calibrated against water flows and pressures measured in the WDN, using water meters and pressure sensors. The developed calibrated model will help to accurately determine where to install variable speed pumps, and pressure reducing valves as well as providing a better understanding to develop the pressure management system.

2.2.5. WDN adjustment algorithm: mathematical formulation and computational demonstration

A WDN adjustment algorithm is needed to predict the required changes of the WDN to reach near optimal level [17]. In order to evaluate and validate the predicted changes the hydraulic model needs to be run considering the current state of the WDN, predicted demand and predicted changes as an input parameters, then validate the expected performance of the WDN based on these changes. If the expected performance of the WDN is acceptable, then control signals will be sent to the actuators to adjust the WDN (adjust the pump speeds [18] or possibly the pressure reducing valves). Otherwise the predicted changes should be modified. The process will be repeated till it reaches an optimal level.

To determine how to change the WDN a mathematical formulation needs to be developed. The complexity of this formulation depends on the number of WDN components that need to be adjusted. Therefore, a proper technique/theory should be used to reduce the complexity of the formulation [17]. The developed mathematical formulation will enable the incorporation of the hydraulic model with WDN adjustment algorithm. Therefore, the adjustment algorithm can be adapted to various WDN's.

2.2.6. Online hydraulic model: real-time adjustment

A real-time pressure management system that will use the WDN adjustment algorithm will be developed to automatically manage the water pressure through the network. In contrast to conventional pressurised systems, the developed system will keep the pressure constant at the consumer site instead of maintaining a constant high pressure at the pump. Some pumps (variable speed pumps) will be chosen to only work hard in the peak hours and pump less water when the consumption drops. In addition, pressure reducing valves will be controlled to respond to water consumption. Therefore, the developed model will save water, energy and money as well as extend the lifetime of the pipes.

2.2.7. Leakage detection and localisation algorithm

Leak detection and localisation algorithms, such as [19, 20, 21] are highly dependent on the type and age of pipes, infrastructure layout and the variation of the water pressure and flow. Most of the existing leak detection and localisation algorithms have been tested either using simulation tools or small laboratory testbeds; the efficacy of these algorithms when implemented in a real water network are unlikely to be optimal due to simulation model inaccuracies that do not take into account latencies and errors. Furthermore, some of these existing algorithms require a high sampling rate at the sensors and significant computing resources at the backend which increase the cost of operation (due to data transfer costs and energy costs) and make them unsuitable to be executed locally at the resource-constrained sensor level. Therefore, there is a clear need to develop distributed leakage detection and localisation algorithms [22] that will be run at the edge of the communications network (i.e. where the sensors are) instead of the backend (or control centre) and tested in a real WDN.

2.3. Active network management

Active network management refers to the management of active components in both the sensor network and the water network [23] that is controlled by the sensor network. To the best of our knowledge, none of the existing WDN systems have considered the implementation of active network management and they focus more on the issue of data analytics. However, without an efficient active network management system, it will become practically very difficult to operate and manage the thousands of sensors and devices envisaged that will be deployed over a wide area. Therefore, there is a clear need to develop an active network management system that is able to monitor, control, reconfigure the network components and ensure the security and efficient operation of the network.

2.3.1. Network management system

Wireless sensor networks (WSN) management is a critical component to ensure that the sensor/actuator nodes are operating correctly and healthy. WSNs are dynamic and consist of large number of heterogeneous, resource constrained and application dependent sensors/actuators. Therefore, configuring and managing these networks is considered a challenging task. Network operators are responsible for configuring the WSN and to respond to the wide range of network events that may occur. In this task, we will develop a heterogeneous WSN management framework that will be used to manage the various aspects of the deployed WSN in the system. The developed framework will be implemented and tested using WSN testbed [24, 25] then in the real water system.

2.3.2. Software defined wireless sensor networks (SDWSN)

Software-Defined Networking (SDN) was developed to facilitate innovation and enable simple programmatic control of the network data-path. The separation of the forwarding hardware from the control logic allows easier deployment of new protocols, applications, network visualization, and management [26]. These features make SDN a promising solution for the various WSN challenges that we mentioned earlier. There is recent interest from the research community to develop several techniques and systems for a WSN based on SDN [27]. However, we will mainly focus on coming up with mechanisms for WSN management and configuration that enable managing and operating the WSN easier.

2.3.3. Secure WDN

Using communication technologies will enhance the flexibility and efficiency of the WDN, however the vulnerabilities that inherently reside in these communication systems transform into security risks in the WDN infrastructures. As compared with wired system, wireless systems have more security risks, because there is no physical protection of the communication medium and wireless communications are broadcast in nature [28]. Therefore, attackers can easily access the network illegally. Therefore, security is a critical component of any smart water management system to ensure the availability, confidentiality, integrity and authenticity of such system and prevent any type of cyber security threats especially for the systems that have control functionality [29]. Therefore, an end-to-end security system should be implemented in the proposed system.

2.3.4. Local decision and situational awareness

One of the major design factors for a large-scale WSN is to reduce the traffic in the network due to the limited available resources and to enhance the reliability of the network. On the other hand, some of the decisions which are not delay-tolerant should be taken directly at the sensor level. Therefore, the following aspects need to be considered:

- Develop a node health monitoring technique to monitor the operation and performance of the sensor/actuator nodes
- Develop an error handling technique to deal with incorrect data that could influence the accuracy of the hydraulic model.
- Develop a distributed control algorithm that is able to take a decision in critical conditions without referring to the back end system and then report the situation for further actions.
- Develop a distributed situational awareness algorithm that is able to predict the status of sensor nodes as well as the WDN components attached to it. This algorithm will predict potential faults for preventative and mitigation measures.

3. Conclusion

Potable WDN hydraulic modelling is an effective way to analyse and diagnose network operation conditions. If the network is analysed frequently based on real input data, it is possible to provide a strong scientific basis for network planning and improvement, achieve advanced network management, and identify operational problems early and hence protect the environment and reduce the risk of pollution. Most of the existing hydraulic models are steady-state models. The steady-state nature of such a model limits the reliability and efficiency of the water network. This paper proposes a complete end-to-end real-time dynamic hydraulic model as an effective approach to implementing an efficient, reliable and adaptive WDN. The proposed system consists of three major components. First, a smart water network which is concerned with the development of various sensor and actuator interface nodes and other network devices. Second, a dynamic hydraulic model that consists of various techniques to enhance the operation and efficiency of the WDN. Finally, active network management to enable better network management and ensure the security of the network.

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