Pressure driven approach in water distribution network analysis: A Review

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Abstract**:** Water distribution network of water supply system is one of the important and critical components of public works. Pipeline network requires high installation cost, around 60 to 80% of total investment cost. It is one of the systems consisting of number of sources supplying water to various points of time varying consumer demand through network of pipes, valves an elevated reservoir. There are two approaches of water distribution network analysis, namely Demand Driven Analysis (DDA) and Pressure Driven Analysis (PDA). DDA method presumes that demands at all nodes are completely satisfied irrespective of hydraulic head available at those nodes. PDA utilizes nodal head discharge relationship. Overall DDA is used for water distribution network analysis under pressure deficient condition can cause large deviation from actual situations and may not be able to simulate accurately. Pressure deficient conditions affect outflow at different nodes in water distribution network analysis and this changes performance of water distribution network inevitably. This study takes review of pressure driven approach in the analysis of water distribution network. It is observed that most of the simulation is carried out for fire flow, pipe outage, burst, leakage and varying source head pressure deficient conditions separately. Proposed review may help in summarizing PDA in analysis of WDN for more realistic results and improvement in hydraulic modeling.

Key words: Water distribution network, Nodal head flow relationship, Pressure Driven Approach, Demand Driven Approach, pressure deficient conditions.

INTRODUCTION

Water is one of the most important commodities required for life. It is used for domestic, public, commercial and industrial purpose.

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Water supply system is used for supplying water to these purposes. Water supply is by means of collecting, storing, pumping and transporting water through water distribution network. The components of water distribution system are reservoir, pumps, tanks, pipes, valves etc. The analysis of water distribution network (WDN) consists of computation of flow and pressure at nodes. It should be designed carefully and maintained properly to reach the consumer. The main aim of WDN is to supply water to all consumers with adequate pressure head. In urban infrastructure WDN represents major portion of investment and it is the most critical component of analysis [1].

Water distribution network of water supply system is one of the important and critical components of public works. As water distribution network is one of an important system for any country, a proper care should be taken while designing it. It also being a vital component in urban infrastructure and it requires considerable investment; optimization of water distribution network has received considerable attention over past 30 years. Demand driven is a conventional approach which is used in the analysis of water distribution network. It is observed that this approach is more suitable in normal conditions. This approach presumes that available nodal demands at all nodes are always equal to the required demand irrespective of hydraulic head available at those nodes. But now day research is in progress in pressure driven approach which is suitable in pressure deficient conditions. PDA utilizes nodal head discharge relationship for analyzing pressure deficient conditions. It has been found that the assumption in DDA is unrealistic in practical situation. But PDA may give realistic results [12]. Software like EPANET 2, EPANET extension, WaterCad Water GEMS, MATLAB code is used for WDN.

1. Materials and Methods

1.1 Theoretical background of Demand Driven Approach and Pressure Driven Approach

The conventional DDA approach is also called as flow dependent analysis or node head analysis. In this approach nodal pressure head and pipe flow are computed from the equation of continuity and energy by assuming fixed nodal demands. Thus it assumes that available pressure at each node is above minimum required pressure under normal condition as per equation 1.

$$q_{avl} = q_{req} \tag{1}$$

q_{avl} = available discharge at node q_{req} = required discharge at node

This approach indicates that consumer may get water under low or negative nodal pressure. But this is unrealistic in practical situation because flow is dependent of pressure head at those nodes. This approach is preferred when there are no pressure deficient conditions in water supply system.

The other approach available now a day is PDA or PDD or head dependent analysis is used to find nodal pressure head discharge relationship for pressure deficient conditions. The PDA differs from DDA with respect of hydraulic grade level as mentioned in equation 2.

$$H^{avl} = H^{req} \tag{2}$$

H^{avl} = available head at node H^{req} = required head at node

In this approach the water delivered as a function of available pressure.

1.2 Overview of various pressure deficient conditions

As discussed DDA is useful and give realistic results in normal conditions, but unsuitable in abnormal conditions. Due to these abnormal conditions pressure fall below minimum required which ultimately lead to reduction in flow supplied to consumer. If the pressure head in each node is less than the required head, the WDN is under pressure deficient conditions. The pressure deficient conditions may rise because of improper design of WDN [36]. The deterioration of water quality in WDN may take place because of pressure deficiency. The various pressure deficient conditions may be leakage because of excessive pressure, fire demand need to be considered for fire frightening purpose, pipe outage need to be done for maintenance purpose, pipe burst, pipe failure may be because of excessive pressure with low consumption, varying demand, water stop conditions because of natural disaster, pump failure, electric shut down, insufficient water supply from water source, variation in reservoir elevation, distance from the source node and elevation of the node etc. [7], [14], [26], [29], [34], [39], [42], [43], [54], [55], [56], [57]. In exception pressure deficient conditions may occur when pressure reducing valves are in operation and there is a fire demand requirement.

Simulation is used for developing hydraulic model to predict the behavior of WDN. The very first step to resolve pressure deficient problems in a network is to identify areas with low pressure. These points can be identified through hydraulic simulation and the problems in pressure deficient network can be resolved in appropriate manner.

1.3 Overview of various head flow relationships

The amount of water that is available at demand node in case of abnormal conditions depends on the available pressure. Hence, a relationship exists between the flow and pressure at a demand node which is termed as node head-flow relationship (NHFR). In PDA, demanded flow rate in each node is function of system's pressure. PDA can be carried out by using nodal head flow relationship.

Bhave (1981) was first to propose NHFR based on hydraulic grade line. The NHFR is represented by equation 3,

$$q_j^{avl} = q_j^{req} \quad (\text{adequate flow}), \text{ if } H_j^{avl} > H_j^{min}$$

$$0 \le q_j^{avl} \le q_j^{req} \ (\text{no flow}, \text{Partialflow or adequate flow}) \text{ if } H_j^{avl} = H_j^{min}$$

$$q_j^{avl} = 0, \ (\text{no flow}) \text{ if } H_j^{avl} < H_j^{min} \tag{3}$$

George Geramnopoulos (1985) considered no flow for hydraulic grade line (HGL) value less than H_j^{min} and exponential increase of a available flow beyond H_j^{min}. The relationships are as per equation 4.

$$\mathbf{q}_j^{avl} = q_j^{req}\,[1-10^{-\beta}], \ (\text{partial flow}), \text{ if } H_j^{avl} > H_j^{min}, \text{ supercritical}$$

$$q_j^{avl} = 0 \ (\text{no flow}), \text{if } H_j^{avl} \le H_j^{min}$$

$$\text{in which } \beta = c_j \left(\frac{H_j^{avl} - H_j^{min}}{H_j^{des} - H_j^{min}} \right) \tag{4}$$

Janet Wagner et al., (1988b), Chandapillai (1991), suggested parabolic relationship between H_j^{min} and H_j^{des} which is given in the equation 5.

$$q_j^{avl} = q_j^{req} \quad \text{if } H_j^{avl} \ge H_j^{min}$$

$$q_j^{avl} = q_j^{req} \left(\frac{H_j^{avl} - H_j^{min}}{H_j^{des} - H_j^{min}} \right)^{1/p} \quad \text{if } H_j^{min} < H_j^{avl} < H_j^{des}$$

$$q_j^{avl} = 0, \ (\text{no flow}) \text{ if } H_j^{avl} \le H_j^{des}$$

$$\text{In which } H_j^{des} = H_j^{min} + R_{ox}\,(q_j^{req})^p \tag{5}$$

Lingireddy and Elango (1989, 1991) presented that according to relationship uncontrolled outlets and nodal outflows wholly dependent on residual heads. The equation 6 represents q_j^{avl}.

$$q_j^{avl} = s_j\,(H_j^{avl} - H_j^{min})^{0.5} \tag{6}$$

Fujiwara and Ganesharajah (1993) suggested a complex differentiable function. The relationships are given in equation 7.

$$q_j^{avl} = q_j^{req} \quad \text{if} \quad H_j^{avl} \geq H_j^{min}$$

$$q_j^{avl} = q_j^{req} \left(\frac{(H_j^{avl} - H_j^{min})^2 \ (3H_j^{des} - 2H_j^{avl} - H_j^{min})}{(H_j^{des} - H_j^{min})^3} \right) \quad \text{if} \ H_j^{min} < H_j^{avl} < H_j^{des}$$

$$q_j^{avl} = 0, \quad \text{(no flow) if} \ H_j^{avl} \leq H_j^{des} \tag{7}$$

Rajesh Gupta and Pramod Bhave (1996) compared various methods for predicting performance under pressure deficient condition. Out of various method reviewed they found that the method which follows parabolic head discharge relationship is the best.

Kalungi and Tanyimboh (2003) suggested a multiple step relationship. In this relationship the number of steps and their sizes depend on number of sets of critical nodes and their hydraulic grade line values. Refer equation 8.

$$q_j^{avl} = q_j^{redl} \quad , \ \text{if} \quad H_j^{avl} > H_j^{des}$$

$$0 \leq q_j^{avl} \leq q_j^{req} \quad \text{if} \quad H_j^{min} \leq H_j^{avl} \leq H_j^{des}$$

$$q_j^{avl} = 0, \quad \text{if} \ H_j^{avl} < H_j^{min} \tag{8}$$

Ang and Jowitt (2006) mentioned that the relationship between the heads at the source nodes and the outflow at each demand node is a bi-product of the analysis and the elevation of demand node itself taken as H_{min}. The available flow at demand node j may be characterized as follows Bhave (1981). Tanyimboh and Templeman (2010) suggested relationship in equation 9, αj and βj are calibrated using field data.

$$q_j^{avl} = q_j^{reql} \ \frac{\exp(\alpha_j + \beta_j * H_j^{avl})}{1 + \exp(\alpha_j + \beta_j * H_j^{avl})} \tag{9}$$

Kovalenko et al. (2014) investigated its convergence properties recently. The Head flow relationship under partial flow conditions for secondary network may be written as in equation 10.

$$H_j^{avl} = H_j^{min} + R\,(q_j^{avl})^{nj}$$

$$\text{where } R_j = \frac{H_j^{des} - H_j^{min}}{(q_j^{req})^{nj}} \tag{10}$$

1.4 Review of use of pressure driven approach in water distribution network analysis

Water distribution networks analysis consist of computing node heads and link flows which is through solving equations of mass conservation for each node and head loss for each link simultaneously. The analysis of water distribution network is done using two approaches viz, demand driven and pressure driven approach. The traditional demand driven approach is valid only if adequate pressures at all nodes, as demand is independent of pressure. Pressure driven approach is more suitable in case of abnormal conditions or pressure deficient conditions. Numerous research works is being carried out by researcher for pressure driven approach. The review of the research work and pressure driven approach for pressure deficient conditions is presented. The study categorizes simulation using nodal head flow relationship and modifying source code in EPANET, by adding artificial element in the network and using other software tools. Fig 1 shows schematic presentation of review research papers.

1.4.1 Simulation of water distribution network using source code modification in EPANET and WaterGEMS

In past researchers have focused on establishing relation between nodal head and discharge or available demand. Few researchers have used this relationship and modified source code in EPANET for pressure deficient analysis. Cheung et al. (2005) proposed extension OOTEN in EPANET to include pressure driven demand modeling. The EPANET source code is modified for data structure and algorithms to model pressure driven analysis. The fire flow condition is modeled as pressure deficient condition. Zheng et al. (2006) proposed efficient approach to simulate variety of low pressure scenarios with pressure dependent demand. They proposed criticality evaluation criteria for quantifying the relative importance of elements that may be out of service. This simulation is done by modifying source code in WaterGEMS and considering fire flow as pressure driven demand and volume based demand. Zheng et al. (2006) proposed efficient approach to simulate variety of low pressure scenarios with pressure dependent demand. The simulation is carried out for pipe outage for small network and fire flow for large network. Tabesh and Dolatkhahi (2006) proposed methodology for performance assessment of water distribution network based on quality parameters. The water quality analysis algorithm is linked with head driven simulation model. The leakage with varying source head conditions is analysed. Orazio Giustolisi et al. (2008) introduced a new steady state network simulation model that fully integrates a classic hydraulic simulation algorithm as that of Ezio Todini and Pilati (1988) with EPANET 2, with a pressure-driven model. It entails a more realistic representation of leakage. It also focuses on review of leakage modeling and importance of simulation allowing leakage analysis. It is concluded that the simulation model developed and presented is robust. Zheng Yi Wu et al. (2009) developed a generic relationship between pressure head and nodal demand. It is first defined according to the practical characteristics of pressure-dependent demand, and then pressure deficient hydraulic network analysis is formulated as a head-driven problem. It is simultaneously solved for nodal heads and flows by extending GGA. Three examples including a benchmark pressure deficient system, criticality analysis example, and a large-scale water system in Florida are simulated using integrated approach for undertaking practically challenging water distribution analysis tasks. Calvin Siew and Tanyimboh (2010) proposed extension EPANET-PDX to incorporate analysis of pressure dependent demand. They developed algorithm of nodal pressure – flow function using line search and backtracking procedure. It showed excellent modeling performance for both normal and pressure deficient conditions. Tanyimboh and Templeman (2010) developed robust Newton Raphson method to model water distribution network for both normal and deficient conditions. They concluded that Head dependent analysis do not take longer than demand dependent analysis. Jun Liu et al. (2011) combined several pressure dependent demand formulation with EPANET. They developed extension in EPANET named EPANET-MNO for analyzing pressure deficient network. The EPANET- MNO showed good performance for simulating pressure deficient conditions. Tabesh et al. (2011) developed optimization procedure for calibration of PDA and DDA models. Genetic algorithm is used for calibration of both hydraulic models. Leakage term is also introduced to evaluate hydraulic simulation more realistically. Calvin Siew and Tanyimboh (2012) proposed integrating continuous function by Tanyimboh and Templeman into global Gradient method which will develop model for handling real networks using EPANET - PDX. The proposed approach can simulate real world network. The conditions analysed are varying source head and random closure of pipe. K. S. Jinesh Babu and Mohan (2012) developed algorithm called M-PDNA for pressure deficient analysis. The algorithm eliminated limitations in PDNA and mainly used for extended period simulation of pressure deficient conditions. They concluded that the elevation and distance from source node influences nodal outflows, among this nodal elevation is crucial factor. Do Guen Yoo et al. (2012) proposed system based pressure dependent demand analysis. To fulfill nodal demand this study optimizes nodal water demand. The optimization is done by Harmony search method. Lin Jun and Yu Guoping (2012) proposed extension of EPANET -MNO for repetitive modification to nodal outflow. Comparison is carried out between four different PDD functions with designated required pressure and minimum pressure required. M. Tabesh et al. (2013) developed improved head discharge relationship for two types of demands volumetric and head dependent. It is prepared using gradient method. The study carried comparison between DDA, EPANET and EPANET based head dependent analysis. Sayyed and Gupta (2013) categorized various nodal head flow relationship in direct and indirect approach. Solved two examples with this approach and concluded that formulation with unknown nodal head or unknown pipe discharge and head is best suited for direct approach. P. Sivakumar and Prasad (2014) proposed modification in M-PDNA which does not require EPANET toolkit which is coupled with pressure reducing valve operation. The approach is used to analyze pressure deficient condition with constant and variable demand pattern. They concluded that the study is useful in simulating pressure deficient conditions without using EPANET toolkit. Only one thing to be considered while simulation is pressure reducing valve should be active throughout simulation. J. Muranho et al. (2014) proposed pressure demand relationship in EPANET by developing extension WaterNetGen. Leakage is considered as pressure driven demand. Both pressure driven and demand driven analysis can be done on same network model. Shokofeh Sharoonizadeh et al. (2016) compared results by analyzing water distribution network using pressure deficient network algorithm (PDNA), modified pressure deficient network algorithm (MPDNA) and complementary reservoir solution (CSR). Found that number of iteration to achieve solution is more in PDNA than other two methods. Ho Min Lee et al. (2016) proposed modification in EPANET to develop PDA model which simulates pressure deficient condition along with it to consider quantitative uncertainty in head outflow relationship.

1.4.2 Simulation of water distribution network by adding artificial element in EPANET

Ang and Paul Jowitt (2006) proposed pressure deficient network algorithm (PDNA) for the solution of water distribution network under pressure deficient conditions. They introduced set of artificial reservoir to initiate nodal flows. They have suggested further studies for networks which include pumps. Suribabu and Neelakantan (2011) proposed connecting balancing reservoir at pressure deficient node which is called as complementary reservoir. The results showed that the approach is promising method. Nikolai and Kodzhespirova (2013) presented simple technique which considers square root relationship between nodal demand and nodal pressure using EPANET 2. The artificial strings made up of flow control valve, pipe with check valve and reservoir are connected at demand nodes. M. A. H. Abdy Sayyed et al. (2015) introduced non iterative method to model pressure deficient condition using check valve, flow control valve and emitter series. The proposed methodology is very practical when used with EPANET toolkit. Ho Min Lee et al., (2015) proposed technique to simulate negative pressure and reverse flow due to pressure deficient condition. This technique is applied to branch type and looped type network. Herman A. Mahmoud et al. (2017) proposed connecting specific set of elements flow control, check valve and emitter at pressure deficient node. This proposed technique uses Janet Wagner (1988) nodal head flow relationship.

1.4.3 Simulation of water distribution network using MATLAB code

Ackley et al. (2001) proposed new technique for the solution of pressure deficient water distribution network based on mathematical programming. Low pressure conditions are achieved by lowering source head from 68 m to 53 m. MATLAB is used for the solution of same. Confirmation of hydraulic feasibility of result was obtained using EPANET. The proposed study requires predetermined head discharge relationship curve to produce realistic results. The author suggests field work to determine nature of head discharge curve. Piller et al. (2003) proposed least action principles appropriate to pressure driven model of pipe network. Computer program is written under the name PORTEAU to model water distribution network. To consider a head dependent consumption function they have modified balancing equations. This approach gives possibility to develop and assess reliability index, based on demand satisfaction. The coding was done in MATLAB. Orazio Giustolisi and Daniele Laucelli (2011) proposed pressure driven approach using Enhanced Gobal Gradient Algorithm. This approach allows accounting for actual leakage and demand patterns along pipes or as complementary feature for network topological simplification. Extended Global Gradient Algorithm analysis was carried out in MATLAB R2010a. Naser Moosavian and Mohammad Reza Jaefarzadeh (2013) introduced optimization model for hydraulic analysis of WDN using Differential Evolution algorithm. The approach proposed is simple to handle pressure driven demand and leakage simulation. It doesn’t require solving linear system of equations. All computations were executed in MATLAB programing language. Enrico Creaco (2016) suggested modification in resilience and failure indices by Todini for DDA. A new resilience and failure indices are developed for PDA. Carlo Ciaponi and Enrico Creaco (2018) used five PDD formulae for analysis of WDN and simulated cases in MATLAB. They compared results considering Janet Wagner et al. (1988) as a benchmark. Experimental data should be used in identifying most consistent formula for real WDN behavior is suggested.

1.4.4 Simulation with other tools

Germanopoulos (1985) proposed a technique of introducing pressure dependent demand and leakage term in simulation models for water distribution network analysis. Mathematical formulation is done by using empirical functions to relate consumer outflow and leakage losses to network. The sparse matrix programming technique is used for Newton Raphson solution. The network is analyzed for leakage and pipe failure condition using extended period simulation. It is concluded that leakage losses have more effect on operation of water distribution network when pressures are high. Proposed approach contributed in identifying the modeling effect of pressure on outflows and losses and proposing a solution without numerical difficulties. Chandapillai (1991) proposed technique in developing countries for simulating water distribution network, where supply is less than demand. The proposed technique is extension of conventional analysis which can be obtained by modifying computer programs for conventional analysis. The proposed approach assumes supply quantity and later it is adjusted with the pressure data from field. It gives actual supply at each node. Fujiwara and Ganesharajah (1993) proposed reliability method using Markov chain method for the analysis of water distribution system with link failure and fluctuations of flow and head at individual nodes. For this study nonlinear programming software was used for Markov chain calculations. The major weakness of proposed approach is, time required for calculation. Okitsugu Fujiwara and Li (1998) proposed model to analyze the system behavior with pipe and pump failure. The cases analyzed are single link failure, single station failure, single link and single station failure, two link failure. The coding was done in FORTRAN and used nonlinear optimization NPSOL 4.0 software. While studying system behavior under contingency conditions due to failure of pipes and pumps they have considered three aspects equity, redistribution of network flows and consideration of pressure dependent demand. It concludes that proposed equity policy is very effective in distributing the impacts of contingency situation. The paper does not discuss any cost aspect. Zheng et al. (2010) developed model based optimization method for detecting leakages in network. The pressure dependent demand leak is simulated as emitter flow at selected nodes. D. Paez et al. (2013) presented approach that combines concept of energy and integer linear programming to find optimal solution. This study is more useful for fire flow, water distribution system designing considering leakage.

1.4.5 Analytical approach

Wagner et al. (1988) proposed analytical method for calculation of probabilistic reliability measures for water distribution network. Authors have carried out review of reliability considerations in water supply system. Reachability and connective, these two probabilistic measures have explained. Two algorithms, one for series parallel and general network are prepared.

Piller and Zyl (2007) proposed explicitly integrity non negative constraints for pressure. The basic study of conservation of mass and energy is done first. They introduced convenient energy minimization. After this surrogate and corrective formulation is proposed. This contribution is theoretical. Sylvan Elhay et al. (2015), established conditions for existence and uniqueness of solution to Pressure Driven Model. These problems are posed as optimization problem one based on weighted least square and other on co content function. A damping scheme based on Goldstein's algorithm was used.

1.5 Result and discussion

Through literature it is observed that the one pressure deficient condition is considered at a time. In these papers different water distribution networks are analyzed for different pressure deficient conditions. Most of the time two pressure deficient conditions but applied on different networks observed are as shown in table 1.

The literature survey study carried out for pressure driven approach found pipe outage, pipe burst, fire flow and leakage to be mostly used pressure deficient conditions. It is also been observed that EPANET is freely available software which is used by most of the researchers. EPANET source code modification by means of extensions has been adopted in most of the cases. It is observed that EPANET software is used in 23, WaterGems in 04, MATLAB in 06 research papers. The other tools are used in 06 research papers.

Summary

The literature review reveals that the conventional demand driven approach gives misleading results. Pressure driven demand helps in predicting how much water will be supplied to consumer under pressure deficient conditions. Pressure driven approach which fulfills demand at node considering pressure at node gives accurate and realistic results. There are various nodal head flow relationships available but it is observed that parabolic head discharge relationship is best for analysis of water distribution network. The pressure deficient conditions analyzed in most of the papers are pipe outage, fire demand and varying source head. The analysis is done by modifying source code in EPANET, by adding artificial strings at demand nodes and optimization techniques. The literature survey for papers referred shows that 21 researches have carried out for pipe break and pipe outage, 13 for leakage, 11 for fire flow and 8 for varying source head. Very few researches have studied pump failure, demand variation pressure deficient conditions. The pressure driven approach is superior than demand driven in case of pressure controlled demand and leakage, there still exist model deficiencies in cases where pressure drops below a physically realistic level. The further study suggested for betterment in PDD approach are, the elevation and distance from the source node are the parameters that influence the nodal outflow values and among these, nodal elevation is the crucial factor. For assessing the accuracy of PDD functions, reliable experimental data on pressure-flow relationships are required. The pressure driven approach is to be conducted to determine most appropriate supply strategy by estimating the pressure variation and available system demand.

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Figure and Table legends

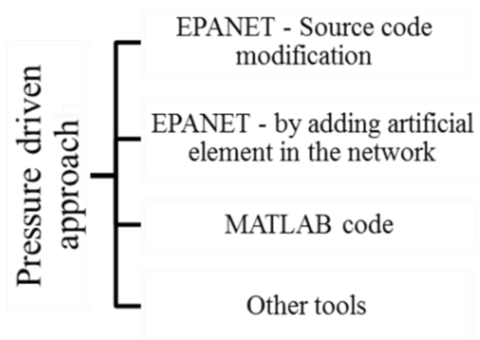

Fig. 1 Schematic presentation of review of journal papers

Table 1. Pressure deficient conditions used for simulation of network

Sr. No	Author	Pressure deficient conditions	Comments
1.	Germonopoulous (1985), Zheng Yi Wu et al. (2010)	Pipe burst , leakage	Extended period simulation, Optimization for leak detection
2.	Wagner (1988), Fujiwara (1998), Tanyimboh (1999), K. S. Jinesh (2012), Ho Min Lee et al. , (2015)	Pipe break, Pump outage	Simulation for reliability assessment, Programming model, Extended period simulation for multisource pump network. Simulation with connecting artificial element.
3.	Rajesh Gupta (1996), Shivakumar (2014), Herman A. Mahmoud et al. (2017)	Fire demand	Nodal flow analysis, Extended period simulation with pressure regulating valve. Extended period simulation with specific elements at pressure deficient nodes.
4.	Tanyimboh (2003), Tanyimboh (2010),	Varying source head	Newton-Raphson Line Search Algorithm, PRAAWDS code with new Pressure dependent function, Extended period simulation
5.	Zheng et al. (2006), Zheng and Thomas (2006), Zheng et al. (2009), Chun Woo Baek et al. (2010), Jun Li (2011), Liu Jun and Yu Guoping, (2012), Abdy Sayyed (2013), Alemtsehay G. Seyoum and Tanyimboh (2014), Abdy Sayyed (2014)	Fire flow and Pipe outage with varying source head	Criticality analysis, Extended period and steady state simulation using WaterGEMS, Pressure driven model with Harmony Search algorithm and EPANET hydraulic simulator, EPANET –MNO extension developed with pressure driven demand, Classification of various nodal head flow analysis, EPANET extension with embedded logistic pressure dependent nodal flow function, Non-iterative procedure in EPANET with artificial elements
6.	Orazio (2008), Orazio (2011), Tabesh (2013), Naser Moo Savian (2013), J Muranho (2014), Enrico Creacoet al. (2016) Carlo Ciaponi and Enrico Creaco (2018)	Leakage	Steady state model was developed for leakage at pipe level. Pressure driven algorithm for leakage and demand along the pipe, Extended period simulation, Leakage and a new term for representing actual nodal discharges when available head simulated in OOTEN toolkit in EPANET Pressure dependent and pressure leakage relationship in EPANET extension WaterNetGen. MATLAB for comparing five PDD formulae.
7.	Tabesh et al. (2011)	Leakage, fire flow	Calibration model formulation in EPANET with Genetic Algorithm for optimization.
8.	Calvin Siew and Tanyimboh (2012), Alemtsehay G. Seyoum & Tanyimboh (2016)	Varying source head, pipe closing	EPANET – PDX extension for pressure driven demand with line search and back tracking procedure