Optimization of Water Distribution Systems: A Review

O.M. Awe 1*, S.T.A. Okolie 1,2, and O.S.I. Fayomi 1,3

1Department of Mechanical Engineering, Covenant University, Ota, Ogun State, Nigeria
2Department of Mechanical Engineering, Gregory University, Uturu, Abia State, Nigeria
3Department of Chemical, Metallurgical and Materials Engineering, Tshwane University of Technology, Pretoria, South Africa
Corresponding Author; awe.michael002@gmail.com

Abstract-
A water distribution system (WDS), being a system of interconnected hydraulic elements ensures water distribution and supply to satisfy demands while optimization is applied in many systems and situations, thus making it an important paradigm in technology. When we try to optimize, we either minimize (resource consumption, cost) or maximize (profit, system performance). This paper reviews optimization of water distribution systems and presents different aspects of WDSs. It also presents the different optimization methods in a detailed manner. Finally, modern sophisticated optimization methods are refined enough to solve complex real-world problems such as WDS design and operations. The categories of challenges being solved include: new WDSs design; expansion and revamping of existing WDSs; pump operation; water quality management; calibration and system partitioning. Reliability, robustness and resilience considerations are often encountered in WDS literature and are still open to analysis because there is no generally acceptable model for permanent inclusion in WDSs optimization.

Key words: Water Distribution System; Optimization; Water; Hydraulics; Configuration

1. Introduction
In a bid to improve life for humanity, engineers and scientists have being trying to modify and improve distribution and transportation techniques of water for an extended period. A water distribution system (WDS) is a system which ensures distribution and supply of water to meet demands in different areas. WDSs are systems which usually contains interrelating modules such as pumps, pipes, valves, pumps, reservoirs and tanks and are a result of combined efforts of engineers and scientists around the world [1].

The global water crisis is not a function of having too little water to go round but a crisis of management and distribution of water to billions of people that are in need. The availability of water sources are reducing drastically across the world and this is what necessitates the crucial requirement of targeted efforts to manage water efficiently and effectively [2]. Water distribution systems (WDSs) are meant to supply sufficient quantity of water and required quality of water without trading-off future capability and standard. Water distribution systems are diverse and interconnected systems that are emerging as a response to the challenges of drought, climate variability, pollution, climate change, and population growth in urban areas. The sustainable aspect of water supply include the three fold objectives of economic, social and environmental factors linked to functional use of water, management of clean and waste water.
Water is majorly used domestically for drinking, cooking, bathing and cleaning, secondly, industrially in production of energy and manufacturing, and thirdly in agriculture for irrigation.

Optimization is applied in many systems and situations, thus making it an important paradigm in technology. When we try to optimize, we either minimize (resource consumption, cost) or maximize (profit, system performance). In truth, money, time, and resources are usually short; hence, optimization is highly paramount in operation [5]. Water systems may include reservoir transfers, alternative supply sources, and centralized management. Operation of water distribution system is typically guided by operating rules that aim to meet multiple and competing objectives, such as minimizing operational cost, energy use, and flood risk; maximizing water security and environmental flows. Determining optimal operating rules for these water distribution systems is challenging due to trade-offs between objectives, uncertainty in forecast flow and demand, and the heterogeneity and complexity of the supply-network. These factors make predicting outputs of operating decisions more difficult in WDSs. Thus optimization, decision support and analysis tools are required for meeting these challenges.

2. **Water Distribution Systems**

A water distribution system (WDS) is the process which from the water source supplies or distributes to meet the end users’ demands. This process is attained by operations of pumps, main and service pipes, storage tanks or reservoirs, and related equipment while under pressure in a closed system. Ostfeld [6] defined water distribution systems as interrelating connection of water sources, pipes, and hydraulic control modules such as valves, pumps regulators, and reservoirs with the purpose of delivering water for end use with standard pressure.

2.1 **Elements of Water Distribution Systems**

Elements of water distribution systems (WDSs) includes all nodes and linking components of the system. The purposes of some of these elements are outlined below;

- **Reservoir:** Node provides water to the system, also known as the source.
- **Tank:** Node Stores and reserves water and intermittently release water within the system to the end user.
- **Junction:** Node keeps pressure level and distributes water towards different directions.
- **Pipe:** Linkage conveys or transports water across nodes
- **Pump:** This node extends hydraulic head or pressure to conquer losses in pressure due to friction and differences in elevation.
- **Valves:** Controls the flow and pressure in the system [7]

2.2 **Types of Water Distribution System Configuration**

The configuration of WDSs depends on the method in which the pipes are connected with each other, the following system configurations are the basic configurations most system are built upon [8]:

- **Serial configurations** are simple configurations with no loops or branches, serial configurations are the most basic configuration of all. It usually consists of a source, end and a pair of in-between demand points also known as nodes.
The direction of flow is predetermined from the water source throughout till the end of the system. Serial configurations are not common and characterized by low reliability and quality challenges resulting from water stagnation in the system. Usually when this configuration is installed to convey water, construction and maintenance cost are high [9].

- Branched configuration is an amalgamation of two or more serial configuration. It mostly contains a source and many demand points. The in-between demand points (nodes) in the system join one upstream pipe with one or more pipes that are downstream. The predetermined flow directions are initiated by the deliveries from the source straight to the systems’ demand points. Branched configurations can be parallel or tree type and they are adequate for less dense communities. However, the main snags are; [10] 1) Intermittent water demand. 2) Possibility of system contamination 3) Low reliability, 4) Sediment accumulation.

- Looped configuration consists of demand points (nodes) that can collect water from more than one side. This is on account of the looped configuration of the system devised to mitigate the snags experienced with branched configurations. Looped configuration can be generated from branched systems by joining its ends together. Looped configurations are hydraulically more complex compared to serial or branched configurations. The pattern of flow in looped system is predetermined or fixed both by configurations and by the system operation. Looped configurations systems are costlier both in installation and cost of operation. They are mostly used in urban/industrial areas for adequate distribution with high reliability [11].

- Combined configuration is commonly used in urban/Industrial areas. Looped layout makes the central aspect of the system whereas the outlying district of the areas supply is produced through a number of linkages

2.3 Optimisation Methods
Mala-jetmarova et al. [12] carried out a reviewed of 107 publications on optimization of water distributions systems. As shown in figure 1 below, the review showed that research works which applied deterministic methods started in the 1980s and stochastic and hybrid approach began in the 1990s
Most optimization models define the design problem basically as minimizing the pipe cost subject to 1) attaining or meeting flow and pressure constraints, 2) meeting of demands at nodes. However, researchers have begun to take reliability considerations into account. WDS Optimization is a little complex due to nonlinear relationships between discharge and pressure.

The optimization methods can be categorized as follows:

- Deterministic optimization techniques: Linear programming (LP), non-linear programming (NLP), and dynamic programming (DP),
- Stochastic optimization techniques (Metaheuristics): Simulated annealing (SA), shuffled complex evolution (SCE), ant colony optimization algorithms (ACOAs), shuffled frog leaping algorithms (SFLA) and genetic algorithms (GA).

The following section expresses the optimization methods in modern day operation research that have been applied to aspects of water distribution systems planning, design and management.

### 2.3.1 Deterministic Optimization

- Linear programming (LP) is a deterministic or exact optimization method which uses the analytical model of the problem to generate a series of solutions that aims at converging to the best or optimal solution. LP is one of the most widely used deterministic optimization methods that guarantee to find the optimum for a continuous problem with a linear objective function subject to linear constraints. WDS optimization problems are nonlinear and consequently, the use of LP in WDS requires linearization. The early success with the application of LP to the design of a WDS was reported by [13]. This
research opened up the way for LP applications on designs and operations of WDS.

- dynamic programming (dp) is another deterministic optimization method proper for solving multistage optimization problems, DP decomposes the multistage problem into a sequence of single-stage decision-making operation and consequently DP is more proper in application in scheduling of pump [1]. Ostfeld [6] presented a unique overview of the DP applications in WDS operation problems. However, the ‘curse of dimensionality’ was one of the challenges the method suffered and consequently limited the extent of its application to complex WDS.

- non-linear programming (nlp) techniques used in WDS are based on the generalized methods of minimized gradient, sequential LP or sequential quadratic programming [14]. NLP limitation is found in the amount of constraints and variables it can manage and therefore can only manage less complex WDS. Similarly to LP, NLP uses continuous variables, but unlike LP solution does not mandatorily converge to the best or optimal solution when applied to WDS.

2.3.2 Metaheuristics (Stochastic)

WDS optimization in the 1990s experienced shift partly due to the emanation of metaheuristics and also the development of improved personal computers. In Operations research, a metaheuristic is a strategy designed to produce a partial search algorithm (heuristic) that may supply the optimal solution to an optimization problem usually with incomplete or imperfect data. A metaheuristic is a high-level algorithm designed to solve a large scope of complex optimization challenges. Metaheuristics share characteristics in common [15]:

- They are inspired by nature i.e. use principles borrowed from physics, biology;
- they are stochastic, i.e. involve random components;
- Linearizing assumptions are not required.

Most of metaheuristics are population-based and are flexible to solve multi-objective optimization problems and provide a near-optimal priority set in one run of the algorithm. The main edge metaheuristics has over deterministic optimization is that they are able to solve complex optimization problems which no specific deterministic algorithm is capable of solving [12].

Mala-Jetmarova et al. [12] reviewed a list a research works that applied various metaheuristics to WDS optimization, some which include: genetic algorithms, harmony search, simulated annealing, cuckoo-search algorithm, shuffled complex evolution, particle swarm optimization, scatter search, immune algorithm, memetic algorithm, honey bee mating optimization, discrete state transition algorithm, differential evolution, mine blast algorithm, and evolutionary algorithm. The researchers also stated that majority of applications solved single-objective design challenges e.g. cost of pipe minimization constrained by required pressure at nodes.

2.4 Review of Optimization of WDSs

A review of optimization of water distribution indicated that formal research in optimization of WDSs commenced about half a century before works in this area was published. In the early
1970s, few researches which reviewed optimization of water distribution systems were published and as times passed more and more works were reviewed with novel ideas applied. The succeeding section addresses the gap by reviewing the early publications till date.

Savić et al. [1] reported in their research work that Tuttle in late 1890s was responsible for the first work which presented standard sizes of pipe in WDSs by utilizing standard flow across pipes. Expansively, Tuttle formulated a theory of knowledge that states that reduction of pipe sizes and costs associated to the pipes consequently increases head losses and the required pressure. He further modelled an equation representing the yearly WDS costs together with initial investment, installation, operation and maintenance costs, and equating the equation derivative to zero, he minimized diameter of pipe and calculated flow. Tuttle’s approach contained some assumptions including the cost of pipes, pipe laying, pumping and other operations, which were initiated as constants and he also declared a factor for varying demand.

In the 1900s, few researchers discredited Tuttle’s formulations and theories as they discovered that his theories did not find solid foundations due to inaccuracies. They took the research further and included pipe and pump operation costs in the yearly total costs and presented pipe diameters derived with turbulent flows as the only limitations. The new search also expanded the work to include the turbulent and viscous flows. This finding got widespread acceptability because they discussed topics on how to determine the cost of pipes and pump operations, how to predict pipe roughness over a period of time and how to denote demand patterns. They also applied the design principles to a concise system with one pump, single tank and demonstrated the relationships between the varying values.

In the 2000s, researches in WDSs optimization experienced a surge in application of new solvers such as Genetic algorithms, multi objective optimization methods, fuzzy logics, Artificial neural networks etc. also notable to point is the fact that most works considered industrial, agricultural or large scale case studies for robust demonstration of results. More generally, researchers took on more complex systems rather than simple ones, made fewer assumptions and moved closer to more reliable result as regards hydraulic systems components and this evidence in the reviews below.

In the early 2000s, Van Zyl et al. [16] and Savic et al. [13] both researched into optimization of pump operation using hybrid genetic algorithm (GA). Savic et al. [13] formulated multi-objective model approach which created an improvement in GA solver used in the past. It generated consequences or penalties for contravening constraints, and introduced feasibility of solution as an objective to guarantee no infeasible solutions in the optimized results. As an improvement over Savic et al. [13]’s research, Van Zyl et al. [16]’s GA solver recognizes the range of optimal solutions and uses a hillclimber method to locate the optimal solution. These research milestones by both researchers were in direct consequence of improvement over the findings of [17]. The research of Coulbeck et al. [17] actually achieved optimal pump operation by considering with priority the predetermined flow, variable flow and variable pump pressures. They also used a pump scheduling framework which was categorized into three levels; (i) High level-dynamic optimization of reservoirs; (ii) Mid-level-static optimization of pump groups (iii) Low level-Static optimization of each pump station.
Research in areas of Optimization and capacity expansion of a water distribution system became even highly necessary as many WDSs experienced shortages and inability to meet demand by reason of unexpected expansion of areas in municipals and exponential increase in population. The researcher’s model was solved by linear programming (LP) and this was done easily using a standard linear programming code. The revaluation tool result helps to discover the challenges in the WDSs and provides alternatives for capacity expansion [18].

Recent works include, Abkenar et al. [19] who evaluated the optimization of pumps in WDSs. In this research, a multi objective nonlinear model was developed from the real life problem alongside with considerable number of constraints. The cost, energy emission, environmental emission objectives were optimized tactically by scheduling of pump cycles. Also, Boano et al. [20] optimized and modeled even more complex and complicated WDSs, the researcher employed the use of a genetic algorithm solver to depict the complex model and recognize the varying operational layouts that lead to optimization of energy consumption and water leakages.

Giustolisi et al. [21] optimized WDSs using GA for a peculiar case study. This research optimized operational cost and losses due to leakage. Pressure and demand driven evaluations were carried out to calculate leaking pressures and water losses within specific time frame. The controls, utilities and auxiliary components of WDSs can minimize loss in resources, energy and leakages in WDSs if optimally located. This led to a research which minimizes energy consumption and fresh water waste through a Markov Decision process model of a WDS. The optimization was carried out with imposed restrictions on the WDS by refraining from water outages and pipe leakages [22].

Dynamic programming DP was applied to search the optimal pump operation of a water distribution system. The results of this research demonstrated that using standby pumps alongside existing pumps is more cost effective. This was shown clearly after cost savings of 6.3% recorded during optimized pump schedules and cost savings of 19.2% recorded while using standby pumps [23]. Giacomello et al. [24] carried out real time pump operation optimization using a Hybrid method. The uniqueness of this work shows off in the fact that the researcher took up time as a factor during optimization. This paper categorizes it methods in two steps. Step 1: linearization and modelling of problem to solve for the optimum solution. Step2: Removal of linearization and launch of search algorithm with EPANET to find the optimal solution. Alvisi & Franchini, [25] also analyzed WDSs applying ranking-based optimization algorithms by linearization approach. Linearization approach was adopted to solve the WDS optimization problems where the algorithm searches out the best solution through ranking.

Pecci et al. [26] was more interested in pressure management while optimizing WDSs. Their paper surveyed optimization methods of managing pressure in WDSs. Mixed Integer Nonlinear programming solvers were evaluated and implemented and the solutions were investigated under different design and operation loading conditions. The paper surveyed optimization methods of managing pressure in WDSs. Mixed Integer Nonlinear programming solvers were evaluated and implemented and the solutions were investigated under different design and operation loading conditions. While Pecci et al. [26] was more concerned about pressure management, Kurian et al. [27] was more interested in intermediate storage facilities location
in optimization of WDSs. This work considered the optimal operation of WDSs. The municipality in study was modelled into a Mixed Integer Nonlinear Program (MINLP) efficiently and solved in 3 stages. The optimal schedule expended 9.3% less energy and 2.5 hour less in time in comparison with heuristic schedule.

Researchers also began to use new metaheuristics methods in optimization of different aspects of WDSs. A WDS optimization by application of two ant colony optimization algorithms on WDSs was researched. The paper adopted Ant Colony Optimization (ACO) as an optimization method. The Max-Min Ant System (MMAS) algorithm was used to search for the best solution [28]. Zheng et al. [29] also presented a new multi-objective optimization method to increase the efficiency of a problematic WDS. The evolutionary algorithm optimizes the sub-networks, and prioritizes subnetworks with great efficiency. A WDS optimization using multi-objective evolutionary optimization was carried out by Tanyimboh & Seyoum [30]. The researchers reported that the method adopted here fosters the development of solutions based on Pareto dominance. The results reveal the optimization algorithm solver to be solid. The best solutions saved 48.1% and 48.2% of the cost of the pipes in the system. Zhang et al. [14] also proposed a multi-objective optimization using sectorization method based on hydraulics, water quality and economic conditions. In application, the method proved to be efficient in churning out positive results with little or no effect on the hydraulics and water quality transported in the WDS.

In a bid to sideline WDSs analysis and simulation software, researchers have now begun to search for optimization methods for analysis and design of WDSs. Do et al. [31] carried out a demand analysis of WDSs using genetic algorithms. This research shows the optimized model can be utilized to evaluate the flow rates and nodal heads or pressure at non-measured points of the WDSs, The results provided from the case study shows GA model can generate good approximation of the state in a WDS. Also, a Multi-objective optimization model approach developed by Cunha & Savi [32] was used to depict and cater for possible future expansion condition. The solution showed that the approach can deal expressly and unambiguously with clashing and incompatible objectives, with no environmental effect and uncertainty.

Gençoğlu & Merzib [33] researched optimization of valve location in WDSs. Their work introduces a GA as optimization model to minimize excess pressures in nodes of WDS by determining the location and controlling the valves. Incorporation of uncertainty in early system design stages of WDSs using optimization of WDSs for security and reliability purpose is highly necessary [34]. A multi-objective GA was structured to solve the challenge. This was applied on simple and complex model WDSs and the application was done to evaluate near-optimal solutions from the range of solutions space which also have ability to solve water contamination issues [35]. Results demonstrated a large exchange surface between the cost and the respective system’s performance, with large diminishing returns.

In summary, this review detects several gaps in different areas of optimization of WDS. Optimization as a method is vast and diverse in the sense that there are many categories under this method. Several techniques of optimization such as quadratic programming and Shuffled Complex Evolution under stochastic optimization techniques have yet to find application in water distribution systems. A more robust research on optimum location of WDSs controls,
utilities and auxiliary components appears elusive and this has caused unimaginable loss in resources, energy and leakages in WDSs.

3. Conclusion
Many researchers agree that the modern sophisticated optimization algorithms are refined enough to solve complex real-world problems related to WDS design and operations. The categories of challenges being solved include: new WDSs design; expansion and revamping of existing WDSs; pump operation; water quality management; calibration and system partitioning. Reliability, robustness and resilience considerations are often encountered in WDS literature and are still open to analysis because there is no generally acceptable model for permanent inclusion in WDSs optimization.

4. Recommendation
Further research which reviews optimization of water distribution systems with case study focusing on West Africa should be carried out in order to comprehend and curb the specific limitation and challenges within the area. Secondly, a more robust research on optimum location of WDSs controls, utilities and auxiliary components appears elusive and should be carried out in order to minimize the unimaginable losses in resources, energy and leakages in WDSs.

Acknowledgements
The authors are grateful to Covenant University and department of Mechanical Engineering, Covenant University for the support granted during the development of this work.

Reference
[1] Savić, D., Mala-jetmarova, H., and Sultanova, N. (2018). History of Optimization in Water Distribution System Analysis.
[2] Vairavamoorthy, K., Akinpelu, É., Lin, Z. & Ali, M. 2001. "Design of sustainable system in developing countries" Proceedings of World Water and Environmental Resources Challenges, Environmental and Water Resources Institute of ASCE, Orlando, Florida. 20-24 May 2001.
[3] Waite, Marilyn. (2010). Sustainable Water Resources in the Built Environment. IWA Publishing: London. http://www.iwapublishing.com/news/sustainability-water-supply.
[4] Fayomi, O.S.I. Olukanni, D.O. Fayomi G.U. And Joseph, O.O. 2017. In situ assessment of degradable carbon effusion for industrial waste water treatment, Cogent Engineering 2017, 4: 1291151 http://dx.doi.org/10.1080/23311916.2017.1291151
[5] Yang X.S., Koziel, S., (2011). Computational Optimisation and Application in Engineering and Industry. Springer, Germany.
[6] Ostfeld, A., (2001). "Reliability Analysis of Regional Water Distribution Systems.", Elsevier Science Ltd., Urban Water.
[7] Walski T.M., Chase, D.V., Savic, D.A.,Grayman, W.,Beckwith, S. and Koelle,E.(2003)."Advanced Water Distribution Modelling and Management.".Bently Institute Press.
[8] Trifunovic, N. (2006). Water Transport and Distribution Systems, 1–20. Retrieved from www.alkema.nl
[9] Dongre, A. (2016). Optimization of Water Distribution Network - A Review, 2(09), 269–272.

[10] Lejano, R. P. (2006). Optimizing the layout and design of branched pipeline water distribution systems. Irrigation and Drainage Systems, 20(1), 125–137.

[11] Swamee, P. K., & Sharma, A. K. (2008). Design of water supply pipe networks. John Wiley & Sons.

[12] Mala-Jetmarova, H., Sultanova, N., & Savic, D. (2017). Lost in optimisation of water distribution systems? A literature review of system operation. Environmental modelling & software, 93, 209-254.

[13] Savic, D. A., & Walters, G. A. (1997). Genetic algorithms for least-cost design of water distribution networks. *Journal of water resources planning and management*, 123(2), 67-77.

[14] Zhang, K., Yan, H., Zeng, H., Xin, K., & Tao, T. (2019). A practical multi-objective optimization sectorization method for water distribution network. *Science of The Total Environment*, 656, 1401-1412.

[15] Nicklow, J., Reed, P., Savic, D., Dessalegne, T., Harrell, L., Chan-Hilton, A., ... & Zechman, E. ASCE Task Committee on Evolutionary Computation in Environmental and Water Resources Engineering (2010) State of the art for genetic algorithms and beyond in water resources planning and management. *Journal of Water Resources Planning and Management*, 136(4), 412-432.

[16] Van Zyl, J. E., Savic, D. A., & Walters, G. A. (2004). Operational optimization of water distribution systems using a hybrid genetic algorithm. *Journal of water resources planning and management*, 130(2), 160-170.

[17] Coulbeck, B., Brdyš, M., Orr, C. H., & Rance, J. P. (2008). A hierarchical approach to optimized control of water distribution systems: Part I decomposition. Optimal Control Applications and Methods, 9(1), 51-61.

[18] Hsu, N. S., Cheng, W. C., Cheng, W. M., Wei, C. C., & Yeh, W. W. G. (2008). Optimization and capacity expansion of a water distribution system. *Advances in Water Resources*, 31(5), 776-786.

[19] Abkenar, S. M. S., Stanley, S. D., Miller, C. J., Chase, D. V., & McElmurry, S. P. (2015). Evaluation of genetic algorithms using discrete and continuous methods for pump optimization of water distribution systems. *Sustainable Computing: Informatics and Systems*, 8, 18-23.

[20] Boano, F., Scibetta, M., Ridolfi, L., and Giustolisi, O. (2015). Water distribution system modeling and optimization: a case study. *Procedia Engineering*, 119, 719–724.

[21] Giustolisi, O., Berardi, L., Laucelli, D., Savic, D., & Kapelan, Z. (2015). Operational and tactical management of water and energy resources in pressurized systems: Competition at WDSA 2014. *Journal of Water Resources Planning and Management*, 142(5), C4015002.

[22] Fracasso, P. T., Barnes, F. S., & Costa, A. H. R. (2014). Optimized Control for Water Utilities. *Procedia Engineering*, 70, 678–687.

[23] Kim, M., Choi, T., Kim, M., Han, S., and Koo, J. (2015). Optimal operation efficiency and control of water pumps in multiple water reservoir system: Case study in Korea. Water Science and Technology: Water Supply, 15(1), 59–65.

[24] Giacomello, C., Kapelan, Z., Nicolini, M., 2013. Fast hybrid optimisation method for effective pump scheduling. *J.Water Resour.Plan.Manag.ASCE* 139(2), 175e183.
[25] Alvisi, S., & Franchini, M. (2015). A linearization approach for improving the computational efficiency of water distribution system ranking-based optimization algorithms. *Procedia Engineering*, 119, 516-525.

[26] Pecci, F., Abraham, E., & Stoianov, I. (2015). Mathematical programming methods for pressure management in water distribution systems. *Procedia Engineering*, 119(1), 937–946.

[27] Kurian, V., Chinnusamy, S., Natarajan, A., Narasimhan, S., & Narasimhan, S. (2018). Optimal operation of water distribution networks with intermediate storage facilities. *Computers and Chemical Engineering*, 119, 215–227.

[28] Zecchin, A. C., Simpson, A. R., Maier, H. R., Leonard, M., Roberts, A. J., & Berrisford, M. J. (2006). Application of two ant colony optimisation algorithms to water distribution system optimisation. *Mathematical and computer modelling*, 44(5-6), 451-468.

[29] Zheng, F., Simpson, A., & Zecchin, A. (2015). Improving the efficiency of multi-objective evolutionary algorithms through decomposition: An application to water distribution network design. *Environmental Modelling & Software*, 69, 240-252.

[30] Tanyimboh, T. T., & Seyoum, A. G. (2016). Multiobjective evolutionary optimization of water distribution systems: Exploiting diversity with infeasible solutions. *Journal of environmental management*, 183, 133-141.

[31] Do, N., Simpson, A., Deuerlein, J., & Piller, O. (2017). Demand estimation in water distribution systems: solving underdetermined problems using genetic algorithms. *Procedia Engineering*, 186, 193-201.

[32] Cunha, M., & Savi, D. A. (2015). Environmental Modelling & Software Multi-objective optimization of water distribution systems based on a real options approach, 63, 1–13.

[33] Gençoğlu, G., & Merzi, N. (2017). Minimizing Excess Pressures by Optimal Valve Location and Opening Determination in Water Distribution Networks. *Procedia Eng.*, 186, 319-326.

[34] Sankary, N., & Ostfeld, A. (2017). Incorporating operational uncertainty in early warning system design optimization for water distribution system security. *Procedia Engineering*, 186, 160-167.

[35] Fayomi G.U, Wusu O, Mini S.E, Fayomi O.S.I, Kilanko O. Data analysis on the level of exposure to pollutions in industrial zone: A case study of Ewekoro and Ota Township Data in Brief, 2018, 19, 859-864