Water Distribution System's Network Reliability, Availability and Maintainability

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Abstract

The purpose of water distribution systems is to provide a satisfactory and reliable supply of safe water to citizens within a specified area. A reliable drinking water distribution system must be able to supply and deliver water with the acceptable quality to all its users at their delivery points. SA is a water scarce country with optimization of water supply crucial to sustainability. The reliability of a water network is a crucial component of delivery but more importantly water sustainability. Reliability, Availability and Maintainability (RAM) are three crucial subsets of a system and its operational support. This study outlines the theory together with an assessment of current practices relative to the RAM theory. The results indicates adoption capacity with recommendations on implementation constraints. The potential impact to the water network is also assessed.

Keywords:
Water, Reliability, Maintenance

1. Introduction

The reliability of water distribution systems is critical in guaranteeing public safety and the continuous operation of urban activities. In this manner, careful preparation of infrastructural planning, resources allocation, maintenance, and operational activities for water distribution systems is essential. Optimal reliability and maintenance schemes are beneficial to the receiver of the service delivery.

Reliability and maintenance of water distribution schemes, if used correctly, will not merely save money for the government, but will also improve government service delivery, improve customer satisfaction and the general quality of life of residents. This is also good for the water distribution systems because it will extend its lifespan.

Water distribution systems comprises interconnected systems such as pipes, intersection joints, water towers, reservoirs, and pumps that require extensive planning to guarantee that water is delivered to the consumers without service interruptions. The water distribution systems are designed and planned to adequately supply the required amount of water for domestic, commercial, industrial and firefighting purposes and therefore its constant maintenance is of supreme importance. It is undeniable that the right distribution system should be able to provide good quality water to every consumer's tap and firefighting hose. Water should have a reasonable amount of pressure fit for purpose. This need has to be realised at minimal costs namely capital costs, operating and maintenance costs.

This study is based on the engineering key concept which focuses on the basic integrity of engineering. The study uses Reliability, Availability, and Maintainability (RAM) to scrutinize the integrity of the water supply system and infrastructural wear and tear of the water infrastructure of the City of Johannesburg. Problems such as burst water pipes, poor water pressure and continuous pipe replacements compromise water security which is being experienced, but could be prevented. Currently, the City of Johannesburg has a reactive maintenance system instead of proactive for the water distribution systems. Developing countries like South Africa have made extraordinary strides in tending to the disparities of the past, through the provision of water. It is unfortunate that the focus on expanding service provision has often been at the expense of maintaining existing infrastructures. This has seen the City of Johannesburg constantly controlling damages caused by aging water infrastructure

2. Literature Review

2.1 Water overview in South Africa

The history of water in South Africa cannot be separated from the history of apartheid which encouraged the infrastructural development of only certain in South Africa. The history of water mirrors that of housing, migration, land, social engineering and development. Unique as the South African perspective is, South Africa is not the only country with water distribution systems problems, and can benefit from the many lessons learned internationally. Water distribution systems can be improved through water infrastructural planning. Literature has shown that many water systems fail because of inadequate maintenance, ineffective management and tight constraints on investments in water supply. The lessons learned from other countries, especially the developed countries, need to be heeded and sound development principles applied if South Africa is to be successful in achieving equitable access to sustainable basic infrastructure for the entire population (Tewari, 2009).

2.2 Johannesburg Water Operation Department

According to the Johannesburg Water [Johannesburg Water, 2016] the Johannesburg Water Operation's department is responsible for operating and maintaining water distribution systems and mechanical equipment at water or wastewater treatment plants and pumping stations. Work is done under the supervision of the General Manager: Operations, Bulk Waste Water Manager, Networks Manager, Technical Service Manager, Contract Engineers and Best Practice, Monitoring and Evaluation Manager. The high-level structure consists of qualified engineers with over five years' experience. Engineers are expected to ensure compliance with global standards for design and safety of products and services, and to guide efforts to ensure reliability and maintainability of equipment, processes, utilities, facilities, controls, and safety/security systems [Johannesburg Water, 2016].

2.3 Water distribution systems best practices and lessons learned from a global perspective

There are generally four types of water distribution system network layouts that are being adopted by most developed countries [Mohanty, 2012]. These systems differ depending on the need and layout of the surface areas. The literature below details the differences and the reasons for adoption by specific countries.

- Dead End or Tree Distribution System: In the dead-end system, one main pipeline runs through the center of the populated area and sub-mains branch off from both sides. The sub-mains divide into several branch lines from which service connections are provided. It is the system in which each street or block is supplied separately from the main. This system is generally adopted in cities or town where irregular development has occurred. Countries such as Egypt, Greece, Italy, North America and the United Kingdom mostly adopted a dead end distribution system [Murty, 2016].

- Grid Iron Distribution System: Murty [Murty, 2016] presents the Grid-Iron distribution as an interconnected water system that can reach the water distribution network from more than one direction. In the case of maintenance or repairs, only a small portion of the water lin is affected. This system is ideal for cities laid out on a rectangular plan resembling a grid-iron. These systems can be witnessed in countries like Pakistan and Russia.
- Ring or Circular Distribution System: In a circular or ring system, the supply main forms a ring around the distribution area. The branches are connected cross-wise to the mains and to each other. Supply to the inner pipes is from the mains around the boundary. This system is more reliable for a town with well-planned streets and roads. In the case of fires, a larger quantity of water is available. China has adopted such a water distribution system [Khartoum, 2009].
- Radial Distribution System: This is a zoned system. The whole area is divided into a number of distribution districts. Each district has a centrally located distribution reservoir from where distribution pipes run radially towards the periphery of the distribution district. This system provides swift service, without much loss of head. The design and pressure calculations are much simpler in this system. Layouts of roads need to be radial to eliminate loss of head in bends. This is the most economical system, if combined pumping and gravity flow is adopted. Britain along with other developed countries adopt such a system [Khartoum, 2009].

2.4 Water Distribution System: Reliability best practices

Water distribution systems is a large system with many interactive and interlinking subsystems. It is extremely difficult to compute the mathematical reliability analytically. Accurate calculations of mathematical reliability require knowledge of the precise reliability of the basic subsystems or components and the impact on accomplishing the mission caused by the set of all possible subsystem (component) failures. However, there is still no convenient evaluation of water distribution system reliability as there are many measures of reliability [Stone, 2015].

Causes of failure of water distribution systems can be operational. These involve the probability of the occurrence of various types of undesirable events that may cause losses of water such as interruptions in the water supply or secondary water pollution in the network. Failures in the water distribution systems can be also be a consequence of the errors made during the system design, construction, and operation.

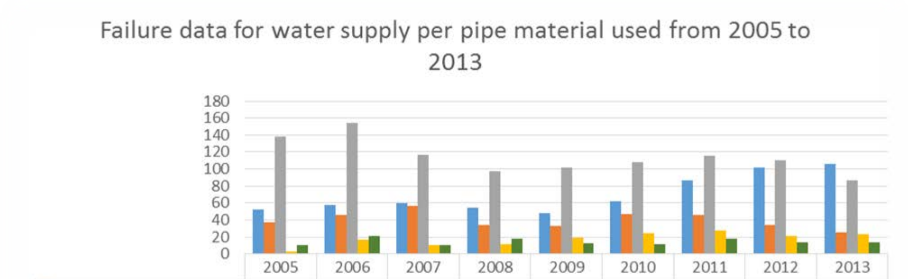
Some of the key challenges to overcome when assessing water distribution systems, as perceived by [Stone, 2015] are:

- How to link the threat to impact
- How to manage different threats that create a similar impact
- How to manage comparative threats that deliver distinctive effects
- How to visualize every single conceivable risk that may influence the system
- How to handle unknown threats

2.5 Material composition and failure modes of water distribution network

Johannesburg Water spends millions of Rands per annum to repair water supply networks. These repair costs will increase in the coming years as networks age and deteriorate. In the best case, decisions to repair are based on practical experiences of residents that lead to reporting of service failures. The material structure and material composition of the water distribution network is an important issue because this parameter indirectly characterises the technical condition of the water supply network [Rostum, 2000]. The percentage of failure of the entire pipe network in the

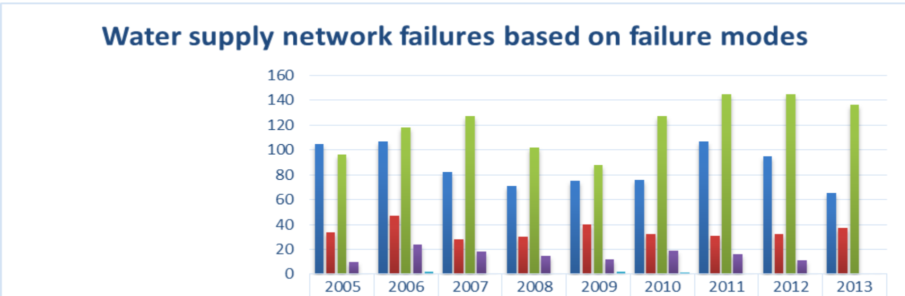
Johannesburg area from 2005 – 2013 on the basis of material used is shown in Figure 1. Cast iron has the highest failure compared to other pipe materials such as UPVC pipes which show the least number of failures.



	2005	2006	2007	2008	2009	2010	2011	2012	2013
Material Steel	52	58	60	55	48	62	87	102	106
Material Galvanized steel	37	46	57	34	33	47	46	34	26
Material Cast iron	138	154	117	97	102	108	116	110	87
Material PE	3	17	10	12	19	24	28	21	23
Material UPCV	11	21	11	18	13	12	18	14	14

Figure 1: Reported water supply network failures based on material used, Source Piedon (2015)

Figure 1 and 2 shows that failure modes unsealing and corrosion contributed the most to water supply failures, whilst mechanical damage has the least impact on the failure of the system through the years 2005 to 2013.



	2005	2006	2007	2008	2009	2010	2011	2012	2013
Failure modes Unsealing	105	107	82	71	75	76	107	95	65
Failure modes Fracture	34	47	28	30	40	32	31	32	37
Failure modes Corrosion	96	118	127	102	88	127	145	145	136
Failure modes Crack	10	24	18	15	12	19	16	11	0
Failure modes Mechanical damage	0	2	0	0	2	1	0	0	0

Figure 2: Reported water supply network failures based on failure modes, Sadiq, Kleiner & Rajani (2004)

2.6 Understanding the RAM theory

There are multiple definitions for RAM. According to the United States of America's Department of Defense; it is a guide for achieving reliability, availability, and maintainability. RAM is composed of three characteristics of a system and its operational support which are: reliability, availability, and maintainability [Department of Defence, 2009].

Reference [Garwood, 2018]details RAM to be important for the analysis of a system. Systems such as those that carry out design modifications are required to achieve minimum failures or to increase the mean time between failures, plan maintainability requirements, optimise reliability and maximise equipment availability.

In engineering, RAM is an important tool that evaluates the equipment performance at different stages in the design process. It addresses both operational and safety issues and aims to identify areas within the system or process where improvements and actions can be initiated. RAM calculates a system's key performance metrics of Mean Time to Failure, Equipment down Time and System Availability [O 'ccnnor, 2012].

2.7 RAM theory analysis tools

There are five tools and processes that need to be in place to ensure the successful execution of RAM. These tools assist with constant monitoring of a system.

- Reliability hazard analysis
- Failure mode and effects analysis
- Reliability-centered maintenance
- Human error analysis
- Water distribution systems technical audit

2.8 Benefits of the RAM theory

The following benefits can be obtained from RAM analysis.

Table 1: RAM benefits analysis

1	**Decision Making**	**2**	**Cost management**
	✓ What maintenance policy should be applied		✓ Managing the cost related to unavailability
	✓ Investment decisions on maintenance		✓ Cost of maintenance
3	**Resource utilization**	**4**	**Integration with other business activities**
	✓ Inspection intervals		✓ All projects on a site have an effect on process RAM
	✓ Optimum spare part purchasing		✓ RAM needs to involve the whole organization
5	**Appropriate maintenance scheduling**	**6**	**Meeting the business demand**
	✓ Understanding the financial implications of maintenance		✓ Reduce outages caused by breakdowns and Reduce the loss of revenues caused by unavailability
	✓ Decision making based on modeling		

2.9 Application of RAM Theory in Water Distribution System

There are two types of water distribution systems reliability, i.e., mechanical reliability and hydraulic reliability. Mechanical reliability focuses on network topology analysis and connectivity of the system but ignores the ability of the system to effectively supply water. Hydraulic reliability refers to the ability of the system to meet the requirements of water flow and pressure and focuses on the failures caused by changes in demand, aging pipes, and insufficient water supply. In some studies, these are merged to evaluate water distribution systems[Atkinson, 2014].

Reference [Liu, 2017]introduced useful measures for managing distribution system reliability. These measures are hydraulic availability and ideal methodology pipe sizing. The combined hydraulic and mechanical availability characterizes the extent of the time the system will satisfactorily satisfy its capacity. Reference [Gunter, 2012] recommend the utilization of system availability from nodal availabilities for finding the perfect repair/replacement strategy.

Maintenance includes activities that keep the system in great operating condition. Maintenance involves condition evaluation, adjusting, repair and replacement of system segments. When maintenance is done before a system component fails, it is called proactive maintenance. Maintenance done after component failure is called reactive maintenance. The goal of maintenance is to preserve the system's proper operating condition, for efficient operation in relation to minimum cost, until depletion of its economically usable [O ‘ccnnor, 2012].

3. Research Methods

According to Wright [Wright, 2015], there are three research methods, qualitative, quantitative and mixed methods. The main objective of this study is to test the applicability of the RAM theory in the Randburg area through employee perceptions and actual practices on the maintenance of the water distribution systems. To best meet the tabled objectives, the study adopted a quantitative research method.

3.1 Data collection method and tools

Having established a theoretical basis, literature identified RAM as a guiding theory. This is achieved through a questionnaire to validate the literature and offer extra context. The 24 technical people that specifically deals with the water distribution network in Randburg area, were selected. They responded to the questionnaire, with the intent that this research could further supplement their own.

The questionnaire is distributed inside the entire expert team in Johannesburg Water, with the principal point being the challenges they confront as well as how they believed these challenges could best be directed. In most cases, these challenges were in line with the identified water distribution system challenges. The data analysis has revealed the inability to handle unknown threats and how to visualize every single conceivable risk that may influence the system as some of the major challenges. This speaks to lack of planning and risk assessment within the water distribution systems. The water distribution system must have the capability to operate under uncertain conditions such as pipe blockages, pipe burst, pipe mechanical failure, and unreliable demand estimation.

3.2 Sample Selection

Most scholars recommend 20-30 questionnaires for quantitative studies whilst others recommend 30-50. This assumption is based on the fact that there is theoretical saturation between 10 and 30 questionnaires where further investigation does not yield additional value. The researcher thus conducted this study utilizing 24 questionnaires so as to facilitate pattern, category, dimension growth and saturation. Purposive sampling is applied. It is defined by Etikan, Musa and Alkassim [Etikan, 2016] to be a sampling method that targets particular respondents that are information-rich experts on the subject matter. The sample size comprises the entire technical team that is assigned to ensure a reliable water distribution systems in the Randburg area from a maintenance and operations perspective in Johannesburg Water. This team comprises senior management, technical, asset management, depot management and engineers.

3.3 Research Limitations

Research limitations are matters and occurrences that arise in the study which are out of the researcher’s control. They limit the extensity to which a study can go and sometimes affect the end results and conclusions that can be drawn. This dissertation has the following limitations:

- Infrastructure planning and operations departments function under constant pressure, which also put limits on the time respondents had to answer questionnaires.
- In some cases, participants were reluctant to criticize the systems and the organization
- A broader overview would have opened up the study into other areas with similar problems

3.4 Data analysis and presentation

Vosloo [Vosloo, 2014] describe data analysis as the process of bringing order, structure, and meaning to the mass of collected data. For analysis of data, Microsoft Excel is utilized to unpack data and make it more presentable. Data from the questionnaires is statistically analyzed and presented using tables, bar charts, and pie charts.

4. Results And Discussion

Johannesburg Water Operations Department implements reliability, availability, and maintenance of water distribution systems in the Randburg area. An overview of the key role-playing department within the water distribution system structure in the Randburg area is illustrated in Figure 3.

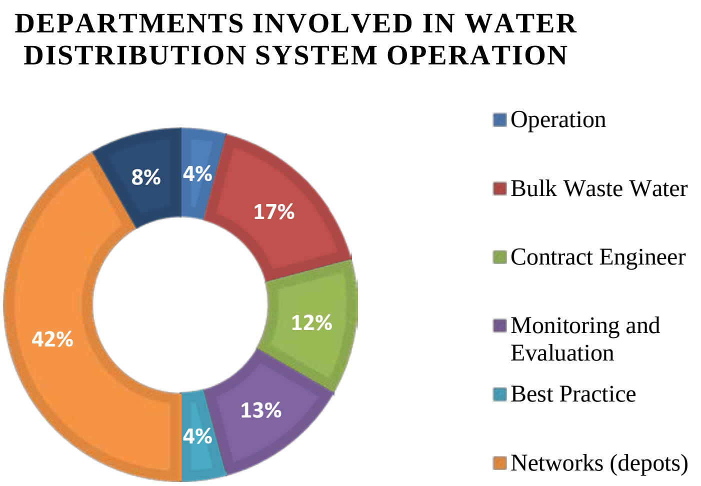


Figure 3: Respondents department of work

As noted in the literature review, the department performs a total scope of duties as assigned, including the execution of routine performance and maintenance duties. The section maintains and operates the Johannesburg Water infrastructure assets which consist of the distribution network of 12,581 km, 115 reservoirs and water towers, and 35 water pump stations. The wastewater is collected and reticulated via 11,786 km of wastewater network, 36 sewer pump stations. 981 Ml/day of sewage is treated at six wastewater treatment works, two of which are biogas-to energy plants converting methane gas to energy. The Johannesburg Water supplies water to domestic, commercial and industrial customers and serves an estimated consumer base of 3.8 million people.

To further understand the respondents and their expertise, the job titles of each role-player is required. This also reflects the variety of skills that are required to create and maintain a water distribution system that is sustainable and reliable. The respondents primarily had a technical and an engineering background. This improves their credibility in participating in this study. As per the literature, work is performed under the general supervision of a General Manager: Operations, Bulk Waste Water Manager, Networks Manager, Technical Service Manager, Contract Engineers, Best Practice Manager, and Monitoring and Evaluation Manager.

The majority of the respondents are highly experienced with over 90% having over five (5) years' experience in water engineering, specializing in water projects, civil engineering, and environmental., As per the literature the engineers are expected to perform a diagnostic evaluation of equipment and recommend corrective action for operational problems, assist in monitoring, inspecting and documenting processes and system performance and train young professionals. This proves that the respondents and their views are credible and informed.

As mentioned in literature, the reliability team is responsible for maintaining and monitoring water distribution systems in order to recommend optimum maintenance activities. They identify and advise repair priorities on all failures, ensure that maintenance and engineering work complies with engineering standards, and corporate quality policies and routines, develop potential reliability orientated solutions and propose alternatives to conform to required changes in a complex and dynamic operational environment. Maintenance teams conduct different types of maintenance to manage the various operating risks of water distribution systems.

In response to the question, what are the key challenges to overcome when assessing water distribution system resilience, data revealed that respondents perceived the inability to handle unknown threats as the major challenge at 38% (n=9), refer to Figure 4. These threats may be unknown because of soil types, or external threats caused by forces of nature. The other major challenge is the inability to visualize every single conceivable risk that may influence the system (n=6) 25%. These risks can include but are not limited to other entities that may run parallel yet be harmful to this water distribution system.

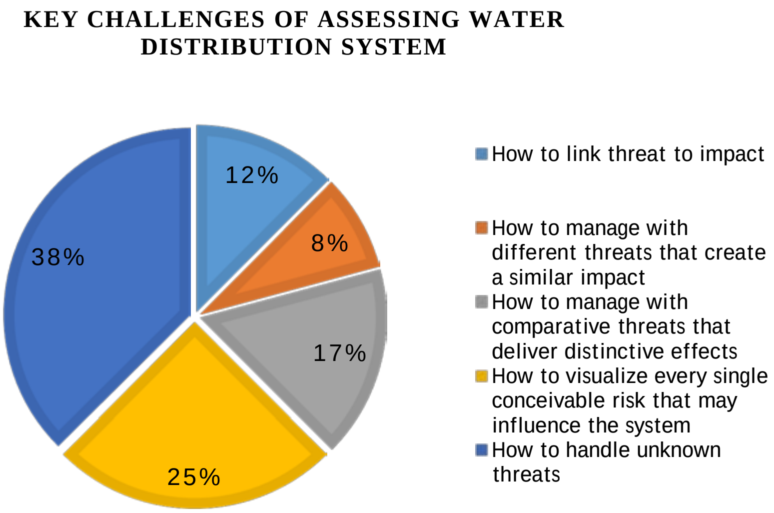


Figure 4: Respondents response to key challenges effecting water distribution system

As mentioned in literature, most water distribution systems have underground infrastructure, which is exposed to soil corrosion, mechanical stress, surface activity, and internal water pressure. Distribution systems usually consist of piping and fittings, pumps and pump stations, meters, storage tanks, backflow prevention devices, hydrants, and valves. There is a combination of factors that affect the assessment of the water distribution systems, none of which is more important than another.

In Figure 5, aging water infrastructure is perceived by the respondents as the major cause of the failure of the water distribution system (n=9) 37%. The other major causes are human error made during system design, construction or operation and pipe blockage due to misuse i.e. illegal connection, overpopulation; both are at (n=5) 21%. Some respondents see this from a procedural point, 17% (n=4) and is credited to incorrect operating procedures. This may cause a disconnect and cause water distribution system failure. Only 4% (n=1) of respondents view external threats such other underground infrastructure services as a major cause of water distribution system failure.

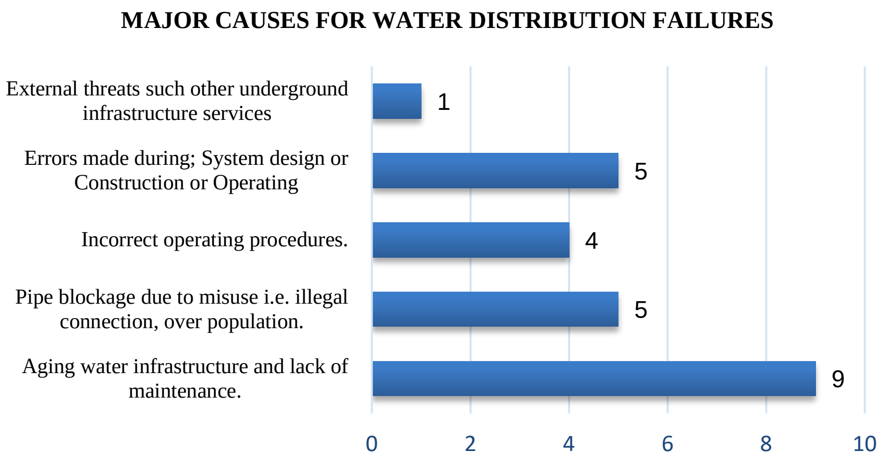


Figure 5: Respondents major causes of water distribution system failures

Issues of aging infrastructure are not surprising because the researcher is of the view that this could be one of the causes for an unreliable water distribution system. The literature is in support of this by pointing out the problem of ailing infrastructure in Johannesburg at large, this means there is a common thread within South Africa. Internal issues of compliance and standard operating procedures within the Johannesburg Water department and the relationship with contractors came to the forefront as a matter of concern that causes water distribution failures.

In the design stage the basic errors could be the following:

- Errors in water-pipe network layout: wrong examination of ground conditions, badly selected route of water pipeline, neglecting the neighboring economic activities of a third party.
- Wrong concept of the water-pipe network geometry and structure.
- Errors in hydraulic calculations: water-pipes diameter, water-pipes length before intersections, network required pressure and pressure drops.
- Wrong concept of the water supply systems and procedures.

In the construction stage:
Deviations from the design codes and the rules of correct construction regarding; technology of pipe laying, connection of individual pipe sections, protection of pipes going under and through obstacles, use of proper anticorrosion protection (passive and active), and the use of the recommended pressure test and other procedures.

In the operating stage: n correct operating procedures, lack of water pipeline monitoring, incorrect emergency water supply capacities, incoherent protection and warning system for water quality, lack of a program to identify the network segment requiring repair, lack of a program to obtain, process and store failure data, causes consequences, and criticalities and lack of failure statistics. Most often the failures in the water distribution systems concern: pipe body (cracks, tearing off, corrosion pits), joints or expansion units (leak in connections), fittings, such as a gate, valve, reducer, hydrant, aeration, band, and spotter.

Figure 6 presents the water distribution system layout in Randburg. The grid iron distribution system is the most commonly encountered system, 16 (n=16) of the 24 respondents selected this system. In accordance with the literature review, this system is ideal for cities because in case of water bursts or repairs only a small portion gets affected.

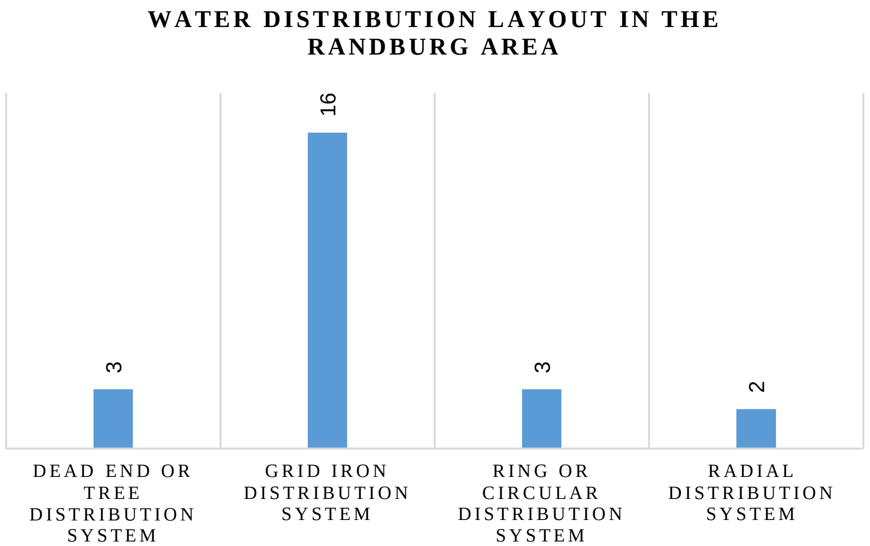


Figure 6: Respondents on WDS layout in Randburg area

The methodologies that are globally adopted in water distribution system redesign problems, consider network arrangements and layout for the identification of optimal solutions that may lead to a lower risk of failure together with a lower redesign cost. The Randburg area is made-up of the grid iron distribution system. This system, as seen in literature [Khartoum, 2009], is the most common in a city's water distribution system provided it is designed and applied correctly. The problem with the water distribution system in the area is due to a combination of factors, with the water distribution system layout being one of the problems. Literature revealed that countries such as Pakistan and Russia are successfully using the water distribution systems layout.

Application of the Grid–Iron Distribution System, the free circulation of water, without any stagnation or sediment deposit, minimizes the chances of pollution due to stagnation. Because of the interconnections water is available at every point with minimum loss of head. Sufficient water is available at street fire hydrants, as the hydrant draws water from the various branch lines and during repairs, only a small area of distribution is affected. Challenges of Grid–Iron Distribution System are; the system is difficult to design and higher costs due to more cutoff valves s longer pipe lengths with larger diameters being required.

According to the data, asbestos cement pipes have the highest failure rate, with 11 (n=11) respondents in agreement. Cast iron is also proving to be problematic as stated by six (n=6) respondents.

Polyethylene (PE), polyvinyl and high-density polyethylene (HDPE) water pipes are the least problematic

The literature revealed no failures of pipes constructed from Polyethylene, polyvinyl chloride (uPVC) and High-density polyethylene (HDPE). The 2005 – 2013 study shows that cast iron had the highest failure while UPVC had the least number of pipe failures. This could be due to the minimal use of these pipes or that it is more durable and should therefore be considered as the pipe of choice to replace all pipes in the water distribution system.

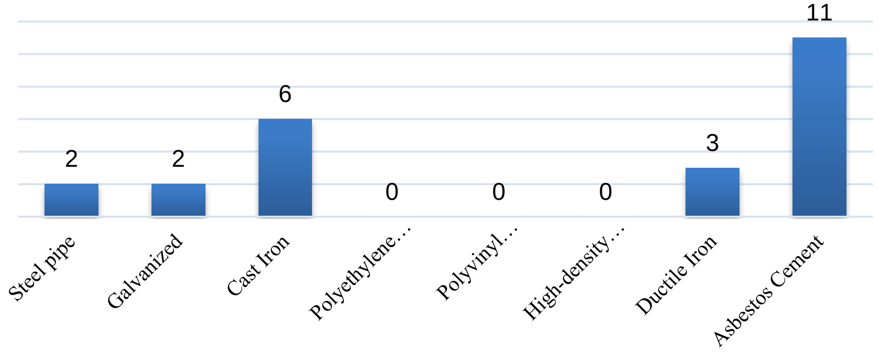


Figure 7: Respondents on pipe material failure rate

5. Conclusion

The research results reveal that there are multiple areas of concern that cause the water distribution system in the Randburg area to be unreliable. With the constant and continuous application of RAM, these system failures can be reduced. This study conclusively brought to light the complex issues that speak uniquely to the Randburg area. These can be attended through multiple interventions such as the creation of maintenance policies, water pipe audits, water pipe replacements, infrastructure revamp and collaborations with other municipality service providers to minimize disruptions of any important municipal service. The study revealed that the water distribution system layout is as per best practice thus it is best suited for the area.

The study makes the following recommendations to maximize the reliability of the water distribution systems:

- Application of new technology to assess water distribution systems such as Monte Carlo Simulation, EPANET, Distributed Acoustic Sensing system.
- The creation of a routine water pipe maintenance policy.
- Ensure thorough training of employees to limit human errors in the system design, construction and operation stages of the water distribution systems.
- Educating the community on protecting the water distribution systems and encouraging its correct use e.g. reporting of illegal connections, how to prevent blockages and protecting the infrastructure.
- Pipeline rehabilitation to improve reliability, availability, and maintainability of water distribution systems.
- A proactive maintenance plan be created as part of a management strategy to reduce destructions to the water distribution systems.
- FThe pipes to be replaced with Polyethylene (PE), polyvinyl and high-density polyethylene (HDPE) as they are the least problematic.

- For the water distribution systems and other municipal infrastructure lines to work in partnership.
- To create systems that can limit destruction to the water distribution systems in the event of natural disasters.
- To include the Reliability and Systems engineering department to assist with assessing the municipal engineering services.

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