Influence of intermittent water supply operations on the vulnerability of water distribution networks

Agathoklis Agathokleous, Chrystalleni Christodoulou and
Symeon E. Christodoulou

ABSTRACT

Water authorities in countries facing water shortage problems are implementing intermittent water supply (IWS) policies, as a measure to conserve and control their national water resources. Implementation of such measures affects the behaviour of the water pipe systems during the operation stage. The research work presented herein presents a model simulating the behaviour of urban water distribution networks (WDNs) under normal operating conditions, as well as during a period of IWS operations. The modelling and analysis, based on an eight-year dataset (2003–2010) from a local Water Board, takes into account information related to breakage incidents within the WDN as well as external factors to perform vulnerability assessment of the pipe network. The results of the performed survival and cluster analysis show that during the implementation period of IWS operations, and right after that period, there is a significant increase in the deterioration rate of the affected network. Further, there is a change in the comparative importance of the factors affecting the network condition and their contribution to the WDN vulnerability.

Key words | clustering, intermittent water supply, risk assessment, survival analysis, urban water distribution networks

Agathoklis Agathokleous (corresponding author)
Chrystalleni Christodoulou
Nireas International Water Research Centre,
University of Cyprus,
Nicosia 1678,
Cyprus
E-mail: *agathokleous.agathoklis@ucy.ac.cy*

Symeon E. Christodoulou
Department of Civil and Environmental Engineering,
University of Cyprus,
Nicosia 1678,
Cyprus

INTRODUCTION

Countries facing extended periods of drought and short supply of fresh water are increasingly turning to intermittent water supply (IWS) operations in order to reduce water consumption and to prolong their national water reserves. In doing so, water distribution network (WDN) managers change the modus operandi of their piping networks and risk affecting negatively the network's vulnerability level. Unfortunately, though, the number of research works in literature on the effects of IWS operations on the vulnerability of WDNs is limited.

In appraising the impact of IWS policies, one should examine the results of implementing such policies on the condition of the pipeline system. Reliable conclusions can only be drawn by thoroughly studying the performance of the WDN before, during and after implementing the IWS measures, and by drawing conclusions on the change of a WDN's vulnerability as a result of IWS policies.

The work presents two different models on the performance of a case-study WDN subjected to IWS operations for a two-year period. The aforementioned IWS period was applied during the period from 31/3/2008 to 31/1/2010 and involved the separation of sub-district metered areas (DMAs) into four areas to which water was sequentially supplied for a time period of 12 hours. During the early months of the IWS period, the plan was fully implemented but thereafter the measures related to the duration of the water supply were loosened, since the period of 12 hours was not enough to fully serve high-altitude areas. The first model, which uses decision trees, studies the variation in the significance of the parameters affecting the vulnerability

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state of the case-study WDN. The analyses included in this model aim for a study of the impact of added IWS data on the time to failure (TTF) of the WDN's elements. If the IWS policy's impact is detrimental to the WDN condition, then the TTF of the elements should be negatively affected. The second model, which is applied on the same WDN, uses survival analysis for the evaluation of the WDN condition under continuous water supply (CWS) and IWS operations. Similarly, if the impact of the IWS policy on the WDN condition is detrimental, then the results given by the CWS and IWS analyses will diverge.

The aforementioned models are an extension of research efforts reported by Agathokleous (2015) and Agathokleous & Christodoulou (2016c).

State of knowledge

Even though a great volume of work on WDNs has already been performed, very little work has been reported in literature with regard to IWS operations and their effects on the vulnerability of WDNs which have been designed for CWS. In the past few decades, researchers have developed several models examining and simulating the operations and condition of WDNs. The models varied from mathematical models expressing the failure pattern or system reliability, to multi-objective failure models, and to multi-factored simulation systems. Recent research activities focused on abnormal operating conditions due to exogenous factors and their effects on the condition of a WDN.

Shamir & Howard (1979) developed mathematical relationships which express the time from pipe installation until the first failure incident, and the failure frequencies after the first failure occurred. Andreou *et al.* (1987) used proportional hazards models to estimate failure at an early pipe age, and a Poisson-type model for the later stages. Also Goulter & Kazemi (1988) presented a non-homogeneous Poisson distribution model which predicts the probability of successive breaks. Kleiner & Rajani (1999) proposed a framework to assess future rehabilitation needs using limited and incomplete data on pipe conditions. An approach that can be used to optimize the replacement and rehabilitation activities for WDN pipes was presented by Hong *et al.* (2006). The method was based on the assumption that the occurrence of breaks in a pipeline segment follows a non-homogeneous Poisson process. Kanakoudis & Tsitsifli (2011) and Tsitsifli *et al.* (2011) was the development of a model that could correctly classify water distribution pipes, to define the pipe characteristics responsible for the behaviour of the pipes and to predict whether a pipe would fail or not. The model uses discriminant analysis classification (DAC) to categorize the pipes in failure or success. The results show that DAC can be a good method for predicting the reliability of the WDN when the available information by the authorities is of good quality. Christodoulou *et al.* (2009, 2010) and Christodoulou (2010) developed a framework for integrated geographic information system (GIS)-based management, risk assessment and prioritization of water leakage actions. A prediction tool, based on genetic algorithms and combined with an economically optimal pipe replacement tool, was presented by Xu *et al.* (2013).

As aforementioned, research on the performance of WDNs operating under abnormal conditions and particularly under IWS has to date been limited, although there is an extensive literature reference for the operation, behaviour and simulation of WDN under normal operating conditions. Among the few studies on IWS, a number of them focus on the design of pipeline systems that operate properly and functionally under IWS conditions. Such are the works of Batish (2003), Sashikumar *et al.* (2003), Vairavamoorthy *et al.* (2007) and De Marchis *et al.* (2011). Batish (2003) presented a study, related to an existing town in India, which is associated with the design of a new water supply system that uses a proposed design method developed by use of the 'EPANET' software. The work suggests that the proposed method is more practical and realistic, for the design of WDNs that operate under IWS. The several modelling issues associated with the design of WDNs that operate under IWS conditions were discussed in the work of Sashikumar *et al.* (2003). Vairavamoorthy *et al.* (2007) presented guidelines for the design and control of intermittent water distribution systems, outlining an approach for the design of WDNs in developing countries that ensures an adequate and equitable water supply under the common conditions of water resource shortage. The work presented by De Marchis *et al.* (2011) analyses the inequalities that take part when intermittent distribution is applied in water scarcity scenarios (users located in advantaged positions of the network are able to obtain water resources soon after the service period begins, while others have to wait much longer, after the network is full). The analysis was performed by means of an unsteady numerical model that was applied to a real case study. The results provided interesting insights into the network filling process, helping to highlight the advantaged and disadvantaged areas of the WDN in different water scarcity scenarios. Moving a step forward, De Marchis & Freni (2015) proposed an alternative solution for the reduction of water volumes supplied to the users and the limitation of pipe leakages.

Work on the effect of IWS on the vulnerability of WDN is reported by Criminisi *et al.* (2009) who studied issues related to water-meter under-registration, and by Andey & Kelkar (2009) CWS with IWS in four Indian cities. Their most important finding is that water consumption does not change appreciably under IWS compared with that of CWS, presuming that water demand is satisfied under IWS. In both cases, though, the reference on the vulnerability of the WDN due to the application of the IWS policy is superficial. Christodoulou & Agathokleous (2012) reported on the performance of WDNs under IWS, citing that of the 12,000 water-loss incidents in a two-year period the majority were related to house connections (HC) and small-diameter pipes, with an increase in incidents during the intermittent supply period of about 28% compared to the normal operating conditions period (uninterrupted supply). Moving a step further, Agathokleous & Christodoulou (2016a, 2016b) reported that WDNs which were designed for continuous operation are negatively affected by the implementation of IWS policies. Furthermore, they concluded based on an eight-year case study that IWS operations are not an efficient water-saving measure but they can be used as a water-management policy.

CASE STUDY AND DATASET

The data utilized in this research work originate from the WDN managed by the Water Board of Nicosia (NWB). The WDN in study is divided into 21 DMAs and, according to the latest known data (2013), it requires for its operation about 19,300,000 m^3 of water per year in continuous flow, while the maximum daily demand in the summer is around 63,700 m^3. The minimum consumption per day is 39,000 m^3, while the daily average water consumption is 52,700 m^3. The NWB has in operation about 112,000 water meters and total length of water mains (WM) more than 1,400 km. Further to the spatial division of the network into DMAs and sub-DMAs, the WBN's WDN is remotely monitored through a supervisory control and data acquisition (SCADA) system consisting of 32 electronic stations across the network, which continually collect and transmit operational information. Apart from the SCADA telemetry system database, the NWB has recently developed and put in operation a database where all information related with the network operations are stored. Finally, all leakage incident data reports since 2003 had been maintained in a specially designed database.

The data utilized for the development of the mathematical model cover a time period of approximately eight years (01/01/2003 to 31/12/2010, with a small gap in the recorded data from 01/08/2009 to 31/12/2009), and include 38,346 incidents. The mathematical framework utilized in studying the impact of IWS policies on the condition of the WDN consists of four survival analyses that use data from four different time periods, as listed below:

- Time period '**A**': The analysis associated with this period uses recorded incidents from 01/01/2003 until 15/08/2005 (the first half of the time period before the day when the IWS policy had come into effect).
- Time period '**B**': The analysis associated with this period uses recorded incidents from 01/01/2003 until 30/03/2008 (the time period before the day when the IWS started).
- Time period '**C**': The analysis associated with this period uses incidents from the total time period for which there are recorded data (the time period before, during and after IWS application).
- Time period '**IWS**': The analysis associated with this period uses incidents that happened during the IWS period.

The analyses for the first three time periods (A, B and C) are the essential ones of the WDN in study, while the analysis that is associated with the IWS period is exploratory and is used to confirm the findings. The case-study dataset was examined by use of decision trees and survival analysis, and by use of data stratifications of various levels.

DECISION TREES

Methodology

Decision-tree analysis is a branch of statistics that is used for classification and regression, with classification and regression trees being used for the development of a decision support tool that classifies a dataset or predicts an outcome by analysing historical data. Whilst in the case of classification trees, though, the response variable could be binary (yes or no) or could have more than two categories, in the case of regression trees the response variable is numeric or continuous. Another important difference between the two models is that classification trees are used when the objective of the analysis is to split a dataset (based on homogeneity of data) into smaller classes, looking for categorical solutions that explain behaviour or describe the characteristics of a specific dataset, whereas regression trees result in numerical answers that predict a future event or action using historical data.

This study aims to investigate whether WDNs are negatively affected by the implementation of IWS policies, and the approach taken in investigating this issue is the study of the occurrence rate of WDN failures during several periods of significance. The hypothesis examined is that if the implementation of IWS negatively affects the condition of a WDN, then the occurrence rate of WDN failures will be increased, i.e. the time period between two successive failure incidents will shorten during and following IWS operations. The analysis utilizes the regression tree algorithm by Breiman *et al.* (1984) which has the ability to analyse historical data and classified it into a tree diagram that predicts the remaining time for a possible future incident to take place.

The historical database used in the analysis and classification consisted of leakage incidents related to two pipe classes (WM and HC), and each pipe class consisted of data of two part types ('Pipe' and 'Fitting' elements). Since the aforementioned analyses examine the effect of IWS on the condition of the WDN for a specific time period, and because the installation date of each element is important to be known, all elements whose 'birth date' was unknown were excluded from the analysis. Additionally, the 'date of failure' and the 'date of rebirth' were considered to be the date that a leak-related incident was reported. The analysis performed was at street (and not component) level and the time from previous action was used as a response variable. Table 1 presents all variables and values used in the regression tree analysis.

The variables used refer to the characteristic properties of the WDN elements associated with the reported leakage incidents, and only variables for which there was sufficient data volume have been used in the analysis. The variable labelled 'Action' refers to the action taken (repair or replace) in response to a leakage event. The 'number of previous breaks (NOPB)' variable denotes the number of observed previous breaks of an element, i.e. the number of repair actions up to that time. The 'Part Type' variable denotes the type of the element, i.e. if the leakage incident is associated with a pipe or fitting, and the 'Material' and 'Diameter' variables refer to physical properties of the element in focus. Since the 'NOPB' and 'Diameter' variables refer to a wide range of possible values, data clustering was used in order to facilitate the analysis and the extraction of results. Finally, black data fields were flagged as 'empty cell' and noted as such in the analysis results.

It should be noted that if the IWS operations are of no impact to the condition of the WDN then the TTF for a specific failure incident type (element of certain material, diameter, part type, etc.) will significantly increase as the length of the time period is increased (i.e. when expanding period A to period B, and then to period C).

Analysis, results and discussion

WM class

Figure 1 illustrates the resulting regression tree diagram for the 'WM Pipe' Class incidents in Time Period 'A' (01/01/2003–15/08/2005), which lasted 957 days. Due to the small volume of data, this regression tree is not sufficiently comprehensive on information. The most important conclusions that can be extracted from the regression tree are as follows:

1. Next replacement action for an asbestos-cement (AC) water-main pipe element which did not experience any previous breaks is expected in 130 days.

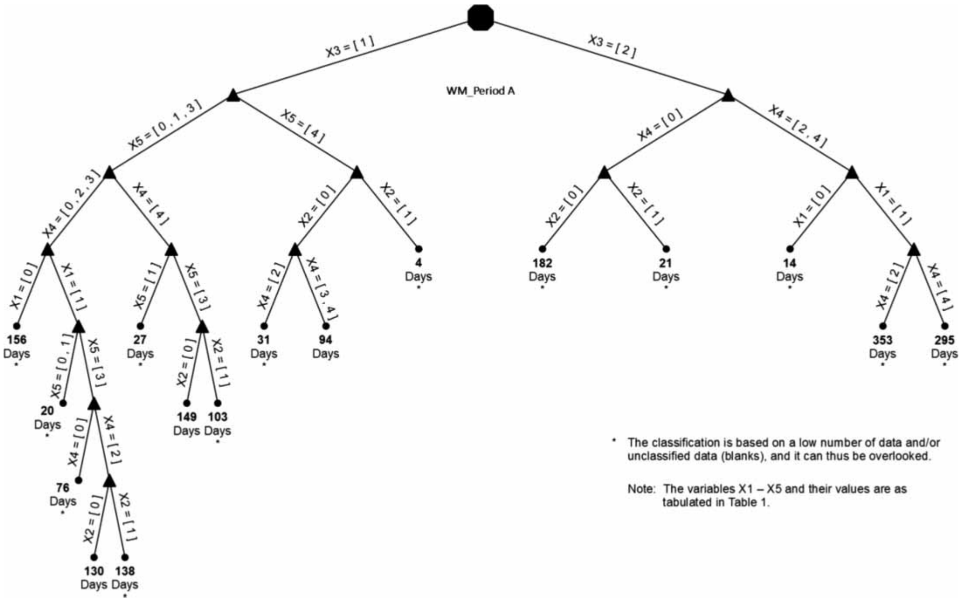
Table 1 | Dataset of the regression tree analysis

				Incidents No											
Symbol	**Variable**	**Value**	**Description**	**HC^2-Period A**		**HC^2-Period B**		**HC^2-Period C**		**WM^3-Period A**		**WM^3-Period B**		**WM^3-Period C**	
x1	Action	0	Repair	2,277	2,466	5,440	5,938	11,501	13,149	27	554	77	1,503	300	2,493
		1	Replace	189		498		1,648		527		1,426		2,193	
x2	NOPB[1]	0	No Breaks	595	2,466	1,129	5,938	2,886	13,149	534	554	1,466	1,503	2,321	2,493
		1	(1–4) Breaks	1,076		2,328		5,544		20		37		165	
		2	(5–8) Breaks	376		1,002		2,097		0		0		7	
		3	(9–12) Breaks	151		518		1,034		0		0		0	
		4	(13–16) Breaks	86		300		555		0		0		0	
		5	(16>) Breaks	182		661		1,033		0		0		0	
x3	Part Type	0	Empty Cell	0	2,466	0	5,938	0	13,149	0	554	0	1,503	0	2,493
		1	Pipe	2,426		5,837		12,883		494		1,285		2,122	
		2	Fitting	40		101		266		60		218		371	
x4	Diameter	0	Empty Cell	120	2,466	374	5,938	1,162	13,149	43	554	188	1,503	316	2,493
		1	Connection Pipe	2,335		5,544		11,937		0		0		0	
		2	Main	0		0		0		140		355		623	
		3	Ring Main	0		0		0		10		24		28	
		4	Small Main	11		20		50		361		936		1,526	
x5	Material	0	Empty Cell	46	2,466	204	5,938	1,043	13,149	66	554	251	1,503	436	2,493
		1	Galvanized	147		365		814		3		3		5	
		2	Plastic	2,273		5,369		11,292		0		0		2	
		3	AC	0		0		0		465		1,207		1,814	
		4	PVC	0		0		0		20		42		234	
		5	DI	0		0		0		0		0		2	

[1] NOPB, Period A: 01/01/2003–15/08/2005.

[2] HC Elements, Period B: 01/01/2003–30/03/2008.

[3] WM Elements, Period C: 01/01/2003–31/12/2010.



* The classification is based on a low number of data and/or unclassified data (blanks), and it can thus be overlooked.

Note: The variables X1 – X5 and their values are as tabulated in Table 1.

Figure 1 | Regression tree of 'WM pipe' class incidents for 'time period A'.

2. Next action for a small-diameter AC water-main pipe element which did not experience any previous breaks is expected in 149 days. This result is in line with the previous one since pipes of the same material and of smaller diameter survive longer.

Figure 2 illustrates the resulting regression tree diagram for the 'WM Pipe' Class incidents in Time Period 'B' (01/01/2003–30/03/2008), which lasted 1914 days. It is expected that as the expanded dataset has WDN elements of longer lifespans, the observed TTF in period 'B' will be on the average higher than that observed in time period 'A'. The most important information extracted from the regression tree analysis for this period is as shown below:

1. Next replacement action for an AC (or PVC) main (or ring main) pipe element which did not experience any previous breaks is expected in 234 days.
2. Next replacement action for an AC (or PVC) small main pipe element which did not experience any previous breaks is expected in 286 days. This result is in line with the previous one since pipes of the same material and of smaller diameter survive longer.

The above results reinforce the hypothesis that the introduction of data associated with the time period from 16/08/2005 to 30/03/2008 has significantly increased the observed TTF. So during that time period, the vulnerability of the network condition has not worsened. Hence, this time period is not negatively affecting the condition of WDNs.

Figure 3 illustrates the resulting regression tree diagram for the 'WM pipe' class incidents in time period 'C' (01/01/2003–31/12/2010), which lasted 2919 days. As with the previous case, it is expected that as the expanded dataset has WDN elements of longer lifespans, the observed TTF in period 'C' will be on average higher than that observed in time periods 'A' and 'B'. The most important information deduced from the analysis is the following:

1. Next repair action for a main pipe element which did not experience any previous breaks is expected in 479 days.
2. Next replacement action for a main pipe element which did not experience any previous breaks is expected in 315 days.
3. Next repair action for a small main pipe element which did not experience any previous breaks is expected in 485 days. This result is in line with the other two, since pipes of smaller diameter survive longer.
4. Next replacement action for an AC small main pipe element which did not experience any previous breaks is expected in 402 days. This result is in line

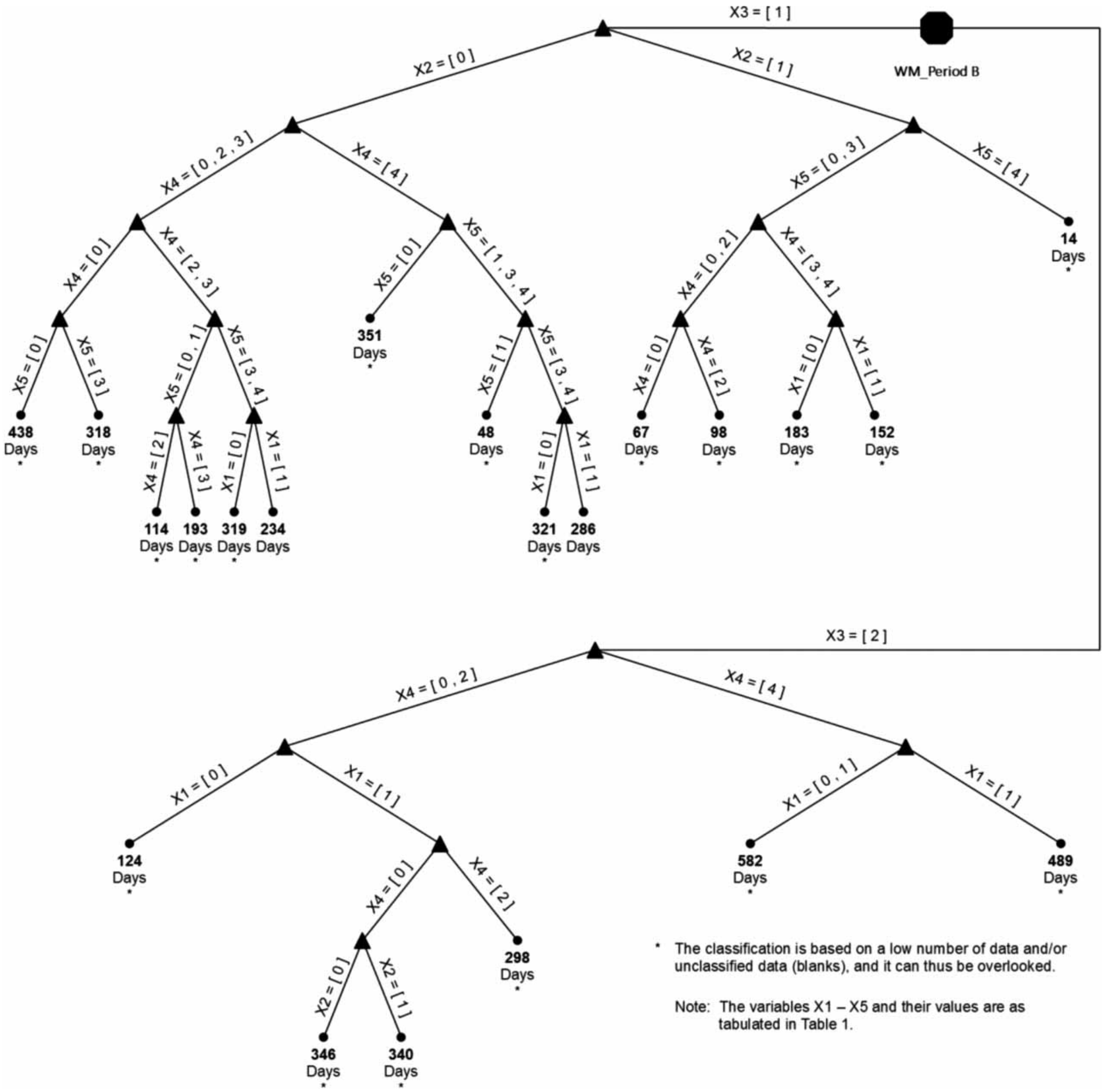
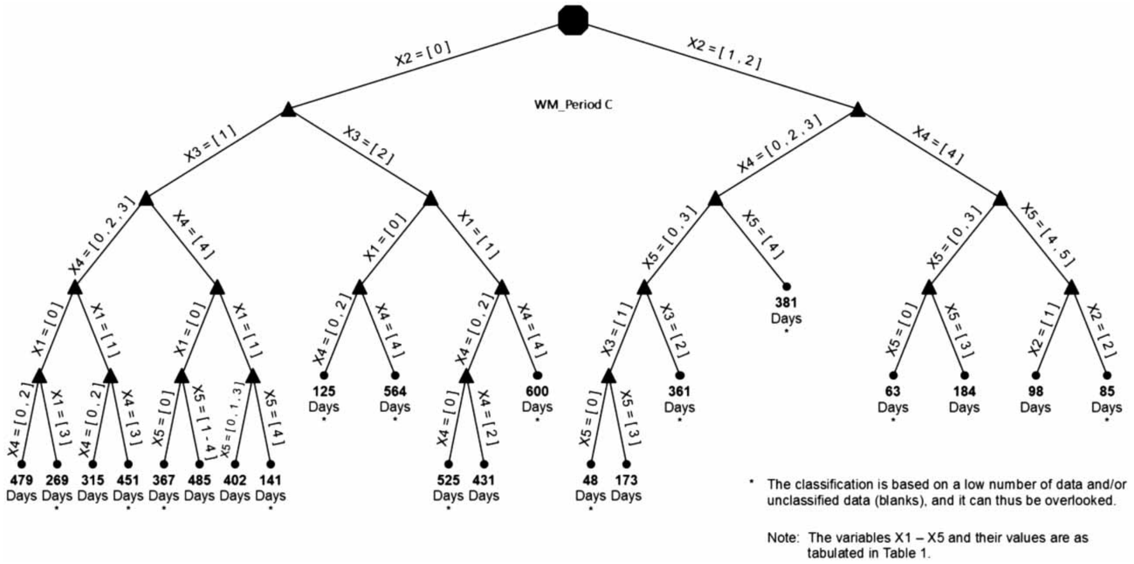


Figure 2 | Regression tree of 'WM pipe' class incidents for 'time period B'.

with the other two since pipes of smaller diameter survive longer.

5. Next replacement action for a small main fitting element which did not experience any previous breaks is expected in 431 days.
6. Next action for an AC main pipe element that has up to four previous breaks is expected in 173 days. This result is in line with the other conclusions because as the NOPB increases, the TTF decreases dramatically.
7. Next action for an AC small main pipe element that has up to four previous breaks is expected in 184 days. This result is in line with the finding (6), since pipes of smaller diameter survive longer.
8. Next action for a Ductile-Iron (DI) small main pipe element that has 1–4 previous breaks is expected in 98 days.

From the above results, it can be deduced that the introduction of data associated with the time period from 31/03/2008 to 31/12/2010 (IWS period) has, as expected, significantly increased the observed TTF for these elements.



* The classification is based on a low number of data and/or unclassified data (blanks), and it can thus be overlooked.

Note: The variables X1 – X5 and their values are as tabulated in Table 1.

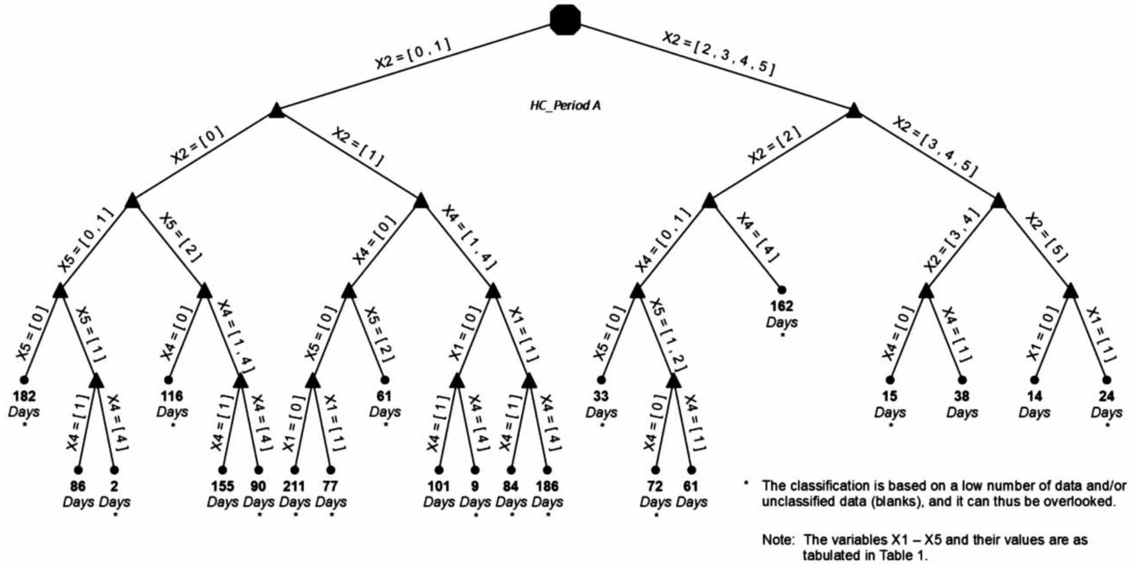
Figure 3 | Regression tree of 'WM pipe' class incidents for 'time period C'.

Hence, 'WM pipe' class elements are not affected by the IWS policies.

HC class

Figure 4 illustrates the resulting regression tree diagram for the 'HC pipe' class incidents in time period 'A' (01/01/2003–15/08/2005), which lasted 957 days. The most important conclusions drawn from the analysis are as follows:

1. Next action for a galvanized connection pipe element which did not experience any previous breaks is expected in 86 days.
2. Next action for a plastic connection pipe element which did not experience any previous breaks is expected in 155 days. This result is in line with the previous one since plastic pipes live longer.
3. Next repair action for a connection pipe element that has 1–4 previous breaks is expected in 101 days.



* The classification is based on a low number of data and/or unclassified data (blanks), and it can thus be overlooked.

Note: The variables X1 – X5 and their values are as tabulated in Table 1.

Figure 4 | Regression tree of 'HC pipe' class incidents for 'time period A'.

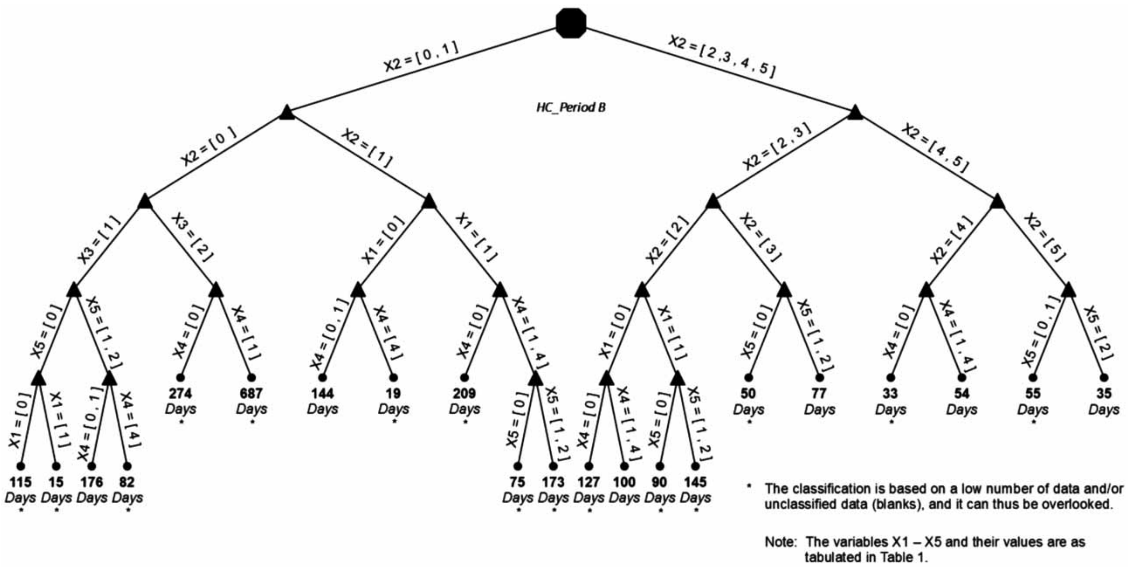
4. Next action for an HC element that has 5–8 previous breaks is expected in 61 days. This result is in line with the previous conclusions because as the NOPB increases, the TTF decreases dramatically.
5. Next action for an HC element that has 9–16 previous breaks is expected in 38 days. This result is in line with the previous statements because as the NOPB increases, the TTF decreases dramatically.
6. Next action for a HC element that has 16+ previous breaks is expected in 24 days. This result is in line with the previous statements because as the NOPB increases, the TTF decreases dramatically.

A regression tree diagram for the 'HC pipe' class incidents of the time period 'B' (01/01/2003–30/03/2008; 1914 days) is depicted in Figure 5. The most important information stemming from the analysis is as follows:

1. Next action for a connection pipe which did not experience any previous breaks is expected in 176 days.
2. Next repair action for a connection pipe element that has 1–4 previous breaks is expected in 144 days. This result is in line with the previous statement because as the NOPB increases, the TTF decreases dramatically.
3. Next repair action for an HC element that has 5–8 previous breaks is expected in 90 days. This result is in line with the previous statements because as the NOPB increases, the TTF decreases dramatically.
4. Next action for an HC element that has 9–12 previous breaks is expected in 77 days. This result is in line with the previous statements because as the NOPB increases, the TTF decreases dramatically.
5. Next repair action for an HC element that has 13–16 previous breaks is expected in 54 days. This result is in line with the previous statements because as the NOPB increases, the TTF decreases dramatically.
6. Next repair action for a plastic element that has more than 16 previous breaks is expected in 35 days. This result is in line with the previous statements because as the NOPB increases, the TTF decreases dramatically.

From the aforementioned results it can be deduced that the inclusion in the analysis of data associated with the time period from 16/08/2005 to 30/03/2008 has increased the TTF. Thus, the aforementioned time period did not negatively affect the condition of HC in the case-study WDN.

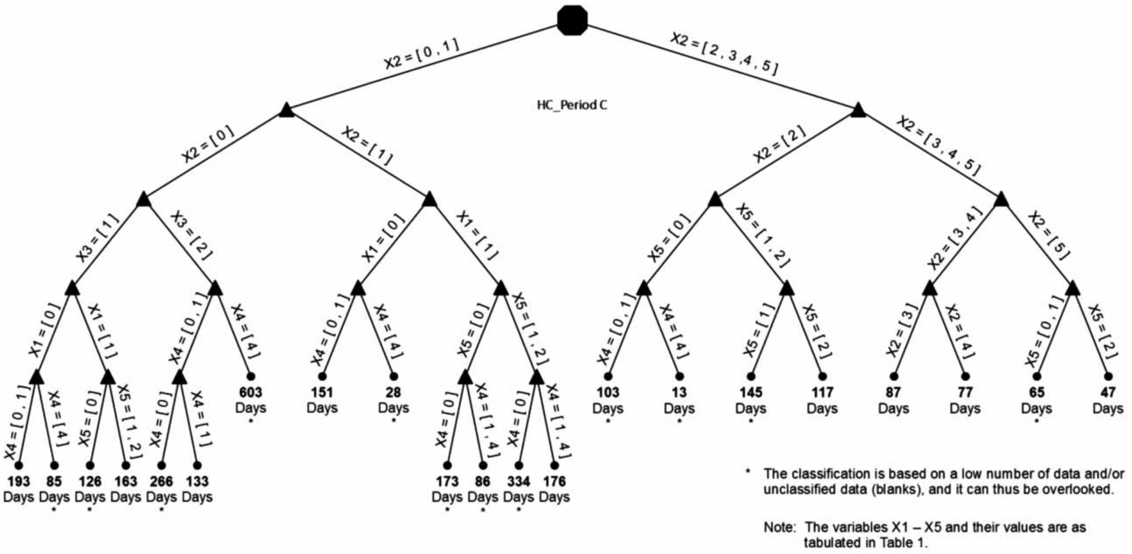
A regression tree diagram for the 'HC pipe' class incidents of the time period 'C' (01/01/2003–31/12/2010; 2919 days) is depicted in Figure 6. Since time period 'C' includes additional data and covers a longer period, it is expected that the TTF will significantly increase compared to the other two periods (period A and period B). The



* The classification is based on a low number of data and/or unclassified data (blanks), and it can thus be overlooked.

Note: The variables X1 – X5 and their values are as tabulated in Table 1.

Figure 5 | Regression tree of 'HC pipe' class incidents for 'time period B'.



* The classification is based on a low number of data and/or unclassified data (blanks), and it can thus be overlooked.

Note: The variables X1 – X5 and their values are as tabulated in Table 1.

Figure 6 | Regression tree of 'HC pipe' class incidents for 'time period C'.

most important information stemming from the analysis is as follows:

1. Next repair action for a connection pipe which did not experience any previous breaks is expected in 192 days.
2. Next replacement action for a pipe element which did not experience any previous breaks is expected in 163 days.
3. Next action for a connection pipe fitting which did not experience any previous breaks is expected in 133 days. This result is in line with the other two since pipes survive longer than fittings.
4. Next repair action for a connection pipe element that has 1–4 previous breaks is expected in 151 days. This result is in line with finding (1), because as the NOPB increases the TTF decreases.
5. Next replacement action for an HC element that has 1–4 previous breaks is expected in 176 days.
6. Next action for a plastic HC element that has 5–8 previous breaks is expected in 117 days.
7. Next action for an HC element that has 9–12 previous breaks is expected in 87 days.
8. Next action for an HC element that has 13–16 previous breaks is expected in 77 days. This result is in line with the previous one because as the NOPB increases, the TTF decreases.
9. Next action for a plastic HC element that has more than 16 previous breaks is expected in 47 days. This result is in line with the conclusion (6) because as the NOPB increases, the TTF decreases.

From the above results it can be deduced that the introduction of data associated with the time period from 31/03/2008 to 31/12/2010 (IWS period) has not significantly increased the TTF, and thus the IWS period negatively affects the condition of the HC elements within a WDN.

SURVIVAL ANALYSIS

To further investigate the effects of IWS on WDN vulnerability, the analysis was complimented with survival analysis. The findings of the survival analysis are discussed below.

Methodology

Survival analysis is a branch of statistics dealing with deterioration and failure over time. It involves the modelling of the elapsed time between an initiating event and a terminal event. In the case of WDNs, an initiating event is represented by the date of pipe installation, a near-terminal event is represented by the date of pipe repair and a terminal event is represented by the date of a pipe replacement. The mathematical model estimates the reliability of a system and its lifetime, subject to multiple risk factors. It aims to analyse the effect of these risk factors on the system's lifetime and the probability of survival, and on the expected mean TTF of each individual part of the system (Lee & Wang 2003; Hintze 2007). The data values used in the analysis are a mixture of complete and censored observations, where 'censored' is data with unknown initiating or terminal events.

There are two main reasons for the selection of survival analysis as the main tool for the development of analytical models for pipe degradation. The first has to do with the nature of the available data. The computerization for the records on leakage incidents in the WDN of NWB was started in 2003 and until then there is no available data record. One of the survival analysis features is that the existence of a completed data packet is not a prerequisite for the analysis. It has the ability to result in a reliable prediction, by making assumptions about the missing data, which are improved on each new data series import. The second reason relates to the behaviour of networks during aging. The initial application of survival analysis was in biology to simulate the effect of different diseases on the human organism through the passage of time. WDNs behave in the same way. Over time and with the increasing of failure incidents in a pipe system, the condition of the WDN worsens. For this reason, survival analysis models were applied since they successfully simulate the behaviour of the WDN's condition while aging and of the effect of any type of event that could happen in the WDN.

The applied mathematical model estimates the survival function by use of the non-parametric Kaplan–Meier (Kaplan & Meier 1958) estimator (Equation (1)):

$$\widehat{S}(t) = \begin{cases} 1 & \text{if} \quad T_{\min} > T \\ \prod\limits_{T_{\min} \leq T_i \leq T} \left[1 - \dfrac{d_i}{r_i}\right] & \text{if} \quad T_{\min} \leq T \end{cases} \tag{1}$$

where T is the elapsed time until the occurrence of a specified event; i is an index; D_t is the set of all failures (deaths) that occur at time T_t and d_t is the number of deaths in this set; R_t is the set of all individuals that are at risk immediately before time T_t and r_t is the number of individuals in this risk set. T_{min} refers to a minimum time below which failures are not considered (often used when data are left truncated).

The survival analysis presented herein is based on incidents related to two pipe classes, namely the WM and the HC. Analysis of each pipe class consists data of two part types that are the 'Pipe' and 'Fitting' elements. Since these analyses are examining the effect on the condition of the WDN for a specific time period and because of the existence of left-censored data causing shifting of survival curves, it was decided that elements whose birth date (i.e. installation date) is unknown they should be excluded. Additionally, the 'date of failure' and the 'date of rebirth' were considered to be the date that a leak-related incident was reported. The analysis performed was at street level.

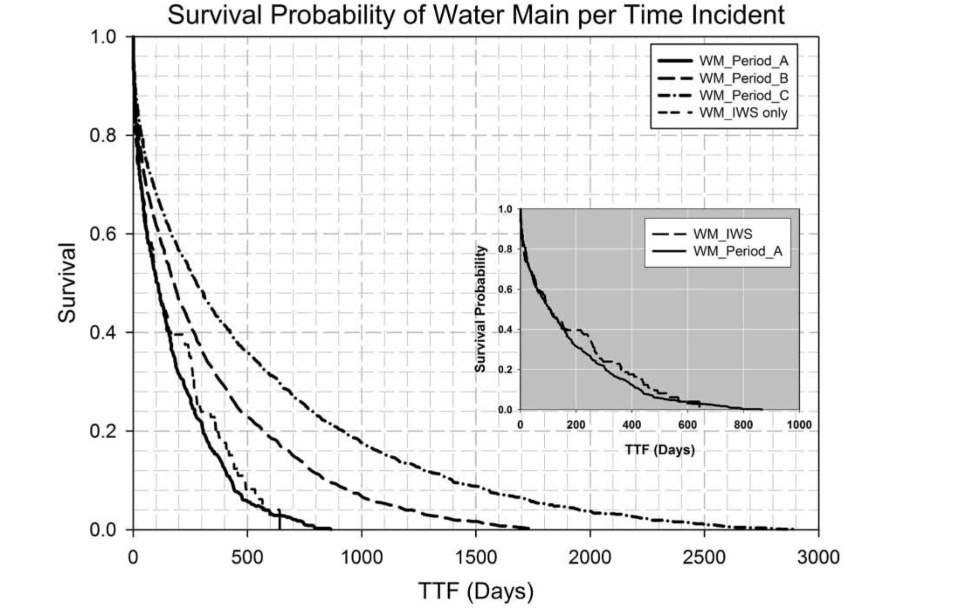
It should be noted that if the IWS operations are of no impact to the condition of the WDN then (1) the survival curves, of the aforementioned four time periods (A, B, C and IWS) will have the same approximate shape, and (2) the TTF and the probability of survival should improve when the time period of analysis and the number of incidents associated with it increase.

Analysis, results and discussion

WM class

The first analysis group refers to the WM class elements. This class includes all those pipe and fitting elements that constitute the main pipeline of a WDN. Figure 7 illustrates the resulting survival probability curves for the 'WM pipe' class incidents, for the time periods in study.

The survival probability curve for time period 'A' (01/01/2003–15/08/2005) lasts 957 days. The curve illustrates that during the first 475 days of an element's life, reduction in the probability of survival is very high, while the total lifetime of the model is 875 days. The elements' age as indicated by the analysis is very low. This is attributed to the type of data that were included in the analysis (the left censored data have been excluded). The focus on this short period (and the computed short survival periods) does not affect the final results since the study's intent is not to estimate the lifetime of an element, but rather it is to compare



Time Period A

Time Range	Total No of Days	Parts Type	Class	Incidents	Terminal Ev.	Censored Ev.	Terminal to Censored Ratio
01/01/2003 - 15/08/2005	957	Pipes Fittings	HC	2520	188	2332	8.1%
			WM	563	527	36	1463.9%

Time Period B

Time Range	Total No of Days	Parts Type	Class	Incidents	Terminal Ev.	Censored Ev.	Terminal to Censored Ratio
01/01/2003 - 30/03/2008	1914	Pipes Fittings	HC	6129	498	5631	8.8%
			WM	1526	1426	100	1426.0%

Time Period C

Time Range	Total No of Days	Parts Type	Class	Incidents	Terminal Ev.	Censored Ev.	Terminal to Censored Ratio
01/01/2003 - 31/12/2010	2919	Pipes Fittings	HC	13831	1648	12183	13.5%
			WM	2556	2193	363	604.1%

Time Period IWS

Time Range	Total No of Days	Parts Type	Class	Incidents	Terminal Ev.	Censored Ev.	Terminal to Censored Ratio
31/03/2008 - 31/01/2010	672	Pipes Fittings	HC	1922	356	1566	22.7%
			WM	249	169	80	211.3%

Figure 7 | Survival plot of 'WM pipe class' incidents per time period.

the ages that are given by the four different scenarios, under the same conditions.

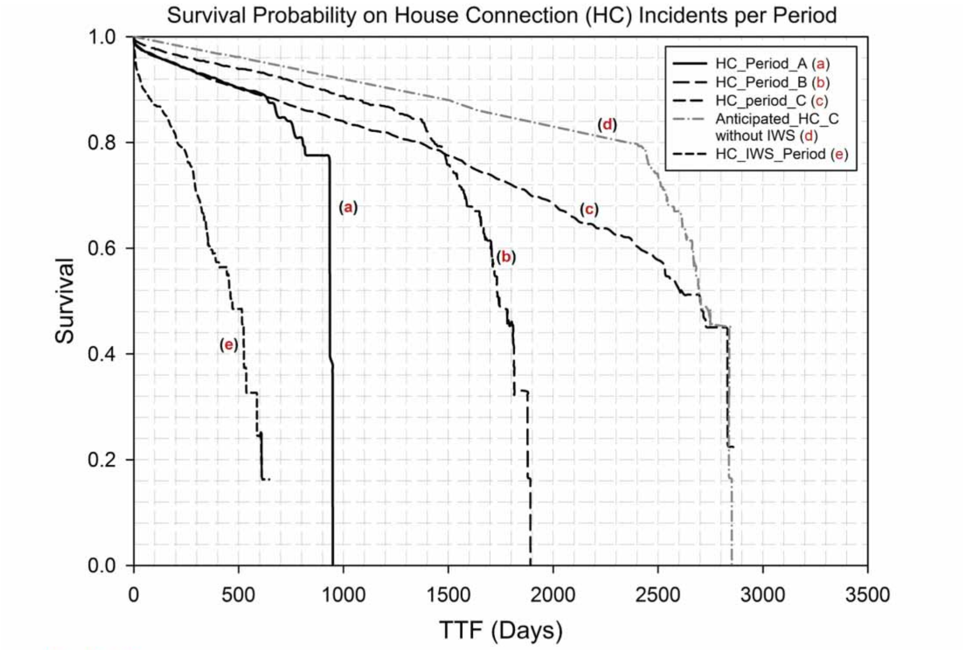
The survival probability curve representing the survival curve for the second time period ('B'), which lasts 1914 days, has the same shape as the curve of 'A', with an increase in the TTF and in the survival probability. This increase was expected, since older elements (compared to those of the first time period) are incorporated into the analysis data, thus positively affecting the survival probability. The curve of survival probability for the time period 'C' is expected to improve compared to the corresponding curve of the time period 'B', while keeping the same shape. Analysis of the data associated with the third time period results in a survival probability curve ('C') that has a similar shape as that of the other two time periods, which has a lifetime of 2900 days. Therefore analysis of the time period 'C' reached an expected outcome. This suggests that with respect to 'WM pipe class' incidents, the IWS did not greatly affect the survival rate of 'WM' pipe class.

Finally, a survival analysis of the recorded data associated with the 'WM' class during the IWS period is performed, aiming for a further study of the effect of the IWS period. The resulting plot is represented by the curve 'IWS only'. As shown, the shape of the curve is similar to that of the other three survival probability curves, as it should be. The TTF of the curve is shorter than that of 'A', as expected. The shown higher probability of survival at higher levels is attributed to the fact that the data regarding the incidents that occurred from 08/01/2009 to 31/12/2009 were not available for inclusion in the analysis. The result of the last analysis confirmed the conclusions that have been derived by the previous three analyses.

HC class

The second analysis group refers to the HC class elements. This class includes all pipe and fitting elements that connect the consumers' water meters to the WM pipeline. Figure 8 illustrates the resulting survival probability curves for the 'HC pipe' class incidents, for the time periods in study.

The survival probability curve of time period 'A' lasts 957 days. The survival probability is reduced by only 17% during the first 600 days of the element's life. The drop in the survival probability is low up to the 925 days of the



Time Period A

Time Range	Total No of Days	Parts Type	Class	Incidents	Terminal Ev.	Censored Ev.	Terminal to Censored Ratio
01/01/2003 - 15/08/2005	957	Pipes Fittings	HC	2520	188	2332	8.1%
			WM	563	527	36	1463.9%

Time Period B

Time Range	Total No of Days	Parts Type	Class	Incidents	Terminal Ev.	Censored Ev.	Terminal to Censored Ratio
01/01/2003 - 30/03/2008	1914	Pipes Fittings	HC	6129	498	5631	8.8%
			WM	1526	1426	100	1426.0%

Time Period C

Time Range	Total No of Days	Parts Type	Class	Incidents	Terminal Ev.	Censored Ev.	Terminal to Censored Ratio
01/01/2003 - 31/12/2010	2919	Pipes Fittings	HC	13831	1648	12183	13.5%
			WM	2556	2193	363	604.1%

Time Period IWS

Time Range	Total No of Days	Parts Type	Class	Incidents	Terminal Ev.	Censored Ev.	Terminal to Censored Ratio
31/03/2008 - 31/01/2010	672	Pipes Fittings	HC	1922	356	1566	22.7%
			WM	249	169	80	211.3%

Figure 8 | Survival plot of 'HC pipe class' incidents per time period.

model's lifespan, and it suddenly increases after that point. The component's lifetime has a probability of 77% to exceed this age, while the total lifetime of the model is 950 days. The survival probability curve representing the survival curve for the second time period ('B'), which lasts 1,914 days, has the same shape as the curve of 'A', with an increase in the TTF and in the survival probability. This increase was expected due to the fact that older elements, compared to those of the first time period, are incorporated into the analysis data, thus positively affecting the survival probability. The survival probability is reduced by only 10% during the first 700 days of the element's life. The drop in the survival probability is low up to the 1,500 days of the model's lifespan, and it suddenly increases after that point. The component's lifetime has a probability of 80% to exceed this age, while the total lifetime of the model is 1,900 days. The curve of survival probability for the time period 'C' is expected to keep the same shape, while having higher survival probability levels than the 'B' curve. Thus, analysis of the data related to the time period 'C' is expected to have resulted in a survival probability curve similar to curve 'd' of Figure 8. Instead of that, the survival probability time period 'C' is reduced by 40% during the first 2,200 days of the element's life. The element's lifetime has a probability of 52% to exceed the lifetime of 2,700 days. Therefore analysis of the time period 'C' does not reach the expected outcome. This result is strong proof that the IWS policies are negatively affecting the condition of the WDN, especially the 'HC' pipe class.

Finally, a survival analysis of the recorded data associated with the 'HC' Class during the IWS period is performed, aimed at the further study of the effects of the IWS period. The resulting plot is represented by curve 'e' in Figure 8. As shown, even though the shape of curve 'e' should have been similar to that of curves 'a', 'b' and 'd', it actually is not. The result produced by the previous analysis confirmed the conclusions that have been derived by the previous three analyses, that the IWS policies are detrimental to the condition of the 'HC' class elements.

CONCLUSIONS

The work presented in this paper examines the behaviour of WDNs during a period of IWS. It investigates the effects of this policy on the behaviour, condition and failure rate of the pipeline system by studying the change in the rate of occurrence of failures, using both regression trees and survival analysis. The analyses show that during the period of implementation of IWS and right after that, there is a significant increase in the number of water loss incidents and a deterioration of the network condition, indicating that IWS operations negatively impact the vulnerability of WDNs. This is particularly evidenced in the case of house-connection pipes ('HC pipe' class).

Decision-tree analysis showed that the 'WM pipe' class elements are not significantly affected by the IWS policies. The TTF for this class of elements is significantly increased as the length of the time period is increased, which means that the vulnerability rate of this class is not increasing during the IWS period. On the other hand, the regression tree diagrams associated with the 'HC pipe' class elements show that this class is negatively affected by the IWS policies. The TTF for this element class is not significantly increased as the length of the time period is increased, which means that the vulnerability rate of the 'HC pipe' class elements increases during the IWS period.

The results extracted from the survival analysis confirm the findings of the decision-tree analysis. The results given by survival analysis of the three discrete time periods show that the IWS policy did not greatly affect the survival rate of the 'WM pipe' class elements. Conversely, the results given by survival analysis of the 'HC pipe' class elements show a significant reduction of the survival rate during the IWS period. This result confirms that the IWS policies are negatively affecting the condition of the 'HC pipe' class elements.

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