© IWA Publishing 2014 Journal of Water Supply: Research and Technology—AQUA | 63.3 | 2014

Impact of weather conditions on pipe failure: a statistical analysis

B. A. Wols and P. van Thienen

ABSTRACT

The occurrence of pipe failures in drinking water distribution networks may be influenced by weather conditions. In this work, a statistical analysis is performed to study the correlations between weather parameters and pipe failure in the Netherlands with the ultimate aim to predict the effects of climate change on network integrity. Failure data from a Dutch national failure database were divided into different cohorts, depending on type of pipe material, year of installation, and diameter class. Weather data related to temperature, drought, and wind were collected. Relationships between weather data and failure data were sought using a linear regression analysis and a frequency analysis. The latter analysis results in a weather variable dependent pipe failure frequency. The most obvious relationships were found between pipe failure and temperature. Failures in asbestos-cement (AC) and steel pipes increased during warm periods, which often simultaneously occurred when water consumptions were high. For cast iron pipes, failures increased at low temperatures. Drought parameters had a smaller effect on pipe failure than temperature, but still an increase in pipe failure was observed during dry periods for AC and steel pipes. No effect of weather conditions on pipe failure were observed for poly(vinyl chloride) and polyethylene pipes.

Key words | asset deterioration, climate change, drinking water distribution systems, failure database, pipe failure, weather

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INTRODUCTION

The occurrence of pipe failures in drinking water distribution networks may be influenced by weather conditions. For example, hot and dry periods as well as cold periods may lead to increased pipe failure (Newport 1981). Climate change may therefore have an important impact on pipe failure in the future. According to UKWIR (2012), little work has been done to predict the effects of climate change on asset performance and deterioration, particularly in sufficient detail to allow these effects to be properly assessed and quantified. The authors of UKWIR (2012) therefore recognize the need for further research into the relationships between parameters expressing climate change and asset deterioration. Models may assist in understanding these relationships, but also to predict asset deterioration in the future. Models therefore assist in asset management decisions for climate change adaptation.

Rajani & Kleiner (2001) and St Clair & Sinha (2012) define different classes of models. The model approaches are either mechanistic-based or data based (e.g., statistical/probabilistic). Mechanistic models are based upon the underlying physics and therefore more robust, but limited by existing knowledge and available data. Few mechanistic models are available to assess the impact of climate change on pipe failure. A model to predict pipe stresses caused by thermal expansion/contraction of the pipe is described in Rajani *et al.* (1996). Recently, we developed a model that predicts pipe stresses induced by soil differential settlements associated with groundwater lowering due to climate change (Wols & van Thienen 2014).

Statistical models derived from observations provide valuable insights into the relationships between pipe failure and all kinds of parameters influencing pipe failure

doi: 10.2166/aqua.2013.088

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(Vloerbergh & Blokker 2010). Although the mechanisms behind these relations remain largely unexplored (black box approach) and the obtained correlations do not necessarily imply causation, the statistical model is based upon real experimental data and is therefore useful to reveal parameters affecting pipe failure. Many statistical analyses on pipe failure have been performed (Newport 1981; Rajani *et al.* 1996; Kleiner & Rajani 2002; Pelletier *et al.* 2003; Gould *et al.* 2011). In general, these studies show that failure rates increase as pipe diameter decreases, as the shrink/swell potential of the soil increases, and as pipe age increases. Fewer studies were performed on dynamical (time-varying) effects related to weather on pipe failure. The mostly observed weather effect is an increased pipe breakage rate during hot and dry summers, related to soil shrinkage and settlements (Newport 1981; Kleiner & Rajani 2002; Hu & Hubble 2007; Gould *et al.* 2011). This weather effect is stronger in more expansive soils (Hu & Hubble 2007; Gould *et al.* 2011), and may also be accelerated by vegetation-induced desiccation (Clayton *et al.* 2010). Since groundwater level data are usually not available, suitable proxies for soil moisture are antecedent precipitation index (Gould *et al.* 2011) or cumulative rain deficit (Hu & Hubble 2007). Gould *et al.* (2011) observed that during dry periods, mainly the circumferential failures are increased, while there is no influence on longitudinal failures.

An increased pipe breakage rate is also observed in cold winters due to frost loads (Newport 1981). Rajani & Tesfamariam (2004) observed a marked increase in pipe failure in the presence of high temperature differences between the water in the pipe (1–2 °C) and adjacent soil (10–12 °C). In the UK, using the UKWIR's national mains failure database (UKWIR 2012), the most reliable climate variable turned out to be days of air frost, showing that both metal and plastic pipe failures increase by 4 to 10% per additional day of air frost in a month.

In this work, a statistical analysis is performed to study the correlations between weather parameters and pipe failure in the Netherlands. Ultimately (beyond the scope of this work), the results of the current study could be combined with climate change scenarios to predict the effects of climate change on network integrity. Hereby, the short-term variations in meteorological elements (expressed by weather variables) are used to identify the effect of long-term variations in meteorological elements (expressed as climate change) on the water distribution network.

MATERIALS AND METHODS

Pipe failure data

Data from USTORE (Vloerbergh & Blokker 2010; Vloerbergh *et al.* 2012), a Dutch national pipe failure database, were used for the statistical analysis, including in total 10,325 pipe and joint failures over a 4-year period (January 2009–December 2012) collected from several Dutch drinking water companies. The failures were divided into different cohorts. For each cohort, the number of failures, the average failure frequency and the average age of the pipe that had failed is shown in Table 1.

Most of the pipe and joint failures occurred in the pipe (≈80%). However, joints fail at a younger age than pipes on average. Note that the joint failure frequency was derived from the total length of the pipe network, not from the total number of joints that were present in the network. In other words, a frequency of 0.01#/km/year implies that on average one joint fails each year in 100 km of pipe (regardless of the joint distance). For the failures occurring in the pipe, a sub-selection was made into pipes that failed by internal and/or external loads or degradation of the pipe (cohort 4), canceling out causes such as third-party interference and wrong installations. Further division into cohorts was made based upon pipe material (cohorts 5–8), pipe diameter (cohorts 9–11), and pipe installation year (cohorts 12–14). The poly(vinyl chloride) (PVC) + polyethylene (PE) cohorts mainly contain failures in PVC (95%). The cast iron (CI) cohort contains failures in gray cast iron (86%) and ductile iron (14%). Also, for the jointed pipes a sub-selection was made into joints that failed by internal and/or external loads or degradation of the pipe (cohort 15), which was further divided into asbestos-cement (AC) joints (cohort 16) and PVC joints (cohort 17).

Weather data

Weather data were collected from KNMI (Royal Netherlands Meteorological Institute), for the weather station De Bilt located in the center of the Netherlands. Since the

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Table 1 | Cohorts selected from USTORE data

Nr.	Object	Cause	Mat.	D m	Year	Fail. #	Fail. freq. #/km/yr	Age Yr
1	All	All	All	All	All	10,325	0.0516	45
2	Joint	All	All	All	All	2,090	0.0104	39
3	Pipe	All	All	All	All	7,795	0.0390	46
4	Pipe	Loads, degr	All	All	All	6,059	0.0303	49
5	Pipe	Loads, degr	AC	All	All	3,697	0.0532	50
6	Pipe	Loads, degr	ST	All	All	768	0.1404	57
7	Pipe	Loads, degr	PVC + PE	All	All	829	0.0088	30
8	Pipe	Loads, degr	CI	All	All	731	0.0264	63
9	Pipe	Loads, degr	All	< 0.2	All	5,437	0.0334	50
10	Pipe	Loads, degr	All	0.2–0.5	All	597	0.0204	48
11	Pipe	Loads, degr	All	> 0.5	All	18	0.0023	37
12	Pipe	Loads, degr	All	All	< 60s	2,627	0.0784	61
13	Pipe	Loads, degr	All	All	60s–80s	2,377	0.0319	43
14	Pipe	Loads, degr	All	All	> 80s	501	0.0058	18
15	Joint	Loads, degr	All	All	All	1,551	0.0078	44
16	Joint	Loads, degr	AC	All	All	727	0.0105	51
17	Joint	Loads, degr	PVC + PE	All	All	350	0.0037	27

Netherlands is a small country, the weather in De Bilt was regarded as representative for the whole country. The following variables were collected on a daily basis (Table 2): temperature, wind, precipitation, potential evapotranspiration. For the potential evapotranspiration, the definition of Makkink was applied (Hiemstra & Sluiter 2011). Rain deficit and antecedent precipitation index were calculated from the KNMI data to characterize the drought (cumulative effect). The parameter API (Linsley *et al.* 1949; Choudhury & Blanchard 1983) is expressed by (Gould *et al.* 2011)

$$API^{(n)} = 0.85API^{(n-1)} + P^{(n)} \quad (1)$$

Table 2 | Weather variables collected from KNMI

Weather variable		
Mean daily temperature	*TG*	C
Maximum daily wind gust	*FEX*	m/s
Daily precipitation amount	*P*	mm
Potential evapotranspiration	*E*	mm
Rain deficit	*RD*	mm
Antecedent precipitation index	*API*	mm

Since we are not interested in the absolute values of API but only in its relation with failure data, the exact value of this parameter is of less importance. In fact, comparable results of our study were obtained if a coefficient of 0.9 or 0.95 was chosen.

Rain deficit was defined over a period starting at the 1st of April until the 1st of October

$$RD^{(N)} = \sum_{1}^{N}\left(E^{(n)} - P^{(n)}\right) \quad (2)$$

where index of 1 refers to 1st April, and N the day of interest. From 1st October until 1st April, the RD is zero. The following weather variables were considered in the statistical analyses: temperature (TG), wind (FXX), and drought (RD, API).

Linear regression analysis

The weather data were used to find correlations between weather variables and pipe failure. Pipe failure was represented by failure frequencies, which were determined over a certain time interval. The time interval needs to be

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chosen small enough to capture the variation in weather patterns, and large enough to have sufficient failures per time interval. Therefore, a time interval of 2 months was chosen. The 2-monthly weather variables were calculated as the average of the daily variables over the specific months. Regression lines between weather variables and failure frequencies were determined by minimizing least-squares errors from a linear fit (using Matlab built-in function regress). This analysis can be performed in different ways: (1) fitting a regression line for each single weather parameter; (2) fitting a combination of predefined weather parameters using multiple linear regression (MLR). For the second analysis, one should be cautious about cross-correlations between weather parameters. MLR was applied for the parameters TG and RD.

Uncertainty bounds on the failure frequency were determined from the number of failures corresponding to that failure frequency. By assuming that the occurrence of failures can be described by a Poisson distribution, the lower and upper bounds for a $(1–\alpha)$ confidence interval can be determined. In our study, $\alpha = 0.2$ was used.

Frequency analysis

Alternatively, instead of using a fixed time interval, a fixed interval of a weather variable can be used in the analysis. In this way, the extremes of a weather variable are better represented. By comparing the amount of failures over a certain weather variable interval with the number of days for which that interval occurs, the effect of a weather variable on the failure is obtained (Figure 1). The method will be explained for the analysis of the relation between daily mean temperature and pipe failure.

First, for a certain cohort, a number of failures is recorded on a daily basis over a certain period, for example 2009–2012. Also, the water distribution network length for which these failures have occurred is recorded on a daily basis (relevant in situations where the distribution network associated with these failures changes). The daily mean temperature over that time interval is recorded as well. The daily mean temperature is divided into an arbitrary number of intervals, for example 10 intervals. For each interval, the number of days that these particular temperatures occur and the number of failures that occur on these days are recorded. A failure frequency is obtained for each temperature interval by dividing the sum of daily failures in each temperature interval by the sum of pipe lengths in the same interval.

RESULTS

The number of failures over time are plotted together with the most relevant weather variables over the period 2009–2012 (Figure 2). The weather data are shown as daily and 2-monthly averages. The 2-monthly period captures the seasonal patterns, but also to some extent particular weather events (hot summer, dry summer, cold spell, etc.).

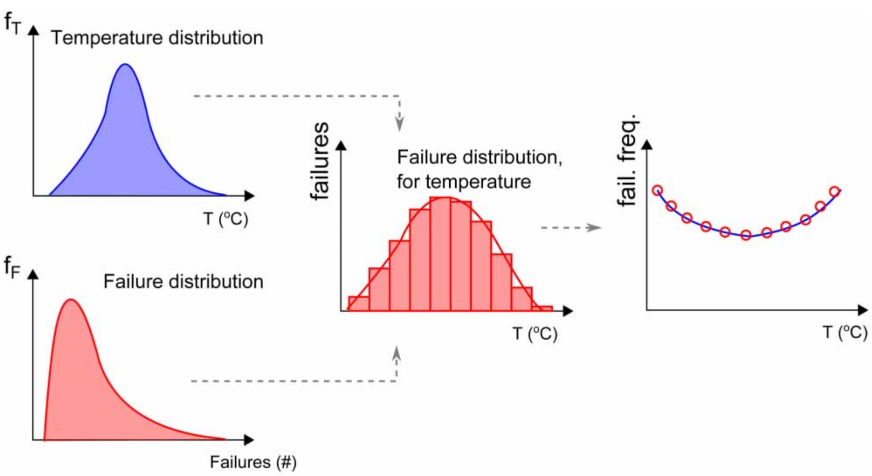

Figure 1 | Schematic overview of frequency analysis.

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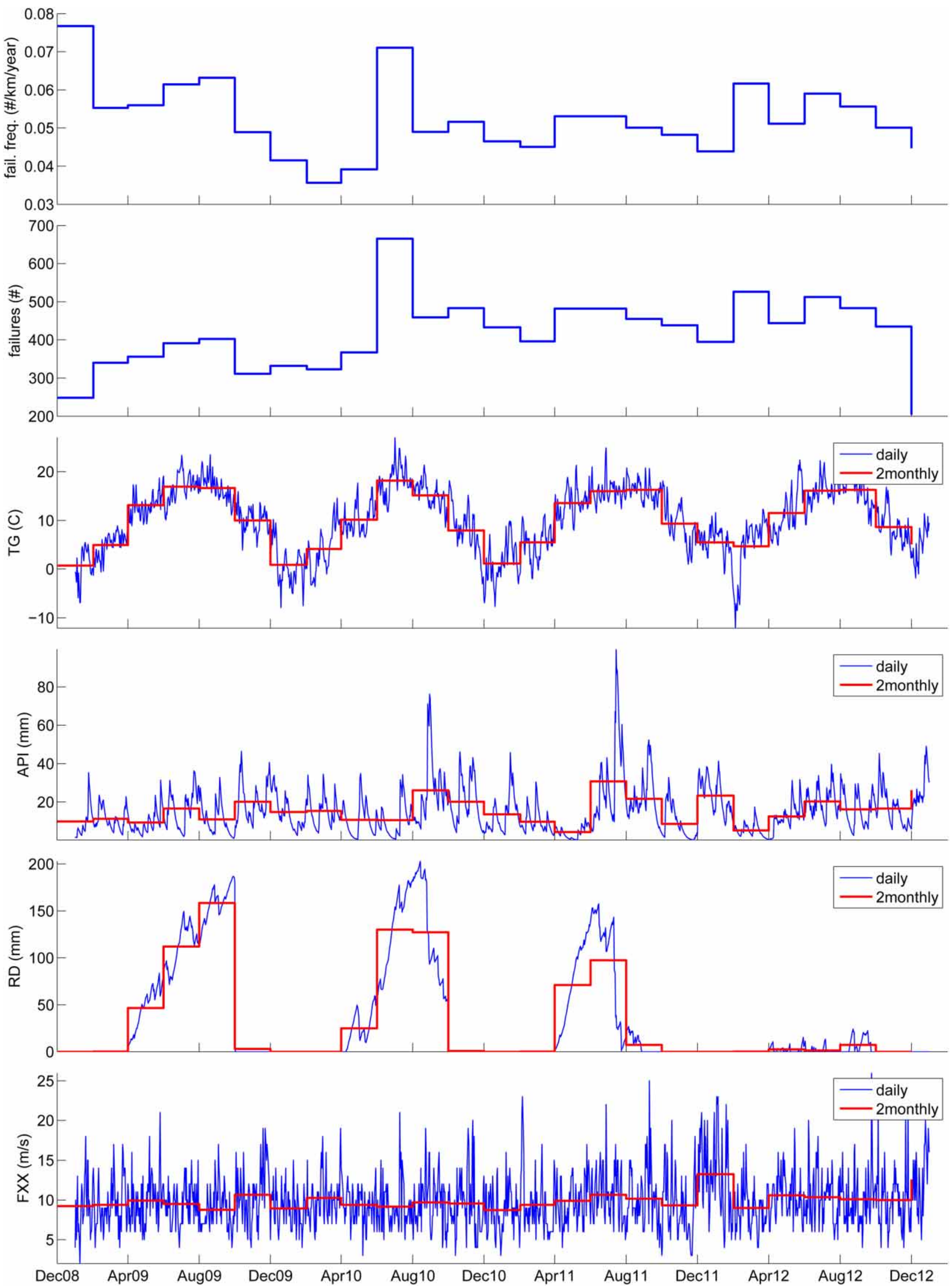

Figure 2 | Time series of failure data and weather data on daily and monthly basis. During the year 2009 the number of failures increased (whereas the failure frequency decreased), because more water companies registered their failure data.

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Linear regression analysis

The correlations of the weather variables and failure frequencies are shown in Table 3 for the selected cohorts. More details of the observed relations between pipe failure and the four weather variables can be found in Figure 3.

No significant correlations were found if all failure data are lumped together (cohort 1). This is also observed for all failures occurring separately in the pipe (cohort 3) or joint (cohort 2). When only considering failures caused by loads on and degradation of the pipe (cohort 4), some minor correlations with rain deficit and temperature were found. Further subdivision of this subset into pipe materials resulted in marked correlations of AC pipe failure with temperature and rain deficit (cohort 5), steel pipe failure with temperature (cohort 6), and CI pipe failure with temperature (cohort 8). No significant weather influence on plastic pipes was found (cohort 7). The combination PVC and PE showed similar results as PVC alone. Note that for steel, PVC, and CI pipes, the number of failures in 2 months was relatively small, resulting in large uncertainties. Subdivision of pipe failure into diameter size (cohorts 9–11) and year of installation (cohorts 12–14) resulted in minor correlations of pipe failure with temperature for the small pipes and for the pipes installed between 1960 and 1980. For joint failures (cohorts 15–17), the AC joints showed correlations with temperature and rain deficit, and a minor correlation with temperature was observed for the plastic joints. No significant correlations of pipe and joint failure with wind was observed for any of the cohorts.

By applying MLR, several weather parameters can be combined. The combination of temperature and RD resulted only in a small increase in R^2, because temperature and drought parameter RD were strongly cross-correlated (Table 4). Droughts often occur during periods of high temperatures. Also, cross-correlations of FXX (wind) and API may be caused by the combination of rainy and windy weather, associated with low-pressure systems.

Frequency analysis

The frequency analysis was applied for the cohorts listed in Table 1. The failure frequency as a function of weather variable was calculated. The relation between weather variable and pipe failure was more pronounced in this analysis (Figures 4

Table 3 | Statistical results for cohorts, showing the coefficient of determination (R^2) between pipe failure frequency and weather variables for each cohort. More details on the regressions of the bold cohorts are provided in Figure 3

Nr.	Cohort	Fail. (#)	TG	API	RD	FXX	TG + RD
1	All	10,325	0.10	0.07	0.16	0.11	0.16
2	Joint	2,090	0.00	0.13	0.07	0.14	0.14
3	Pipe	7,795	0.15	0.03	0.15	0.06	0.18
4	Pipe, loads + degr	6,059	0.20	0.00	0.22	0.03	0.26
5	**Pipe, loads + degr, AC**	**3,697**	**0.54**	**0.04**	**0.31**	**0.01**	**0.54**
6	**Pipe, loads + degr, ST**	**768**	**0.70**	**0.01**	**0.38**	**0.04**	**0.71**
7	**Pipe, loads + degr, PVC + PE**	**829**	**0.03**	**0.00**	**0.08**	**0.15**	**0.08**
8	**Pipe, loads + degr, CI**	**731**	**0.54**	**0.03**	**0.15**	**0.02**	**0.56**
9	Pipe, loads + degr, D < 0.2	5,437	0.17	0.00	0.21	0.03	0.23
10	Pipe, loads + degr, 0.2 < D < 0.5	597	0.17	0.12	0.07	0.00	0.17
11	Pipe, loads + degr, D > 0.5	18	0.02	0.10	0.05	0.02	0.05
12	Pipe, loads + degr, <1960	2,627	0.05	0.00	0.00	0.02	0.09
13	Pipe, loads + degr, 1960–1980	2,377	0.37	0.01	0.27	0.01	0.39
14	Pipe, loads + degr, >1980	501	0.00	0.00	0.01	0.07	0.04
15	Joint, loads + degr	1,551	0.03	0.13	0.16	0.17	0.18
16	**Joint, loads + degr, AC**	**727**	**0.47**	**0.01**	**0.31**	**0.02**	**0.49**
17	**Joint, loads + degr, PVC + PE**	**350**	**0.36**	**0.06**	**0.05**	**0.07**	**0.42**

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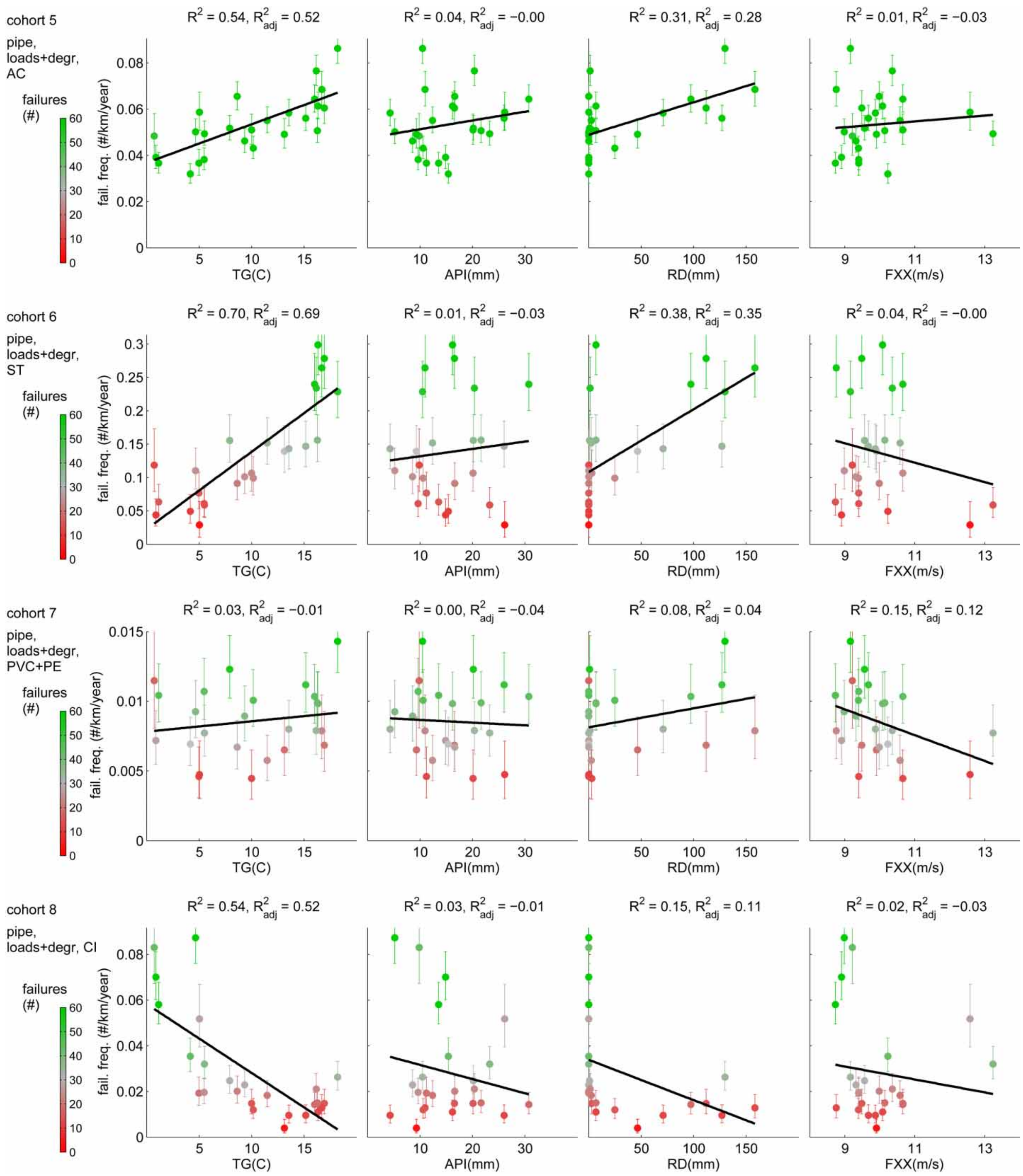

Figure 3 | Failure frequencies as a function of weather variables (temperature, drought, wind) for different pipe material cohorts. Each point represents a 2-month period. Error bars indicate the 80% confidence intervals. The number of failures is indicated using a scale.

and 5). A distinct amplification of pipe failure at low and high temperatures was already found for all failed objects (pipe and joint, cohort 1), which had not been observed in the regression analysis. This effect became larger when considering only the pipe (cohort 3) or only the pipe that had failed due to loads and degradation (cohort 4). Again, when considering the cohorts

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Table 4 | Cross-correlations of weather parameters, showing Pearson's coefficient of correlation

	TG	API	RD	FXX
TG	1.00			
API	0.19	1.00		
RD	0.67	0.06	1.00	
FXX	– 0.00	0.60	– 0.24	1.00

of the different pipe materials, the relations were most obvious. Similar trends as for the linear regressions were found, but the relations were more distinct and also non-linear. For AC pipes (cohort 5), an increase in pipe failure at high temperatures as well as at low RD (drought) was found. For steel pipes (cohort 6), a strong increase in pipe failure at high temperatures was observed. Consequently, at lower temperatures fewer pipe failures occurred. The same trend is visible for low RD, resulting in an increase in pipe failures during periods of drought. For plastic pipes (cohort 7), pipe failures are seemingly unaffected by the weather variables. For CI pipes (cohort 8), a strong increase in failure at low temperatures was found.

Also, for the joint failures, distinct relations with temperature were observed (Figure 5). An increase in joint failure at both the low and high temperatures (cohort 15) was found. The AC joints followed the same trend (cohort 16). In contrast to AC pipe failures, AC joint failures also increased at low temperature. Even for plastic joints (cohort 17), an increase in joint failure at low temperatures was observed, although the uncertainty is largely due to the low number of failures. This low temperature increase had not been observed for the plastic pipes. Thus, analysis of the jointed cohorts gives some indications that joints are more vulnerable to low temperatures than pipes.

DISCUSSION

The linear regression analysis and frequency analysis show that pipe failure is affected by weather variables. Temperature has the largest effect, followed by drought (mainly RD). An influence of wind on pipe failure, supposedly caused by uprooting of trees, has not been observed. However, no severe storms had occurred in the investigated period. Therefore it is not excluded that severe storms or hurricanes (which are not likely to occur in the Netherlands) may affect buried infrastructure, as studied after the hurricane Katrina (Allouche *et al.* 2008). For a better understanding of the influence of climate change on pipe failure, the (possible) mechanisms behind these relations are investigated.

First, the increase of pipe failure at high temperatures (mainly for AC and steel pipes) may be explained by the following.

- During hot periods in combination with droughts, lowering of ground water levels occur, resulting in additional external loads on the pipe due to (differential) settlements or soil shrinkage. These effects were also observed in other studies (Kleiner & Rajani 2001; Hu & Hubble 2007; Gould *et al.* 2011). For AC pipes that exhibited circumferential failure (about half of the failures, Figure 7), bending of the pipe caused by settlements may indeed be the cause.
- Increased water consumption during hot periods may result in increased internal loads on the pipe due to increased pressures (in some parts of the system) and/or velocities. Therefore, drinking water consumption data were considered for the Wieringen area (the Netherlands, total water use of approximately 0.5×10^6 m^3/year). Figure 6 shows the consumption data as a function of temperature and failure rate for the cohorts that showed the most pronounced influence by high temperatures: steel pipes (cohort 5) and AC pipes (cohort 6). Moderate correlations between mean temperature and water consumption as well as between failure and water consumption were found. These correlations were, however, weaker than the correlation between pipe failure and temperature. Thus, the increase in failure may partly be attributed to increased internal loads due to increased water consumption. Increase of water pressure as a cause for pipe failure at high temperatures can also be observed from the type of failures (Figure 7): steel pipes mainly exhibited point leaks, whereas AC pipes exhibited both circumferential and longitudinal failure. Longitudinal failure as well as point leak may be caused by higher internal loads (Rajani & Kleiner 2001), resulting from increased water pressures.
- During hot periods, soil temperatures may rise, resulting in thermal stresses caused by temperature differences between the soil and water in the pipe or thermal expansion

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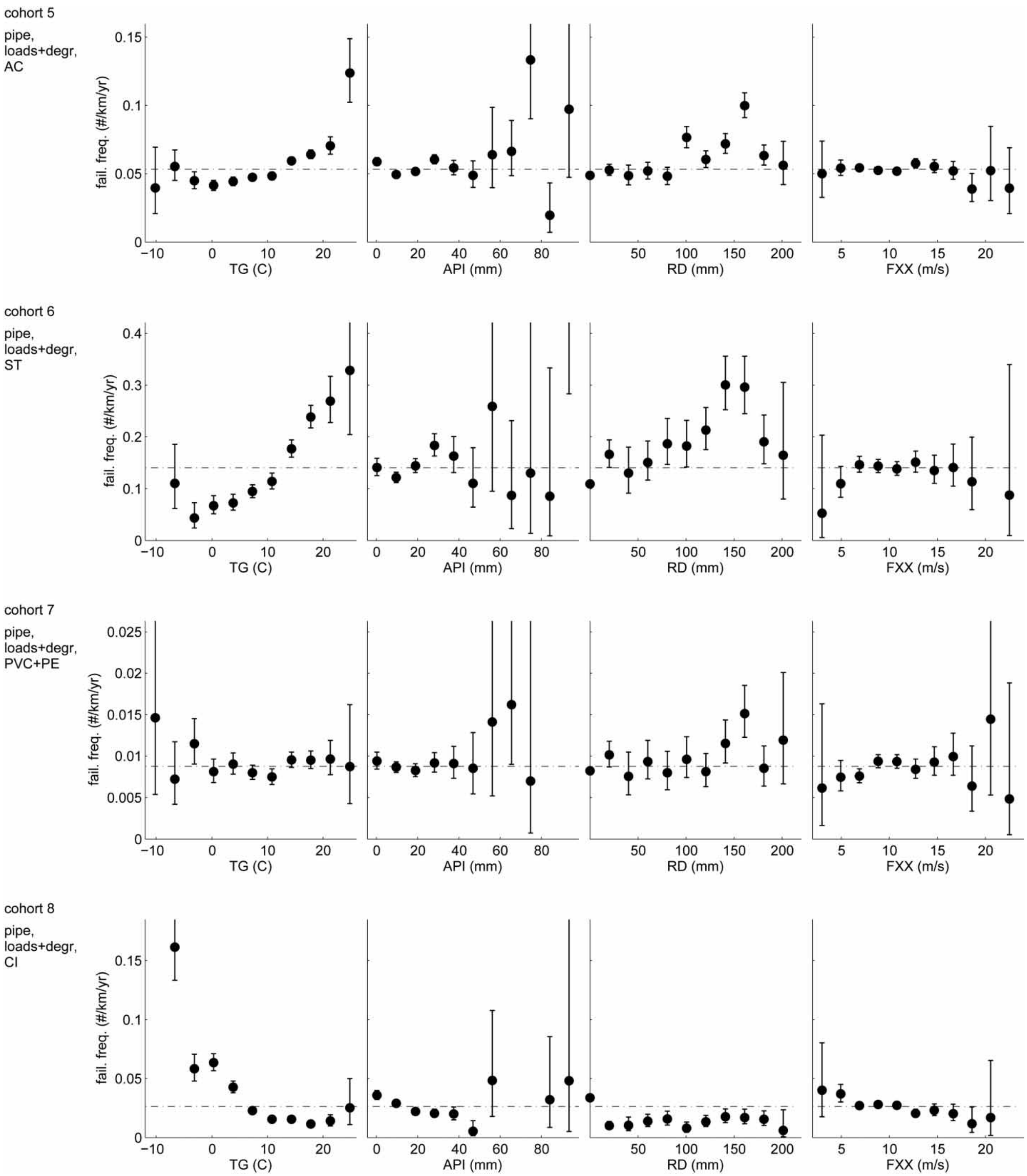

Figure 4 | Failure frequency as a function of weather variables (temperature, drought, wind) for different pipe material cohorts using the frequency analysis. Each point represents a number of failures over a fixed interval of the weather variable. Error bars indicate the 80% confidence intervals.

of the pipe in longitudinal direction (Rajani *et al.* 1996). Kuraoka *et al.* (1996) showed that variations of axial and hoop stresses as a result of seasonal variation of pipe temperature occurred, whereas the effect of water pressure variation was relatively low. The circumferential failures in AC may also be interpreted as a result of thermal stresses.

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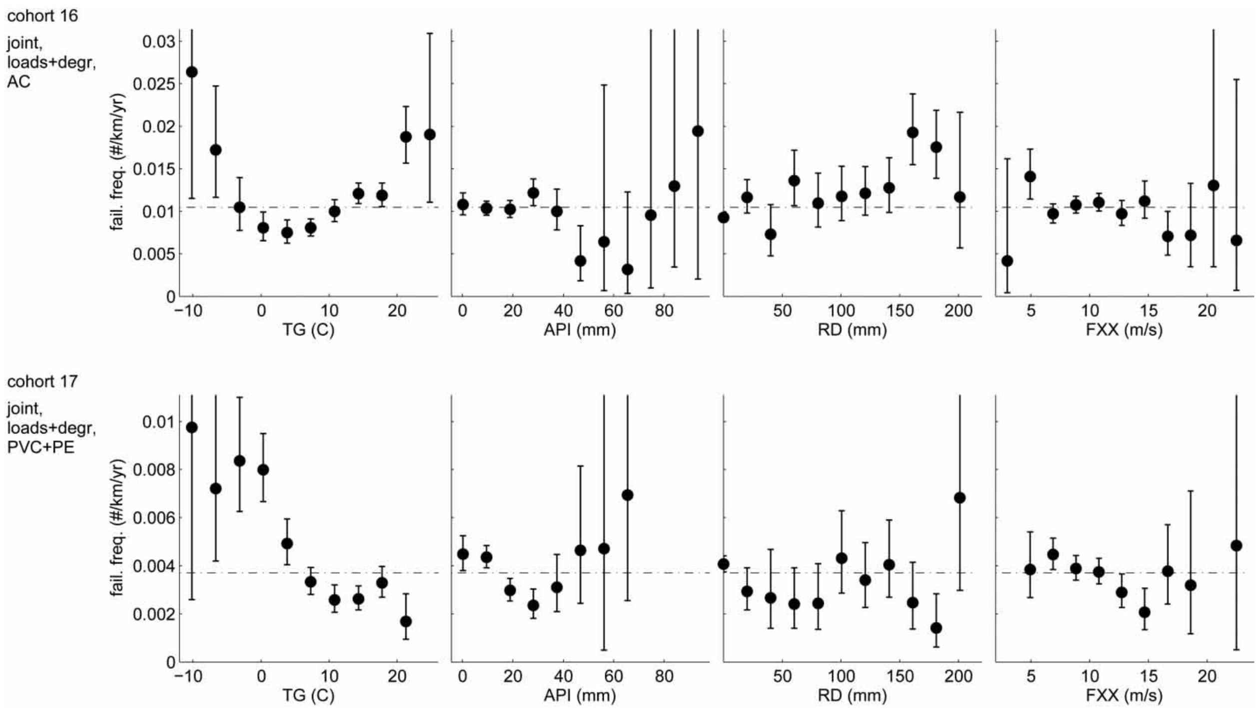

Figure 5 | Failure frequency as a function of weather variables (temperature, drought, wind) for different joint cohorts using the frequency analysis. Each point represents a number of failures over a fixed interval of the weather variable. Error bars indicate the 80% confidence intervals.

- Degradation processes (mainly corrosion) may be accelerated by higher temperatures (Rajani & Kleiner 2001), resulting in reduced strength of the pipe. However, time scales of these degradation processes (order of years) are much longer than the period of heat waves (order of weeks). Nevertheless, the pipes that were already partly degraded can more easily fail when pipe stresses increase due to settlements, thermal expansion or increased internal pressure.

Possible explanations for pipe failure at low temperatures (mainly for CI pipes) are as follows.

- During cold periods, soil temperatures drop, resulting in thermal stresses caused by temperature differences between the soil and water in the pipe. In Rajani *et al.* (1996), a mechanical model has been developed that predicts the stresses in the pipe due to temperature differences. CI mainly exhibited circumferential failure, which may point to thermal stresses.
- Freezing and melting of moisture in the ground surrounding the pipe (Rajani & Kleiner 2001). Although cold spells in the Netherlands are not severe enough to reach subzero ground temperatures at the pipe installation depth, soil displacement may occur due to freezing of the upper soil layer. The circumferential failure observed for CI pipes may also point to soil displacement.

This study also reveals a marked difference in behavior of AC and CI pipes. Although both materials are brittle, AC pipe failure increases with temperature, whereas the opposite occurs for CI pipes. A small increase in failure frequencies can also be observed for CI pipes at high temperatures, but this effect is small compared to the increase in failure rates at low temperatures. Possibly, the differences in joints between AC and CI provide an explanation: AC joints (similar to PVC joints) are flexible, whereas CI joints are rigid. Soil displacement, possibly occuring at low temperatures, therefore results in increased stresses in CI pipes, and increased joint rotations in AC pipes. The higher joint failure rate observed at low temperature in AC pipes (Figure 5) confirms this explanation.

The statistical analysis correlating weather data and failure data can be used to assess the impact of climate change.

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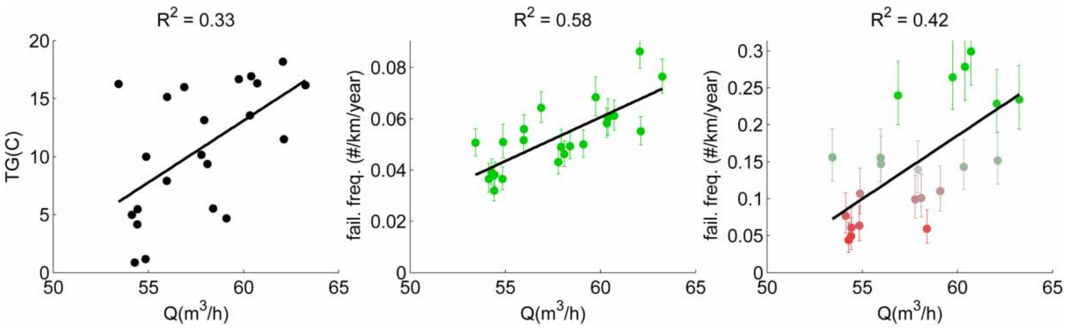

Figure 6 | Correlation between water consumption and mean temperature (left panel), water consumption and pipe failure for AC pipes (middle panel), and for steel pipes (right panel). Water consumption is represented by the flow rate *Q*.

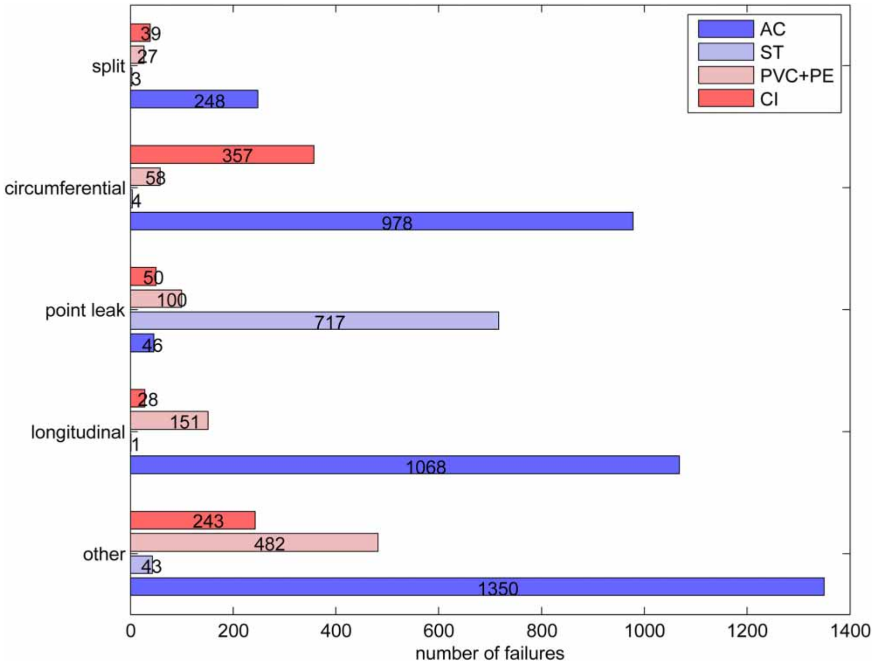

Figure 7 | Type of failures for the different pipe materials registered by USTORE.

The short-term variations in weather conditions have resulted in relationships between weather variables and pipe failure. These relationships can be used to assess the effect of long-term variations (climate change) in weather conditions on pipe failure. For example, the higher temperatures expected from climate change will result in an increased pipe failure rate for AC and steel pipes in the future. On the other hand, failure rates of CI pipes may decrease due to the higher temperatures, whereas the PVC pipes seem to be insensitive to temperature changes (although the failed PVC pipes are much younger – 30 years on average – than the other ones – 60 years on average). Since most of the pipes in the Netherlands are gradually being replaced by PVC pipes, the influence of climate change may be most pronounced in the medium term (in the coming 30 years).

CONCLUSIONS

A statistical analysis was employed to investigate the effect of weather conditions on pipe failures in drinking water distribution networks. The most obvious relationships were

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found for the pipe material specific cohorts. Linear regression analysis showed that marked correlations between pipe failure and temperature were found. Failures in AC and steel pipes increased at high temperatures, which can partly be attributed to higher water consumptions. For CI pipes, failures increased at low temperatures. The drought parameters had a smaller effect on pipe failure than temperature, but still an increase in pipe failure was observed during dry periods for AC and steel pipes. The joint failures followed similar trends as the pipe failures, except that joint failures also seemed to increase at the low temperatures. No effect of wind on pipe failure was observed. The relationships between weather variables and pipe failure in the short term can be used to assess the effect of long-term variations in weather conditions (climate change scenario data predicted by climate change models) on pipe failure, which will be the topic of future work.

ACKNOWLEDGEMENTS

This study was carried out in the framework of the Dutch national research program Knowledge for Climate (http://knowledgeforclimate.climateresearchnetherlands.nl/) and the joint research program of the Dutch Water Utility sector (http://www.kwrwater.nl/BTO/). The authors would also like to thank Peter Horst (PWN) for providing water use data.

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First received 1 May 2013; accepted in revised form 28 September 2013. Available online 30 November 2013

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