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Impact of climate on pipe failure: predictions of failures for drinking water distribution systems.

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The integrity of drinking water distribution systems (DWDS) may be influenced by climate change. Using the statistical relations between failure frequencies and weather conditions described in our previous work (Wols & Van Thienen 2014*a*), a methodology is proposed to assess the effect of climate change on future DWDSs. The effect of climate change is combined with the evolution of the DWDS. This analysis can be conducted for any DWDS, for which historical failure registrations and weather parameters are available. The proposed methodology can therefore assist in the construction and maintenance planning of DWDSs. The methodology has been worked out for the Dutch drinking water distribution network. The results show that failures in networks with high AC proportions will increase as a result of expected climate change in the Netherlands, whereas failures in networks with high PVC and GCI proportions will even slightly reduce.

Keywords: *Climate change, Pipe failure, Drinking water distribution systems, Failure database*

1 Introduction

The drinking water distribution system (DWDS) consists of a large number of underground pipes that transport water from treatment installations to households and companies. These underground pipes form a piece of infrastructure that play a vital role in maintaining our health and living standards. Underground drinking water infrastructure is designed to withstand a variability of forces during its lifetime before failure occurs. As a result of variations in loads on and deterioration of the pipe, early failures may occur. Climate change may accelerate or decelerate these processes, and is therefore relevant for maintenance decisions on the drinking water distribution system (DWDS). There is a lack of knowledge on quantitive relationships between climate change and asset deterioration (UKWIR 2012).
Several studies were conducted analyzing the influence of local weather conditions on pipe failure (Clark 1971, Newport 1981, Habibian 1994, Rajani et al. 1996, Rajani & Kleiner 2001, Kleiner & Rajani 2002, Rajani & Tesfamariam 2004, Hu & Hubble 2007, Clayton et al. 2010, Hu & Vu 2011, Gould et al. 2011, UKWIR 2012, Rajani et al. 2012, Laucelli et al. 2014). Increased pipe failure was observed in winter and summer periods, mainly during periods of freezing and drought. Consequently, temperature and temperature changes, freezing index, days of air frost, soil moisture deficit, antecedent precipitation index and rain deficit were identified as most important weather parameters. Fewer studies were performed to obtain predictive models for pipe failure that included variations in weather conditions. In the review paper of Rajani & Kleiner (2001), they referred to a study on

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artificial neural network modelling that included temperature, rainfall and operating pressure to predict pipe breakage. Hu & Hubble (2007) used a multi-variate exponential model to predict pipe breakage based on historical data. They included the variates background ageing, freezing index and rainfall deficit. Kleiner & Rajani (2002) used Fourier analysis of historical climate patterns to forecast climate in the coming years, which was combined with pipe ageing patterns to forecast water-main breaks. Such a Fourier analysis can be used as a fast alternative when more robust climate forecasts are not available. Kleiner & Rajani (2010) presented a tool called I-WARP to predict pipe breakage patterns based upon pipe-dependent covariates and time dependent climate variables (freezing index and rain deficit). They demonstrated pipe failure predictions over a 5 year period in a small DWDS based upon 40 years of historical pipe breakage data. In the work of Rajani et al. (2012) and Laucelli et al. (2014), pipe bursts were found to be influenced by temperature related covariates, such as water and air temperature, changes in temperature and freezing index. Laucelli et al. (2014) used evolutionary polynomial regression methods (Savic et al. 2009) to relate pipe bursts with weather data and was able to make good predictions of pipe bursts in the cold season for the upcoming 1 or 2 years. So far, all these predictive models have focused on short-term predictions of pipe failure (order of a few years), whereas significant changes in climate occur on a longer time scale. This study focuses on the predictions of pipe failures on these longer time scales. The objective is to develop a model that predicts future pipe failures to assess the effect of changes in climate and composition of the DWDS.
Recently, we performed a statistical analysis on the effects of weather parameters on pipe failure (Wols & Van Thienen 2014*a*). The weather parameters temperature and drought were recognized as most influencing on pipe failure. Based upon failure data of a large part of the Dutch DWDS, a weather parameter dependent pipe failure frequency could be determined. A model has been introduced to predict future pipe failure rates under changing weather conditions. In the current work, these results are used to assess the impact of climate change (long-term weather variations) on pipe failure. A clear graphical presentation of the impact of climate change on a DWDS is proposed that also considers the evolution of the DWDS (changes in material composition). These analyses can be useful for the planning and maintenance of the DWDS, particularly in the context of climate change adaptation.

2 Materials and methods

2.1 Pipe failure data

Data for the statistical analysis was obtained from a Dutch national pipe failure database (this database called USTORE (Vloerbergh & Blokker 2010) contains information on failures in the DWDs and composition of the DWDS for about half of the Dutch DWDS). The data consists of 10325 pipe and joint failures over a 4 years period (Jan 2009 - Dec 2012) collected from several Dutch drinking water companies. Failures caused by third-parties were removed. Both failures occurring at the joints as well as at the pipe were considered (about 80% of the failures recorded in the database occur at the pipe). The failures were divided into different cohorts (Table 1), classified by pipe material. For this selection of cohorts, it was shown that each cohort has its specific response to variations in weather conditions (Wols & Van Thienen 2014*a*). For predicting the effect of climate change on pipe failure, no distinction of pipe age, pipe diameter and soil material was made. The validity of this assumption was verified by calculating the relation between temperature and failure using a rough classification of cohorts: old (year of installation before 1960) and young (year of installation after 1960) pipes, small (diameter of 0-150 mm) and larger (diameter of 150-300mm) pipes as well as sandy (sand and loam) and clay (clay and peat) soils.

2.2 Weather data

Weather data was collected from KNMI (Royal Netherlands Meteorological Institute), for the weather station De Bilt located in the center of The Netherlands. Data was collected on a daily basis. Future weather data under various climate scenarios were also obtained on a daily basis using the climate explorer tool developed by KNMI (Trouet & Van Oldenborgh 2013). Four different climate scenar-

Table 1. Cohorts selected from USTORE data.

Nr	object	cause	mat.	D m	year	fail. #	freq #/km/yr	age yr
1	pipe, joint	loads, degr	AC	all	all	5398	0.0659	50
2	pipe, joint	loads, degr	PVC	all	all	1311	0.0132	30
3	pipe, joint	loads, degr	GCI	all	all	886	0.0315	63

ios were defined (van den Hurk et al. 2006): moderate (G), moderate plus changes in wind circulations (G+), warm (W) and warm plus changes in wind circulation (W+). The historical weather pattern of 1976-2005, which is representative for the climate of 1990 was used as a reference. For the different climate scenarios these historical patterns were transformed (online tool KNMI climate explorer) into a pattern representative for the climate of 2050 (daily pattern over the period 2036-2065) and 2100 (daily pattern over the period 2086-2115). These daily patterns were used to obtain a probability density function of a weather variable for the different climate scenarios in 2050 and 2100 (Figure 1).

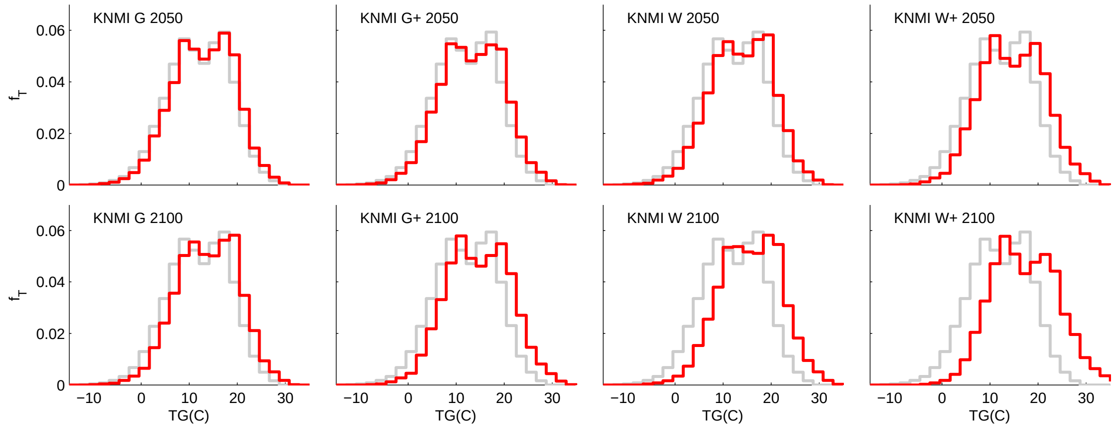

Figure 1. Distribution of daily mean temperature (calculated over a 30 year periods) for different climate scenarios in the year 2050 (daily pattern over the period 2036-2065) and 2100 (daily pattern over the period 2086-2115). The reference distribution (1976-2005) is shown by the gray line.

2.3 *Predictive modelling*

The failure frequency as a function of a weather variable (e.g. temperature) has been determined in Wols & Van Thienen (2014*a*). By combining the weather dependent failure frequency with the expected weather variable distribution, the distribution of failures as a function of weather variable can be determined for a specific climate scenario. This method is illustrated for temperature in Figure 2. From this distribution of failures, the total failure frequency for a future climate scenario can be determined.

Ambient temperature turned out to be the most influencing weather parameter, followed by antecedent precipitation index (drought) (Wols & Van Thienen 2014*a*). Since drought was also strongly correlated with temperature, the predictive model only considers the expected change in ambient temperature. The expected change in pipe failure (C_M) for a specific climate change scenario is calculated from:

$$C_M = \frac{\int f_{T,scen}(T) N_{M,T}(T) dT}{\int f_{T,cur}(T) N_{M,T}(T) dT} \tag{1}$$

where $f_{T,scen}(T)$ is the temperature distribution for a specific climate scenario and $N_{M,T}(T)$ the temperature dependent failure frequency for a specific pipe material. C_M was determined by numerical integration. The effect of climate change itself is visualized by ternary plots using three

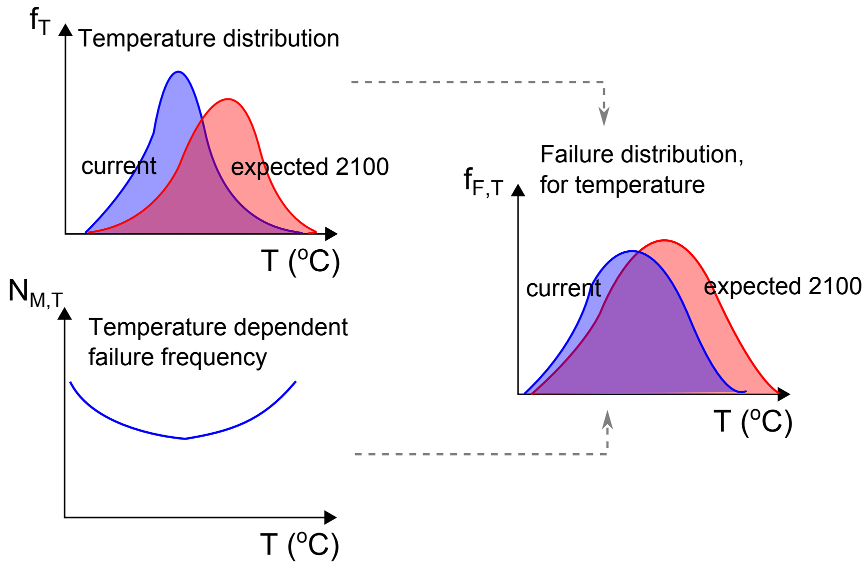

Figure 2. Predictive modelling of the effect of climate change on pipe failure, illustrated for temperature.

different pipe materials on each axis of the ternary plots. For any composition of a DWDS, the effect of climate change is represented by the colour in the graph. Climate change effects on current and future DWDSs can then be assessed. For the Dutch DWDS, the most commonly used materials are considered: polyvinyl chloride (PVC), asbestos cement (AC) and grey cast iron (GCI).
Next to the effects of climate change, ageing will also influence pipe failure. For each pipe material, an exponential function is used for ageing of the pipes (Shamir & Howard 1979):

$$N_M(t) = N_{M,0} \exp(-A_M * t) \tag{2}$$

where N_M is the failure frequency as a function of age (t), $N_{M,0}$ the initial failure frequency and A_M is the ageing factor. The factors $N_{M,0}$ and A_M can be fitted from historical failure data. For each pipe material, failure frequencies as a function of pipe age were obtained from USTORE. The uncertainty of each data point was determined from the number of failures representing each data point assuming a Poisson distribution (see below). The built-in Matlab function `nlinfit.m` (Mathworks 2014) was used to obtain a fit minimizing least-squares errors from an exponential function. The inverse squared of the uncertainty interval of each historical data point was used as a weighting criterium during the fitting.
The next step is to obtain the expected age of the pipes in a future DWDS. Therefore, the evolution of the DWDS is simulated using a particular replacement strategy that consists of an age dependent and an age independent replacement. The age dependent replacement strategy uses a triangular distribution: the replacement starts at an age of 80 years, with a peak at an age of 100 years, and all material should be replaced at 140 years. In addition to that, also every year 0.5% of the pipes are replaced irrespectively of age. This replacement can for example be driven by pipe failure(s) or construction works. Replacement because of pipe failure may lower the pipe failure rate, but this effect is already incorporated in the ageing curve, which is based upon actual failure data. All the GCI and AC pipes are replaced by PVC. The total length of the DWDS will remain the same. Using the replacement strategy the composition of pipe materials and pipe installation year of the DWDS can be constructed for every future year. This results in a distribution of pipe lengths of different ages $l_M(t)$ for each pipe material. Subsequently, the expected future failure frequency $N_{M,f}$is calculated for a particular pipe material by:

$$N_{M,f} = \frac{\int N_M(t) l_M(t) dt}{\int l_M(t) dt} \tag{3}$$

which was solved numerically with intervals of 1 year over a time span of the installation year of the oldest pipe until the considered future year. Combining ageing of the pipes and climate change, the future failure frequency in a DWDS can now be determined from:

$$P_f = \frac{\sum_M N_{M,f} L_M C_M}{\sum_M L_M} \tag{4}$$

where L_M is the total length of material M in the DWDS, calculated from $L_M = \int l_M(t)dt$. The failure frequency in a future DWDS was calculated for each climate scenario and associated year of the considered climate scenario (in this study 2050 or 2100).
The uncertainties in the predictions were also calculated using the following error sources and assumptions:

- Error in the failure frequency as a function of weather variable ($N_T(T)$). The error was calculated from the number of failures in a certain temperature class (Figure 3) assuming a Poisson distribution of pipe failures (see below).
- Error in the pipe ageing curve ($N_M(t)$), determined from the fitted failure frequency as a function of age for each pipe material (Figure 4). The Matlab function `nlpredci.m` was used to obtain the 95% confidence intervals.
- Under assumption of the Poisson distribution for the number of failures, the lower and upper boundary of a (1-α)% confidence interval for an estimation of the Poisson mean μ can be determined from:

  $$0.5\chi^2(\alpha/2;2s) \leq \mu \leq 0.5\chi^2(1-\alpha/2;2s+2) \tag{5}$$

  where s is the observed number of failures, and χ^2 the chi-squared statistical distribution. In this work, a value of α=0.2 was used.
- The uncertainty in weather parameters is represented by the different climate scenarios.
- For the propagation of errors in the (numerical) integrals and summations (equation 1, 3 and 4), it is assumed that the underlying events were dependent, which results in higher uncertainties than for independent events. In reality, the events will be partly dependent (but to what extent is unknown).

3 Results

3.1 Effect of climate change for different pipe materials

Pipe failure predictions for the most severe climate scenario (W+ 2100) are shown in Figure 3 for the three pipe materials. The change in temperature distribution (Figures on the left) in combination with the temperature dependent failure frequency (Figures in the middle) resulted in the expected pipe failure distribution (Figures on the right). The largest increase in pipe failure can be observed for AC pipes, which show a strong increase at high ambient temperatures (hot summers). PVC and GCI are most vulnerable at low temperatures. Therefore, as a result of climate change, a slight decrease in pipe failure is observed for PVC pipes, and a larger decrease is observed for GCI pipes due the lower incidence of cold periods.
The changes in pipe failure were also calculated for the other climate scenarios in 2050 and 2100 (Table 2). The other scenarios show the same trends as the W+ 2100 scenario, but less severe, because the change in temperature is smaller (see Figure 1). The effects seem to become stronger in the period 2050-2100 than the period 2010-2050, probably due to an expected acceleration of climate change in this period. The uncertainties in the prediction of pipe failure by the effect of climate prediction are small. The effects of climate change for the three pipe materials are shown in the ternary plots for all the Dutch climate scenarios (Figure 6). Failure frequencies increase if the AC amount in the DWDS increases, the opposite occurs for DWDSs with higher proportions of PVC and GCI.

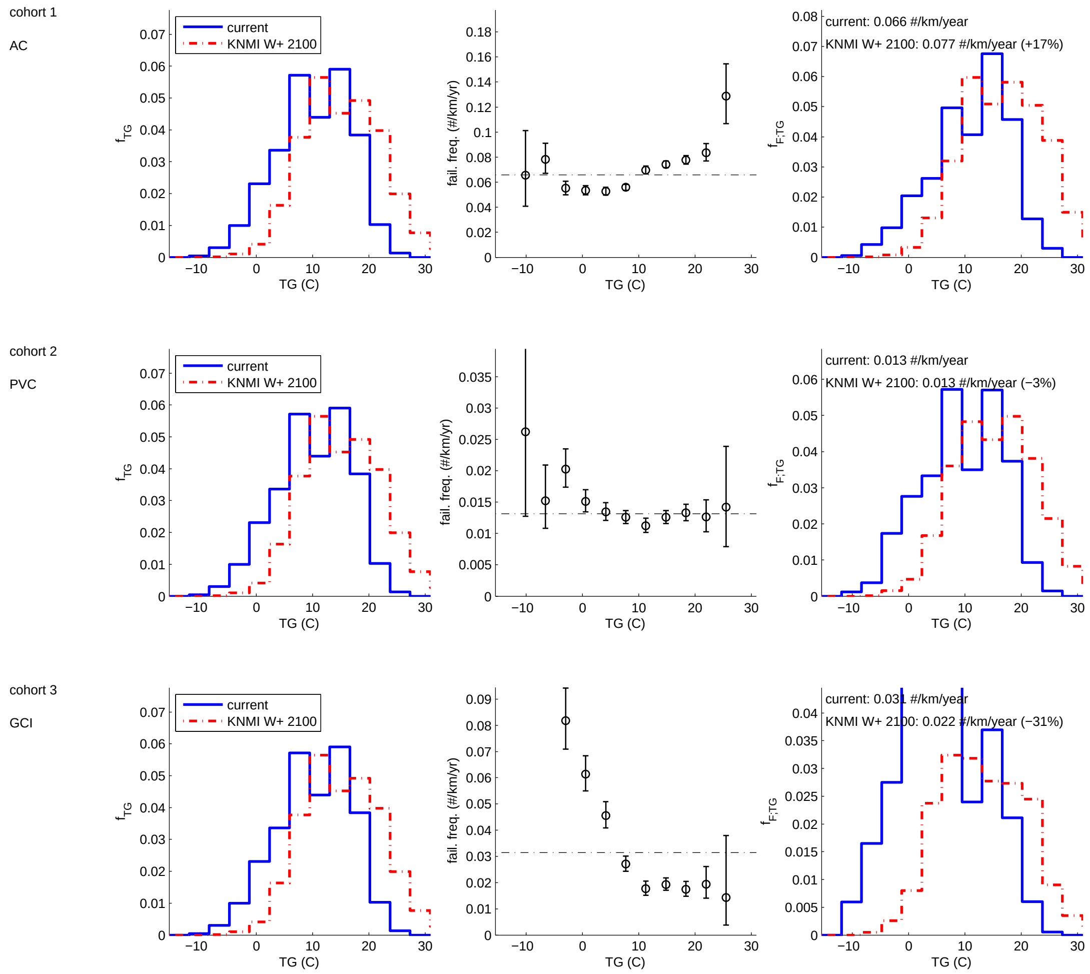

Figure 3. Temperature distribution (left), temperature dependent failure frequency (middle) and distribution of failures per temperature interval (right), shown for AC, PVC and GCI pipes. The error bars in the middle figure indicate the 80% confidence interval.

Table 2. Expected failure frequency (#/km/yr) for the different climate scenarios in 2050, and percentual difference with the current climate. Uncertainties in predictions are shown in parentheses.

cohort	current	G 2050	G+ 2050	W 2050	W+ 2050
AC	0.066	0.067 (±0.001)	0.068 (±0.001)	0.069 (±0.001)	0.070 (±0.001)
		+2%	+3%	+4%	+7%
PVC	0.013	0.013 (±0.000)	0.013 (±0.000)	0.013 (±0.000)	0.013 (±0.000)
		-2%	-2%	-2%	-3%
GCI	0.031	0.029 (±0.001)	0.028 (±0.001)	0.027 (±0.001)	0.025 (±0.001)
		-8%	-10%	-15%	-19%

Table 3. Expected failure frequency (#/km/yr) for the different climate scenarios in 2100, and percentual difference with the current climate. Uncertainties in predictions are shown in parentheses.

cohort	current	G 2100	G+ 2100	W 2100	W+ 2100
AC	0.066	0.069 (±0.001)	0.070 (±0.001)	0.072 (±0.001)	0.077 (±0.002)
		+4%	+7%	+10%	+17%
PVC	0.013	0.013 (±0.000)	0.013 (±0.000)	0.013 (±0.000)	0.013 (±0.001)
		-2%	-3%	-3%	-3%
GCI	0.031	0.027 (±0.001)	0.025 (±0.001)	0.023 (±0.001)	0.022 (±0.001)
		-15%	-19%	-25%	-31%

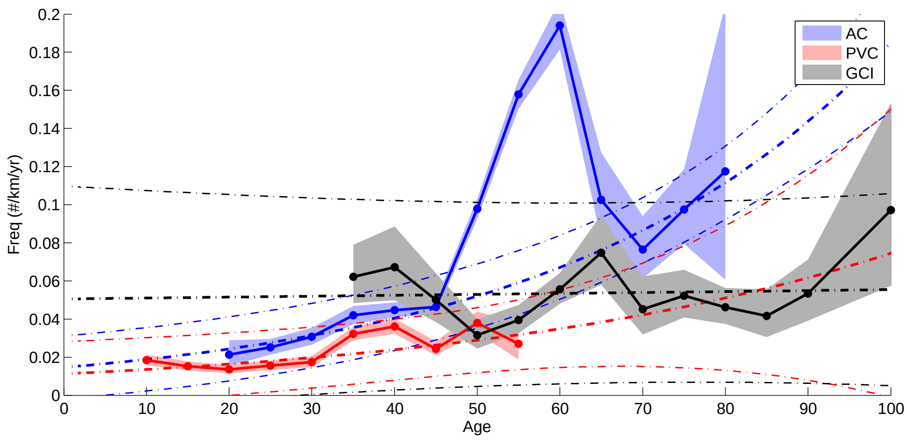

Figure 4. Failure frequency (pipe and joint) as a function of pipe age [years] for the three pipe materials. An exponential function is fitted: for AC: $N_0 = 0.0146$ #/km^{-1}/yr, $A = 0.0254$ yr^{-1}; for PVC: $N_0 = 0.0112$ #/km^{-1}/yr, $A = 0.019$ yr^{-1}, for GCI: $N_0 = 0.0505$ #/km^{-1}/yr, $A = 0.0009$ yr^{-1}.

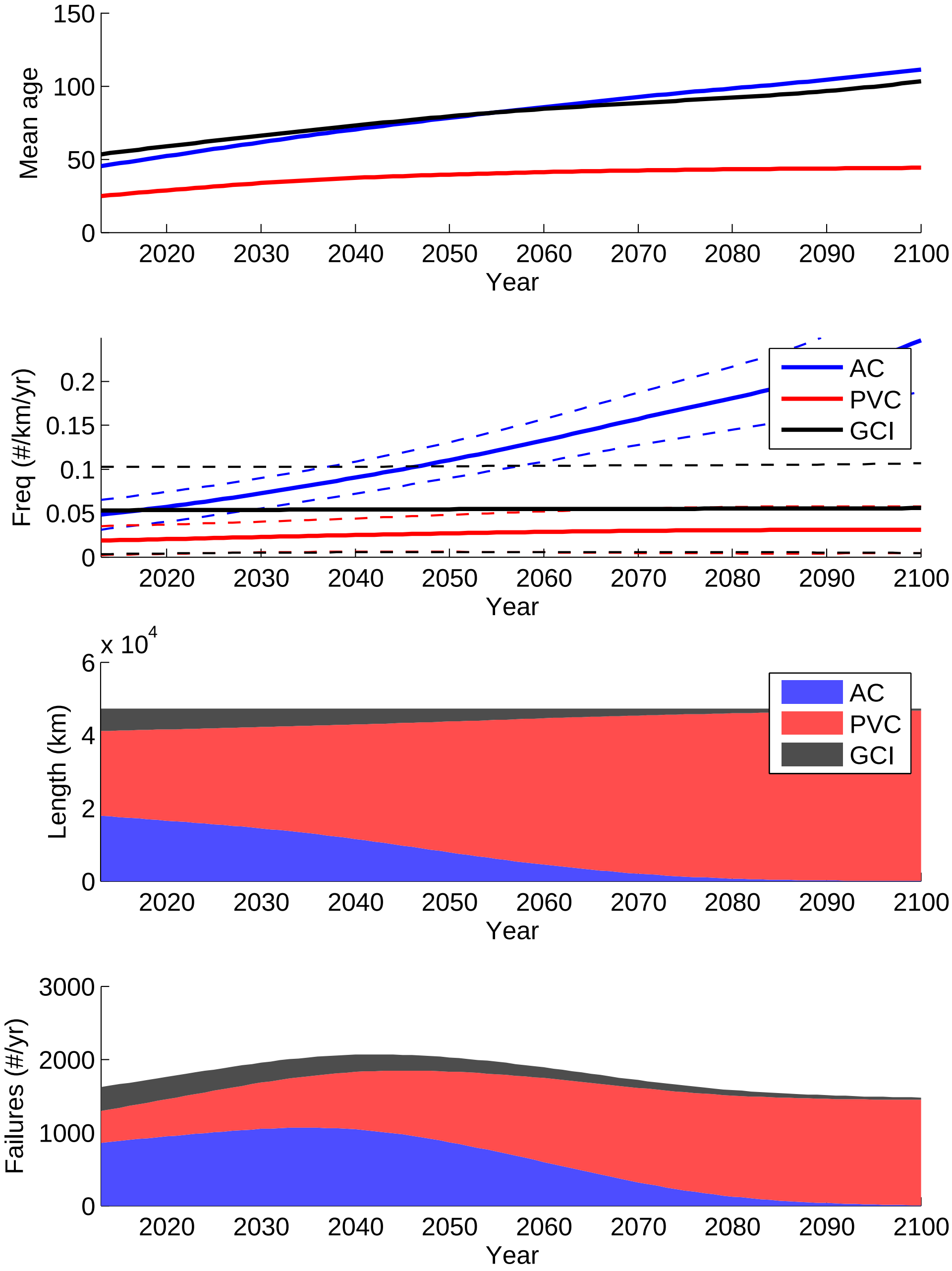

Figure 5. Development of DWDS: ageing of pipes (upper panels), change of failure frequency due to ageing (middle panels), change in material composition.

3.2 Assessment of the Dutch DWDS

The vulnerability of a current and future DWDS towards climate change is evaluated. As an example, about half of the Dutch DWDS is considered, which is composed of $18.1{\cdot}10^3$ km AC (39%), $22.6{\cdot}10^3$ km PVC (48%) and $6.2{\cdot}10^3$ km of GCI (13%) in 2012. Over the years the materials and standards for constructing and replacing infrastructure have changed, resulting in a moving inventory of pipes and pipe materials of different quality causing changes in pipe failures. Historical failure data is used to fit the ageing curve (Figure 4). Note that the peaks for 50-60 years old AC and 30-40 years old PVC were omitted in the fitting procedure, since these pipe materials installed in that period seem to be of lower quality at production. The production process of AC pipes in the Netherlands was changed in 1959 to improve the quality of the pipes and joints. Incorporating these failures in the fitting would result in unrealistic high failure frequencies when extrapolating the results towards older ages. The uncertainty in the fitted failure frequency becomes large for old PVC (older than 55 years) due to extrapolation of data. The uncertainty for GCI is also large due the strong variations in failure frequencies. Moreover, the ageing of the GCI seems to be small, which may be biased by the fact that the lower quality old GCI pipes have already been replaced over the years. This also explains the reduction in failure frequency for the oldest AC pipes.

The evolution of the DWDS and failures in the DWDS are shown in Figure 5. The mean ages of the three materials in the evolution of the DWDS are shown as a function of future years, followed by the expected failure frequency derived from the ageing curve of each material. Since AC and GCI are replaced by PVC, the remaining AC and GCI are getting older. The composition of the DWDS for the three materials is shown in the third panel of Figure 5. In 2100, 97% of the DWDS will be composed of PVC. The total number of failures is shown in the bottom panel. First an increase is observed due to the ageing of the AC and GCI pipes, followed by a decrease when most of the pipes are replaced by PVC. Due to the increased age of AC pipes, the number of failures in AC is still relatively high even if the total amount of AC is much reduced.

The effect of climate change is considered using the relation between failure and temperature for the different pipe materials. The expected composition of the DWDSs in 2050 and 2100 are plotted in the ternary plots (Figure 6). Due to the increased use of PVC pipes, failure frequencies will drop and the effect of climate change will be slightly positive. The composition of DWDSs of Dutch drinking water companies is also plotted. Some DWDSs have high proportions of AC and are therefore more vulnerable to climate change than other DWDSs that have higher proportions of PVC and GCI.

The failure frequencies for the Dutch DWDS are shown in Table 4 for all the climate scenarios. Pipe ageing has a stronger influence than climate change. Failure frequencies increase up to 2050 due to ageing of the remaining AC and GCI pipes. In 2100 failure frequencies will decrease caused by the reduced amount of AC and GCI in the DWDS. This calculation is based upon extrapolation of the exponential ageing curves and a fixed replacement strategy. The uncertainties are high due to extrapolation and uncertainty in the ageing curves, almost up to the same values as the predictions itself in 2100. Furthermore, it is questionable whether AC really has such high failure frequencies at ages above 80 years and if so, it is likely that water utilities will speed up replacement of AC. The effect of climate change seems small, since most of the DWDS consists of PVC that shows little correlation with temperature. The highest effect of climate change occurs for the W+ scenario in 2050, where the highest increase in temperature occurs in a DWDS with a relatively large amount of AC.

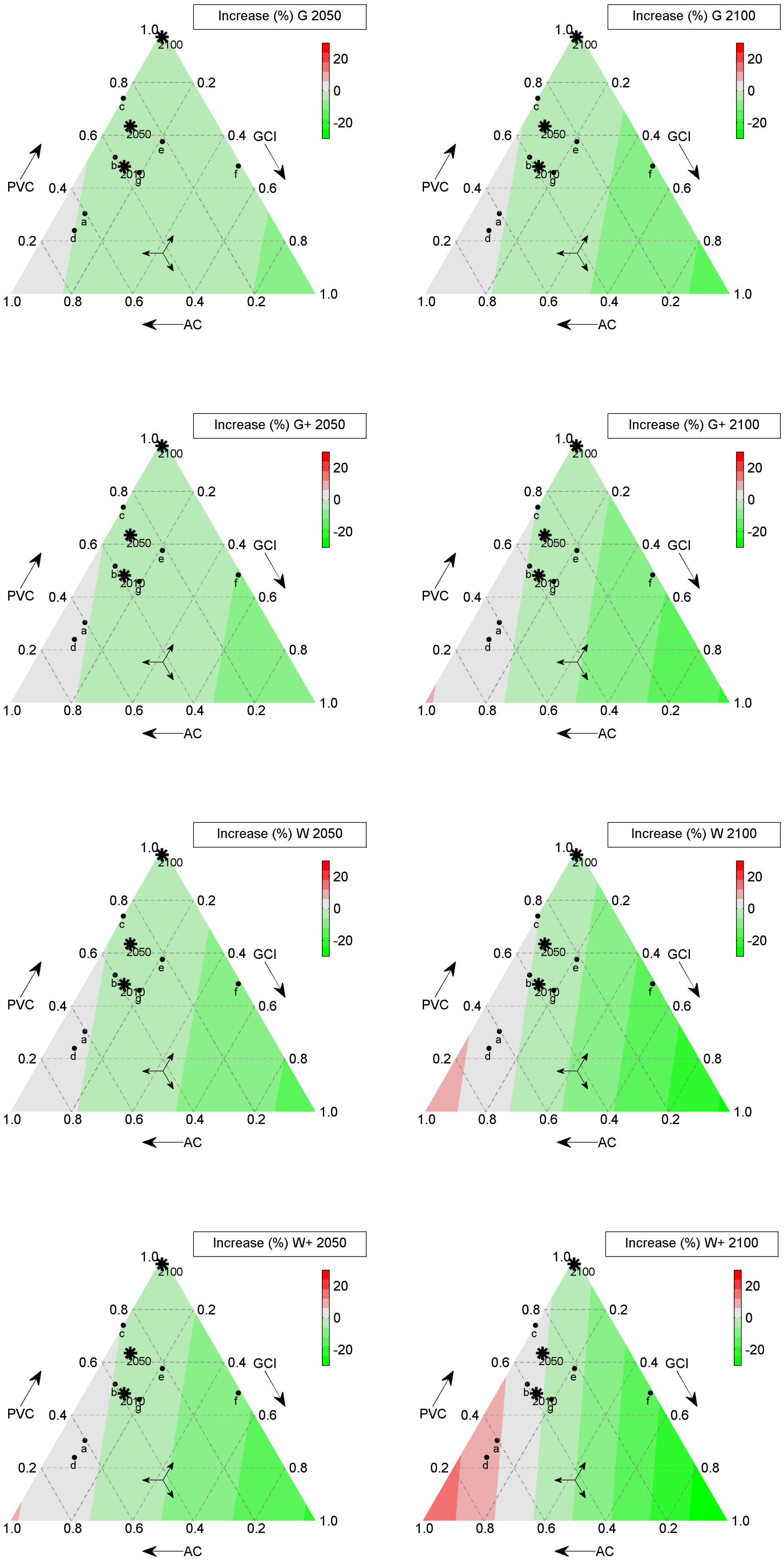

Figure 6. Ternary plots of joint and pipe failure: the three sides show the proportions of each pipe material in the DWDS. The colors show the increase or decrease in pipe failure due to climate change for the different scenarios. The stars show the Dutch DWDS of today and the future.

Table 4. Current and predicted failures in Dutch DWDS for the different climate change scenarios.

Scenario	Freq (#/km/yr)	Dif with current climate
current 2013	0.0343 (+/- 0.0121)	0.0 %
current 2050	0.0571 (+/- 0.0157)	0.0 %
current 2100	0.0335 (+/- 0.0251)	0.0 %
G 2050	0.0571 (+/- 0.0155)	-0.0 %
G+ 2050	0.0574 (+/- 0.0155)	0.5 %
W 2050	0.0576 (+/- 0.0155)	0.8 %
W+ 2050	0.0582 (+/- 0.0155)	1.9 %
G 2100	0.0330 (+/- 0.0246)	-1.3 %
G+ 2100	0.0331 (+/- 0.0246)	-1.2 %
W 2100	0.0330 (+/- 0.0244)	-1.4 %
W+ 2100	0.0333 (+/- 0.0245)	-0.4 %

4 Discussion

The presented ternary plots provide an insightful view of pipe failure now and in the future as a result of climate change for a complete DWDS composed of different materials. It reveals the vulnerability of a DWDS towards climate change, and may assist in asset management decisions related to climate change adaptation. The results for the Netherlands show that replacing AC by PVC results in a more robust DWDS towards climate change. The methodology could also be used for asset managers to evaluate different replacement strategies and to identify weak spots in the DWDS.

Note that the underlying data is based upon failure registrations over a 4 year period for a part of the Dutch DWDS (∼50 000 km). Since almost half of the DWDS is covered, the results can be used to assess the DWDS of the complete Netherlands. However, the results can not be used one-to-one for other countries. But the methodology is very well suited for other countries as long as pipe failure registration systems and climate scenarios are available. In addition, the 4 year period used in our study is relatively short, so that not all extreme weather events can be captured. A longer historical record may therefore result in more accurate results.

So far, the only variates considered were temperature, pipe material and age. The ternary plots were made for three different pipe materials, since pipe material was identified as most sensitive towards climate change. However, other variates, soil composition, pipe diameter etc. may also play a role (Hu & Hubble 2007, Kleiner & Rajani 2010). If these variates show different behaviour towards climate change, the analysis could be made for more specific cohorts, for example cohorts of different pipe diameters or pipe ages. For the variate age, older pipes may have less resistance and may therefore be more vulnerable to increased forces on the pipe induced by extreme weather conditions. However, division into smaller cohorts would require a much larger failure dataset. With the current data set, it was possible to make a rough division to examine if covariates, such as pipe age, pipe diameter and soil composition change the relation between temperature and failure (Figure 7). In fact the error bars become larger due to the sparsity of data, especially at the more extreme weather conditions (lowest and highest temperatures). Nevertheless, the differences between the cohorts are however small (mostly within each others error bars) and similar relations between temperature and failure are found. This confirms the validity of the approach followed here using only pipe material cohorts. In addition, the ageing curves could by expanded with other variates as well, as for example described by the time-exponential models in Kleiner & Rajani (2001).

Moreover, other (combinations of) weather parameters, such as rain deficit, freezing index etc., may also play a role. For example, differential soil settlements may increase as a result of climate change during long periods of drought (Wols & Van Thienen 2014*b*). These drought events are only partly captured by the temperature (drought and high temperatures are correlated in the Netherlands), and may play an important role in soft soils. Considering these parameters would require advanced climate models to obtain future patterns of these parameters. For data used in the present

study, no significant influence of other weather parameters was found.
Propagation of uncertainty in the model revealed that the largest uncertainties were related to pipe ageing. Especially for the predicted pipe failure frequencies in 2100, when the DWDS contains large proportions of old PVC, the uncertainties are large. Further research into the failing behaviour of older PVC is required to narrow the uncertainty in the predictions.

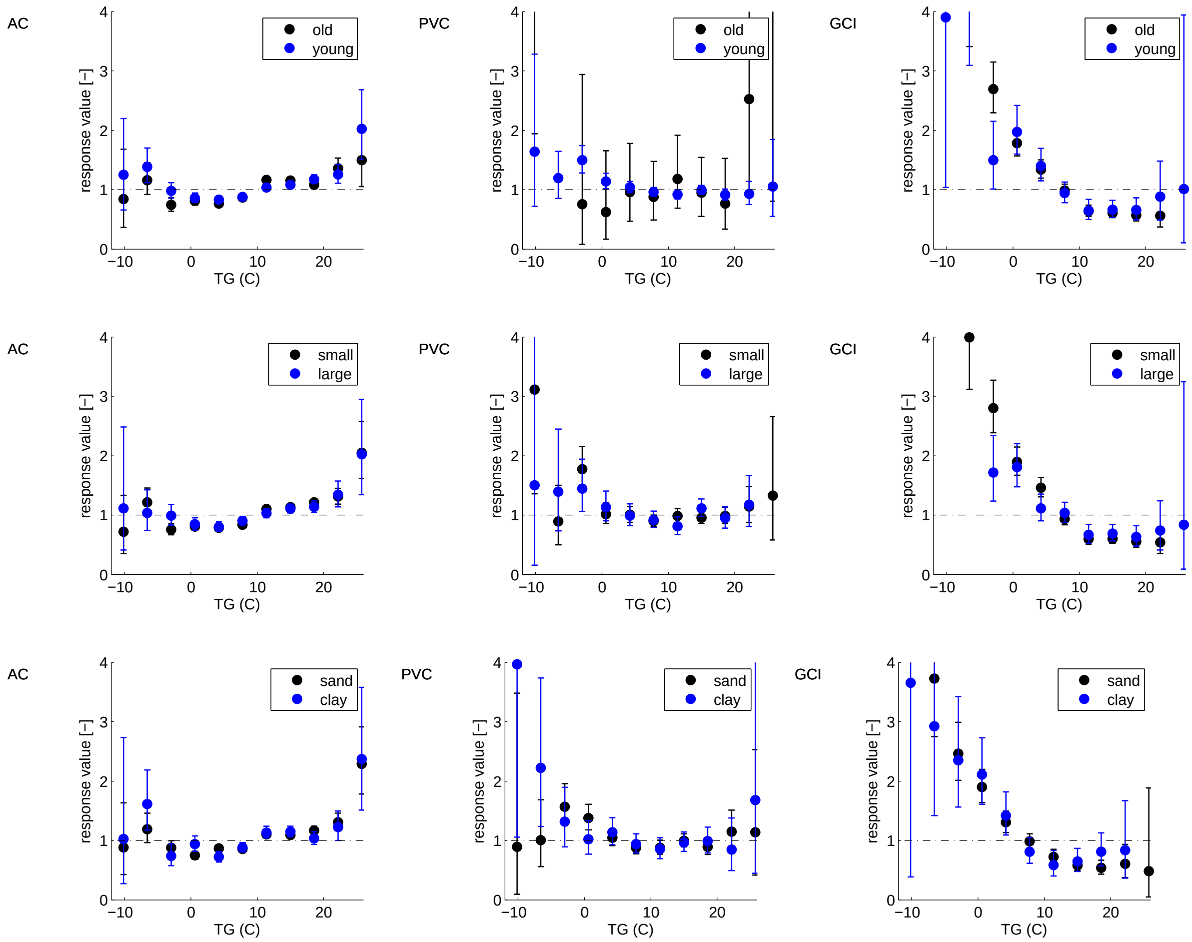

Figure 7. Temperature dependent failure for the three pipe materials using different cohorts: young (<50 years) and old (>50 years), small diameter (0-150 mm) and larger diameter (150-300 mm), sandy soils and clay (both clay and peat) soils. The failure response shows the increase (>1) or decrease (<1) of failure by temperature.

5 Conclusions

A methodology is developed to assess the effect of climate change on the drinking water distribution system (DWDS): From failure registration data as well as weather data, statistical relations between failure frequencies and weather conditions are obtained. Using these statistical relations in combination with climate scenario predictions, the change in failure in DWDS as a result of climate change is estimated. This is combined with the evolution and ageing of the DWDS using a particular pipe replacement strategy. The methodology comprises an error analysis to account for several uncertainties in the extrapolation of results. The methodology results in an insightful representation of the vulnerability of an existing and future DWDS towards climate change. This analysis can be conducted for any DWDS, for which historical failure data and weather parameters are available. The proposed methodology can therefore assist in the construction and maintenance planning of DWDSs. For the Dutch situation, over a time scale of 50-100 years the effect of climate change seems to be small in comparison with the expected changes in the DWDS. However, the ageing curve of the DWDS is accompanied by large uncertainties, which requires more research, particularly for the material PVC.

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