Effect of Seasonal Climatic Variance on Water Main Failures in Moderate Climate Regions

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INTRODUCTION

Studies of water main failure histories indicate that a drop in seasonal temperatures is almost followed by an increase in the number of failures in many cities in cold regions of North America. Ciottoni (1985) suggested that failure frequency in winter is at least twice as high as during summer (Rajani et al., 1996). Kleiner and Rajani (2009) introduced a water main failure prediction model which considers time-dependent factors such as temperature, in the form of freezing index, and soil moisture, in the form of rainfall deficit. Considering these time-dependent influences in deterioration the prediction accuracy for the case study areas in Canada has been improved. The motivation for the described analyses was to find out if seasonal climatic variance and water main failure occurrence correlate as well in the climate regions of Austria. Further specific correlations to material types, diameters and failure modes are of interest. Several climate areas, like alpine or pannonian climate zones, exist in Austria. The correlation between seasons of different severity with the occurrence of water main failures have not been examined for Austrian supply areas so far. Therefore long time series of air temperature, precipitation and water main failure statistics of 5 Austrian regions (anonymized supply areas with the abbreviation A, B, C, D and E) have been analysed. The investigations and the results are described in this paper as follows. In section 1 a reviewing of previous work and researches on the topic seasonal climate variance and occurrence of water main failures is given. Section 2 describes the method and parameters to characterize the severity of different seasons and climate impacts on water main failures. Section 3 gives results for the 5 selected supply areas in Austria and section 4 comprise an outlook for further research work on this topic.

REVIEW OF PREVIOUS WORK

The occurrence of a water main failure is a complex interaction of several different effects. Water main failures are influenced by material characteristics, internal and external impacts and boundary conditions (backfill material, sidefill material, installation depth, installation quality, compaction quality, ground water influence and road superstructure). Internal and external impacts can be: high internal pressure, third party interference, dynamic traffic load, seasonal variance of climate, corrosion and material deterioration. The boundary conditions and impacts lead to different failure modes: circular or circumferential break, longitudinal break or split, joint failure, holes due to corrosion, shell collapse or blow out.

Environmental and operational conditions as well as quality of manufacturing and installation exert stresses on water mains. Water main failures occur when these stresses exceed its structural resiliency. While the structural deterioration of the pipe is generally considered to be a steady, monotonous process, some of the environmental and operational stresses could be time-dependent, steady or transient. The objective is to identify and attribute the cause of random stresses on water mains to measurable phenomenon (e.g., temperatures, precipitation, etc.) (Kleiner and Rajani, 2000).

The three-stage process of pipe collapse has been documented by several researchers (Jones, 1985; Hoffman and Lerner, 1992; Lerner, 1994; and others).

Davies et al. (2000) has published work within the identification of the basic mechanism by which pipes deteriorate and finally fail. A description of this mechanism is presented in 3 stages:
Stage 1: An initial defect. Collapse of a pipe normally originates, where an initial, often minor, defect allows further deterioration to occur.

Stage 2: Deterioration. Deterioration often involves the loss of support from the surrounding soil due to dynamic impacts or earth-moving due to water leakages.

Stage 3: Collapse. Collapse is often triggered by some random event, that may not be related to the cause of the deterioration. Such a random event may be earth-moving due to frost load and frost heave.

The fact that the majority of the water mains fail in the circular or circumferential mode and that these failures occur during or at the end of the winter season suggest that the axial pipe-soil interaction is the responsible mechanism (Rajani et al., 1996). Additionally Rajani et al. (1996) described an analytical "pipe-soil interaction model" that reflects the change in stress condition in water mains as the consequence of the change in ground temperature. A circular break is evidence that a longitudinal tensile stress condition caused this type of failure. Longitudinal tensile stresses in water mains may be induced through several possible mechanisms: earth-moving due to soil shrinking, soil swelling, frost heave or faulty bedding and increased earth loads due to frost load as a consequence of frost penetration in the area of buried pipes. A longitudinal break is a result of circumferential or hoop stress (Rajani and Zhan, 1996). Plastic water mains with the type material pvc in superposition with high internal pressure often induce the failure mode in the form of longitudinal break. The statstics on the modes of failures vary from supply area to supply area in Austria.

Kleiner and Rajani (2000) report that several researchers (e.g., Lackington and Large, 1980; Newport, 1981; Needham and Howe, 1981; Walski and Pelliccia, 1982; Cittoni, 1985; Lochbaum, 1993; Habibian, 1994; Chambers 1994; and others) observed the effects of temperature and moisture conditions on the failure rate of water mains. The influence of temperatures on water main failures are reported in the way of a typical annual pattern of failure rates that peaks during or towards the end of the winter seasons, when the ground temperatures are below normal. The influence of soil moisture on water main failures was observed by Baracos et al. (1955), who observed the occurrence of water main failures during September and January and during dried soil conditions which are existing after a hot summer or just before to spring thaw. Morris (1967) and Clarke (1971) report that volumetric swelling and shrinkage for clays is an important factor towards a high number of water main failures. Newport (1981) observed failure rate peaks following very hot and dry summers in the UK. Hudak et al. (1998) described that extreme dry periods lead to an increase in water main failures in expansive soils in Texas. Rajani et al. (1996) developed a "pipe-soil interaction model", which demonstrates how temperature and soil moisture interact to influence water main failures. The Rajani and Zhan (1996) "estimation of frost loads – model" describes the mechanics und circumstances that lead to frost loads. These factors are frost penetration, frost heave of trench fill and sidefill (native soil) and the interaction at the trench backfill-sidefill interface. Effective planning for the renewal of water distribution systems requires accurate quantification of the structural deterioration of water mains. Direct inspection of all water mains in a distribution network is often prohibitively laborious and expensive. The application of physical models to assess the structural resiliency of each individual pipe is also not realistic in most cases because accurate data are rarely available and are very costly to obtain. Using statistical methods to identify breakage patterns over time is an effective and inexpensive alternative for measuring the structural deterioration of water mains (Kleiner and Rajani, 2002). Most failure prediction models for water mains developed so far deal almost with static factors (e.g., material type, diameter, soil type, installation practices, etc.). The reasons for that are the historically unavailable data and the high costs to get data in the future and the problem to predict temperature and precipitation data reliable for a wide period of time in the future (Kleiner and Rajani, 2000).

METHODS AND PARAMETERS TO DESCRIBE SEASONAL CLIMATIC VARIANCE

To describe seasonal climatic variance in the form of several indicators specific methods are described in literature (Boyd, 1973; Harflinger and Knees (1999); Pregl (2002); and others).For the severity of a considered time period in winter the Freezing Index (FI) is used as an indikator. FI is expressed in units of degree-days (°Cd) and is calculated by summing the average daily temperature in all days in a given time period in which the average daily temperature is below a given range (Pregl, 2002). For example the average FI in Canadas settled regions is between 1.000°Cd and 3.000°Cd (Boyd, 1973). In Austria the average FI ranges between 100°C in the east and around 900°Cd in alpine regions (Pregl, 2002). Further the average laying depth of water mains in Austria is 150 cm due to the frost depth in winter or warming of the drinking water in summer (ÖNORM B 2533; ÖNORM B 5012; EN 805).

1) Freezing-Index (FI): Cold air temperatures effect a specific frost depth and an occurrence of frost load and frost heave in the unterground and in the installation area of buried pipes. FI gives a measure of the severity of a winter during a specific period. FI is expressed in degree-days, which is the cumulative average daily temperature T_m below normal during a given period in days d. According to Figure 1 specific relationships, durations and amounts of local and global FI´s form the proper rated value of FI.

$$FI = \sum_{i=1}^{n} T_{m,n} * d \; [°Cd] \text{ (Swiss Standard 670 140b)} \qquad (1)$$

The calculation of the frost depth is related to FI and further on specific soil characteristics like soil moisture content, soil thermal heat capacity and soil thermal heat conductivity. Using only FI for calculating frost depth is not satisfactory, like pictured in Figure 3. Soil characteristics exert a dominatic influence on frost depth spreading areas. Frost depth can be calculated using several formula: Brown’s formula (after Brown, 1964 in Raymond et al, 1999); Neumann´s formula; Stefan´s formula; Berggren´s formula; Skaven-Haug´s formula; Hain´s formula; Pusakow´s formula; Behr´s formula and many others.

$$d_{frost} = 0{,}0174 * FI^{0,67} \text{ (Brown´s formula)} \qquad (2)$$

Where d_{frost} is the depth of frost for an uncovered surface in m.

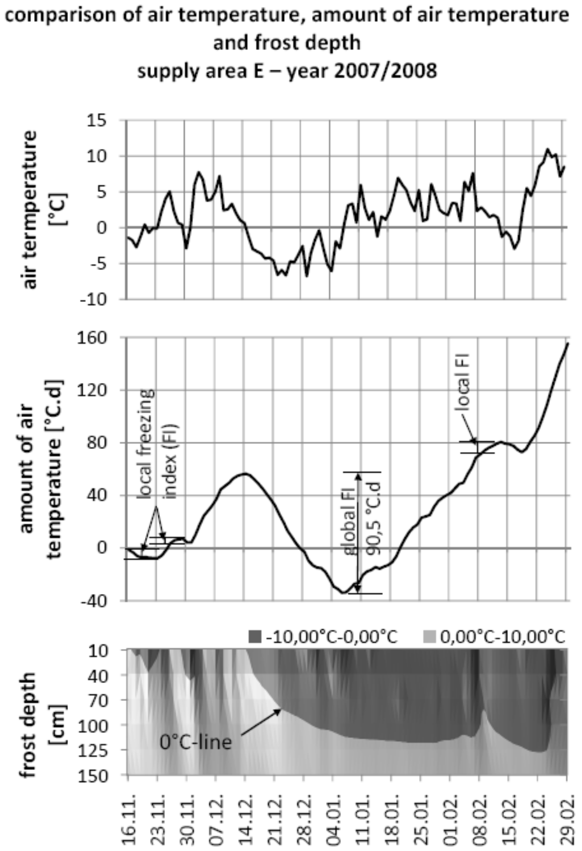

Figure 1: comparison of air temperature, cumulative curve of air temperature and frost depth in the supply area E in the time-period 2007/2008

A comparison of air temperature, cumulative curve of air temperature and frost depth in the supply area E in the time-period 2007/2008 is pictured in Figure 1. According to the amount, duration and characteristics of FI a specific frost area is formed in the underground. According to Figure 1 the process of thawing is very important to the frost area in the underground.

A correlation between the measured frost depth and the adjusted formula for frost depth is described in Figure 2. A side road in the supply area E, a state road in the supply area C and grassland in the supply areas A, C and E are compared. The road superstructure and soil characteristics have significant influences on the frost depth.

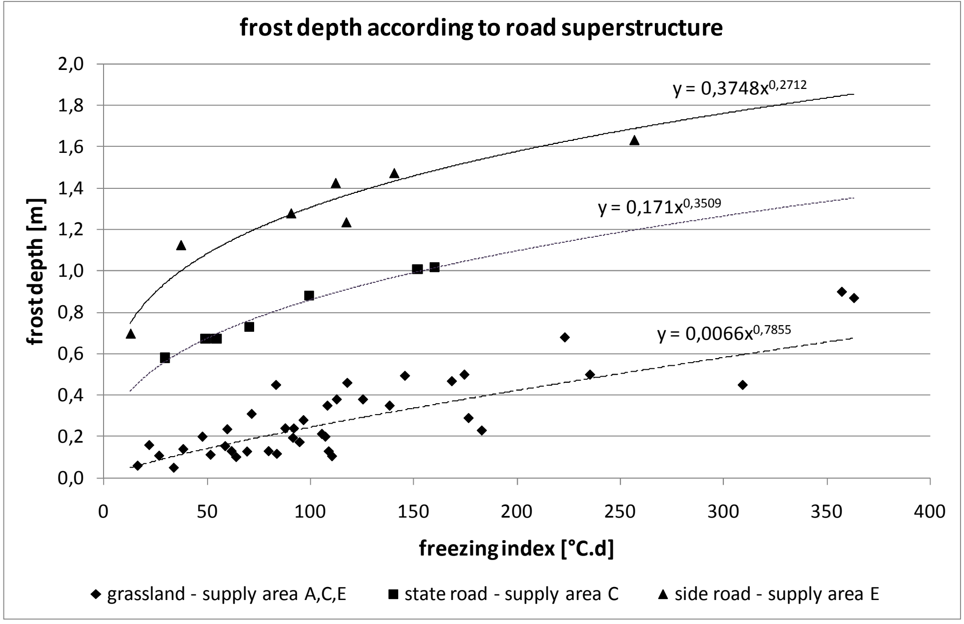

Figure 2: Measured frost depth and adjusted formula for frost depth according to road superstructure for Austrian supply areas

2) Dry-Index (DI): Soil moisture can influence pipe failure rate by several mechanisms as well like soil shrinking during a long dry period and frost penetration during a cold winter following a dry summer and a sudden fall of temperature (Kleiner and Rajani, 2000). Harflinger and Knees (1999) describe a dry index (DI) to be used as a surrogate measure for soil moisture in a considered time period.

$$DI = \frac{3 * T(°C)}{P(mm)} \qquad (2)$$

Where T ist the average temperature of the considered time period (e.g. a month) and P is the cummulative precipitation of the considered time period. DI is considered for the whole year or especially for summer time, as explained below.

3) Dry-index for summer period (DI summer): DI summer is used as a surrogate measure for soil moisture in the summer period.

4) Rain Deficit: As previously described, low soil moisture levels may affect pipe failure rates both in warm (soil shrinkage) and cold (soil shrinkage and increased frost penetration) regions (Kleiner and Rajani, 2000). In the case of frost penetration and no ground water influence in the pipe installation depth area there is the effect of soil shrinking in the pipe installation area and frost heaving in the road superstructure area (Kottmann, 1978). One of the method to quantify the moisture depletion in the underground is the Thornthwaite method. It is a function of temperature, precipitation and latitude. The data required to calculate RD comprise average monthly temperature and precipitation and records for the period of available water main failure history. Rain deficit is considered for the whole year , in the way of rain deficit snaphot for a certain month (e.g. month before freezing starts) or rain deficit for the summer period as presented below.

5) Rain deficit snapshot (RD snapshot): RD snapshot accounts for the soil moisture at the beginning of a typical time-period, e.g. cold season.

6) Rain deficit for the summer period (RD summer): RD summer is used as a surrogate measure for soil moisture in the summer period.

7) Amount of very hot days in the summer (AHD): The amount of successive hot days in the summer season accounts for the soil moisture at the end of a summer season.

8) Amount of very cold days in winter season (ACD): The amount of successive cold days in a winter season.

RESULTS

In Figure 3 the FI for the 5 selected Austrian water supply areas A, B, C, D and E are compared. Depending on the membership of a specific climate zone there are not negligible differences in the amount of FI. The maximum amounts of FI vary from 350 [°Cd] in supply area C to 100 [°Cd] in supply area B according to the specific climate zone.

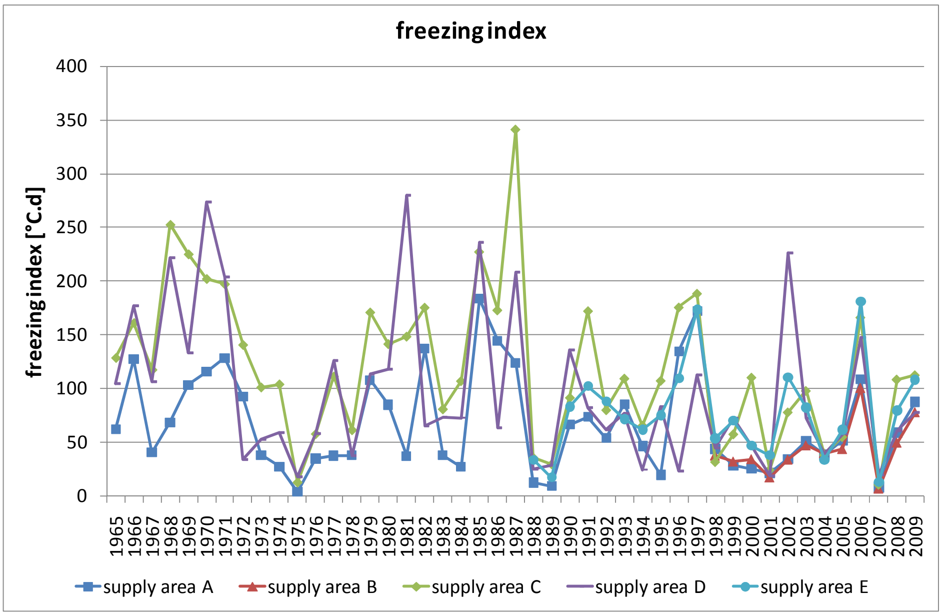

Figure 3: Comparison of freezing index for supply area A, B, C, D and E (observation period 1965 to 2009)

In Figure 4 differences in the amount of FI are shown for the large supply area A, which is divided into 5 sub-areas. A difference in the amount of FI, up to 50 %, within the same winter season for the large supply area A has been calculated.

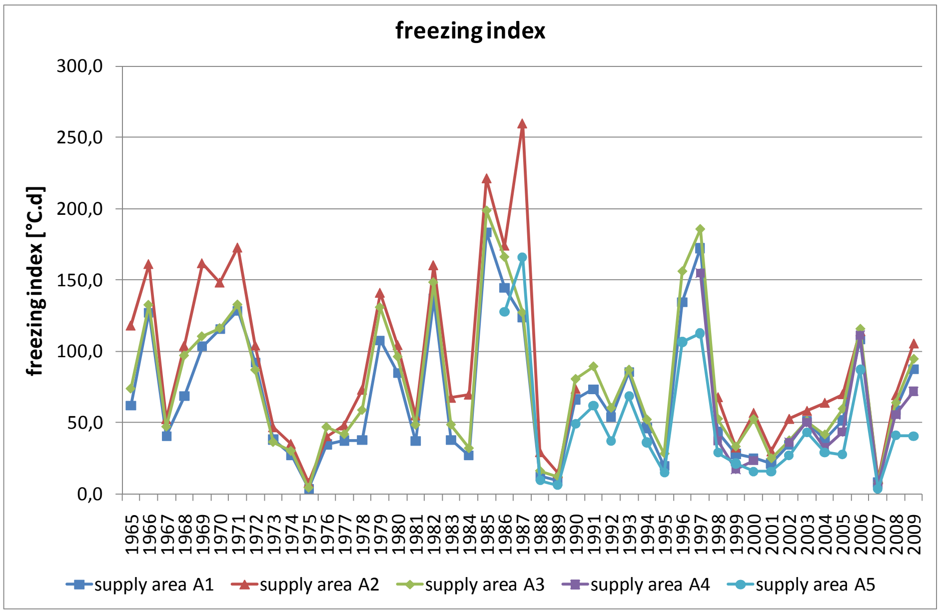

Figure 4: Variability of FI for different sub areas in supply area A

Analyses of available data on the performance of water mains indicate that water main failure is influenced by seasonal climate variance, material type and diameter. Figure 5 describes the cumulated monthly failure frequency for the whole failure observation period in supply area D. This failure distribution is characteristic for all examined supply areas in Austria. A significant correlation between seasonal climate variance and occurrence of water main failures on cast iron pipes are in evidence.

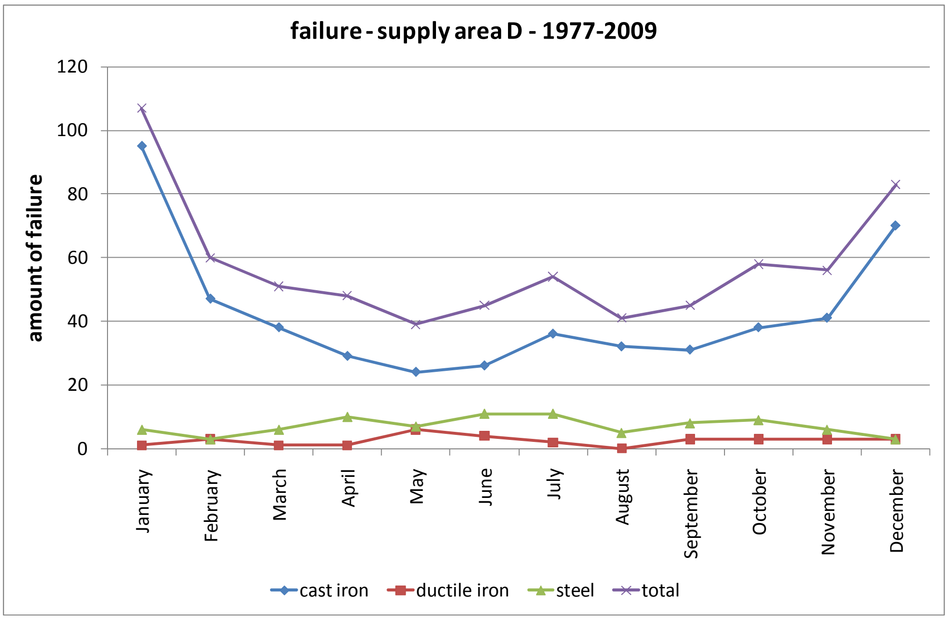

Figure 5: Cumulated monthly failure frequency of supply area D (observation period 1977-2009) for different material types

A typical annual pattern in Figure 5 for all supply areas shows that the peak in failure frequency occurs during the period when the ground temperatures are below normal, especially for cast iron pipes. Water main failures occur in one of several modes of failure. Figure 6 shows, that there is an increase in circular breaks in the period of ground temperatures below normal. Rajani et al. (1996) shows in the calculation of his pipe-soil interaction model that axial stresses increase with a decreasing ground temperature. This could be the reason of an increase in circular breaks, because the additional stresses imposed on deteriorated water mains can be responsible for a collapse of the water mains.

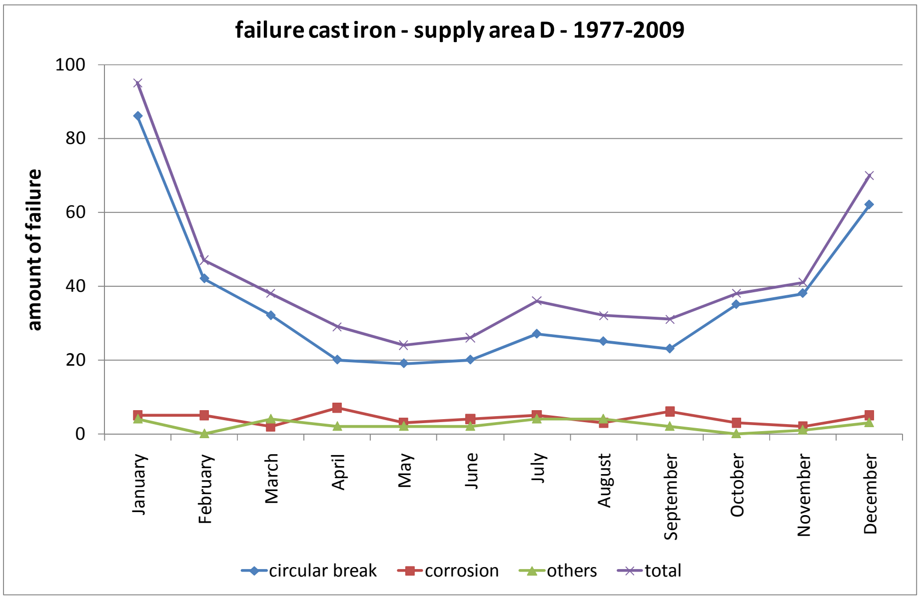

Figure 6: Monthly failure frequency for failure mode circular break on cast iron pipes (area D)

Figure 7 shows that the frequency of failures increases with a decrease in pipe diameter. In (Kettler and Goulter, 1985) the high pipe failure frequency for small pipes is attributed to thinner pipe wall thickness, with a consequent reduction in the time to failure by corrosion.

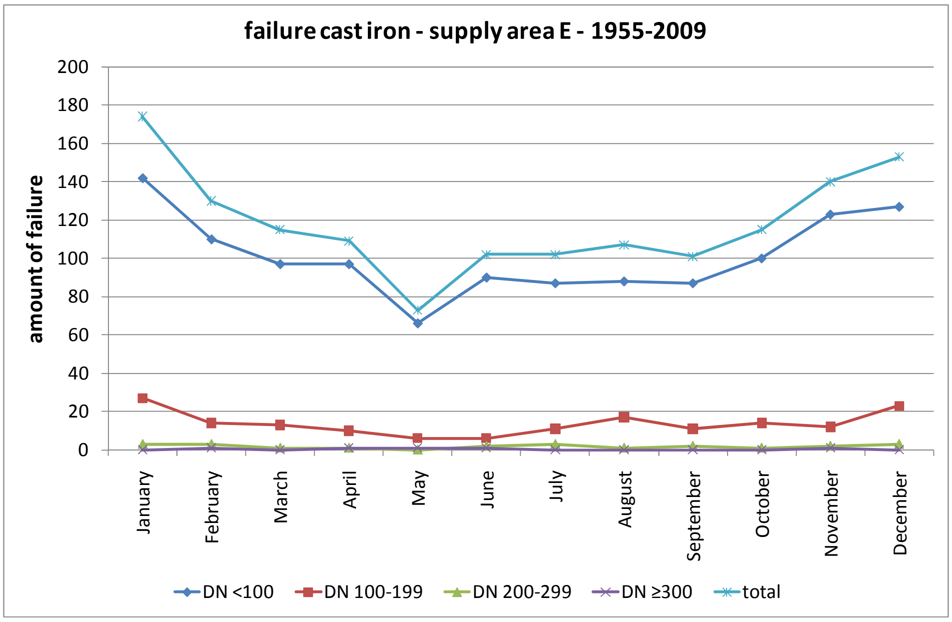

Figure 7: Monthly frequency for the material type cast iron in the time-period 1955-2009 for different diameters (area E)

In Figure 8 the boxplot-picture shows the variability of the failure frequency for the material type cast iron for each month in the supply area D in the time-period from 1977 to 2009, which is typical for all examined Austrian supply areas. This variability of the failure frequency is caused by winter seasons which differ in severity. The severity of a winter is expressed with the freezing index (FI).

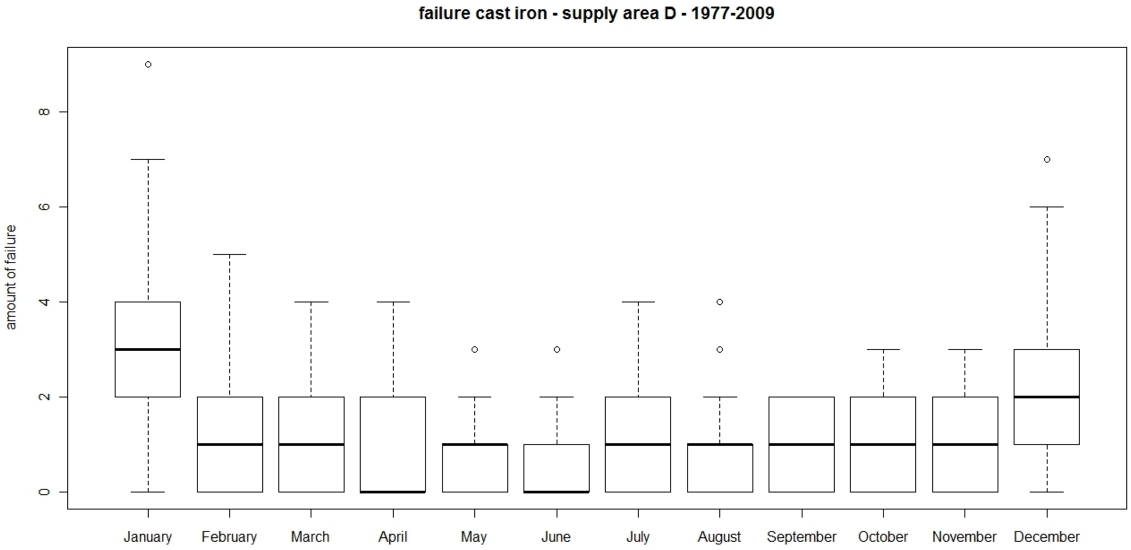

Figure 8: Variability of cast iron failure frequency for supply area D in the period 1977-2009

In Figure 9 the correlation between the variability of the amount of FI and the occurrence of failures on cast iron pipes is shown. The influence of strong freezing periods in supply area D on cast iron pipes is in evidence.

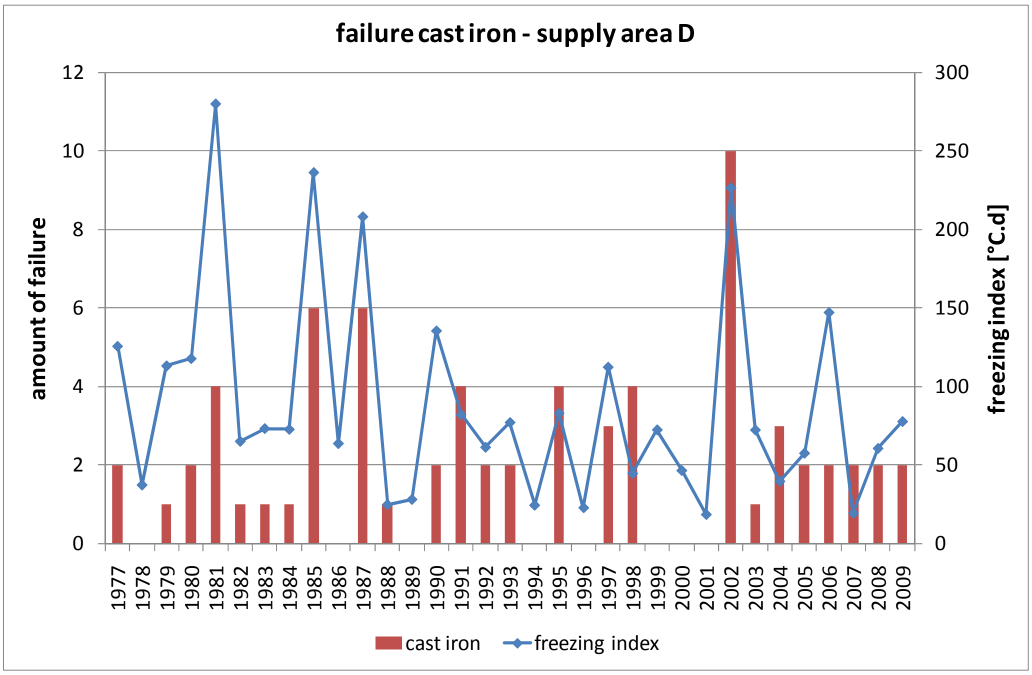

Figure 9: Correlation between cast iron failure frequency and FI in supply area D

Supply area B belongs to the pannonian climate zone which is characterized by moderate and dry winter seasons and dry and hot summer seasons. For the supply area B the characteristic annual pattern of failure rates with peaks during or towards the end of the winter season is not given. One reason is a moderate climate and winter seasons with low amounts of FI. Another reason is the absence of cast iron pipes in the supply area B.

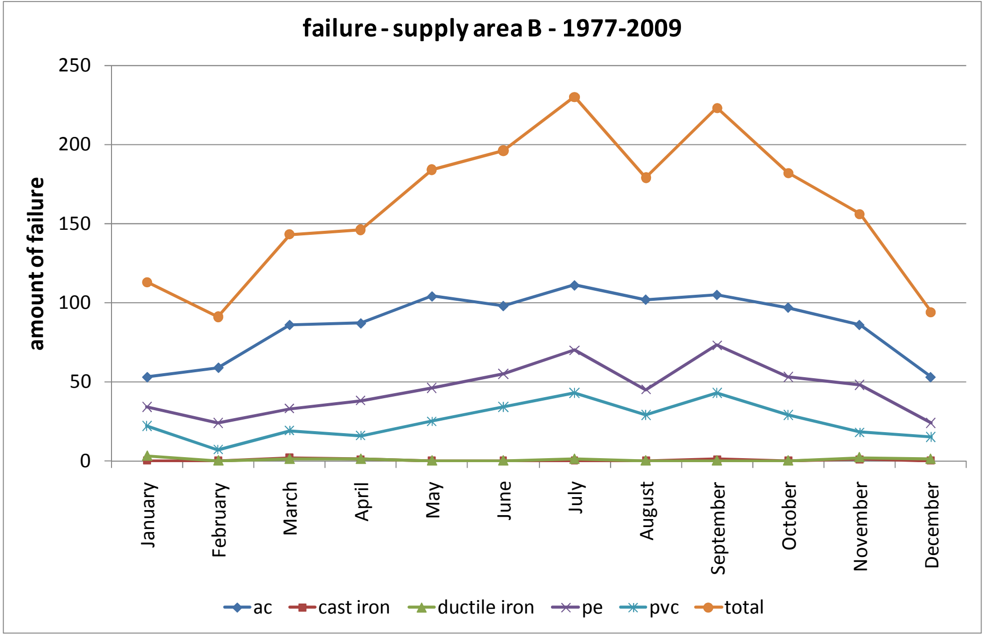

Figure 10: Monthly failure frequency for material types in the time-period 1977-2009 (area B)

However, for all relevant material types and additional for small diameters, peaks in the amount of failure during or towards the end of the summer season, are recognizable.

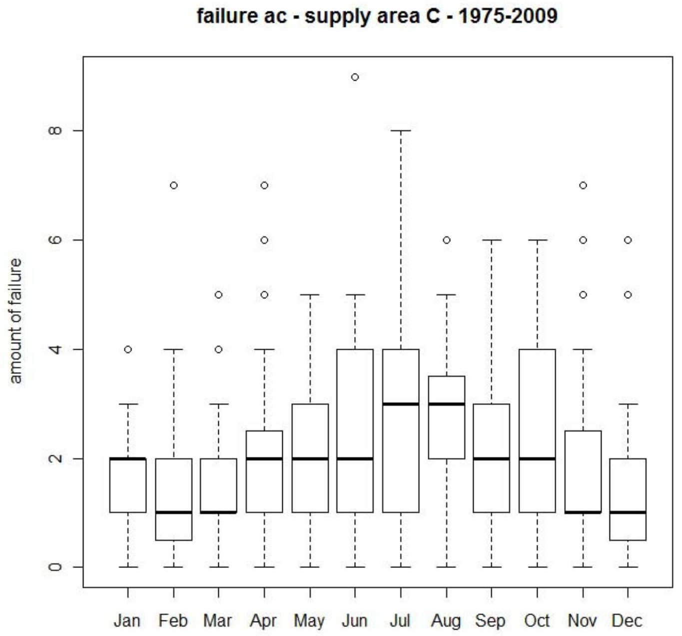

Figure 11: Failure frequency for the material type asbestos cement (ac) from 1975-2009 (area B)

Figure 11 describes the typical annual pattern of the failure frequency for the material type ac for all examined Austrian supply systems. It shows a high variability in the amount of failure in the summer season, e.g. supply area C.

In a next step a the influence of additional climatic parameters on water main failures was investigated. This are the dry-index for the whole year (DI), dry-index for the summer period (DI summer), rain deficit for the whole year (RD), rain deficit snapshot (RD snapshot), rain deficit for the summer period (RD summer), the amount of successive very hot days in the summer period (AHD) and the amount of cold days (ACD) according to the calculation of the frost-index (FI).

Statistical multiple bivariate correlation calculations, shown in Figure 12, explain the correlation between the cast iron failure frequency in winter seasons for the failure mode cirular break and FI and the duration of freezing in supply area E (observation period 1989 to 2009). No statistical correlation between cast iron breaks and the parameter rain defict or dry index can be distinguished. Further no statistical correlation for water main failure frequency and the parameters rain-deficit, dry-index, amount of successive very hot days (AHD) and the FI of the winter season before is in evidence. The result of the multiple bivariate correlation, shown in Figure 12, is typical for all examined Austrian supply areas.

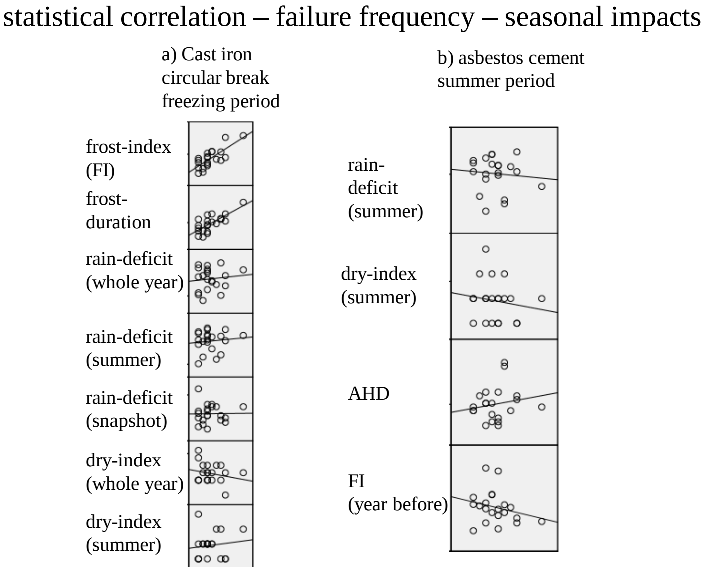

Figure 12: statistical correlation between failure frequency and seasonal climate impacts in supply area E

Conclusions and Outlook

Considering seasonal climatic effects on water main failure, such as severe winter in the form of freezing index (FI), soil moisture in the form of dry index (DI) or rain-deficit, for moderate climate regions is of important interest. The results of the statistical analysis have confirmed a correlation between the severity of a winter season and the occurrence of water main failures of specific material types, like cast iron with small diameters. The typical peak in failure frequency in the summer season for the material type asbestos cement can not be explained by parameters like dry-index and rain-deficit. The purpose of the ongoing analysis is to determine a correlation between the peak in failure history in summer season and further impacts, like third party interference. This is expected to lead to a better understanding if and how water main failure is influenced by seasonal climatic variations in moderate climate regions and additional impacts. Further research on the implementation of the results into failure prediction models and combining such a model with realtime weather data is planned. This kind of models are expected to support a risk oriented maintenance planning and to improves failure risk prevention.

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