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Climate stress on drinking water infrastructure: a global review of meteorological drivers and pipe failures

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ABSTRACT

Urban drinking water distribution networks are critical infrastructure increasingly exposed to meteorological hazards, such as extreme temperatures, floods, and droughts, which are likely to intensify under climate change. Given the urgency of this challenge, this paper presents a state-of-the-art review of 29 peer-reviewed studies (selected from an initial 226 studies) that systematically examine the relationship between climatic variables and pipe failures, including efforts to predict failures under future climate-change scenarios. The review reveals that, despite growing research interest, only six studies explicitly incorporate climate-change projections, underscoring a critical gap in current research. It also identifies several overlooked factors, such as soil temperature, and outlines clear directions for advancing the field. Additionally, to ensure that the review reflects real-world needs and emerging concerns, a global survey conducted by the lead author captures perspectives from water professionals on the impacts of future climate change on drinking water networks and their practical experiences with pipe failures. By combining a comprehensive literature analysis with practitioner insights, this paper provides the most up-to-date assessment of the field, highlights key research gaps, and establishes priorities for improving failure prediction, ultimately supporting efforts to enhance the climate resilience of water distribution networks.

Key words: climate change, drinking water distribution networks, water main failures

HIGHLIGHTS

- Provides insights from a global survey on expert perspectives linking climate change and water infrastructure.
- Synthesises how climate-driven meteorological factors affect the structural integrity of drinking water mains.
- Identifies key weather-related stressors, such as extreme temperature and precipitation, and their influence on pipe failures.
- Outlines research gaps to guide future strategies for infrastructure resilience and adaptation under climate-change scenarios.

1. INTRODUCTION

Drinking water distribution networks (DWDNs) are critical infrastructures, supplying about 50% of the global population in 2012, increasing to around 74% in recent years, with higher coverage in urban areas (Savić *et al.* 2013; Rajapakse *et al.* 2023). Failure of the DWDN can result in economic losses such as the loss of treated drinking water, and social issues, such as the outages of service (Almheiri *et al.* 2020; Khashei *et al.* 2024). Despite the DWDN being buried and designed to withstand several different loads during its lifespan, unexpected variations may lead to failures in its structural integrity (Wols & van Thienen 2016). Meteorological factors such as floods, droughts, heat waves, cold snaps, soil moisture loss, freezing/thawing processes, and others, worsened by climate change, may speed up pipe deterioration, causing damage to infrastructure and unplanned service outages (Wols *et al.* 2014; Ahmad *et al.* 2023; South East Water 2023; Khashei *et al.* 2024; Żywiec *et al.* 2024).

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However, despite growing research interest, only a small number of studies explicitly incorporate climate-change projections, revealing a critical gap in current research. Several important factors, such as soil temperature, soil moisture, and groundwater conditions, have been largely overlooked in previous analyses. In addition, real-world needs and emerging concerns are rarely captured through systematic surveys with water professionals, meaning that practical perspectives, climate-related risks to drinking water networks, and utility-based experiences with pipe failures remain underrepresented in the literature.

To address these gaps, this paper identifies key concerns regarding the future impact of meteorological events on drinking water pipelines by combining two complementary approaches: a survey of water sector professionals and a targeted review of the scientific literature. Together, these methods constitute a qualitative approach aimed at providing a clearer understanding of current challenges, practitioner perspectives, and knowledge gaps. The survey captures insights from professionals working in the water sector, while the literature review synthesises current scientific knowledge on climate-related impacts on drinking water infrastructure. In particular, the literature review highlights existing modelling approaches and analytical methods that can support future efforts to quantify the impacts of different climate projections on drinking water pipelines.

The structure of this paper is as follows. Section 2 presents the survey and its results. Section 3 details the procedure used to identify relevant literature through search engines, and delivers an overview of the state-of-the-art. Section 4 provides the conclusions, covering insights from the survey, the search methods, and the literature review; this section also outlines the identified gaps in current research.

2. SURVEY

In 2024, the first author conducted an online survey to **gather qualitative insight** from professionals in the water sector. The survey was distributed through the authors' professional and academic network, including contacts within Dutch drinking water utilities and water-related organisations across several countries. This purposive sampling approach was adopted to capture expert perspectives on DWDN, climate-related risks, and future challenges facing water infrastructure. The **survey was exploratory and qualitative in nature**, aiming to identify emerging concerns, practitioner experiences, and knowledge gaps, rather than to produce statistically representative results.

The survey consisted of two main questions, addressing concerns over two future horizons: 10–30 and 50–100 years. It was distributed among people working in the water sector worldwide, across different positions, institutions, and aimed at various levels of experience. The goal of the survey was to complement the information available in the scientific literature by gathering the perspectives of practitioners and researchers on the future challenges for DWDN. People's opinions share a common concern regarding the ageing and condition of DWDN and the impact of increasing temperatures.

The survey collected responses from 64 participants, representing 21 nationalities from Europe, South America, Africa, Australia, and Asia. They are working in 13 countries across the water industry (mostly in Europe), including water utilities, academia, and research institutions. These individuals have been working in the water sector for periods ranging from 6 months to 41 years, holding positions such as managers, consultants, contractors, and researchers.

The survey included two main questions. Question 1 asked: *'Which factors do you believe may impact water distribution systems over two future time horizons (10–30 years and 50–100 years)? Considering factors such as: temperature increases, temperature extremes (maximum and minimum), precipitation patterns (including extreme events), floods, droughts, changes in snow patterns, soil conditions, land use changes, sea level rises, wildfires, and any other relevant factors'.*

Summarising the answers for question 1: For the 10–30-year time horizon, 70% of respondents identify droughts as the primary concern. Extreme events and changes in precipitation patterns rank second, cited by 52% of respondents. In third place, with slightly more than 50%, are rising temperatures and flood events. For the 50–100-year time horizon, the main concern is sea level rise (36%), followed by prolonged droughts (34%). Continued temperature increases rank third, with nearly 30% of respondents expressing concern. Overall, the results show a shift in the relative importance of concerns, from droughts and extreme events in the 10–30-year time horizon to sea level rise and prolonged changes in the 50–100-year time horizon.

To better understand the real-world challenges already faced by water utilities, respondents were also invited to share concrete examples of how climatic factors have affected DWDN in their regions. The examples presented below reflect the experiences and observations reported by survey participants and are intended to illustrate the range of climate-related

impacts currently encountered by drinking water utilities. Respondents in the Netherlands reported that soil settlement has led to ground movement, causing leaks and main bursts (Wols *et al.* 2014). Participants from the UK highlighted the 2022 freeze–thaw event (South East Water 2023), which resulted in severe outages and economic losses. They also noted that droughts and reduced soil moisture have led to soil movement and pipeline bursts, while extended warm periods have led to restrictions on water usage. In contrast, heavy rainfall (Holley *et al.* 2022) has raised groundwater levels, affecting parts of the DWDN.

A respondent from Sydney indicated that the 2017–2020 drought and the 2019–2020 bushfires (Jackson *et al.* 2024), followed by extreme rainfall events in 2021–2022 (Visual Stories Team & Gilmore 2022), have severely degraded raw water quality. Furthermore, low soil moisture has contributed to an increase in pipe breaks, while increasingly hot summers have raised water demand and placed additional pressure on the DWDN, leading to leaks and failures.

In Cochabamba, Bolivia, a respondent highlighted the Misicuni multipurpose project (Hoogendam & Boelens 2019), which includes a drinking water and hydropower dam, as well as planned pipelines for DWDN and irrigation. The project has been implemented to enhance water supply reliability in response to recurring service outages and water scarcity, driven by declining precipitation and prolonged droughts, and anticipated future climate impacts. Similarly, a respondent in La Paz noted that heavy rainfall has damaged public water infrastructure (Hardy 2009) and triggered flash floods and landslides across the city (Associated Press 2024). In some areas, the absence of sewer systems has further exacerbated slope instability, as wastewater infiltration weakens the soil, particularly in hillside zones. As a result, entire residential areas and associated water supply infrastructure have been lost due to landslides. These events have increased in frequency in recent years and are expected to intensify under future climate-change scenarios.

Conversely, respondents from Argentina and Peru highlighted historical drought crises along the Paraná River (Meteorological Organization 2021), as well as prolonged dry spells in Tayacaja – Huancavelica province of Peru (Observatorio CEPLAN 2023). These conditions have prompted efforts to identify new water sources, thereby increasing the need for adaptations for (DWDN), such as the expansion of transmission mains, changes in supply configurations, and the integration of alternative sources. Collectively, these examples underscore the perceived urgency of implementing adaptive strategies to mitigate the impacts of climate change on water systems.

The second question of the survey focused on the water infrastructure itself: *‘Based on your working experience, which factors (water availability, changes in water demand, the age and condition of the water infrastructure, and water treatment and disinfection) will be most affected in the water supply networks in urban areas? Considering both future time horizons: 10–30 years and 50–100 years’.*

Summarising answers for question 2: For the 10–30-year time horizon, respondents identified water infrastructure age and network condition (66%) and water demand changes (66%) as the most affected factors, followed by water availability (59%), while water treatment and disinfection were considered less critical (44%). For the 50–100-year time horizon, concerns shift slightly, with water availability and infrastructure condition receiving the highest responses (both >30%), whereas water demand and treatment-related issues were reported less frequently (just over 20%). Overall, response levels for the 50–100-year time horizon are lower than for the 10–30-year horizon, showing reduced perceived urgency and uncertainty regarding longer-term impacts. The same factors are identified across both time horizons, with differences mainly in their relative importance.

Comments from the respondents were also collected in the survey. Several critical concerns were highlighted related to ageing infrastructure in DWDN. The issues of ageing, deterioration, and a lack of past investment emphasised the urgent need for increased funding and infrastructure renewal. Responses to each factor appear strongly influenced by the respondent’s country of origin. For example, a participant from the UK noted that, given a low replacement rate (0.4% per annum), existing systems may take several centuries to be fully renewed, highlighting the need for water companies to accelerate infrastructure replacement.

Specific material concerns were raised regarding the use of asbestos cement (AC), brittle PVC, and cast iron (CI), all of which require timely replacement. Additionally, today’s demand profiles have revealed inefficiencies in the design of many existing networks. Rising maintenance costs, driven by reactive approaches and periods of underinvestment, further exacerbate the situation. Looking ahead, respondents also expressed concerns about increasing deterioration rates, insufficient funding, and worsening leakage levels in water distribution systems.

The survey comments also referred to changes in water demand driven by various factors. Respondents from the UK noted that changing the behaviour of users influences water-use patterns, contributing to a general increase in demand.

Post-COVID-19 shifts have altered user expectations and water consumption habits, while weather-related demand fluctuations, such as those caused by heat waves, have further increased water demand. Additionally, respondents from the Netherlands noted the scarcity of water supply and groundwater resources, as well as population growth, as major challenges, leading to rising water demand and highlighting the need for adaptive management strategies.

Water availability emerged as a major concern due to the impact of climate change, which in some countries has led to more frequent droughts and declining aquifer levels. In Scotland, growing awareness of water scarcity has initiated discussions about historical perceptions and the need for environmental regulations, such as restrictions on abstraction licenses to safeguard resources. Quality concerns were also highlighted, with issues related to nitrates and treatment costs affecting overall water quality. Respondents emphasised the importance of viewing water as a precious resource, drawing a comparison with the situation in Australia. Extreme climatic events (including droughts, bushfires, and intense rainfall) have affected water availability and raw water quality in Australia, as well as increased stress on DWDN. Worldwide, future availability remains uncertain, as population growth and the need for substantial infrastructure investment threaten the long-term reliability of supply. Additionally, the preservation of drinking water sources is essential, as there are indications of a decline in their quality and availability.

Finally, there were comments about the challenges in water treatment and disinfection. For instance, the need for more advanced treatment technologies in Australia emerged from extreme weather and bushfire incidents, increasing raw water pollution (sediment, nutrients, organic matter, ash and charcoal from burned catchments, PFAS, and microplastics). UK respondents noted that issues such as blue-green algae require continuous pilot testing and real-time water quality monitoring to adjust treatment processes.

The survey provided a valuable and up-to-date perspective on current concerns regarding future climate impacts. Two key findings emerged: (i) *the critical role of 'Water Infrastructure Age and Condition'* and (ii) *the increasing relevance of climatic factors such as 'Extreme Temperatures', 'Droughts', and 'Floods'*. **Based on these insights, the literature review focuses on identifying and analysing studies that examine climate variables and climate-change scenarios, and their relationship to failures in DWDN.**

3. LITERATURE REVIEW

3.1. Search settings and results

To examine the current state of the art of understanding how climatic variations affect drinking water mains and associated failures, a literature review was conducted using two search engines: Scopus and Connected Papers. Scopus enabled a systematic review (Elsevier 2025), while Connected Papers provided an AI-driven, visual citation-based exploratory search (Eitan *et al.* 2020). An advanced Scopus search using terms such as 'drinking water main failures', 'climate change', and 'climate variability' initially identified 226 documents. After refining with additional keywords (e.g., drought, floods, rainfall, adaptation, soil moisture), the list was narrowed to 31 documents.

Connected Papers complemented the literature search by generating a graph based on a seed paper addressing pipe failures and climate-related variables. The generated network highlighted the relationships among relevant studies and identified the most strongly connected papers within the research field. This process yielded 41 related documents, which were combined with the initial search results (Scopus list), and after removing duplicates, 67 papers remained.

Finally, after a manual review applying selection criteria (excluding studies lacking meteorological variables and focusing solely on greenhouse gas emissions or failure-based machine learning models), the final literature set includes 26 relevant papers and 3 previous studies. Figure 1 shows the described process in a flowchart.

In the present review, a clear distinction was made between *climate-related studies* and *climate-change scenario studies*. Climate-related studies are defined as those that incorporate observed or historical climatic variables (e.g., temperature, precipitation, and related climate-derived variables) as explanatory variables in pipe-failure analyses. In contrast, climate-change scenario studies are defined as those that explicitly use projected future climate information, such as Representative Concentration Pathways (RCPs), SSPs, national climate scenarios, or climate model projections, to estimate future pipe-failure behaviour.

3.2. Literature overview

Among the 29 documents that were identified, three are literature reviews published in 2019, 2023, and 2024.

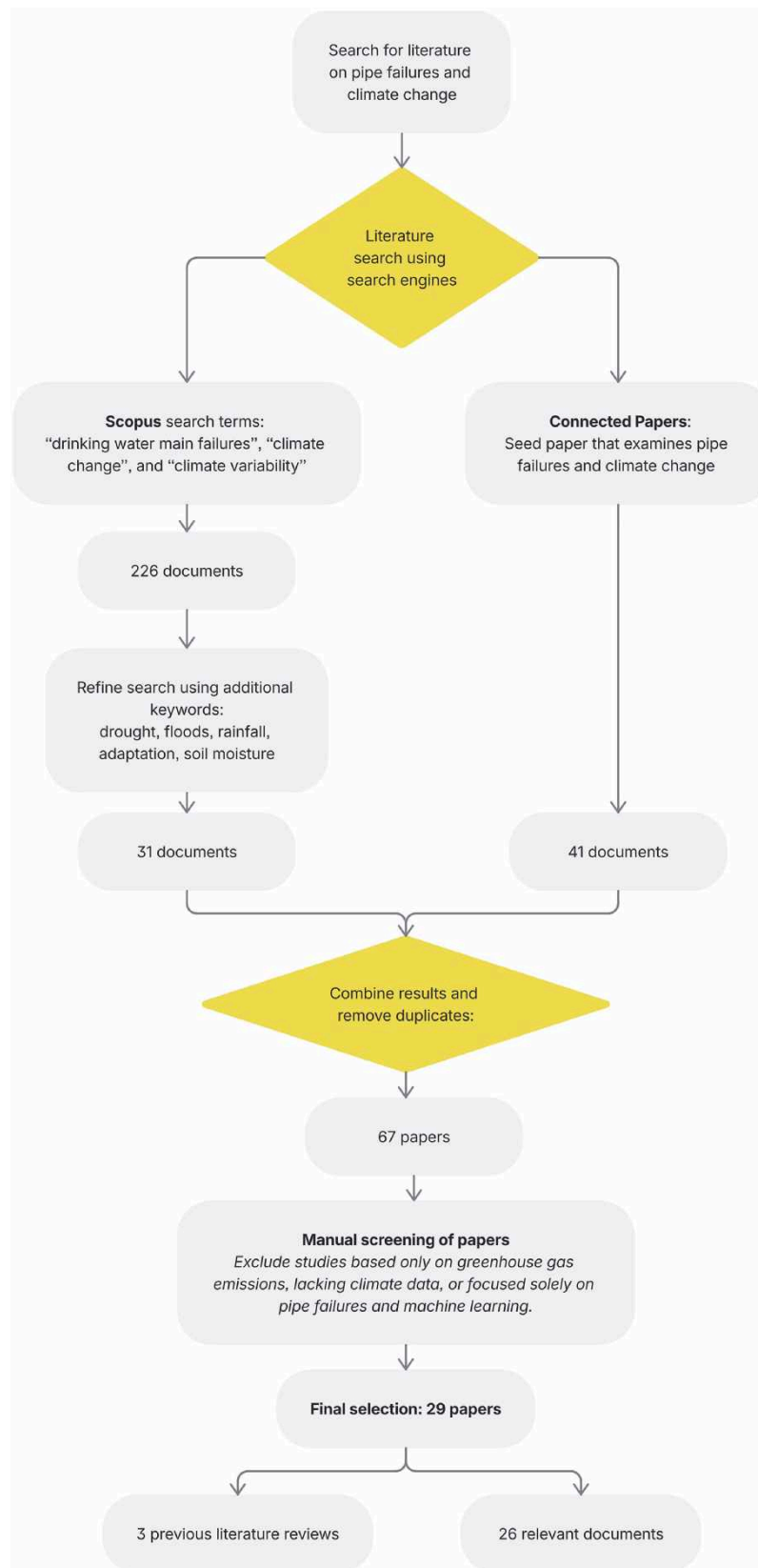


Figure 1 | Literature identification, screening, and selection procedure.

The present review differs from previous literature reviews not only in the studies included (Table 1 shows that two of these six analysed studies were not considered in the three earlier reviews) but also, more importantly, in its analytical focus. Dawood *et al.* (2019) primarily concentrated on pipe deterioration and risk-of-failure modelling, in which climate variables were treated as only one of several explanatory factors, and climate-change scenarios were not explicitly incorporated into the reviewed predictive models. Ahmad *et al.* (2023) examined the influence of climatic conditions on pipe deterioration and failures, but did not systematically analyse the climate projection adopted in the underlying studies. Żywiec *et al.* (2024), in contrast, addressed broader climate-change impacts on water supply systems, water quality, emerging pollutants, infrastructure resilience, and water demand, while studies explicitly focusing on scenario-based pipe-failure prediction constituted only a minor component of their review.

In contrast, the present review specifically focuses on how future pipe failures are predicted under explicit climate-change scenarios. To achieve this, the review provides a structured comparison of key dimensions across studies, including climatic variables, pipe-failure datasets, soil properties, pipe materials, climate projection frameworks, and prediction methodologies (e.g., statistical models, hydraulic simulation, and machine learning approaches). Furthermore, the review systematically examines the types of climate-change scenarios, distinguishing between single-model, multi-model, and multi-scenario projections. Therefore, the contribution of this review extends beyond simply updating the literature by providing a coherent and comparative framework that explicitly links climate-change scenarios, projection approaches, and predictive methodologies in the context of pipe-failure assessment.

Overall, these three existing literature reviews provide a useful initial overview of how climatic factors are related to pipe failures, while also revealing clear limitations. Notably, none of them offers a detailed or systematic examination of how climate-change scenarios are incorporated into pipe-failure predictions. In several cases, the classification of studies as ‘climate-related’ does not accurately reflect how climate data are used analytically. Collectively, these reviews indicate that a limited number of studies employ climate-change projections to assess future pipe-network integrity, highlighting that this area remains relatively underdeveloped.

Applying the classification framework described in Section 3.1, only six studies were identified as explicitly incorporating climate-change scenarios into future pipe-failure prediction. This finding underscores that many studies previously labelled as climate-related rely solely on historical climatic observations rather than forward-looking projections, reinforcing the novelty and necessity of a more structured and scenario-focused analytical approach.

Table 1 | Comparison of previous literature reviews and the current study

Review	Main objective	Studies using climate-change scenarios for pipe-failure prediction	Relation to the six studies analysed in the present review
Dawood <i>et al.</i> (2019)	Review of water pipe deterioration and risk-of-failure prediction models, focusing on predictor variables and modelling approaches.	None of the reviewed studies explicitly assessed future pipe failures using climate-change scenarios. Climate was treated as an explanatory variable in only three studies.	None of the six climate-scenario studies analysed in the present review were included.
Ahmad <i>et al.</i> (2023)	Review of climatic impacts on water main deterioration and failures, including climate-related factors affecting pipe performance.	Wols & van Thienen (2016), Bruaset & Sægrov (2018), and Żywiec <i>et al.</i> (2019)	Included three of the six studies analysed in the present review.
Żywiec <i>et al.</i> (2024)	Review of climate-change impacts on water supply systems, with emphasis on water quality, emerging pollutants, infrastructure resilience, and climate-related challenges.	Wols & van Thienen (2016), Bruaset & Sægrov (2018), Żywiec <i>et al.</i> (2019), and Fan <i>et al.</i> (2023)	Included four of the six studies analysed in the present review.
Present review	Assessment of how climate-change projections are incorporated into pipe-failure prediction studies.	Wols & van Thienen (2016), Bruaset & Sægrov (2018), Żywiec <i>et al.</i> (2019), Bondank <i>et al.</i> (2022), Fan <i>et al.</i> (2023), and Khashei <i>et al.</i> (2024)	Provides a detailed methodological assessment of all six identified climate-scenario studies.

The six papers are examined in detail in the following section, comparing their input data, methodological approaches, and use of machine learning and climate-change scenarios to identify methodological gaps and opportunities for future research. The remaining 20 papers rely solely on historical or meteorological variables and are briefly reviewed to illustrate how existing work has incorporated climatic information into pipe-failure analysis without explicit future climate projections.

3.3. Synthesis of the relevant six papers

Table 2 shows a summary of the six papers that examine the relationship between pipe failures and meteorological variables, including the use of data coming from climate-change scenarios in their analysis. The table shows the authors, year of publication, the climatic variables used, whether a historical record of pipe failures was available, whether soil properties, pipe materials, and climate-change scenarios were considered, and the methodological approach that was used.

The primary climatic variable considered in the studies is temperature, while some studies also considered precipitation (used to identify droughts). Most studies rely on historical failure records, while a few also incorporate soil properties such as type, density, or soil deformation properties. Moreover, studies cover a variety of pipe materials, including CI, AC, polyvinyl chloride (PVC), ductile iron (DI), polystyrene (PE), and steel (ST).

The reviewed studies covered regional variations, but all climate scenarios come from global circulation models (GCMs), mainly from European models (e.g. UKESM1-0-LL from the UK, CMCC-CM2-SR5 from Italy, EC-Earth3 from the Netherlands, etc.). Only one of the six studies applied a wider approach using multiple GCM products (Fan *et al.* 2023), including MIROC (developed in Japan) and CanESM (from Canada). These GCMs are part of international modelling efforts like the Coupled Model Intercomparison Project (CMIP6), which uses the Shared Socioeconomic Pathways (SSPs), a newer set of scenarios that supersede the older RCPs used in CMIP5. National climate scenarios also evolve alongside these global efforts. Several studies applied region-specific climate-change scenarios. For instance, the Dutch KNMI'06 scenarios are based on CMIP3, but the recent version, KNMI'24, is based on CMIP6, and it has not been widely applied yet. Although scenarios will inevitably be updated over time, they are not revised annually; for instance, the RCPs used in CMIP5 guided climate studies for more than a decade, and the Dutch KNMI scenarios were updated only after about 17 years

Table 2 | Summary of the six papers using climate change in the context of pipe failures (sorted from newest to oldest)

Authors	Year	Climatic variables	Pipe failures	Soil properties	Pipe material	Climate-change scenarios	Approach or model
Khashei, Dziedzic, Roshani	2024	Air temperature, precipitation	Historical records	No	AC, CI	SSP1-2.6, SSP2-4.5, and SSP3-8.5	LSTM
Fan, Zhang, Yu, Speitel, X.Yu	2023	Air temperature, precipitation	Historical records	No	CI, DI, unkonwn	CESM2, CanESM5, MIROC6, SSP1-2.6, SSP3-7.0, and SSP5-8.5	Universal Krigging
Bondank, Chester, Michne, Ahmad, Ruddell, Johnson	2022	Air temperature	Failure probability from EPANET + reliability model	No	PVC, CI	RCP4.5 and RCP8.5	Probabilistic model + hydraulic simulation
Zywiec, Piegdo, Tchrzewska-Cielak	2019	Air temperature	Historical records	No	CI, ST, PE, PVC	RCP4.5 and RCP8.5	Statistical correlation and Linear regression
Stian Bruaset, Sveinung Sægrov	2018	Air temperature	Historical records	No	CI, PVC, AC, PE, ST	Norwegian Climate Scenarios (2070)	Linear regression
Wols, van Thienen	2016	Air temperature, precipitation (droughts)	Historical records	Yes, soil type	AC, PVC, CI	KNMI 2006 for the Netherlands	Probabilistic model

Abbreviations: AC, asbestos cement; CI, cast iron; DI, ductile iron; ST, steel; PE, polyethylene; PVC, polyvinyl chloride; SSP, Shared Socioeconomic Pathway; RCP, Representative Concentration Pathway; CESM2, Community Earth System Model Version 2; CanESM5, Canadian Earth System Model Version 5; MIROC6, Model for Interdisciplinary Research on Climate Version 6; KNMI, Royal Netherlands Meteorological Institute; LSTM, long short-term memory.

(from KNMI'06 to KNMI'23). Therefore, the issue is not the timing of updates, but the fact that current pipe-failure studies use a narrow selection of climate scenarios, often without exploring how the scenario choice affects the results.

The six reviewed studies adopted a range of climate projection approaches. [Khashei et al. \(2024\)](#) employed CMIP6-based climate projections under multiple SSP scenarios (SSP1-2.6, SSP2-4.5, and SSP3-8.5), representing a multi-scenario approach, although further details of the climate models used were not reported. [Fan et al. \(2023\)](#) adopted a multi-model, multi-scenario framework based on three CMIP6 climate models (CESM2, CanESM5, and MIROC6) and three SSP scenarios (SSP1-2.6, SSP3-7.0, and SSP5-8.5). Similarly, [Bondank et al. \(2022\)](#) employed a multi-model ensemble and multi-scenario framework based on CMIP5 projections, incorporating 19 climate models with 42 simulation runs for RCP4.5 and 20 climate models with 41 simulation runs for RCP8.5. [Żywiec et al. \(2019\)](#) used temperature projections from the CHASE-PL dataset under RCP4.5 and RCP8.5 scenarios, evaluating impacts for both mid-century (2036–2050) and end-of-century (2086–2100) periods. [Bruaset & Sægrov \(2018\)](#) adopted a multi-scenario approach using RCP2.6, RCP4.5, and RCP8.5 pathways derived from downscaled Norwegian climate projections and assessed impacts using low (10th percentile), median (50th percentile), and high (90th percentile) temperature increases for 2070. Finally, [Wols & van Thienen \(2016\)](#) applied the KNMI'06 G (moderate warming), G+ (moderate warming with changes in atmospheric circulation), W (warm scenario), and W+ (warm scenario with stronger changes in atmospheric circulation) pathways for 2050 and 2100 using national climate-scenario outputs.

Overall, all six studies adopted multi-scenario frameworks; however, only [Bondank et al. \(2022\)](#) and [Fan et al. \(2023\)](#) explicitly incorporated multiple climate models, with [Bondank et al. \(2022\)](#) employing the largest climate-model ensemble. The remaining studies relied on aggregated projection products or national climate scenarios without explicitly analysing individual model outputs. While some studies addressed uncertainty within their pipe-failure prediction models, none explicitly quantified or analysed uncertainty associated with the climate projections themselves.

[Table 2](#) shows the six studies that used climate-change scenario dataset apply a range of analytical methods, from linear regression and probabilistic models to more advanced machine learning techniques like long short-term memory neural networks (LSTM) ([Khashei et al. 2024](#)) and Universal Kriging ([Fan et al. 2023](#)), aiming to predict pipe failures under climate-change conditions.

3.4. Synthesis of common findings across the remaining 20 relevant papers

Supplementary Table S2 presents the 20 remaining relevant papers identified in this review, excluding the six scenario-based studies shown in [Table 1](#) and the three literature review papers.

The reviewed literature consistently demonstrates that meteorological conditions are a key driver of pipe failure, with the underlying mechanism being soil movement induced by moisture variations ([Gould et al. 2011](#); [Hu & Vu 2011](#); [Wols & van Thienen 2013](#)). Across studies conducted in Australia, Europe, and North America, several similarities appear. These can be summarised into three findings regarding the influence of climatic conditions on pipe-failure mechanisms.

First, pipe failures are mainly triggered by external stresses associated with soil movement. These movements are driven by fluctuations in soil moisture content, which are in turn controlled by climatic variables such as temperature and precipitation ([Friedl et al. 2012](#); [Kakoudakis et al. 2018](#); [Shi et al. 2020](#)). Rather than direct climatic variables, many studies rely on derived indicators (such as evaporation, antecedent precipitation, freezing index, and rainfall deficit), as proxies for soil moisture conditions ([Gould et al. 2011](#); [Laucelli et al. 2014](#); [Wols et al. 2019](#)).

Second, the influence of climatic conditions depends on pipe material. CI pipes are consistently identified as highly vulnerable to low temperatures and freeze–thaw cycles, whereas AC and steel pipes are more sensitive to high temperatures and soil shrink–swell processes ([Rajani et al. 2012](#); [Wols & van Thienen 2013](#); [Barton et al. 2019](#)).

Third, failure patterns show seasonal and regional variability. In colder climates, such as Canada, Austria, and the Netherlands, failure rates peak during winter due to freezing conditions ([Friedl et al. 2012](#); [Żywiec et al. 2021](#)). In contrast, warmer and drier regions, such as Australia, show increased failures during summer, primarily linked to soil moisture loss ([Gould et al. 2009, 2011](#)). These findings highlight the importance of local climatic and geotechnical conditions in shaping failure mechanisms.

To clarify these processes, [Figure 2](#) presents a conceptual diagram illustrating how meteorological variables may contribute to pipe failures. The left side of the figure focuses on temperature-related mechanisms, while the right side focuses on precipitation-related mechanisms.

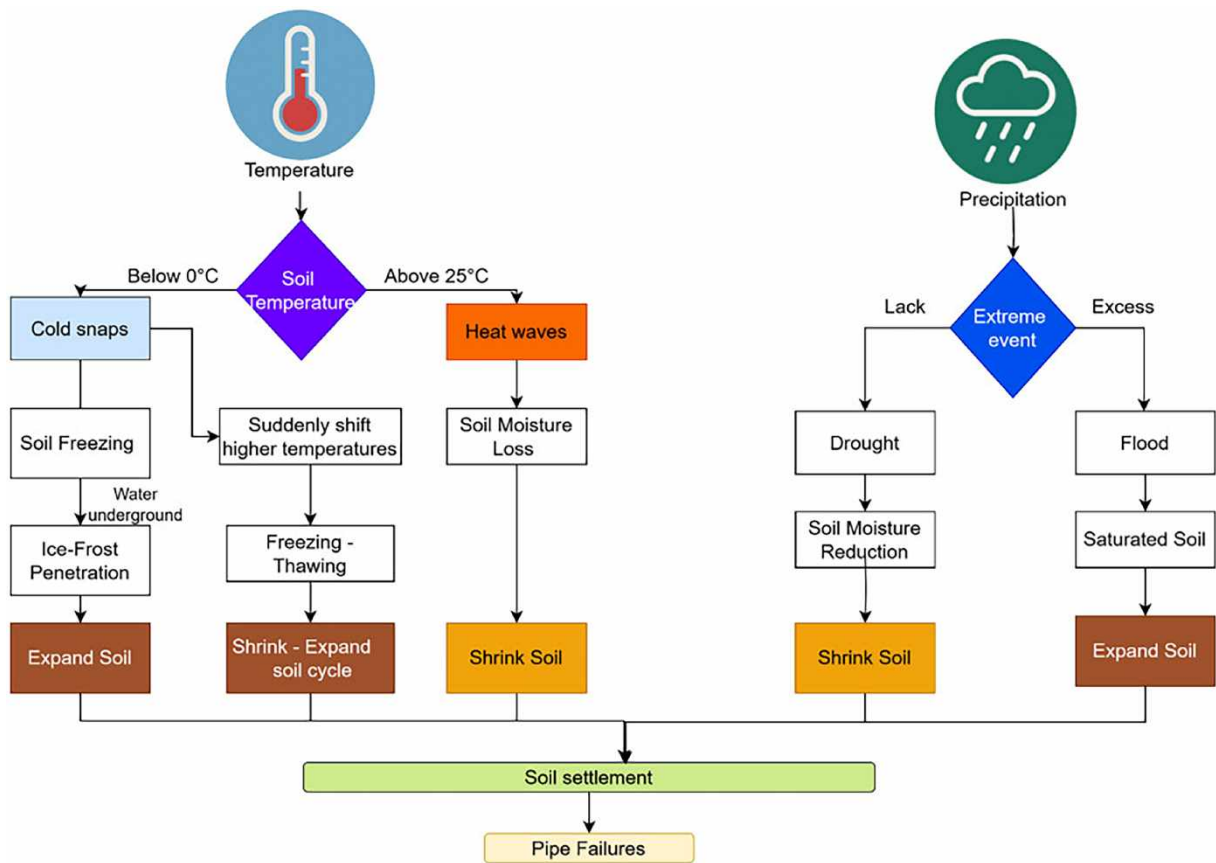


Figure 2 | Conceptual framework illustrating the influence of temperature and precipitation on pipe failures.

With respect to temperature, extreme cold events such as cold snaps can cause soil moisture to freeze, resulting in soil expansion. Where the groundwater table is shallow, freezing may also extend below the surface through frost penetration. These freeze-related processes can induce soil movement, which may result in pipe failures. Subsequently, when temperatures rise above 0 °C following a prolonged cold period, the frozen soil moisture thaws. This freeze–thaw cycle causes repeated expansion and shrinkage of the soil, causing soil movement and settlement that may further contribute to pipe failures. Conversely, extreme high-temperature events, such as heat waves, reduce soil moisture due to evaporation, potentially creating voids and leading to soil settlement, which also increases the likelihood of pipe failures.

With respect to precipitation, excessive rainfall or flooding can saturate the soil. Depending on the soil type, this may lead to soil expansion and associated soil movement, which can contribute to pipe failures. In contrast, prolonged periods of low precipitation may result in drought conditions, reducing soil moisture and causing soil shrinkage. This process leads to ground settlement, which may also increase the risk of pipe failures.

3.5. Identified research gaps and future directions

From the literature review, several remaining gaps in understanding the relationship between climate and pipe failure were identified.

3.5.1. Inclusion of future climate scenarios

A major limitation is the lack of integration of future climate-change scenarios into failure prediction models. Most studies focus on historical relationships and remain diagnostic rather than predictive, with only a limited number incorporating

climate projections (Wols & van Thienen 2016). This is partly due to challenges in obtaining suitable climate projections at the required spatial and temporal scales, as well as difficulties in linking these projections to pipe-failure mechanisms. As a result, the ability to assess long-term infrastructure vulnerability under changing climatic conditions remains limited.

3.5.2. Standardisation of methodologies and variables

In addition, there is considerable variability in methodologies, climatic indicators, and modelling approaches across studies. A wide range of techniques, including regression models, Bayesian networks, and machine learning, are applied using different temporal resolutions and climatic indices, making direct quantitative comparison between studies challenging (Demissie *et al.* 2017; Kakoudakis *et al.* 2018). While general qualitative trends can often be identified, the diversity of approaches and the context-specific nature of many models make it difficult to determine which methods are most robust or transferable across different regions and conditions. This reflects the emerging nature of the field and highlights the need for further research to evaluate and compare modelling approaches.

3.5.3. Quantification of soil–pipe interaction

There is a limited quantification of soil–pipe interaction mechanisms. While soil movement is widely acknowledged as the primary driver of pipe failures, most studies rely on statistical correlations rather than physically based models. Recent work incorporating direct monitoring of soil conditions and pipe deformation highlights the potential for more mechanistic understanding, but such approaches remain scarce (Shi *et al.* 2020; Latifi *et al.* 2026).

3.5.4. Limited availability of covariate data

Important non-climatic variables (such as construction quality, operational practices, and external loads) are often excluded due to data limitations, despite their recognised influence on failure processes (Martínez García *et al.* 2018). Among the six climate-scenario studies reviewed, only one study (17%) (Wols & van Thienen 2016) explicitly incorporated soil-related factors, while none (0%) considered construction quality, operational practices, or external loading conditions.

3.5.5. Expansion to other climate hazards

The research has predominantly focused on temperature and precipitation-driven mechanisms, while other climate-related hazards (such as flooding and groundwater changes) remain underexplored. Emerging studies suggest that these factors may significantly affect network vulnerability, indicating the need for broader hazard assessments (Mahdaoui & Tahiri 2021).

4. CONCLUSIONS AND DISCUSSION

4.1. Main findings

The combined analysis of the survey and literature review shows that both water professionals and the existing research body identify ageing infrastructure and climate-related stressors as important drivers of pipe failures in DWDNs. Although respondents' perspectives were influenced by their geographical location, professional experience, and local infrastructure challenges, common concerns emerged regarding droughts, temperature extremes, and the deteriorating condition of existing assets. These concerns are consistent with the literature, which indicates that climatic variables, particularly temperature and precipitation, affect pipe failures primarily through their influence on soil behaviour.

Based on the six reviewed climate-related pipe-failure studies discussed, all include a temporal component. However, only two explicitly integrate this with spatial or network information. Therefore, integrated spatiotemporal approaches account for approximately 33% of the studies. Examples include Bondank *et al.* (2022), who coupled a hydraulic network model with time-dependent temperature-driven component failures to estimate service outages, and Fan *et al.* (2023), who combined GIS-based pipe and failure locations with dated failure records and climate variables. In contrast, other authors (Wols & van Thienen 2016; Bruaset & Sægrov 2018; Żywiec *et al.* 2019; Khashei *et al.* 2024) mainly focus on temporal climate-failure relationships, material or age cohorts, or system-level predictions, with limited explicit spatial analysis.

Combining the six principal studies incorporating climate-change projections with the remaining 20 additional studies, a total of 26 studies investigating climate impacts on water pipe failures were identified. The review reveals several methodological gaps that remain insufficiently addressed in the literature. Although temperature was considered in approximately 92% of the studies, only 69% incorporated additional climate drivers, such as precipitation, drought indicators, rainfall

deficits, soil moisture, or evapotranspiration, suggesting that the combined influence of multiple climate stressors is still underexplored. Furthermore, while 62% of the studies considered soil-related properties, their integration with climate variables was often limited to explanatory analyses rather than fully coupled modelling frameworks. A strong reliance on statistical and regression-based approaches was observed (approximately 58% of the studies), whereas machine learning techniques accounted for only 19% and physics-based approaches for around 12%, indicating that advanced hybrid modelling frameworks remain relatively uncommon. In addition, despite the growing availability of geospatial infrastructure datasets, only around 12% of the studies incorporated explicit GIS-based spatial analyses, and fewer than 10% combined both spatial and temporal dimensions in an integrated spatiotemporal framework. Finally, future climate projections were incorporated in only about 23% of the reviewed studies, highlighting that long-term climate adaptation remains underrepresented relative to historical climate-failure analyses. Overall, these findings indicate the need for future research to prioritise integrated spatiotemporal modelling frameworks that combine climate projections, multiple hydro-meteorological variables, soil conditions, asset deterioration processes, and advanced machine learning or hybrid physics-informed models, to better support climate-resilient water infrastructure management.

An important observation is the gap between research and practice. While practitioners increasingly recognise the potential impacts of climate change on network performance, the incorporation of climate information into asset management and failure prediction remains limited. In particular, soil-related processes are widely acknowledged as critical factors in failure mechanisms, yet they are not consistently represented in existing analytical frameworks.

4.2. Discussion

The reviewed literature indicates that climatic factors rarely act as independent causes of pipe failures. Instead, failures typically result from the interaction between environmental stressors and pre-existing infrastructure vulnerabilities, including pipe age, material properties, corrosion, soil conditions, and accumulated structural degradation. While numerous studies have identified direct statistical relationships between climatic variables (particularly temperature, precipitation, drought conditions, and failure occurrence), suggesting that climate-related factors can act as immediate triggering factors (Rajani *et al.* 2012; Bruaset & Sægrov 2018; Żywiec *et al.* 2019), growing evidence indicates that climatic stressors primarily amplify underlying deterioration processes. For example, freeze–thaw cycles may accelerate damage in corroded metallic pipes, whereas drought-induced soil shrinkage can disproportionately affect older AC or CI pipes. Consequently, pipe failures are often the result of the combined effects of infrastructure ageing and climate-related stresses rather than either factor acting in isolation (Bondank *et al.* 2022; Fan *et al.* 2023; Khashei *et al.* 2024).

4.3. Recommendations for future research

Based on the findings of this review, several recommendations for future research can be identified.

First, future studies should investigate the combined effects of climatic stressors and infrastructure deterioration processes rather than considering these factors independently. Understanding how temperature extremes, droughts, freeze–thaw cycles, and precipitation interact with pipe ageing, material degradation, corrosion, and soil conditions would improve the understanding of failure mechanisms and long-term system vulnerability.

Second, there is a need to develop predictive models that integrate climate-change projections with historical pipe-failure data and infrastructure characteristics to assess future failure risks under different climate scenarios. Such models would support long-term asset management and adaptation planning.

Third, future research should more comprehensively incorporate soil–pipe interaction processes, including soil temperature, soil moisture, shrink–swell behaviour, frost action, and differential settlement, as these factors play an important role in the relationship between climate variability and pipe deterioration.

Fourth, comparative studies are needed to evaluate the performance of different modelling approaches, including statistical, machine learning, and physics-based methods, to identify frameworks that are both robust and transferable across diverse climatic regions and water distribution systems. This should include care in the choice of climate models, scenarios, ensembles, and treatment of uncertainty to ensure compatibility and traceability when comparing different studies.

Fifth, future research should expand the geographical coverage of studies investigating climate-related pipe failures. The concentration of studies identified in this review in Europe, North America, and Australia reflects the current availability

of published research rather than an intentional exclusion of studies from Asia, Africa, or other regions. To improve the generalisability of findings, future investigations should account for the specific characteristics of different ecoregions, including climatic conditions, soil properties, and water management, among others. These factors may influence both pipe deterioration processes and the effectiveness of adaptation strategies. Consequently, the relationships, vulnerabilities, and adaptation measures reported in the existing literature may not fully represent conditions in underrepresented regions. The lack of studies from Asia and Africa, therefore, highlights an important research gap for further investigation.

Finally, future research should further explore integrated spatiotemporal approaches that combine climate, infrastructure, and failure data to improve predictions of where and when pipe failures may occur. Such approaches could support water utilities in planning maintenance activities, developing adaptation strategies, and enhancing the resilience of water distribution systems under future climate conditions.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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