Improving Sustainability by Reducing Water Damage in Buildings
- A Holistic Perspective on Occurrence, Causes, Effects and Solutions

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LUND
UNIVERSITY

DOCTORAL DISSERTATION

By due permission of the Faculty of Engineering at Lund University to be publicly defended on 30 of November at 13.00 at lecture hall V:A, V-Huset, John Ericssons väg 1

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	Date of issue: 2026-09-28
	Sponsoring organizations: Formas 2019-00649 and SBUF 14360

Title and subtitle: Improving Sustainability by Reducing Water Damage in Buildings - A Holistic Perspective on Occurrence, Causes, Effects and Solutions

Abstract: Water damages are among the most common and costly building defects in the built environment. Beyond repair costs, they cause resource use, operational disruptions, and environmental impacts associated with repair and reconstruction. Despite their significance, knowledge of water-damage occurrence, causes, consequences, and prevention remains fragmented, particularly for public buildings. This thesis aims to improve the understanding of leakage-related water damage from a holistic sustainability perspective. Literature reviews, statistical analyses, building-stock analyses, stakeholder interviews, cost assessments, and life-cycle assessment (LCA) were used to investigate water-damage occurrence, causes, consequences, and prevention. The analyses included approximately 89 500 reported water-damage incidents in Swedish residential buildings, corresponding to an annual occurrence rate of around 2.9% of the building stock. In public buildings, 3 030 verified incidents were identified across 2 243 buildings in three municipalities. The annual frequency of recorded water-damage corresponded to one damage in average of approximately 15% of the studied public-building stock when a building was used as the functional unit, with the highest rates observed in nursing and care facilities (42%). Most incidents originated from building services installations, particularly tap-water and sewage systems, and wet-room environments. The findings show that water damage develops through interactions between technical, organizational, and behavioral factors. Ageing systems, corrosion, installation deficiencies, and waterproofing failures were identified as major causes, while maintenance practices, communication, operational conditions, and user behavior influenced both occurrence and severity. Vulnerability differed between building categories, highlighting the need for context-specific prevention strategies. Water damage was also found to generate substantial economic and environmental consequences. Average repair costs in public buildings were approximately 9 200 € per damage case, while annual costs averaged 1 400 € per public building compared with 340 € per residential building. Environmental assessments showed greenhouse-gas emissions ranging from 26-35 $kgCO_2e$ for minor repairs to 454-749 $kgCO_2e$ for severe damage scenarios. In several cases, the climate impact of repair exceeded that of the original bathroom construction. No single preventive measure was found to eliminate all water-damage risk. Effective prevention was instead associated with condition-based maintenance, systematic inspections, replacement of ageing systems, leak-detection technologies, automatic shut-off devices, digital monitoring, and organizational learning. The results show that reducing water-damage risk requires a combination of technical, organizational, and maintenance-related measures, supporting more sustainable and risk-based management of residential and public building stocks.

Keywords: Water damage, building defects, costs, causes, leakage, building services system

ISRN: LUTVDG/TVIT-26/1010-SE	**Language:** English
ISSN: 1652-6783	**ISBN:**978-91-85415-26-7 (printed) 978-91-85415-27-4 (e-version)
Recipient´s notes	**Number of pages:** 254
	Security classification:

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- A Holistic Perspective on Occurrence, Causes, Effects and Solutions

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Faculty of Engineering
Department of Building and Environmental Technology
Division of Building Services

ISRN LUTVDG/TVIT-26/1010-SE
ISSN 1652-6783
ISBN:978-91-85415-26-7(printed)
ISBN: 978-91-85415-27-4 (e-version)
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Acknowledgment

This thesis marks the end of a rewarding and challenging journey, and there are many people and organizations whom I would like to thank for their support along the way. First and foremost, I would like to express my sincere gratitude to my supervisors, Birgitta Nordquist, Dennis Johansson, Hans Bagge, Petter Wallentén and Ulla Janson. Thank you for your guidance, encouragement, patience, and constructive feedback throughout the years. Your support has challenged me to develop as a researcher and has been invaluable in bringing this thesis to completion.

This work was funded by FORMAS (the Swedish Research Council for Sustainable Development) through Grant No. 2019-00649 and by SBUF (The Development Fund of the Swedish Construction Industry) through Grant No. 14360. Although the funding bodies had no involvement in the writing of the appended papers or this thesis, I am deeply grateful for their and LTHs financial support and for making this research possible. I would also like to express my sincere appreciation to Rörläggaren AB and the industry organizations Säker Vatten AB and Vattenskadecentrum for their engagement in the project. Through seminars, industry discussions, and valuable exchanges of knowledge and experience, they have contributed greatly to this research journey.

I am grateful to the industry organizations, building owners, municipalities, and all other participants who generously shared their time, expertise, insights, and data. Without your willingness to contribute, this research would not have been possible. I hope that the findings presented in this thesis can support the ongoing efforts to reduce leakage-related water damage and contribute to a more sustainable built environment. To my colleagues and friends at Lund University and within the project, thank you for the many discussions, collaborations, coffee breaks, and moments of encouragement throughout the years. Your support has made the doctoral journey more enjoyable. Finally, and most importantly, I would like to thank my family. Thank you for your endless love, patience, understanding, and unwavering belief in me. This thesis would not have been possible without you, and I am deeply grateful for everything you have done along the way.

Lund, November 2026

Christian Mattsson

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Abstract

Water damages are one of the most common and costly building defects in the built environment. Beyond repair costs, water damage leads to resource consumption, operational disruptions, and environmental impacts associated with repair and reconstruction activities. Despite its significance, knowledge of water damages occurrence, causes, consequences, and prevention remains fragmented, particularly for public buildings. The aim of this thesis is to improve the understanding of leakage-related water damage in buildings from a holistic sustainability perspective by investigating its occurrence, causes, consequences, and prevention. A mixed-methods approach was applied, combining literature reviews, statistical analyses, building-stock analyses, stakeholder interviews, cost assessments, and life-cycle assessment (LCA).

The results show that water damages is a recurring challenge in both residential and public buildings. The analyses included approximately 89 500 reported water-damage incidents in Swedish residential buildings, corresponding to an annual occurrence rate of around 2.9% of the building stock. In public buildings, a number of 3 030 verified incidents were identified across 2 243 buildings in three municipalities. The annual occurrence rates were considerably higher in public buildings, averaging 15% of the studied building stock with one annual damage in a building as a functional unit, with the highest damage rates observed in nursing and care facilities (42%). Incidents originated from buildings services installations such as tap water and sewage systems, and wet-room environments. The findings demonstrate that water damage develops through the interaction of technical, organizational, and behavioral factors. Ageing systems, corrosion, installation deficiencies, and failures in waterproofing systems were identified as major technical causes, while maintenance practices, communication, operational conditions, and user interaction influenced both the occurrence and severity of damage. Vulnerability differed between building categories, indicating that susceptibility to water damage is shaped by different combinations of building characteristics, technical systems, usage patterns, and organizational factors. This highlights the need for context-specific risk management and prevention strategies tailored to different building functions and operational contexts.

Water damage was also found to generate substantial economic and environmental consequences. Based on data from the study period, average repair costs in public buildings were approximately 9 200 € per damage case, while annual costs averaged 1 400 € per public building compared with 340 € per residential building. The economic burden extends beyond direct repair costs through deductibles, depreciation, operational disruptions, and administrative costs. Environmental assessments showed that greenhouse-gas emissions increased markedly with damage severity, ranging from 26 - 35 $kgCO_2e$ for minor repairs to 454 - 749 $kgCO_2e$ for severe damage scenarios. In several cases, the climate impact of repairing after a severe water-damage event exceeded that of the original bathroom construction.

No single preventive measure was found to eliminate all water-damage risk. Instead, effective prevention was associated with a combination of condition-based maintenance, systematic inspections, replacement of ageing systems, leak-detection technologies, automatic shut-off devices, digital monitoring, and organizational learning. The results further indicate a need for

guidelines specifically targeted at public buildings, together with preventive strategies adapted to different building categories and operational conditions.

This thesis provides new knowledge on the occurrence, causes, consequences, and prevention of water damage in residential and public buildings. The results show that water damage is influenced by a combination of technical, organizational, and user-related factors, and that the occurrence differ considerably between building categories. The findings also demonstrate that effective prevention requires a combination of technical solutions, maintenance strategies, and organizational measures rather than single interventions. These insights can support more risk-based management of building stocks and contribute to reducing the economic and environmental impacts of water damage. The results showed that water damage should not be viewed solely as a technical defect, but as a recurring sustainability challenge affecting buildings throughout their service life.

Sammanfattning

Vattenskador är en av de vanligaste och mest kostsamma byggrelaterade skadorna i den byggda miljön. Utöver direkta reparationskostnader medför de ökad resursanvändning, störningar i verksamheter och boendemiljöer samt miljöpåverkan från reparations- och återställningsarbeten. Trots problemets omfattning är kunskapen om vattenskadors förekomst, orsaker, konsekvenser och förebyggande åtgärder fortfarande begränsad, särskilt för offentliga byggnader. Syftet med denna avhandling är att öka förståelsen för läckagerelaterade vattenskador i byggnader ur ett hållbarhetsperspektiv genom att studera deras förekomst, orsaker, konsekvenser och förebyggande åtgärder. Studien bygger på en kombination av litteraturstudier, statistiska analyser, byggnadsbeståndsanalyser, intervjuer med fastighetsförvaltare och teknisk personal, kostnadsanalyser samt livscykelanalyser (LCA). Resultaten visar att vattenskador är ett återkommande problem i både bostäder och offentliga byggnader. Analysen omfattade cirka 89 500 rapporterade vattenskador i svenska bostäder, vilket motsvarar en årlig förekomst på omkring 2,9 % av byggnadsbeståndet. För offentliga byggnader identifierades 3 030 stycken verifierade vattenskador i 2 243 byggnader i tre svenska kommuner. Förekomsten var betydligt högre i offentliga byggnader, där i genomsnitt 15 % av detta byggnadsbestånd drabbades av minst en vattenskada per år. De högsta förekomstnivåerna återfanns i vård- och omsorgsbyggnader (42%). Majoriteten av skadorna hade sitt ursprung i ledningssystem, tappvatteninstallationer och våtrum.

Resultaten visar vidare att vattenskador uppstår på grund av såväl tekniska, organisatoriska och användarrelaterade faktorer. Åldrande installationer, korrosion, installationsbrister och tätskiktsfel identifierades som viktiga tekniska orsaker, medan underhållsstrategier, kommunikation, verksamhets-förutsättningar och användarbeteenden påverkade både risken för att skador uppstår och hur omfattande de blir. Olika typer av byggnader och verksamheter uppvisade också olika utsatthet för förekomsten av vattenskador, vilket understryker behovet av byggnadsanpassade strategier för riskhantering och förebyggande arbete.

Studien visar även att vattenskador dessutom medför betydande ekonomiska och miljömässiga konsekvenser. Den genomsnittliga reparationskostnaden i offentliga byggnader uppgick till cirka 101 000 kronor per skadetillfälle. Den årliga reparationskostnaden relaterat till vattenskador uppgick i genomsnitt till cirka 15 000 kronor för en offentlig byggnad jämfört med cirka 3 700 kronor för en enfamiljsvilla. De ekonomiska konsekvenserna sträcker sig dock längre än de direkta reparationskostnaderna och omfattar även självrisker, åldersavdrag, verksamhetsstörningar och administrativa kostnader. De utförda livscykelanalyserna visade att klimatpåverkan från reparationsarbeten ökar kraftigt i takt med skadornas omfattning. Den beräknade klimatpåverkan varierade från 26 - 35 kg CO_2e för mindre skador till 454 - 749 kg CO_2e för omfattande skador. I flera fall översteg klimatpåverkan från reparationen av en allvarlig vattenskada den klimatpåverkan som uppstod vid det ursprungliga uppförandet av det berörda badrummet. Ingen enskild åtgärd visade sig kunna eliminera alla risker för vattenskador. Framgångsrikt förebyggande arbete bygger i stället på en kombination av tillståndsbaserat underhåll, systematiska inspektioner, utbyte av åldrande installationer, läckagedetektering, automatiska avstängningssystem, digital övervakning samt

erfarenhetsåterföring i organisationen. Resultaten visar också att förebyggande åtgärder behöver anpassas efter olika byggnadstyper och verksamheters förutsättningar. Särskilt för offentliga byggnader finns ett behov av mer sektorsspecifika riktlinjer och branschgemensamma arbetssätt.

Avhandlingen bidrar med ny kunskap om vattenskadors förekomst, orsaker, konsekvenser och förebyggande åtgärder i både bostäder och offentliga byggnader. Resultaten visar att vattenskador påverkas av en kombination av tekniska, organisatoriska och användarrelaterade faktorer samt att risknivåerna skiljer sig avsevärt mellan olika byggnadskategorier. Studien visar även att ett effektivt förebyggande arbete kräver en kombination av tekniska lösningar, underhållsstrategier och organisatoriska åtgärder snarare än enskilda insatser. Denna kunskap kan bidra till en mer riskbaserad förvaltning av byggnadsbeståndet och till att minska de ekonomiska och miljömässiga konsekvenserna av vattenskador. Resultaten visar att vattenskador är mer än ett tekniskt problem; de utgör en återkommande hållbarhetsutmaning som påverkar byggnaders funktion, ekonomi och miljöpåverkan genom hela livscykeln.

List of Publications

Paper I: A quantitative and qualitative state-of-the-art literature review of water damage occurring from pipes, appliances, and wet rooms in buildings

Authors: ***Christian Mattsson****, Birgitta Nordquist, Dennis Johansson, Petter Wallentén, Hans Bagge*

Published journal article in Indoor and Built Environment, Vol 33, Issue 7, pp.1173-1189. Available at: https://doi.org/10.1177/1420326X241248331

Paper II: Water damages in HVAC, tap water and sewage systems in cold climates

Authors: ***Christian Mattsson****, Birgitta Nordquist, Dennis Johansson, Petter Wallentén, Hans Bagge*

Published conference paper at *Cold Climate HVAC & Energy 2021* (E3S Web of Conferences, Vol. 246, Article 12001). EDP Sciences. https://doi.org/10.1051/e3sconf/202124612001

Paper III: Cost performance analysis of water damages for sustainable prevention measures

Authors: ***Christian Mattsson****, Birgitta Nordquist, Dennis Johansson, Petter Wallentén, Hans Bagge*

Published conference paper at *Indoor Air 2022: 17th International Conference of the International Society of Indoor Air Quality and Climate*, Kuopio, Finland, 12-16 June 2022. International Society of Indoor Air Quality and Climate (ISIAQ). Available at: https://www.isiaq.org/docs/IA22_1824.pdf

Paper IV: Examination of Water Damage Statistics in the Nordic Countries to Identify and Suggest Preventive Cost-effective and Sustainable Measures during the Maintenance and Operation Phase

Authors: ***Christian Mattsson****, Birgitta Nordquist, Dennis Johansson, Petter Wallentén, Hans Bagge*

Published conference paper at ASHRAE and SCANVAC HVAC Cold Climate Conference 2023, Anchorage, USA, 5-10 March 2023. 9 pp. Available at: https://www.ashrae.org/conferences/topical-conferences/hvac-cold-climate-conference-2023

Paper V: Similarities, differences, and tendencies of water damage in the Nordic countries

Authors: ***Christian Mattsson****, Birgitta Nordquist, Dennis Johansson, Petter Wallentén, Hans Bagge*

Published conference paper at the 2nd International Conference on Moisture in Buildings (ICMB23), London, UK, 3-4 July 2023. Science Open. Available at: https://doi.org/10.14293/ICMB230012

Paper VI: Water damage occurrence in Swedish public buildings

Authors: ***Christian Mattsson****, Birgitta Nordquist, Dennis Johansson, Ulla Janson, Petter Wallentén, Hans Bagge*

Published journal article in Journal of Building Pathology and Rehabilitation, Volume 11, article number 159 (2026). https://doi.org/10.1007/s41024-026-00828-4

Paper VII: Water Damage in Public Buildings: Causes, Vulnerabilities, and Preventive Strategies

Authors: ***Christian Mattsson****, Birgitta Nordquist, Dennis Johansson, Ulla Janson, Petter Wallentén, Hans Bagge*

Submitted journal article, manuscript to the journal Facilities

Paper VIII: Climate impact of water damage in public buildings: linking water leakage time with lifecycle emissions

Authors: ***Christian Mattsson****, Birgitta Nordquist, Petter Wallentén, Hans Bagge, Dennis Johansson, Ulla Janson*

Submitted journal article, manuscript to Journal of Cleaner production

Glossary

Appliances (water-using appliances)

Devices connected to a building's water system, such as dishwashers, washing machines, and refrigerators, which can cause water damage in the event of malfunction or failure.

Building service systems

Integrated technical systems within a building that provide essential services such as water supply, sewage, heating and ventilation.

Cast-iron piping

Pipes made of cast iron, commonly used in older buildings, characterized by high durability but increased susceptibility to internal corrosion over time.

Corrosion

The gradual material degradation of metals due to chemical or electrochemical reactions, often leading to weakening, leakage, or failure in piping systems.

Deductible

The fixed amount or proportion of repair costs that is paid by the policyholder in connection with an insured water-damage event. Deductibles constitute a direct economic consequence of water damage and are incurred in addition to any uninsured losses, disruptions, or administrative costs.

Depreciation

The reduction in value of a building component, installation, or asset over time due to age, wear, deterioration, or obsolescence. In the context of water damage, depreciation may reduce insurance compensation and increase the share of repair costs borne by the building owner.

Digital monitoring systems

Sensor-based technologies used to monitor building systems in real time, enabling the detection of abnormal conditions such as water leakage or pressure changes.

Drain stoppage by user (sewage floor drain trap)

Blockages in drainage systems caused by improper use, such as flushing unsuitable materials or accumulation of grease, debris, or foreign objects.

Drain trap

Plumbing components that retain a small volume of liquid to prevent sewer gases from entering indoor spaces while allowing wastewater to pass.

Dwellings

Residential units intended for human habitation, such as houses, single-family homes, or other forms of permanent housing.

Early detection
The identification of system failures, such as leaks, at an early stage, typically through monitoring systems or inspections, in order to minimize damage extent.

Fixtures
Permanent installations in buildings that use water, such as sinks, toilets, and showers, connected to water supply and drainage systems.

Installation environment (inaccessible installations)

The physical conditions in which building systems are installed, where limited accessibility, such as in confined shafts or concealed spaces, can hinder inspection, maintenance, and repair.

Leakage (water leakage)

The unintended escape of water from pipes, fittings, valves, or appliances into surrounding building components or spaces.

Leakage alarm

A device or system designed to detect the presence of water outside intended pathways and alert users or maintenance personnel for rapid intervention.

Moisture-tolerant materials

Materials selected for their ability to withstand prolonged exposure to moisture without significant deterioration or loss of performance.

Pipe threads (coupling)

Threaded connection points on pipes and fittings that allow mechanical joining and sealing within piping systems.

Pipes and connections

Water-bearing pipes and their associated fittings, joints, valves, and couplings within a building's plumbing and drainage systems. These components are designed to transport water or wastewater and may cause water damage if they fail or leak.

Preventive maintenance

Planned and systematic maintenance activities carried out to reduce the likelihood of system failures and extend the service life of building components.

Relining
A rehabilitation technique in which existing pipes are internally lined with a new material to restore functionality and reduce leakage risk without full pipe replacement.

Shafts (installation shafts)

Designated vertical or horizontal spaces within buildings for routing technical systems such as pipes, ducts, and cables.

Shut-off valve (automatic or manual)

A device used to stop or isolate water flow within a system, either manually or automatically, to limit the extent of leakage or enable maintenance work.

Tamper-resistant fixtures

Fixtures designed to resist deliberate damage or misuse, particularly in environments where vandalism or improper handling is common.

Valves
Mechanical components used to regulate, control, or shut off the flow of fluids or gases within piping systems.

Water damage

Damage caused by the unintended release of water from indoor water-bearing systems, installations, appliances, or components in a building due to failure, deterioration, malfunction, or improper use. The term includes damage to building materials, components, and building services resulting from such events.

Waterproof membranes

Protective barrier layers installed in areas exposed to water or moisture, such as bathrooms, wet rooms, roofs, and foundations, to prevent water penetration into building components and structures. Failure, deterioration, improper installation, or damage to waterproof membranes can allow water intrusion and contribute to water damage.

Workmanship errors

Deficiencies resulting from improper installation practices, insufficient quality control, or construction errors that can lead to system failures.

1 Introduction

Buildings are intended to provide safe, healthy, and comfortable indoor environments for their occupants. To achieve these conditions, modern buildings rely on a range of technical systems, including buildings services systems such as; water supply, wastewater, heating and ventilation installations. The reliable operation of these systems is essential for maintaining indoor environmental quality and occupant well-being. A well-performing building must therefore maintain structural integrity, deliver stable thermal and hygienic conditions, and operate technical systems without introducing risks to health or safety for the occupants [1]. If one of these systems fails, operates improperly, or reaches the end of its service life, building defects and damage may occur. Among the most recurring and consequential of these defects are moisture-related problems, and in particular water damage occurring from building services and water installations [2-16].

Studies from Europe, Asia, North America, and Australia have identified leakage-related failures and moisture damage as recurring challenges in the built environment [2, 7-12, 14-19]. The majority of the identified studies originate from Europe and Asia and focus primarily on residential buildings. Across regions, deficiencies in design, construction quality, material performance, maintenance, and management are consistently highlighted as important contributing factors. Research has further demonstrated that inadequate building management and maintenance can significantly contribute to the occurrence of building damage, functional failures, and moisture-related defects [2-4, 6, 7, 9, 10, 12, 14, 15, 19-21]. Although approaches to documenting, managing, and preventing water damage vary between countries and organizations, common challenges include rising repair costs, ageing building stocks, and the lack of consistent and comparable damage statistics. These challenges highlight the need for improved national and international knowledge sharing, harmonized data collection, and effective preventive strategies to reduce the occurrence and consequences of water damage in buildings.

Moisture-related defects have repeatedly been identified as one of the most significant challenges in the built environment [22]. The significance of moisture-related defects extends beyond material deterioration and repair costs. Moisture imbalance in buildings has been associated with reduced building performance, increased maintenance needs, indoor environmental problems, and adverse health outcomes among occupants. Recent research has further highlighted the need to address moisture as a systemic building-performance issue requiring interdisciplinary approaches that integrate technical, environmental, and human factors [23]. A Swedish investigation of defects, deficiencies, and damage in the construction sector concluded that moisture- and water-related problems dominate the overall damage picture in the built environment and represent both the most common and the most costly categories of building damage in Sweden [22]. Building industry surveys involving more than 800 respondents identified water intrusion through roofs, terraces, and façades, leakage from pipes and connections, and defects in wet rooms as some of the most frequently occurring building-related problems [22].

In Sweden, water-damage statistics are compiled annually by the Swedish Water Damage Centre (Vattenskadecentrum, VSC) [24], a collaboration between insurance companies and industry stakeholders established to identify damage patterns, monitor trends, and support preventive measures. This statistics do not cover damages from exterior sources such as rain water intrusion. The water-damage statistics have been collected systematically since 1989 and currently constitute one of the most comprehensive sources of information on leakage-related failures in Swedish residential buildings [24]. According to the latest available statistics, approximately 57 000 water-damage claims were reported in insured buildings, dwellings, and holiday homes during the year 2024, resulting in insurance reimbursements exceeding 4.5 billion SEK (approximately 390 million €) [24, 25]. Water damage represented the insurance claim category associated with the highest repair costs, with pipe systems, pipe connections, appliances, and wet-room installations accounting for a substantial share of reported incidents and repair costs. [22, 26]. Analyses conducted by the Swedish National Board of Housing, Building and Planning (Boverket) of insurance datasets comprising more than 700 000 reported water-damage cases have consistently shown that pipe systems, pipe connections, appliances, and wet-room installations account for a substantial proportion of reported incidents and repair costs [22, 26].

These recurring patterns have formed the basis for several preventive initiatives, technical recommendations, and industry guidelines intended to reduce the occurrence and consequences of water damage. Although these detailed national statistics are primarily available for the residential sector, water damage and leakage-related failures are not unique to dwellings and are also reported in other parts of the built environment. The database regarding water damage is based on reported and reimbursed insurance claims and primarily reflects damage events that meet insurance reporting and compensation criteria. The statistics generally exclude damages that are repaired directly by property owners, fall below insurance deductibles, occur in uninsured buildings, or are otherwise not reported. Several studies and industry reports have therefore suggested that insurance-based statistics underestimate the actual extent of water damage within the Swedish building stock, as they capture only reported and compensated claims and exclude many minor or self-financed repairs [22, 27]. Furthermore, a Swedish investigation indicated that approximately 22% of residential buildings show signs of moisture-related deficiencies, making dampness one of the most common building-related environmental problems and one of the costliest categories of building defects to remediate [27].

Moisture and water damage are also common causes of deteriorating indoor environmental quality. Prolonged exposure to damp indoor conditions has been associated with a range of health problems, including asthma, respiratory illnesses, allergies, and eczema among occupants [28-30]. The Swedish Environmental Health Report 2017 found that 19% of the respondents reported dampness, mold, or moisture-related problems in their homes. Furthermore, national environmental health assessments have identified the residential indoor environment as an important determinant of public health, affecting both adults and children through exposure to moisture-related problems and other indoor environmental hazards [27, 31]. Furthermore, the Swedish Environmental Health Reports from the years 2021 and 2024 identify housing conditions and indoor environmental quality as important factors for

occupational health and well-being. Water- and moisture-related damage should be regarded not only as a technical and economic challenge, but also as a public health issue. [32, 33]. Research has shown that moisture-related problems and poor indoor environmental conditions are associated with building-related symptoms, including irritation of the eyes and airways, headaches, fatigue, and reduced well-being among building users [34, 35]. Swedish research has further linked dampness in buildings to increased risks of asthma and allergic symptoms, particularly among children [36], while more recent studies have reported associations between perceived indoor environmental problems and reduced well-being among building users [35]. These findings suggest that the impacts of moisture-related problems extend beyond technical deterioration and economic losses, affecting indoor environmental quality, occupant well-being, and the social dimension of sustainability. Furthermore, moisture- and water-related defects, deficiencies, and damage in the Swedish construction sector were estimated to generate annual property-related costs of approximately 5.3-6.6 billion €, increasing to 7.5-10.1 billion € when indirect effects are included. These findings illustrate that moisture- and water-related failures represent not only technical challenges but also major economic and societal concerns [22]. The frequency and cost of these damages continue to rise, suggesting that current technical systems and construction practices do not sufficiently mitigate the risk of water leakage-related failures [22, 26].

Last but not least, water damage represents a significant sustainability challenge. Beyond the direct costs associated with repair and restoration, each damage event requires additional materials, energy, transportation, and labor that would otherwise have been unnecessary had the failure been prevented. Water damage generates avoidable greenhouse-gas emissions and resource consumption throughout the building's life cycle. From a social perspective, water damage can negatively affect occupants, building users, and organizations through disruptions to daily activities, reduced indoor-environment quality, and interruptions to essential services. In schools, healthcare facilities, and care homes, such disruptions may affect education, care provision, and workplace conditions. The impacts of water damage extend beyond material losses and repair costs, influencing health, well-being, comfort, and the functioning of society [31].

The significant costs and consequences associated with water damage have led to the development of numerous preventive initiatives within the building and insurance sectors. These include the systematic collection of water-damage statistics, industry guidelines, installation standards, technical recommendations, and monitoring programs [22, 24]. Such efforts aim to reduce leakage-related failures through improved design, installation quality, maintenance practices, and stakeholder awareness. Despite these initiatives, the frequency and costs of water damage continue to increase, indicating that current preventive measures are not sufficiently effective in reducing the occurrence of leakage-related failures [22, 24]. Several approaches for preventing and mitigating water damage from building water installations have been described in scientific literature. These include leak detection systems, real-time flow monitoring, automatic shut-off valves, condition-based maintenance, and systematic inspection routines. However, the implementation in buildings, rather than water distribution lines has not been studied to the same extent [37, 38]. In addition, proactive replacement of aging plumbing

components has been identified as a potential strategy for reducing the risk of failures and leakage-related damage. Recent review studies have highlighted both technological and maintenance-based approaches as key areas of development for water-damage prevention in buildings [2, 8, 12, 18, 37, 38].

Research on water damage has largely been conducted within the broader fields of building defects and building pathology rather than as a distinct research area. [2, 9, 11, 12, 14, 19, 39]. Existing studies have primarily focused on specific technical systems and failure mechanisms, including wet rooms, waterproofing membranes, watertightness, construction defects, and post-handover failures in residential buildings [2, 9, 11, 12, 14, 19, 39]. The literature further shows a strong emphasis on residential buildings, while water damage in public buildings, offices, healthcare facilities, and other non-residential buildings has received considerably less attention [16, 28, 30, 40]. Research has also highlighted the importance of design quality, workmanship, inspection routines, and maintenance practices as key contributors to building defects and water damage [9, 10, 15]. However, water damage research remains fragmented across disciplines and is often embedded within the broader fields of building defects and building pathology [4, 5, 17] [41]. Similarly, studies focusing on kitchen-related water damage, appliance leakage, and building service systems are relatively scarce despite increasing damage frequencies reported in Nordic statistics [24]. Academic publications and industry reports indicate that such defects occur in a wide range of buildings, including multi-family residential buildings, schools, offices, healthcare facilities, and other public buildings [2, 8, 18, 19]. However, compared with the residential sector, the occurrence, causes, and consequences of water damage in non-residential buildings remain considerably less documented. This lack of systematic knowledge limits the understanding of the broader impacts of water damage across the built environment and highlights the need for further research in this area.

Several factors, including technical, organizational, environmental, economic, and social aspects, influence the occurrence, extent, and consequences of water damage and cannot be adequately understood through a single methodological perspective. This is particularly relevant for public and municipally owned buildings, such as schools, preschools, nursing homes, and healthcare facilities, where water damage may affect vulnerable occupants, disrupt essential public services, and result in substantial repair costs. These buildings are often characterized by intensive use, extensive user interaction, high levels of wear and tear, and dense building service installations, all of which may contribute to the occurrence and complexity of water-damage events. Nursing and care homes comprise elderly care facilities, health-care centers, support- and service housing, such as special residential care, for people with significant and long-term disabilities, all of which operate with continuous water use and sensitive environments. In this category, buildings with specially adapted housing for support and services for people with mental or physical disabilities are included. These buildings are designed to provide security, independence and a meaningful everyday life.

Public buildings represent a particularly relevant area of study due to their societal importance and intensive use. Schools, healthcare facilities, nursing homes, and other municipally owned buildings often accommodate large numbers of occupants, including, as mentioned, vulnerable

groups. At the same time, these buildings commonly contain extensive building service installations and are exposed to considerable wear resulting from daily operation and user interaction. Water damage in such buildings may affect both building performance and service delivery, while repair costs are largely financed through public funds.

Given the substantial economic burden of water damage, its increasing frequency, and its documented effects on building durability and indoor environmental quality, there is a need for coordinated efforts among researchers, industry stakeholders, insurance companies, and authorities to reduce leakage-related failures in buildings. Improving the reliability of building service systems, particularly tap water, wastewater, and heating installations, could enhance the resilience and long-term performance of buildings while reducing the environmental impacts associated with repair and replacement activities.

This thesis focuses on water damage originating from building service systems and installations, including tap water systems, wastewater systems, heating systems, appliances, and wet-room waterproofing systems. Such damage occurs when water reaches building components that are not designed to withstand prolonged moisture exposure, potentially causing material deterioration, impaired indoor environmental quality, and adverse consequences for occupants and building owners.

Despite the widespread occurrence of water damage and its well-documented economic, health, and environmental impacts, important knowledge gaps remain regarding its extent, underlying causes, distribution, and broader sustainability implications. Addressing water damage therefore requires a holistic perspective that considers technical, organizational, environmental, economic, and social factors across the building life cycle, rather than focusing solely on individual damage events.

1.1 Aim

The overall aim of this thesis is to contribute to a more sustainable built environment by improving the understanding of leakage-related water damages in buildings and by identifying measures that can support its prevention and mitigation. To achieve this aim, the thesis pursues four objectives: to investigate the occurrence of water damage in buildings; to identify and analyze its underlying causes, to examine its economic and environmental consequences and to investigate stakeholder experiences and perspectives regarding technical and organizational measures for water-damage prevention and management. By adopting a holistic sustainability perspective that integrates building performance, resource use, climate impact, indoor environmental quality, organizational and management processes, and the continuity of building operations and services, the thesis seeks to provide knowledge that supports more resilient, resource-efficient, and sustainable buildings throughout their service life.

1.2 Limitations

This thesis focuses on leakage-related water damage originating from sources within the building from technical building service systems and appliances and follows the categorization used by the Swedish Water Damage Centre (Vattenskadecentrum, VSC [24]), which forms the basis for the national water-damage statistics used by the Swedish insurance and building sectors. This limitation was chosen because it provides a well-established and systematically documented framework for analyzing recurring water-damage events and their consequences. The thesis does not investigate water and moisture damage caused by factors external to the building, such as flooding, stormwater intrusion, or leakage through the building envelope. Nor does it include moisture problems primarily related to building physics phenomena, such as condensation-induced moisture accumulation in foundations, walls, crawl spaces, or cold attics that may eventually result in mold growth or material degradation. Instead, the focus is on water damage associated with technical installations and building service systems. The following categories of components and water damage are included in the scope of this thesis:

- The first category comprised **pipes and connections**, including water damage caused by unexpected leakage or discharge from tap-water, wastewater, or heating systems, such as leaking pipes, joints, connections, or valves (see example in Figure 1(a)).
- The second category comprised **appliances, equipment, and installations**, where water damage is caused by unexpected leakage from water-using equipment or installations located in rooms without floor drains, such as dishwashers, washing machines, refrigerators, freezers, coffee machines, and ice machines (see example in Figure 1(b)).
- The third category comprised **waterproof membranes**, where water damage resulted from leakage or moisture penetration through defective
  or inadequate waterproofing systems in wet rooms equipped with floor drains (see example in Figure 1(c)).

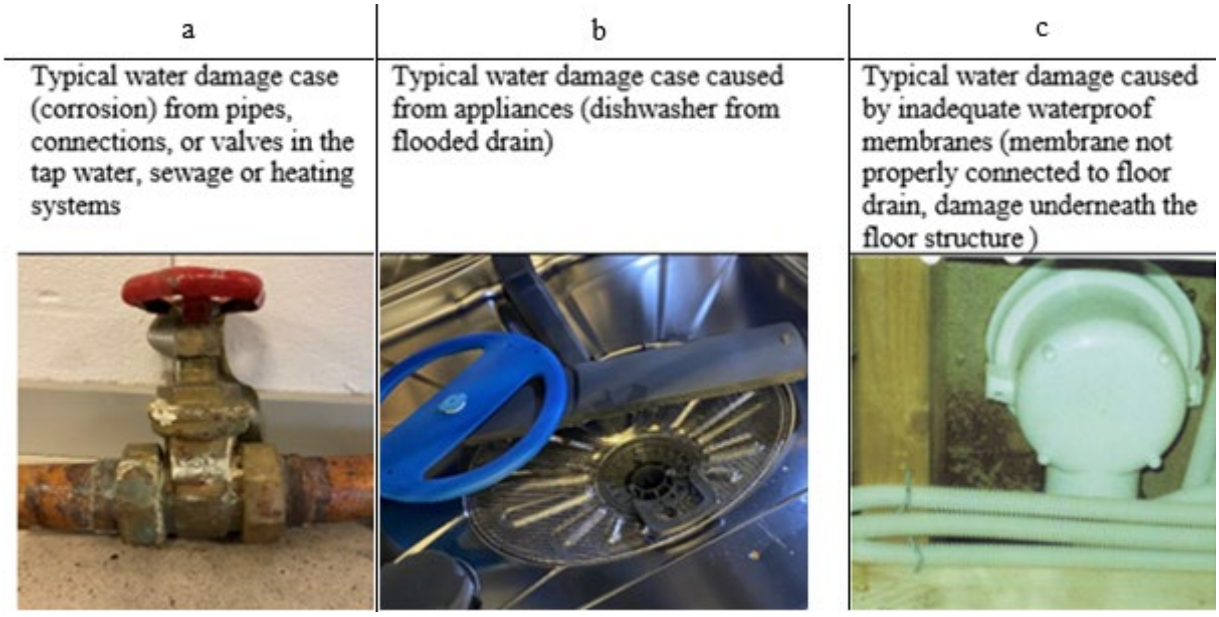


Figure 1. Examples of water damage cases studied in this thesis. Picture (c) provided by Swedish industry organization BKR [42].

The empirical basis of the thesis is derived primarily from Swedish conditions [1, 18]. However, many of the challenges investigated, including ageing installations, leakage-related failures, maintenance needs, and damage prevention strategies, are also relevant in other countries. While the specific occurrence and characteristics of water damage may vary depending on local regulations, construction practices, climate, and building stock, the methods and findings presented in this thesis may provide insights that are applicable beyond the Swedish context. Furthermore, although water damage can influence indoor environmental quality and may be associated with health-related outcomes through secondary effects such as dampness and mold, health impacts are not investigated directly in this thesis. Instead, the thesis focuses on the occurrence, causes, economic consequences, environmental impacts, and prevention of leakage-related water damage in buildings to try to avoid health implications for users and residents. While the primary emphasis is on economic and environmental dimensions, the broader implications for indoor environmental quality and building operation are also considered within a sustainability perspective.

1.3 Research Questions

Although previous studies have increased the understanding of water damage, significant knowledge gaps remain regarding its occurrence, underlying causes, consequences, and prevention, particularly in public buildings. Current knowledge is fragmented across different disciplines and data sources, limiting the ability to develop effective and sustainable risk-management strategies. There is therefore a need for a more comprehensive understanding of how water damage occurs, what drives it, what consequences it causes, and which measures are most effective in reducing its impact. To address these gaps, the following research questions were formulated.

I. What is the occurrence and distribution of leakage-related water damage in buildings across different building types, activities, and building service systems?
II. What are the economic and environmental impacts of leakage-related water damage?
III. What are the primary causes and underlying mechanisms of leakage-related water damage?
IV. Which technical and organizational measures can prevent leakage-related water damage or reduce its consequences to contribute to a more sustainable and resilient built environment?

1.4 Contribution of the thesis

This thesis contributes to the understanding of leakage-related water damage in buildings by extending previous research beyond occurrence statistics and repair costs towards a broader sustainability perspective. Addressing major knowledge gaps concerning water-damage occurrence, costs, consequences, and prevention, this thesis advances the understanding of how leakage-related failures affect the built environment and identifies opportunities to reduce their impacts. A central scientific contribution of this thesis is the recognition that water-damage occurrence, causes, consequences, and prevention are interconnected and therefore need to be understood and managed as parts of the same system. While previous studies have examined individual aspects of water damage, such as the environmental and economic impacts of repair measures [80] and the influence of building management and maintenance practices [2], this

thesis advances a more holistic perspective. In particular, the novelty lies in the empirical characterization of water damage in both residential and public buildings and in demonstrating how technical vulnerabilities, operational demands, and organizational practices interact to shape water-damage risks and outcomes. This provides a basis for developing building-specific strategies for prevention and management. More specifically, the thesis contributes by:

- Providing new empirical evidence on the occurrence and distribution of water damage in residential and public buildings, addressing a significant knowledge gap regarding public buildings for which systematic data, until now, have been limited.
- Improving the understanding of the causes and underlying mechanisms of leakage-related failures, including technical, organizational, and management-related factors that influence water damage occurrence.
- Strengthening the knowledge base for water-damage prevention by combining occurrence data, cost analyses, environmental assessments, and stakeholder experiences to support the development of more effective preventive measures, systematic damage management, and evidence-based industry guidelines.
- Quantifying the carbon impact associated with water-damage repairs, thereby highlighting a previously underexplored environmental consequence of leakage-related failures.
- Identifying and suggesting measures for reducing water damage occurrence and consequences, in private and public buildings, including both technical solutions and organizational practices throughout the building life cycle.
- Advancing a holistic approach to water-damage management by integrating occurrence, causes, consequences, and prevention within a framework that supports decision-making by building owners, facility managers, designers, insurers, and policymakers.

Through these contributions, the thesis extends existing knowledge on water damage from a predominantly technical and cost-oriented perspective towards a holistic sustainability-oriented understanding that integrates occurrence, causes, consequences and prevention of leakage-related failures in buildings.

1.5 Outline of the Thesis

This thesis is presented as a compilation thesis consisting of an introductory chapter and appended scientific papers. The introductory chapter provides the background, research context, methodological framework, and synthesis of the findings presented in the included studies. Following this introductory chapter, Chapter 2 presents the research methodology, including the overall research design, data sources, analytical methods, and methodological considerations applied throughout the research project. Chapter 3 presents the results and summarizes the main findings from the appended papers regarding the occurrence, causes, consequences, and prevention of leakage-related water damage in buildings. Section 3.5 is specifically intended for industry practitioners and stakeholders and therefore synthesizes key findings, practical implications, and preventive measures identified throughout the thesis. As a result, some overlap and repetition with the findings presented in the appended papers may occur, as the section aims to provide an integrated and practice-oriented summary of the

research outcomes. Chapter 4 discusses the findings in relation to previous research and examines how water-damage occurrence, causes, consequences, and preventive measures interact throughout the building life cycle, as well as the implications for building management and sustainability. The chapter further reflects methodological strengths and limitations and discusses the applicability of the results. The chapter also identifies implications for building owners, managers, designers, contractors, insurers, and policymakers, and proposes directions for future research. Chapter 5 presents the main conclusions of the thesis and highlights its scientific and practical contributions.

1.6 Included Papers, Relevance and Contribution

This thesis is based on the appended papers that collectively examine the occurrence, causes, environmental consequences, and prevention of leakage-related water damage in public buildings. Together, the papers provide a holistic perspective on water damage in a Swedish perspective and contribute knowledge needed to support more sustainable and resilient building management.

Paper I: ***A Quantitative and Qualitative State-of-the-Art Literature Review of Water Damage Occurring from Pipes, Appliances, and Wet Rooms in Buildings***

A literature review of water damage occurring from pipes, appliances, and wet rooms in buildings. The literature distribution, the status, consequences, effects, and strategies and methods for prevention of water damage were assessed by compiling and reviewing literature using quantitative and qualitative methods.

Contribution statement:

The study was jointly conceptualized by all authors. Christian Mattsson served as the main author and principal researcher and was responsible for the literature search, screening and assessment of publications, data extraction, synthesis and analysis of findings, interpretation of results, and manuscript preparation. Dennis Johansson, Birgitta Nordquist, Petter Wallentén, and Hans Bagge contributed to the development of the research questions, study scope, and scientific framing of the review. Birgitta Nordquist further contributed substantially to the critical evaluation of findings, development of the manuscript, and scientific review throughout the research process. The remaining co-authors contributed through expert input, scientific discussions, and manuscript review.

Paper II: ***Water damages in HVAC, tap water and sewage systems in cold climates***

Review of water-damage statistics and existing literature to examine the occurrence, causes, and characteristics of water damage in HVAC, tap water, and sewage systems in cold climates. Particular attention was given to climate-related factors, such as freezing, and their influence on damage patterns. The findings were used to identify common damage mechanisms and provide a foundation for preventive measures and future research on reducing water damage in cold-climate regions.

Contribution statement:

The study was jointly conceptualized by all authors. Christian Mattsson conducted the literature review, data collection, analysis, interpretation of results, and preparation of the manuscript. Birgitta Nordquist contributed substantially to the development of the study, interpretation of findings, manuscript refinement, and scientific review. Dennis Johansson contributed to the development of the research objectives and overall scientific direction. Petter Wallentén and Hans Bagge contributed with expert knowledge, scientific discussions, and manuscript review.

Paper III: ***Cost Performance Analysis of Water Damages for Sustainable Prevention Measures***

An analysis of water damage costs regarding several costs including insurance reimbursements, in single- and multi-family buildings, along with indirect costs related to water damage, such as deductible and depreciation together with age reduction. The methods used were a parametric analysis of existing Swedish insured residential building dataset, from the insurance industry organisation Svensk Försäkring and quantitative methods to attain datasets on repair costs from insurance companies and multi-family buildings methods also included questionnaire and discussions with stakeholders. The gathered data was analysed using extrapolation and estimation to present a cost of each studied cost category.

Contribution statement:

The study was jointly conceptualized by all authors. Christian Mattsson carried out the data collection, analysis, interpretation of findings, preparation of figures and tables, and manuscript writing. Birgitta Nordquist contributed substantially to the development and refinement of the analyses, interpretation of results, development of the manuscript, and scientific review. Dennis Johansson contributed to the scientific framing and development of the research objectives. Petter Wallentén and Hans Bagge provided expert input and critically reviewed the manuscript.

Paper IV: ***Examination of Water Damage Statistics in the Nordic Countries to Identify and Suggest Preventive, Cost-Effective and Sustainable Measures during the Maintenance and Operation Phase***

Study of actions and measures that could reduce the impact and cost of water damage in buildings, examining the actions and measures, and analysing the payback time of the investments using qualitative analysis and a parametric analysis of the studied actions.

Contribution statement:

The study was jointly conceptualized by all authors. Christian Mattsson was responsible for data collection, analysis of Nordic water-damage statistics, interpretation of results, and manuscript preparation. Birgitta Nordquist contributed substantially to the development of the study, evaluation of findings, manuscript improvement, and scientific review. Dennis Johansson contributed to the overall scientific framing and development of the research. Petter Wallentén and Hans Bagge contributed through scientific discussions and manuscript review.

Paper V: ***Similarities, Differences, and Tendencies of Water Damage in the Nordic Countries***
The occurrence, causes, and trends of water damage in the Nordic countries were investigated through a comparative study involving representatives from Sweden, Norway, Denmark, Finland, and Iceland. The analysis compared reported occurrence rates, dominant damage causes, affected building-service systems, and observed trends in water-damage development. Responses from the questionnaire, together with estimated reimbursement costs per inhabitant in each country, formed the basis for identifying similarities, differences, and tendencies across the Nordic countries.

Contribution statement:

The study was jointly conceptualized by all authors. Christian Mattsson conducted the data collection, analysis, interpretation of results, and manuscript preparation and served as the lead author throughout the work. Birgitta Nordquist contributed substantially to the development of the analyses, interpretation of findings, manuscript development, and scientific review. Dennis Johansson contributed to the development of the study objectives and scientific direction. Petter Wallentén and Hans Bagge contributed through expert discussions and manuscript review.

Paper VI: ***Water Damage Occurrence in Swedish Public Buildings***

This paper investigates the occurrence, causes, and repair costs of water damage in publicly owned buildings in Sweden. Based on more than 3 000 reported water-damage cases from three municipalities, the study provides new empirical knowledge regarding the frequency, distribution, and characteristics of water damage in public buildings, a sector for which systematic data have previously been limited.

Contribution statement:

Christian Mattsson served as the main author and principal researcher and was responsible for study design, data collection, statistical analyses, interpretation of results, and manuscript preparation. Dennis Johansson, as principal supervisor, contributed primarily to the conceptualization of the study, methodological discussions, and the overall scientific direction of the research. Birgitta Nordquist played a major role in the development, evaluation, and refinement of the analyses and results, contributed to manuscript development, and provided extensive scientific review throughout the study. Ulla Janson, Petter Wallentén and Hans Bagge contributed with expertise related to public buildings and supported the interpretation of findings and through scientific discussions and critical review of the manuscript.

Paper VII: ***Water Damage in Public Buildings: Causes, Vulnerabilities, and Preventive Strategies***
This paper examines why water damage occurs in public buildings and how it can be prevented. By combining statistical water-damage data with interviews conducted with municipal facility managers and technical staff, the study identifies technical, organizational, and user-related causes of water damage and proposes preventive measures and technical solutions for reducing future incidents.

Contribution statement:

Christian Mattsson served as the main author and principal researcher and was responsible for study design, data collection, statistical analyses, interpretation of results, and manuscript preparation. Dennis Johansson, as principal supervisor, contributed primarily to the conceptualization of the study, methodological discussions, and the overall scientific direction of the research. Birgitta Nordquist played a major role in the development, evaluation, and refinement of the analyses and results, contributed to manuscript development, and provided extensive scientific review throughout the study. Ulla Janson, Petter Wallentén and Hans Bagge contributed with expertise related to public buildings and supported the interpretation of findings and through scientific discussions and critical review of the manuscript.

Paper VIII: ***Climate Impact of Water Damage in Public Buildings: Linking Water Leakage Time with Lifecycle Emissions***

This paper investigates the environmental consequences of water damage using life-cycle assessment (LCA). The study quantifies greenhouse gas emissions associated with different damage scenarios and repair strategies and demonstrates how leakage duration and damage extent influence lifecycle emissions.

Contribution statement:

Christian Mattsson served as the main author and principal researcher and was responsible for study design, data collection, statistical analyses, interpretation of results, and manuscript preparation. Dennis Johansson, as principal supervisor, contributed primarily to the conceptualization of the study, methodological discussions, and the overall scientific direction of the research. Birgitta Nordquist played a major role in the development, evaluation, and refinement of the analyses and results, contributed to manuscript development, and provided extensive scientific review throughout the study. Petter Wallentén, Hans Bagge, Ulla Janson contributed with expertise related to public buildings and supported the interpretation of findings and through scientific discussions and critical review of the manuscript.

The doctoral candidate was responsible for all data collection, data processing, analyses, calculations, preparation of figures and tables, and the writing of both the appended papers and the thesis synthesis. All co-authors reviewed the manuscripts and approved the final versions of the appended papers.

1.7 Research Projects, Process and Funding

The research presented in this thesis was carried out within two externally funded research projects. The licentiate project, *Reducing Water Damage by Using a Holistic Approach to Costs, Occurrence and Solutions in Buildings,* was funded by Formas (FORMAS 2019-00649) and focused on water-damage occurrence, costs, and preventive measures in buildings. The project identified significant knowledge gaps regarding water damage statistics, associated costs, sustainability impacts, and the limited availability of data for building categories beyond single-family dwellings.

The doctoral research was further supported by the SBUF (The Development Fund of the Swedish Construction Industry) project *Increased Sustainability through Reduced Water Damage: A Holistic Perspective on Sustainability, Causes and Effects* (SBUF Project No. 14360), which expanded the research towards public buildings, preventive strategies, and environmental impacts associated with water damage. Together, the two projects provide the scientific foundation for this thesis and reflect the gradual development of the research from broad investigations of water damage in buildings towards detailed studies of public buildings, sustainability impacts, and preventive solutions.

2 Research methods

To address the research questions, both qualitative and quantitative research methods were employed, drawing upon literature reviews, statistical analyses, case studies, life-cycle assessment methods, and empirical investigations of building performance and water-damage occurrence. This chapter describes the overall methodological approach adopted in the thesis, the research design, the holistic framework guiding the investigations, and the methods applied in the included studies.

2.1 Research Approach

Leakage-related water damage is a complex phenomenon that involves interactions between technical systems, building characteristics, organizational practices, occupant behavior, and sustainability-related outcomes. The consequences of water damage extend beyond physical deterioration of buildings and include economic losses, environmental impacts, reduced indoor environmental quality, and adverse effects on building users. As a result, no single research method is sufficient to fully capture the occurrence, causes, consequences, and prevention of water damage in buildings. A holistic research approach was therefore adopted in this thesis. The holistic approach is based on the premise that water damage should not be regarded solely as a technical failure but as a challenge affecting multiple dimensions of the built environment throughout the building life cycle. The research considers technical, organizational, environmental, economic, and social perspectives when investigating leakage-related failures. Attention is given to how different actors, building types, building service systems, and life-cycle phases influence both the occurrence of water damage and its resulting impacts.

To address the research questions, the thesis applies a mixed-methods approach that combines quantitative and qualitative research methods. Quantitative methods were primarily used to investigate water damage occurrence, repair costs, resource use, and climate impacts using empirical datasets and building-related information. Qualitative approaches were employed to investigate causes of water damage, evaluate preventive measures, and interpret relationships between technical, organizational, and management-related factors. The combination of these approaches enabled the research problem to be examined from multiple perspectives and contributed to a more comprehensive understanding of leakage-related water damage.

The research was further guided by a sustainability perspective, where water damage is assessed in relation to its environmental, economic, and social consequences. This perspective enables the evaluation of water damage not only as a building defect but also as a source of resource consumption, greenhouse-gas emissions, monetary costs, and reduced indoor environmental quality. Although the empirical analysis was conducted in a Swedish context, the issues studied are not unique to Sweden. Leakage-related failures occur internationally, and many of the technical, organizational, and sustainability-related challenges identified in this thesis are relevant to other countries with comparable building stocks and building service systems. The thesis investigates both the direct effects of water damage and the broader implications for sustainable building management and operation. Water damage has implications across all three dimensions of sustainability: economic, environmental, and social. Selected parameters

associated with these dimensions are presented in Figure 2. All parameters except IAQ, health effects, and occupant wellbeing are examined in this thesis. Although these aspects are not studied directly, they are addressed indirectly through the focus on reducing water damage and thereby mitigating its potential impacts on occupants' health and wellbeing. The conceptual framework illustrates how leakage-related water damage influences the environmental, economic, and social dimensions of sustainability.

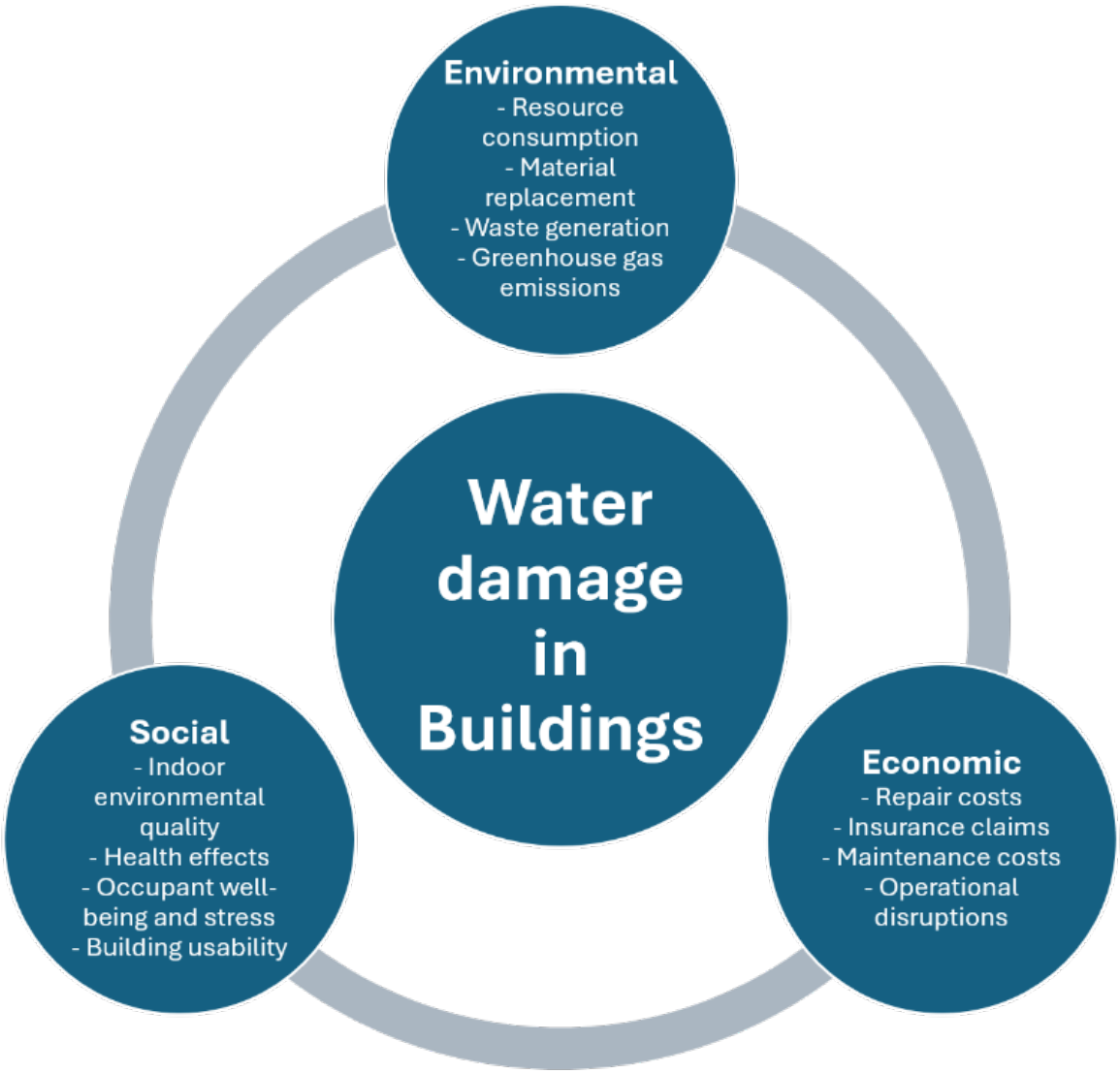


Figure 2. Leakage-related water damage in buildings and its impacts across the environmental, economic, and social dimensions of sustainability.

The occurrence and consequences of water damage are influenced by technical systems, organizational factors, stakeholders, and building characteristics, while preventive measures can be implemented throughout the building process. The different addressed aspects of building types, stakeholders, water damage occurrence, causes, consequences, costs, and preventive measures that together form the basis of the research design and the analyses presented in the included studies and is illustrated in Figure 3.



Figure 3. Overview of the parameters regarded in the framework of reducing water damage occurrence, cost and consequences.

2.1.1 Holistic Framework

To be able to address the parameters in Figure 2 and 3 a holistic framework developed in this thesis was used to structure the investigation of leakage-related water damage and to integrate the different dimensions addressed in the included studies. The framework consists of four core components: occurrence, causes, consequences, and prevention. Occurrence describes the extent and distribution of water damage within different building types and building service systems. Causes include the technical, organizational, and behavioural factors contributing to leakage-related failures. Consequences encompass the environmental, economic, and social impacts resulting from water damage, both in a primary and secondary view, including repair costs, greenhouse-gas emissions, resource consumption, indoor environmental quality, and occupant well-being. Prevention refers to technical and organizational measures intended to reduce either the occurrence of water damage or its resulting impacts. These four components are examined within a building life-cycle perspective and are influenced by technical, economic, environmental, social, and organizational conditions. The framework therefore enables findings from different studies to be integrated within a common structure and facilitates a broader understanding of water damage than would be obtained from studying individual failures in isolation.

2.2 Research Design

Given the broad scope of investigating leakage-related water damage in buildings, the work was organized as a series of interconnected studies addressing different aspects of water damage while contributing to an improved understanding of leakage-related failures in building service systems. The research design was developed to address the four research questions presented in Chapter 1. Together, these questions investigate the occurrence, causes, consequences, and prevention of leakage-related water damage. Rather than examining these aspects independently, the studies were designed to build upon each other and progressively increase the understanding of the research problem. The research process followed an iterative approach in which findings from earlier studies informed the design and focus of subsequent investigations.

The initial investigations focused on establishing the extent and distribution of water damage and identifying existing knowledge gaps within the research field. This was followed by studies investigating technical, organizational, and management-related factors contributing to water damage occurrence. The subsequent studies expanded the analysis by examining the environmental and economic consequences of water damage, including repair costs, resource use, and climate impacts. To address the research questions, a combination of quantitative and qualitative methods was applied, as seen in Table 1. The selected methods were chosen to investigate different aspects of leakage-related water damage, including occurrence, causes, consequences, and prevention. Table 2 provides an overview of the principal methods applied in the studies included in this thesis.

Table 1. The studied aspects and type of method used in appended Papers I-VIII. (note that all public buildings in this study are municipal buildings)

Aspects studied	Residential buildings		Public buildings	
	Quantitative	Qualitative	Quantitative	Qualitative
Occurrence	Papers I,II, IV, V	Paper I	Paper VI	Paper VII
Causes	Papers I,II, IV, V	Paper I	Papers VI-VII	Paper VII
Costs	Paper III	Paper I	Paper VI	Paper VII
Environmental impact		Paper I	Paper VIII	
Building service system analysis	Papers I, IV, V	Paper I	Papers VI-VII	Paper VII
Solutions	Papers III, IV, V	Paper I	Paper VII-VIII	Paper VII

Table 2. Relationship between the appended studies, applied methods, and primary research focus.

Study	Main method(s)	Primary focus	Data sources
Paper I	Quantitative and qualitative literature review	Current knowledge, research gaps, occurrence, causes, costs, consequences, and preventive measures	Scopus, Web of Science, Boverket [22], Svensk Försäkring [26],
Paper II	Statistical analysis and literature review	Water damage in HVAC, tap-water and sewage systems in cold climates; occurrence, costs, causes, and freezing-related damage	Svensk Försäkring [26], Vattenskadecentrum [43-45], Statistics Iceland [46], Finans Norge [47], Forsikring & Pension [48], SMHI [49-51] Meteorologisk institutt [51], Scopus, Engineering Village, Web of Science
Paper III	Statistical analysis and literature review	Water-damage occurrence, causes, costs, and trends in Sweden	Svensk Försäkring [25], Vattenskadecentrum [23, 43-45], Statistics Sweden (SCB)
Paper IV	Statistical analysis and cost modelling	Economic consequences of water damage and cost-effective prevention measures	Svensk Försäkring [25], Vattenskadecentrum [23, 43-45], SCB building statistics, cost data from Boverket [22]
Paper V	Questionnaire survey and comparative analysis	Similarities, differences, and trends in Nordic water-damage statistics; identification of knowledge gaps regarding public buildings	Questionnaire survey of Nordic experts, national insurance associations, authorities Statistics Finland [51] Statistics Iceland [46], Finans Norge [47], Forsikring & Pension [48] Vattenskadecentrum [24, 43-45, 53]
Paper VI	Statistical analysis and building stock analysis	Occurrence and distribution of water damage in municipal buildings	Municipal water-damage databases, municipal building stock registers
Paper VII	Statistical analysis and semi-structured interviews	Causes of water damage and preventive measures	Municipal water-damage records, semi-structured interviews with facility managers and property professionals

Paper VIII	Life-cycle assessment and scenario analysis	Environmental consequences and climate impact	Municipal water-damage statistics, repair and replacement scenarios from Paper VII, environmental product declarations (EPDs) in LCA databases [54-58]. Boverkets climate database [59].

Although the individual studies focus on specific aspects of water damage, the findings are synthesized in this thesis to develop a more comprehensive understanding of how water damage occurs, why it occurs, what consequences it causes, and how its occurrence and impact can be reduced. By integrating the findings from multiple studies and perspectives, the research contributes to a more holistic and evidence-based approach to water damage management within the built environment and is elaborated in the following sections.

2.3 Data sources and Empirical Material

The research presented in this thesis is based on the integration of multiple data sources and analytical methods. Given the multifaceted nature of leakage-related water damage a combination of quantitative and qualitative data was required to address the research questions. The empirical material therefore consists of scientific and grey literature, Swedish insured residential building dataset, from the insurance industry organisation Svensk Försäkring and international water damage statistics, insurance data, municipal water damage records, public building databases, stakeholder interviews, and life-cycle assessment data.

2.3.1 Literature Review

Literature data were collected to establish the current state of knowledge regarding leakage-related water damage in buildings and to identify relevant research areas and knowledge gaps. The literature review included both scientific and grey literature sources and was conducted using a combination of quantitative and qualitative review methods. The review focused on water damage originating from building service systems, including tap water, wastewater, heating systems, appliances, and waterproofing systems. Moisture-related defects caused primarily by flooding, groundwater intrusion, precipitation, or condensation phenomena were not within the scope of the review. Scientific literature was identified through systematic searches in the Scopus and Web of Science databases. These databases were selected due to their extensive coverage of international and peer-reviewed literature within engineering, construction, building technology, and sustainability-related research.

The search strategy was developed according to established literature review methodology and included the identification of keywords, formulation of inclusion and exclusion criteria, selection of databases, and systematic screening of the identified publications. Search strings were constructed using keywords related to water damage, water leakage, defects, buildings, indoor environments, building services, installations, costs, and sustainability. Boolean

operators, truncations, phrase searching, and combinations of search terms were used to improve the accuracy and relevance of the search results. The search process was iterative and evolved throughout the review. Initial searches were performed using broad combinations of keywords related to water damage and buildings. Subsequently, additional concepts and search terms were progressively incorporated using Boolean operators, primarily AND, to investigate specific themes and relationships identified during the review process. For example, searches addressing water damage were successively expanded by adding terms related to indoor environment, building services systems and costs. Each additional search concept was introduced and assessed separately to explore how the scope and characteristics of the retrieved literature changed when different aspects of water damage were included. Relevant terminology identified in reviewed publications was further used to refine and develop subsequent search strings. The search strategy consisted of a series of interconnected searches rather than a single predefined search string. The searches were primarily limited to bibliographic information, including titles, abstracts, keywords, and author information. The identified publications were initially screened based on their titles, abstracts, and keywords. Publications considered relevant to the scope and objectives of the research were subsequently subjected to a more detailed review. The selection process focused on literature describing water damage occurrence, causes, consequences, preventive measures, management practices, and sustainability-related aspects associated with leakage-related failures in buildings.

In addition to scientific literature, grey literature sources were reviewed to complement the scientific findings and provide information that is often not available through peer-reviewed publications. These sources included technical reports, regulations, industry guidelines, insurance statistics, governmental publications, and reports published by research institutes and industry organizations. Relevant material was identified through organizational websites, reference lists, and recommendations from industry professionals and researchers. The collected literature was analysed using both quantitative and qualitative methods. Quantitative analysis was used to document characteristics of literature, such as publication types, geographical distribution, research areas, and methodological approaches. The qualitative analysis focused on identifying recurring themes related to water damage occurrence, causes, consequences, and preventive measures.

To maintain an up-to-date knowledge base throughout the research project, the original literature review was complemented by a series of iterative literature searches conducted after the publication of the review article. The updated searches followed the same databases, search principles, and screening procedures as the original review and focused on three main areas: (i) causes and contributing factors of water damage in buildings, (ii) facility management, operation, and maintenance practices related to water damage prevention, and (iii) recently published studies identified using the original water damage search strings. These additional searches enabled continuous refinement of the theoretical foundation and ensured that the subsequent studies were informed by the latest scientific developments within the field.

2.3.2 Water Damage Statistics (residential)

Water damage statistics constituted one of the principal empirical data sources used throughout this research project. These datasets were used to investigate the occurrence, distribution, causes, and consequences of leakage-related water damage in buildings and to support analysis of both Swedish trends and specific damage categories. The primary statistical data sources used in this thesis were the statistics published by Swedish insurance industry organization Svensk Försäkring and the Swedish Water Damage Centre (Vattenskadecentrum) [24]. Svensk Försäkring compiles and publishes insurance claims statistics reported by Swedish insurance companies. The statistics cover household and commercial insurance types, including home, villa, holiday home, boat, and business/property insurance. For each insurance category, the data includes the number of reported claims, regardless of when the loss occurred, and is classified by cause of damage. The database contains information on several damage categories, such as fire, theft, weather and natural events, and water damage. Water damage claims include losses caused by leakage, moisture intrusion, freezing, or other failures in water supply and drainage systems, excluding water-related damages classified as natural hazards. Svensk Försäkring aggregates insurance claim data submitted by participating insurance companies and publishes industry-level statistics covering home, residential, commercial, and property insurance.

These data provide a comprehensive overview of water damage occurrence within the Swedish building stock and constitute one of the most extensive longitudinal sources available for analyzing national trends in water damage claims and associated repair costs [25]. The aggregated datasets were used to analyze temporal trends in both the frequency of water damage incidents and the corresponding economic impacts. Because the statistics are based on insurance claims reported by major insurers operating in Sweden, they capture a substantial share of the insured building stock and offer valuable insights into the scale and development of leakage-related water damage over time. Although the exact market coverage varies between years and insurance segments, the participating companies represent major actors in the Swedish insurance market, suggesting that the reported trends are broadly representative of leakage-related water damage in Sweden [26]. Furthermore, the long time series enables the identification of recurring patterns, shifts in damage causes, and changes in repair costs that may not be observable in smaller case-specific datasets.

Additional information regarding the origin of the water damage, the type of system in which the failure occurred, affected building systems, room location, and the age of the installation at the time of the damage was obtained from the annual water-damage investigations published by Vattenskadecentrum [24]. These investigations are based on data compiled by Vattenskadecentrum, a collaboration between the insurance companies Dina Försäkringar, Folksam, If, Länsförsäkringar, and Trygg-Hansa, together with several industry organizations. Participating in insurance companies collect information from reported water-damage claims and completed damage inspections using a common and structured survey template. This standardized reporting framework enables systematic monitoring of water-damage occurrence, causes, and trends over time and provides one of the most comprehensive datasets on leakage-related water damage in Swedish buildings. The survey records information on where the

damage occurred, which building service system was involved, which component failed, how the leakage originated, the age of the installation, and the circumstances surrounding the damage event. The questionnaire records information regarding building type, building and installation age, damage location, affected systems, technical details of the installation, and the identified cause of the damage. Damage cases are classified into three main categories: pipe and connection systems, appliances and equipment, and waterproofing systems in wet rooms. The database further includes information regarding system type, material, room location, construction details, and cause classifications such as corrosion, wear and ageing, freezing, installation errors, defective products, mechanical impact, and waterproofing failures. The collected data are compiled and analysed annually by the Swedish centre for water damage, "Vattenskadecentrum", to identify trends, recurring causes, and areas where preventive measures may reduce future water-damage occurrence.

To estimate the share of water-damage costs borne directly by property owners, policy conditions from five major Swedish insurance companies were reviewed [59-64]. The insurance companies were selected based on their substantial presence in the Swedish residential property insurance market and the availability of policy documentation relating to water-damage claims. The review focused on deductible structures, depreciation rules, and age-related reductions in compensation applicable to water-damage events. To support the interpretation of policy conditions and improve the understanding of how compensation rules are applied in practice, consultations were conducted with representatives from insurance companies. Deductible costs were estimated by analyzing the deductible structures specified in the reviewed insurance policies. The analysis considered variations associated with claim value and insurance conditions. Depreciation and age-related reductions were estimated by reviewing insurers' reimbursement rules for damaged building components and technical installations. These rules were analyzed to identify the proportion of repair and replacement costs that may be transferred from the insurer to the property owner as a result of component age, condition, or expected service life. Based on the reviewed policy conditions, representative deductible and depreciation cost intervals were established and used in subsequent calculations of owner-borne water-damage costs. A distinction should be made between damage costs and insurance reimbursements. The damage cost reflects the estimated cost of repairing and restoring the building after a water-damage event, whereas the insurance reimbursement represents the amount paid by the insurer after deductibles and age-related depreciation deductions have been applied. The insurance statistics used in this study are based on the assessed damage costs; therefore, the financial burden borne by the property owner through deductibles and depreciation deductions is not directly visible in the dataset, even though it forms part of the total economic impact of the damage. The resulting estimates were intended to capture economic consequences that are not reflected in formal insurance reimbursements but are instead borne directly by property owners.

The deductible and depreciation cost intervals established from the insurance policy review were extrapolated using Swedish insurance statistics on reported and reimbursed water-damage claims. The calculations were based on approximately 82 500 annual water-damage events and

enabled estimation of the aggregate costs transferred from insurers to property owners through deductibles, depreciation, and age-related reductions in compensation

Additional data on water-damage costs and management practices in multi-family residential buildings were collected as part of Paper III. As detailed cost data are rarely publicly available, direct data collection was necessary to estimate and compare water-damage costs in the residential sector. The data were obtained from responses of three private housing companies selected through purposive sampling from large private housing companies in larger Swedish cities to represent variation in company size, geographical location, ownership structure, and housing-stock characteristics. Data collection was carried out through structured discussions with property managers and technical personnel responsible for maintenance and water-damage management. The discussions addressed water-damage reporting procedures, data availability, maintenance strategies, inspection routines, replacement planning, organizational responsibilities, and preventive measures. Information on annual water-damage costs, building-stock characteristics, and tenure forms was also collected. Where available, internal documentation and statistical summaries were used to verify and supplement the information provided by the respondents.

Based on the collected data, water-damage cost indicators were calculated and related to the number of apartments managed by each company. Particular attention was given to how water-damage incidents were documented and followed up, as well as how organizations used collected data to support preventive maintenance and investment decisions. This analysis provided insights into current water-damage management practices within the residential sector and helped explain observed differences in water-damage costs between housing companies. To increase the robustness of the analysis and reduce the influence of the limited sample, the company-specific data were complemented with information of water damage occurrence and cost per damage from a national report commissioned by the Swedish National Board of Housing, Building and Planning (Boverket) [22], comprising data from 88 housing companies and more than 417 000 apartments. The national dataset was used to contextualize the findings and assess whether the observed cost levels and management practices were broadly consistent with conditions in the Swedish multi-family residential sector.

Earlier Nordic studies and existing Swedish insured residential building dataset, from the insurance industry organisation Svensk Försäkring were also incorporated in this study to provide a broader context and facilitate cross-sector and cross-country comparisons, Paper V. The statistics were obtained from Swedish insurance organizations and insurance companies and included information on reported water-damage claims and associated reimbursement costs. These data were complemented by findings from a Nordic questionnaire survey, conducted in the study, of industry organizations, insurance companies, and university, providing additional insights into data collection procedures, reporting systems, and water-damage trends across the Nordic countries [26, 46-48, 51, 65, 66]. These data were used to investigate water-damage occurrence in different building sectors and national contexts, and to complement the Swedish insurance statistics by providing a broader perspective on water-damage patterns, reporting practices, and building-related risks. Building stock statistics from

Statistics Sweden (SCB) [67] and property data from the Swedish Real Property Register (Lantmäteriet) [68] were also used to place the water damage data in relation to the size, composition, and age distribution of the Swedish building stock. It should be noted that the appended Papers II and III are presented in their original published form, including the data, assumptions, and methods used in those studies. However, the extrapolation of national water-damage costs presented in this thesis has been updated using Statistics Sweden (SCB) building stock data for 2022 [67], rather than the building stock data available when Papers II and III were published.

A comparative approach was employed to investigate how water-damage statistics are collected, reported, and utilized in Sweden, Norway, Denmark, Finland, and Iceland. Data for this comparison was gathered through a structured questionnaire distributed to insurance associations, industry organizations, and other stakeholders responsible for managing water-damage statistics in the respective countries. The questionnaire covered the collection, management, and reporting of water-damage data, including responsible organizations, reporting procedures, building categories, causes of damage, repair costs, and follow-up activities. The responses were analyzed through a comparative assessment of insurance reporting systems to identify similarities, differences, and common trends. In addition, publicly available data on reported water-damage incidents, insurance reimbursements, and population size were compiled for each country. These data were used to estimate the annual reimbursement cost per capita and to compare overall trends across the Nordic countries. While the primary focus of this thesis is on Swedish water-damage statistics, information from Norway, Denmark, Finland and Iceland, where available, to provide context and enable comparisons of reporting systems, building stocks, and preventive practices.

The primary analysis of water-damage occurrence was based on the number of buildings as the functional unit, expressed as the annual number of reported water-damage cases relative to the total number of buildings within the investigated building stock. This approach enabled comparison between building categories as well as with previously published insurance-based statistics. To investigate the influence of the selected functional unit on the interpretation of water-damage occurrence, an additional analysis was performed using gross floor area as the denominator. In this approach, water-damage occurrence was calculated as the number of reported water-damage cases per unit of floor area and year. The indicator was expressed as the number of reported water-damage cases per 100 000 m² of gross floor area and year. Detailed floor-area data were available for Municipality 1 and were therefore used for the area-based analysis. The gross floor area was obtained from the municipal property management system and aggregated according to the building categories used throughout the study, including schools, offices, nursing and care homes, residential buildings, leisure buildings, and cultural buildings.

To enable comparison with Swedish residential buildings, existing Swedish insured residential building dataset, from the insurance industry organisation Svensk Försäkring were converted to the same floor-area-based functional unit. The conversion was based on a ten-year average of 60 516 reported water-damage incidents annually in Sweden and an average floor area of

122 m² for one- and two-dwelling buildings. In this analysis first the annual occurrence rate was estimated by relating the average number of reported water-damage incidents to the approximately 2.1 million single-family houses in Sweden, resulting in an annual occurrence of approximately 2.9%. The occurrence rate was then converted to an area-based metric by determining the number of average-sized detached houses represented by 100 000 m² and applying the calculated annual occurrence rate. This resulted in a reference value expressed as water-damage cases per 100 000 m² and year, allowing direct comparison with the municipal building portfolios. The area-based analysis was intended to complement the building-based analysis by providing a size-normalized measure of water-damage occurrence. While the building-based functional unit reflects the frequency of reported incidents relative to the number of buildings managed, the floor-area-based functional unit allows comparison between building portfolios of different sizes and building compositions. Together, the two approaches provide a broader understanding of water-damage occurrence within municipal property portfolios.

Throughout the thesis, costs are presented in Swedish krona (SEK) and euro (€). Currency conversions were performed using an exchange rate of 1 € = 11.1 SEK, based on the European Central Bank reference rate for August 2026 [69].

2.3.3 Public Building Data

To investigate water damage outside the residential sector, empirical data were collected from publicly owned and managed building portfolios. These data were particularly important because detailed water-damage information for public buildings is generally limited compared with the residential sector, where insurance statistics from Svensk Försäkring and Vattenskadecentrum are available but primarily focus on single-family dwellings and residential buildings. The data collection process began by identifying municipalities with large publicly owned building portfolios and established digital systems for property management, maintenance, and fault reporting. Six of the ten largest municipalities in Sweden were contacted regarding access to historical water-damage records and related building information. To ensure sufficient data quality and comparability, a set of inclusion criteria was established. The municipalities were required to provide access to records from municipally owned and managed buildings, contain sufficient information to distinguish water damage originating from internal building systems from weather-related events, and include data allowing identification of building type, damage characteristics, and occurrence. The municipalities were selected based on predefined criteria. To be included in the study, municipalities were required to (i) own and manage a substantial portfolio of public buildings, (ii) maintain digital property-management and maintenance systems containing historical water-damage records, (iii) provide sufficient information to distinguish water damage originating from internal building systems from weather-related or external moisture events, (iv) include building-specific information such as building type and use, and (v) grant access to data of sufficient quality and completeness to support statistical analysis and comparison across building categories. Three municipalities fulfilled these requirements and were therefore included in the study.

The participating municipalities used different reporting structures, property-management systems, and maintenance databases. To understand the structure and limitations of each

dataset, meetings and discussions were conducted with municipal property managers, maintenance personnel, technical specialists, and data administrators. These discussions helped clarify reporting practices, database structures, terminology, and historical changes within the reporting systems. They also provided contextual information regarding how water-damage incidents were registered and managed within each municipality.

Approximately 18 000 reported incidents from three Swedish municipalities were reviewed as part of the data collection process. From these reports, 3 030 cases could be confirmed as falling within the scope of this study and were therefore included in the analysis. Some of the remaining cases were excluded because they were attributable to external factors such as precipitation, flooding, and other nature-related events. While additional relevant cases may have been present among the approximately 15 000 excluded reports, limitations in the reporting system and the sampling methodology prevented their reliable classification and inclusion in the analysis. The primary dataset therefore consisted of 3 030 reported water-damage cases collected from three Swedish municipalities.

The data covered different time periods depending on data availability: 2017-2022 for Municipality 1, 2008-2021 for Municipality 2, and 2015-2024 for Municipality 3. The available information varied between municipalities but generally included case descriptions, dates of occurrence, repair measures, repair costs, affected properties, and comments from maintenance staff or contractors.

Prior to analysis, all records were reviewed to determine whether they met the scope of the study. Because the participating municipalities used different reporting systems and levels of categorization, different extraction procedures were required. In Municipality 3, water-damage records were initially identified using a keyword-based search including the term “vattenläck” and related variations such as “vattenläcka” and “vattenläckage”. This search served as an initial screening step to identify potentially relevant cases rather than as a final classification. Only water damage caused by unintended water flow originating from internal building systems, appliances, installations, and waterproofing systems was included. Cases associated with precipitation, flooding, groundwater intrusion, storm events, roof leakage caused by external weather conditions, and other nature-related moisture sources were excluded. The screening process involved a manual review of available metadata, case descriptions, maintenance notes, and work-order records. For Municipality 3, records identified through the keyword search were subsequently reviewed manually using the available documentation to determine whether the reported damage originated from internal building systems and fulfilled the study inclusion criteria. Based on this information, each record was assessed against the study's inclusion and exclusion criteria and classified as either a verified water-damage incident or a non-relevant maintenance event. Records lacking sufficient information to determine the cause of damage were excluded from further analysis. In this study, a verified water-damage incident refers to a record that, following manual review of the available documentation, could be classified as originating from an internal building-related water-damage source within the defined system boundaries.

This procedure was undertaken to ensure consistency in the classification process and to separate relevant water-damage incidents from general maintenance activities and other building defects. The investigated building stock included schools, healthcare facilities, nursing homes, offices, administrative buildings, sports facilities, and cultural and leisure buildings. For analytical purposes, the buildings were grouped into four categories: schools, nursing and healthcare facilities, offices and premises, and culture and leisure buildings. The categorization was performed based on the building-use classifications available in municipal property-management systems and the Swedish Real Property Register. Similar building functions were aggregated into broader categories to provide sufficient sample sizes for analysis and to facilitate comparisons between different types of public buildings. These categories were selected to correspond to the classification system used in the Swedish Real Property Register and to enable comparisons between different public building functions.
Building-specific information was obtained by linking the water-damage records to property and building databases. The collected variables included building age, building type, floor area, ownership, and building use. Additional building-stock information was obtained from the Swedish Real Property Register (Lantmäteriet) and Statistics Sweden (SCB), allowing the municipal data to be analyzed in relation to the broader Swedish public building stock. The building-stock data were further used to determine the number and distribution of public buildings within each building category.

Following data collection and screening, the datasets from the three municipalities were harmonized and compiled into a common database. Differences in reporting structures, building classifications, naming conventions, and documentation practices were standardized to enable comparison between municipalities. The harmonization process included aligning building categories, unifying terminology, and reviewing inconsistencies in damage descriptions and repair records.

The collected water-damage records were reviewed and classified according to water-damage occurrence, damage origin, affected building systems, and repair costs. To facilitate comparison with the existing Swedish insured residential building dataset, from the insurance industry organisation Svensk Försäkring, the identified incidents were categorized using the same principal framework applied by the Swedish Water Damage Centre (Vattenskadecentrum). Water-damage cases were grouped into three main categories: pipes and connections, appliances, and waterproofing systems in wet rooms. Cases lacking sufficient information for reliable classification were categorized as unknown. Several classifications required manual review of case descriptions and associated metadata to ensure consistency between municipalities.

Descriptive statistical analyses were performed to identify recurring damage patterns, common causes, distribution between building categories, and differences in occurrence rates. To enable comparisons between building categories of different sizes, the number of reported water-damage incidents was related to the number of buildings within each category. The municipal water-damage data was subsequently used to establish occurrence indicators and cost indicators for the investigated building categories. These indicators were calculated as the average number

of water-damage incidents and associated repair costs per building and year. Repair-cost data were further analysed using descriptive statistics and distribution analyses to account for the skewed nature of the cost data and the presence of extreme high-cost events. This enabled the identification of both typical repair costs and unusually costly incidents affecting the municipal building stock.

The resulting key figures were then combined with national building-stock data from SBC [67] to extrapolate the occurrence and cost of water damage to the Swedish public building stock. The extrapolation procedure assumed that the occurrence rates observed within the studied municipalities were representative of similar public buildings in Sweden. Estimated annual occurrence and repair costs were therefore calculated by multiplying the occurrence and cost indicators derived from the municipal dataset by the corresponding number of buildings within each category in the national building stock. The combination of municipal water-damage records, building-stock information, and national property-register data, from Lantmäteriet [68], enabled both detailed analyses of individual water-damage incidents and broader assessments of water-damage occurrence and repair costs within the Swedish public building stock. These data provided new empirical evidence regarding a building category that has received limited attention in previous water-damage research.

2.3.4 Interview Data

The statistical analysis provided an overview of the occurrence, distribution, and trends of water damage claims in Sweden. However, the municipality water damage data did not provide sufficient detail to determine why the damage occurred or to assess the practical and organizational circumstances that may have contributed to them, such as maintenance routines, construction practices, and responsibilities among involved actors. Therefore, qualitative interviews were conducted with key stakeholders and practitioners involved in water damage prevention, investigation, remediation, and building management. The interviews complemented the quantitative analyses by providing deeper insights into damage causes, operational practices, organizational conditions, and preventive measures in public buildings.

A qualitative research design was adopted using semi-structured interviews with stakeholders involved in the management, maintenance, and operation of public buildings. Participants were selected based on their professional responsibilities and experience of water damage management. The interviewees included facility managers, technical specialists, and operational staff from three Swedish municipalities that had previously participated in the quantitative study. Using the same municipalities in both studies enabled the statistical findings on water-damage occurrence to be interpreted and contextualized through the experiences of personnel responsible for managing water-damage incidents. To ensure confidentiality while retaining contextual information, each participant was assigned a code based on their municipality and building category or organizational role (e.g., MU1-PS for a preschool representative from Municipality 1) as described in Table 3.

Table 3.Overview of interview participants and anonymization codes. The code MU1 stands for the municipality, and the last two letters are short for the building category/role.

Building category / Role	**Municipality**	**Code**
Preschool – Facility Management	MU1	MU1-PS
Elementary School – Facility Management	MU1	MU1-ES
Culture & Leisure Buildings – Operations/Technical Staff	MU1	MU1-CL
Nursing and Care Facilities – Facility Management	MU1	MU1-NC
Residential Buildings – Technical Specialist	MU1	MU1-RB
Overall Operations and Building Mangement	MU2	MU2-OA
Operations & Management	MU3	MU3-OM

In total, seven interviews were conducted with representatives responsible for schools, nursing and care facilities, residential buildings, cultural and leisure buildings, and overall municipal property management. The participants were identified through the participating municipalities and selected to represent different building types and operational contexts. A semi-structured interview guide was used for all interviews to ensure comparability between participants while allowing respondents to elaborate on issues relevant to their own professional context. The interviews addressed topics including:

- common causes of water damage,
- maintenance and inspection routines,
- organizational responsibilities and communication,
- building-specific challenges,
- repair costs and consequences,
- preventive measures and technical solutions,
- implementation barriers and future needs.

All interviews were conducted remotely using Microsoft Teams and typically lasted between 45 and 60 minutes. With participant consent, the interviews were audio-recorded and transcribed. The transcripts were subsequently reviewed, corrected where necessary, and translated from Swedish to English when required. Additional notes were taken during and after each interview to capture contextual observations and emerging themes. The interview material was analysed using reflexive thematic analysis according to the six-phase approach developed by Braun and Clarke [70, 71]. The analysis included familiarization with the data, generation of initial codes, development of themes, review and refinement of themes, theme definition, and reporting of findings. Coding was conducted inductively, allowing themes to emerge from the interview material rather than being predetermined. The thematic analysis focused on identifying recurring patterns related to water damage causes, technical vulnerabilities, preventive strategies, organizational practices, and implementation barriers.

The interview data were primarily used to complement the quantitative findings obtained from municipal water damage statistics and building stock analyses. Combining quantitative and qualitative methods enabled a broader understanding of water damage occurrence by integrating statistical evidence with practitioner experiences and organizational perspectives.

2.3.5 Life-Cycle Assessment of Water Damage Repairs

The environmental consequences of water damage were assessed using a life-cycle assessment (LCA) approach. The objective was to quantify greenhouse-gas emissions associated with repair and restoration activities resulting from leakage-related water damage in public buildings and to evaluate how leakage duration influences the environmental impact of repair measures. The assessment was based on empirical water damage data obtained from public buildings together with representative repair scenarios. The scenarios were developed from documented water damage cases, such as included from the dataset and interviews, and reflected different leakage durations and resulting damage extents. Leakage duration was selected as a central parameter because it was assumed to influence the extent of moisture exposure, the amount of damaged material requiring replacement, and the overall scope of repair activities. The scenarios therefore represented increasing levels of damage severity associated with progressively longer leakage periods. For each scenario, the affected building components, required repair measures, and replacement materials were identified.

The environmental assessment included the production of replacement materials, demolition and removal of damaged materials, waste handling, transportation, and installation of new building products. The assessment was limited to building materials and building assemblies typically covered in current life cycle assessment (LCA) practice. Accordingly, the analysis included only floor, indoor walls, and intermediate floor (floor-ceiling) assemblies. The scenario definitions were informed by empirical observations from the water-damage dataset, interviews with maintenance and repair professionals, and published investigations of moisture-related building damage [81]. A water flow of approximately 10 L/min was applied which is representative to the Swedish industry standard [82]. The figure 10 L/min was also mentioned by one respondent in the interviews. Interviews further indicated that water supply shut-off is often delayed following the onset of a leakage event, resulting in continued water intrusion and increased moisture exposure of surrounding building materials. In addition, studies commissioned by Länsförsäkringar and conducted by RISE Research Institutes of Sweden [81] have demonstrated that leakage through waterproofing systems may lead to moisture penetration into adjacent floor and wall assemblies, often necessitating material replacement and drying measures. The testing also revealed that several approved waterproofing systems exhibited leakage despite being installed according to manufacturers' instructions and current industry requirements. This suggests that compliance with existing installation standards alone does not eliminate the risk of moisture intrusion and subsequent water damage.

The assumed leakage volumes, exposure durations, replacement extents, and drying requirements were therefore defined as representative damage scenarios rather than deterministic relationships derived from the LCA model. While larger leakage volumes were assumed to generally result in more extensive repair measures, the relationship between leakage

volume and damage extent is influenced by several case-specific factors, including leakage location, material properties, moisture migration, and detection time. This assumption is further supported by evidence [81] showing that moisture intrusion through failed waterproofing systems primarily affects floors, wall assemblies, and adjacent structural layers, which constitute the components most commonly requiring remediation and replacement following water damage events. The scenarios should be interpreted as plausible damage levels intended to represent minor, moderate, and severe water-damage events based on available empirical evidence and professional judgement from the interviews. For the analyzed scenarios, the assumed leakage duration were 5 min, 30 min, and 60 min, respectively.

The leakage volumes were estimated using a 5 m² reference bathroom and assumed retained water depths corresponding to the analyzed damage scenarios. The severe-damage scenario was based on an assumed water depth sufficient to exceed the waterproofing upturn at the room boundaries [82-83]. This assumption reflects a worst-case moisture exposure scenario and was used to estimate the maximum water volume retained within the reference space. However, actual water accumulation depends on several building-specific factors, including threshold design, floor slope, drainage capacity, drain blockage, leakage location, and the time required to detect and stop the leakage. Water may spread to adjacent rooms before reaching the assumed depth, resulting in a larger affected area but a lower retained water depth than represented in the reference scenario. The adopted assumptions were therefore intended to provide a consistent basis for comparing damage severities rather than to predict the exact distribution of water during leakage events.

Repair measures assigned to each scenario were based on documented water-damage cases, interviews with practitioners, and common remediation practices. Replacement of the load-bearing floor structure was included only in the severe-damage scenario to represent a conservative remediation case where moisture penetration extends beyond surface finishes and waterproofing layers into the supporting structural assembly. In many water-damage situations, technical drying and local replacement of damaged materials may be sufficient to preserve the existing structure. The assumed replacement of structural elements reflects the extent of moisture damage and remediation requirements rather than a loss of structural load-bearing capacity. Because structural replacement may significantly influence the calculated environmental impacts, its contribution was identified as an area requiring separate evaluation beyond the baseline repair scenarios presented in this study.

The assessment was limited to modules A1-A3 according to EN 15978 and focused on the embodied greenhouse-gas emissions associated with the production of replacement materials required during repair and restoration activities. Repairs, replacements, and new components related to building service systems (e.g., plumbing and technical installations) were not included due to a lack of consistent LCA data at the system level. The environmental assessment included the production of replacement materials, demolition and removal of damaged materials, waste handling, transportation, and installation of new building products. The assessment was limited to building materials and building assemblies typically covered in current life cycle assessment (LCA) practice. Accordingly, the analysis included only floor,

indoor wall, and intermediate floor (floor-ceiling) assemblies. Particular emphasis was placed on assemblies protected by waterproofing systems, as failures in wet-room waterproofing membranes constitute a significant source of water damage in residential buildings. As a result, the estimated environmental impacts should be regarded as conservative and are likely to underestimate the total impacts associated with water damage remediation. The focus on A1-A3 was motivated by data availability and the objective of evaluating how the extent of material replacement influences the environmental impact of water-damage repairs. Operational energy use during the repair process and activities directly associated with restoring the building to its original condition were included when relevant. Climate impact calculations were performed using environmental product declarations (EPDs), life-cycle inventory databases, and published environmental data relevant to the Swedish construction sector. The calculations were conducted in Microsoft Excel by combining material quantities and repair scenarios with corresponding greenhouse gas emission factors. No dedicated life-cycle assessment software was used, as the analyses were based on a desktop assessment of secondary environmental data. Material quantities were estimated based on the selected repair scenarios and typical repair practices for water-damaged building components. Greenhouse-gas emissions were quantified using life-cycle assessment methodology and reported as carbon dioxide equivalents (CO_2e). Electricity-related greenhouse gas emissions were calculated using an emission factor of 0.059 $kgCO_2e/kWh$, based on values published by the Swedish Environmental Protection Agency (Naturvårdsverket) for climate impact calculations [72]. The scenario-based approach enabled comparisons between different leakage durations and repair extents, allowing the environmental consequences of delayed leakage detection to be evaluated.

3 Results

3.1 Overview of the Results

This chapter presents the results of the research conducted in this thesis. The results are organized according to the four research themes addressed in the thesis: occurrence, consequences, causes and prevention of leakage-related water damage. The chapter begins by examining the extent and characteristics of water damage within residential and public buildings. The subsequent sections present the economic and environmental consequences of water damage, including both repair costs and climate impacts associated with water-damage events and repair activities. This is followed by an analysis of the technical, organizational, and building-specific factors contributing to water-damage occurrence. Finally, preventive measures identified through the literature review, empirical analyses, and stakeholder interviews are presented.

3.2 Extent and Characteristics of Water Damage

Water damage is a frequently reported building defect that may occur throughout the service life of buildings. It can originate from a range of technical systems and building components and may affect building owners, facility managers, occupants, insurers, and other stakeholders. This section presents the extent and characteristics of water damage based on the datasets and analyses included in this thesis.

3.2.1 Water Damage in the Residential Building Sector

Analysis was made of the dataset related to existing Swedish insured residential buildings, distributed by the insurance industry organisation Svensk Försäkring presented in Figure 4 gathered from 1985 and 2022, this insurance statistics showed that approximately 89 500 water-damage incidents were reported in 2022 (Papers II-V), Figure 4 [25].

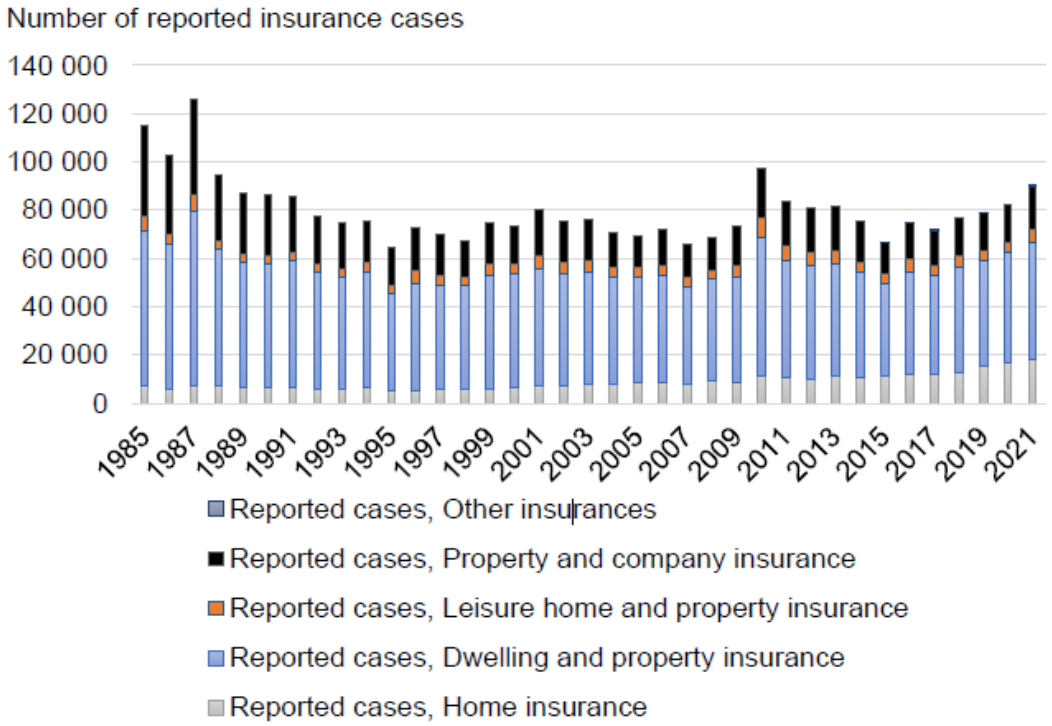


Figure 4. Number of reported water damage cases in Sweden, between 1985 and 2022, in insurance companies gathered by Svensk Försäkring [26].

Of these, approximately 35 000 incidents were included in the detailed annual investigations conducted by Vattenskadecentrum [24], providing information regarding damage occurrence, affected building systems, damage locations, and installation age, as shown in Figure 5. Which has been carried out by Vattenskadecentrum since 2002. The resulting dataset in this study formed an important empirical foundation for this thesis and was further analysed, complemented with additional data sources, and developed to support investigations of water-damage occurrence, causes, costs, consequences, and preventive measures in both residential and public buildings. The following figures are based on data obtained from the Swedish Water Damage Centre (Vattenskadecentrum, VSC). The figures were developed by the author based on the original dataset to illustrate the distribution of water-damage incidents across building spaces, sources of leakage, and contributing technical systems.

First, the yearly distribution of water damage is presented (Figure 5) together with its correlated cause of either pipes and connections, waterproof membrane or appliances.

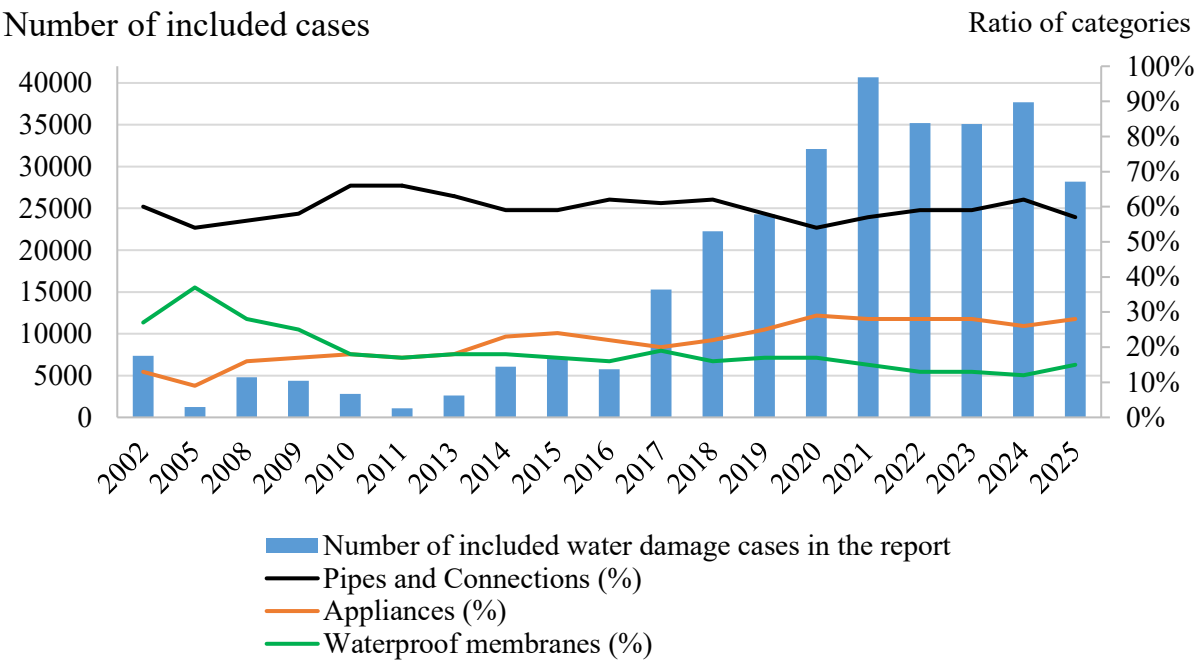


Figure 5. Annual number of reported water damage incidents in buildings in Sweden. Left axis, number of included water damage cases in the water damage report from Vattenskadecentrum [24]. Right Axis, distribution of water damage causes (——).

The results show that pipe and connection systems represented the largest category of reported water damage throughout the study period, accounting for 57% of reported incidents for year 2025. Appliance-related damage accounted for 28% of reported cases in 2025 [24], while waterproofing-related damage represented approximately 13–15% of incidents. Although the overall distribution between the main damage categories remained relatively stable, appliance-related damage exhibited a gradual increase over time. The increase in appliance-related incidents was accompanied by changes in the distribution of reported damage locations. By 2022, kitchens had become the most frequently reported location of water damage in Swedish single-family buildings, accounting for approximately 35% of all reported cases, as shown in Figure 6. Wet rooms represented the second largest category, while laundry rooms, sanitary spaces, and other areas accounted for smaller proportions of the reported incidents.

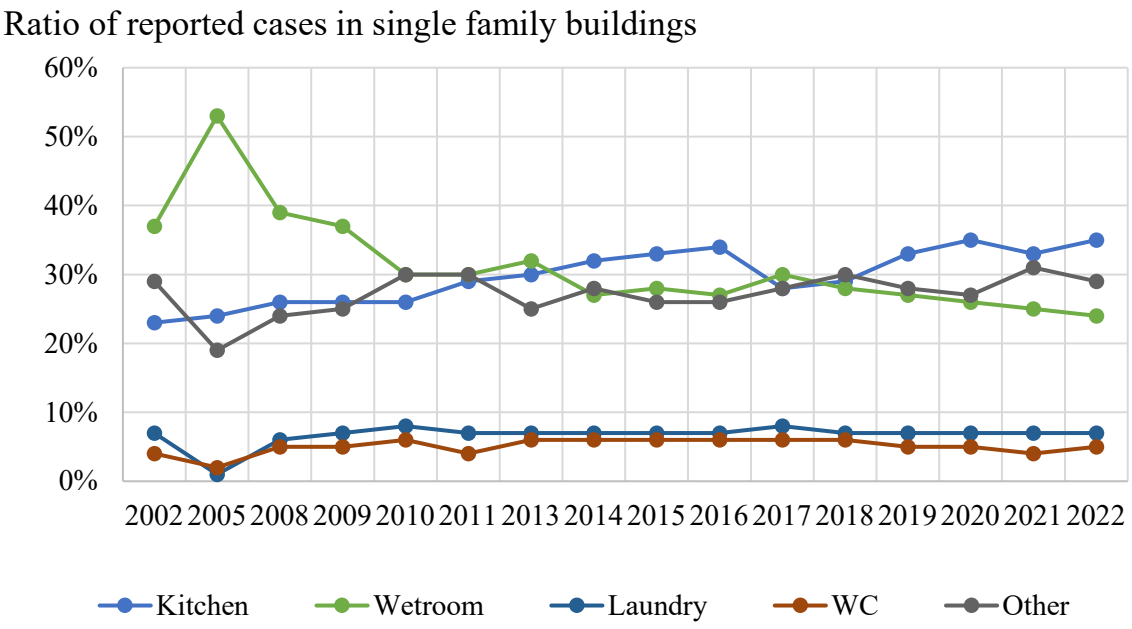


Figure 6 Distribution of water damage occurrence by room type [24].

Analysis of installation age, conducted in 2022, showed that a substantial proportion of water damage occurred relatively early during the service life of building service systems. For tap-water systems, approximately 43% of reported damage incidents occurred within the first ten years after installation. Similar patterns were observed for several other installation categories, as shown in Figure 7. The results showed that a substantial proportion of reported water-damage cases occurred during the first 10 years after installation, particularly for radiant floor heating, cold-water systems, hot-water systems, and sewage systems, indicating that the risk of damage is generally highest during the early service life of these installations [24, 43-45].

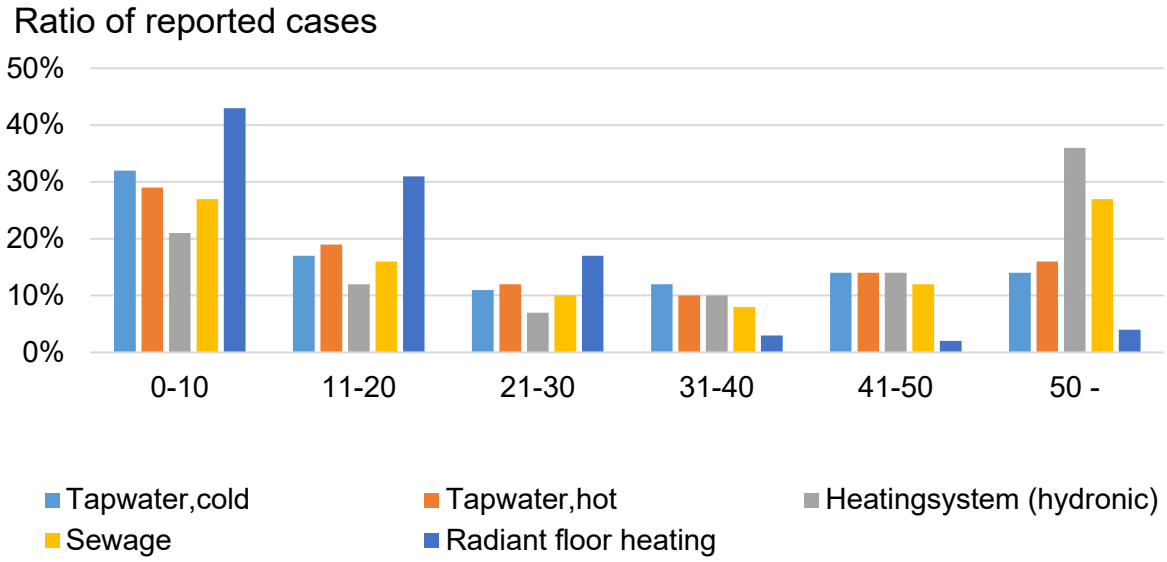


Figure 7. Distribution of reported water damage, divided by a 10-year span, according to installation age data from 2022.

Analysis of long-term statistics from the Swedish insurance industry further revealed that reported water-damage incidents have increased during recent years. A more detailed analysis of occurrence by damage origin showed that corrosion and age-related deterioration accounted for approximately 72% of all pipe and connection-related water damage cases (Figure 8). Within the appliance category, refrigerators/freezers and dishwashers together accounted for 56% of reported cases (Figure 9). For waterproof membranes, faulty membranes and faulty connections to floor drains were the dominant causes of damage (Figures 10-11)

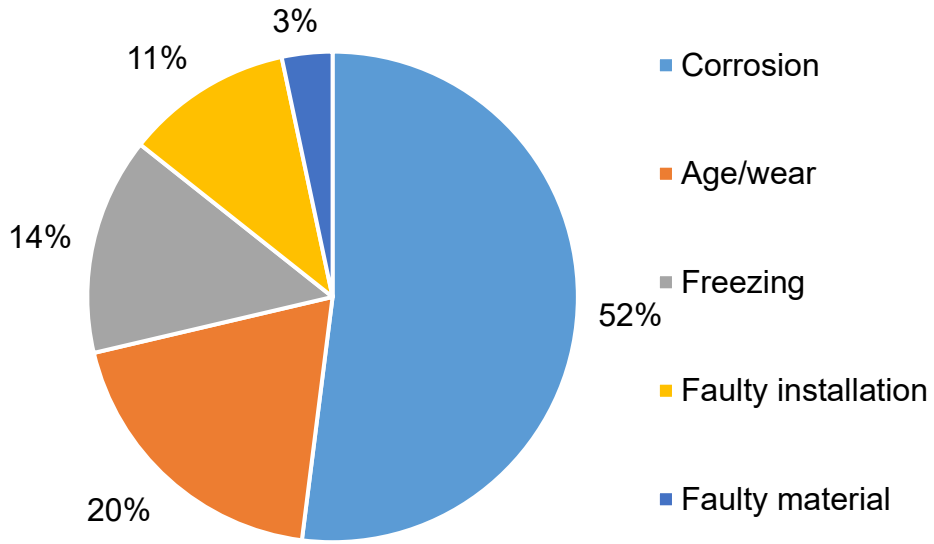


Figure 8. Distribution of water damage causes in the category pipes and connections between 2020 – 2022. [24, 43-45].

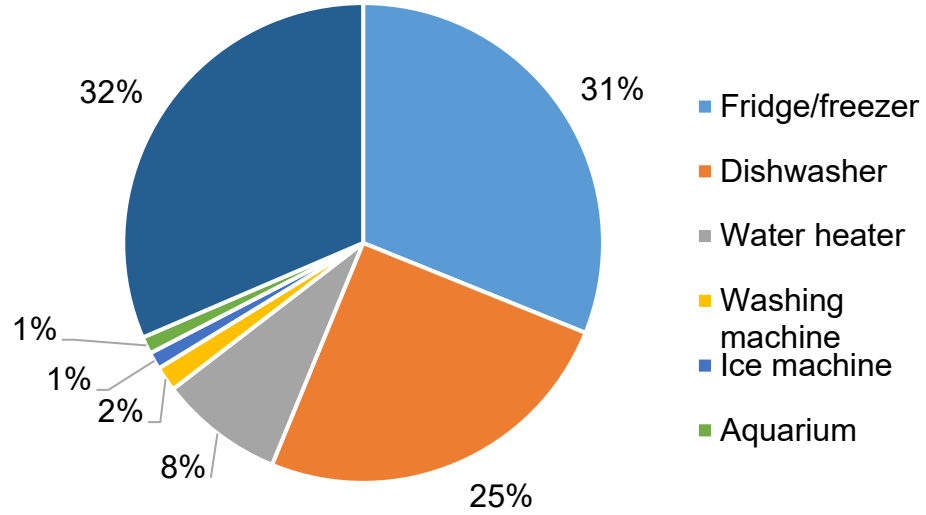


Figure 9. Distribution of water damage causes in the category appliances between 2020 – 2022. [24, 43-45].

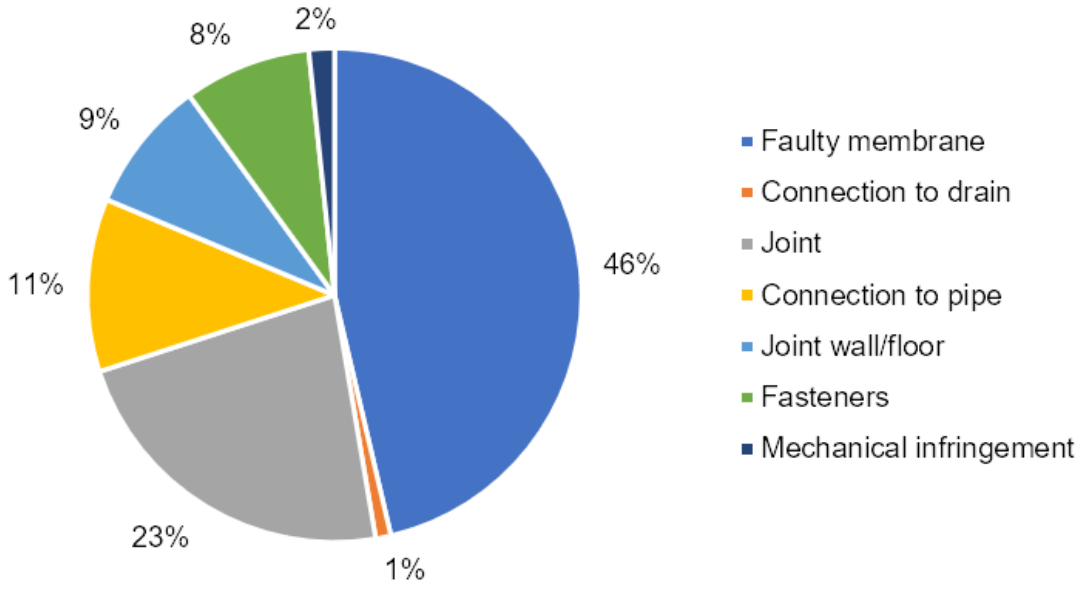


Figure 10. Distribution of water damage causes occurring from wall membranes between 2020 – 2022 [24, 43-45].

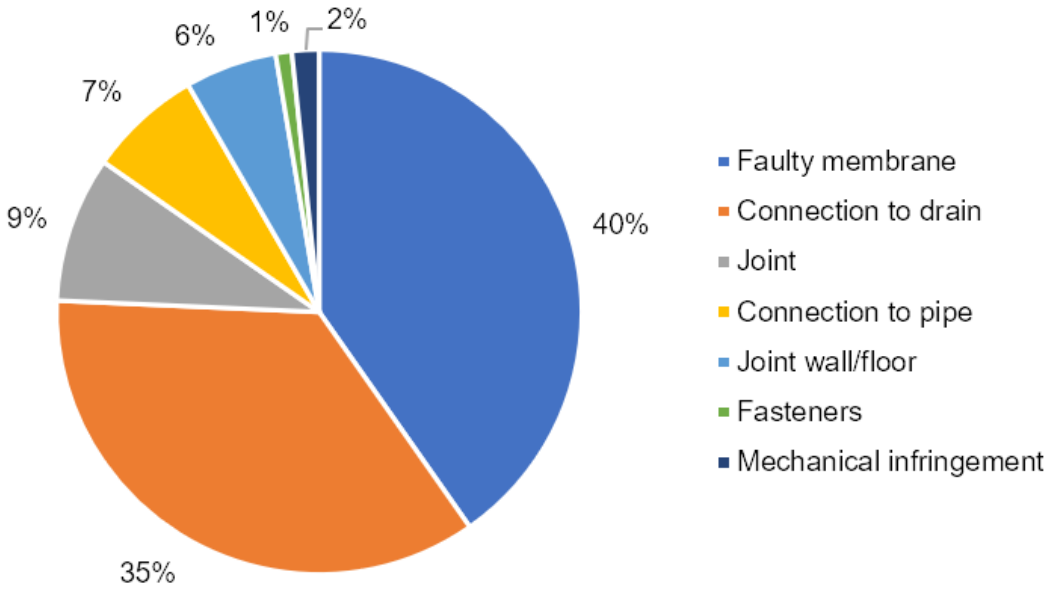


Figure 11. Distribution of water damage causes occurring from floor membranes between 2020 – 2022 [24, 43-45].

The Swedish residential building stock consisted of approximately 5.16 million dwellings in 2022, of which 41% were single-family dwellings, 52% multi-family dwellings, 5% special housing, and 2% other residential buildings [67]. The distribution of the residential dwellings is presented in Figure 12 and Table 4.

Table 4. Number of residential dwellings in Sweden divided into the form of tenure and building purpose [67].

Form of tenure	Single-family		Multi-family		Special housing		Other	
Tenancy	95 096	4%	1 555 049	58%	274 053	98%	65 434	82%
Condominium	104 365	5%	1 117 045	42%	4 487	2%	14 133	18%
Tenant owned	1 925 375	91%	2 853	0%	0	0%	0	0%
Not specified	433	0%	322	0%	6	0%	48	0%
Sum	2 125 269	100%	2 675 269	100%	278 546	100%	79 615	100%

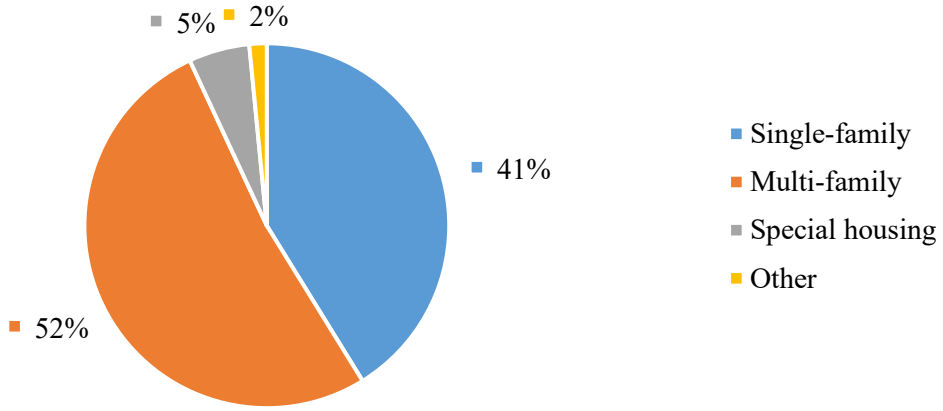


Figure 12. Distribution of residential dwellings in Sweden 2022 [67].

However, the analyses also revealed important limitations in the available statistical data. The detailed water-damage statistics published by Svensk Försäkring and Vattenskadecentrum are primarily based on insured single-family dwellings and leisure homes. Comparison with national building-stock statistics, from SCB [67], showed that these datasets mainly represent approximately 2.1 million dwellings within the Swedish residential building stock, corresponding to approximately 41% of all residential dwellings in Sweden [67]. The results therefore indicate that the available occurrence statistics provide detailed information regarding water-damage occurrence and system of which the damage occurred in, and damage characteristics within a large part of the residential sector. It is notable that more than half of the residential building stock, primarily consisting of multi-family dwellings and other residential building categories, is not represented in the detailed occurrence statistics. The reported occurrence rates should be interpreted as representative of the covered building stock rather than the entire Swedish residential sector.

The age distribution of residential building stock is presented in Figure 13. A large proportion of the Swedish housing stock was constructed between 1951 and 1980, with the largest buildings built during 1961-1970. These buildings constitute a significant share of the existing

stock and may therefore influence the future occurrence of water damage as building service systems, installations, and waterproofing systems continue to age.

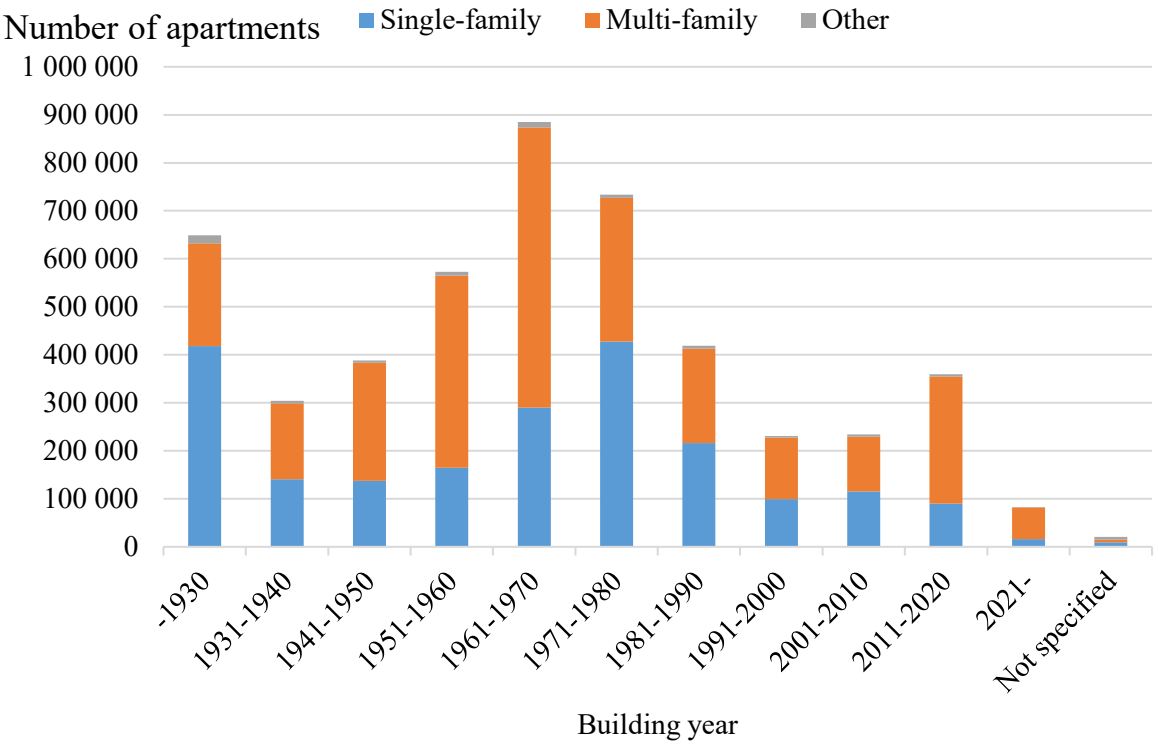


Figure 13. The residential building stock´s building age is divided into building purposes, excluding the special housing [73]

Multi-family residential buildings constitute the largest segment of the Swedish residential building stock, accounting for approximately 2.7 million apartments and more than half of all residential dwellings in Sweden. Despite their importance within the building stock, detailed occurrence statistics regarding damages are not available through a national reporting system comparable to the system used for insured single-family dwellings. Nevertheless, available studies and industry data indicate that water damage represents a recurring challenge within the sector.

The investigation of housing companies and residential property owners showed, in Paper III, that water damage occurs regularly throughout multi-family residential building portfolios and represents a recurring maintenance-related issue. The participating building management companies managed building stocks ranging from approximately 4 100 to 30 000 apartments and reported annual water-damage costs between 60 000 € and 1.9 million €. These values are reported in corrected form in Table 5. The corresponding figures published in Paper II contained a factor-of-ten error and have therefore been revised in this thesis. The corresponding cost factors ranged from 24 € to 260 € per apartment and year, with most reported values falling within the interval of 24-64 € per apartment and year. Table 5 summarizes the factors identified by the participating building management companies as important for water-damage prevention and management. Since the data obtained from the companies comprised repair-cost information rather than records of water-damage occurrence, the results are presented in this section, where the cost-related analyses are discussed. In response to questions regarding

preventive measures and water-damage management practices, respondents highlighted maintenance practices, inspection routines, technical installations, organizational responsibilities, staff competence, and preventive measures. Regular inspection of piping systems, wet rooms, technical installations, and water-using equipment was consistently identified as part of water-damage management. Preventive maintenance and replacement of ageing installations were also reported as important measures within the studied building stocks. Several respondents also emphasized the importance of clear responsibilities, staff training, and organizational routines for reducing the occurrence and consequences of water damage.

Table 5. Factors influencing water-damage prevention and management as identified by the participating building management companies, including maintenance practices, inspection routines, technical installations, organizational responsibilities, staff competence, preventive measures, and water-damage reporting procedures within multi-family residential building portfolios. **Note:** Costs are reported in current prices for the respective study period (2022 – 2025) and have not been adjusted for inflation.

Building managing company	**Building stock**	**Main form of lease**	**Approximate annual repair costs (€)**	**Key factor (€ per apartment and year)**
1	30 000	tenancy	1 930 000	64.4
2	25 800	tenancy, residential owned apartments	60 000 – 100 000	24 - 40
3	4 100	tenancy	100 000	260

The results further showed that water-damage statistics for multi-family residential buildings are mainly collected internally by individual housing companies and property owners. Available data are fragmented and not coordinated through a national reporting system. As a result, knowledge regarding the occurrence and distribution of water damage in multi-family residential buildings remains more limited than for single-family dwellings. The building management companies reported that organizational factors such as defined responsibilities, maintenance procedures, and inspection activities form part of their water-damage management processes. In addition, staff competence and preventive actions related to water-using installations were identified among the parameters considered when managing water-damage risks. Considering that the Swedish multi-family housing stock comprises approximately 2.7 million apartments, Table 4, the results indicate that even relatively low occurrence rates correspond to a substantial number of annual water-damage incidents. The findings therefore demonstrate that leakage-related failures affect a considerable number of multi-family residential buildings and apartments each year.

A comparison of publicly available insurance statistics from the Nordic countries further demonstrated (Paper V) that water damage is a widespread challenge across the region (Table 6). Annual reported water-damage cases ranged from approximately 7 000 in Iceland to 125 000 in Denmark, while reported reimbursement costs ranged from 20 million € to 510 million

€ per year. Despite differences in population size and reporting practices, reimbursement costs per inhabitant were of a similar magnitude across the countries studied, ranging from 31 € to 94 € per inhabitant and year. The most commonly reported causes also showed similarities, with pipe-related failures, corrosion, age-related deterioration, and concealed pipe systems identified as dominant contributors to water damage occurrence. The cost estimates are presented within the occurrence section because the methodology used for their estimation is described in this context. This placement maintains a clear link between the analytical procedures and the resulting estimates.

Table 6. Comparison of the Nordic countires, based on the questionare and public statistics. **Note:** Costs are reported in current prices for the respective study period (2022 – 2025) and have not been adjusted for inflation.

	Sweden [26, 46]	**Denmark [48, 66, 73]**	**Norway [47, 75]**	**Finland [51, 65]**	**Iceland [46]**
Reported water damage	90 000	125 000	104 000	31 000	7 000
Reported reimbursement cost (€)	420 000 000	360 000 000	510 000 000	170 000 000	20 000 000
Population	10 400 000	5 800 000	5 400 000	5 500 000	400 000
Cost per inhabitant per year (€)	40	62	94	31	50
Number of damage per inhabitant per year (per 1 000 inhabitants)	8.7	21.6	19.3	5.6	17.5
Most common cause	Corrosion of pipes	Hidden pipes	Wear and age of pipes	Corrosion of pipes	Damaged pipes

The questionnaire responses revealed that the Nordic countries share similar insurance-based approaches to collecting water-damage statistics. However, important differences were identified in how occurrence data are categorized and reported. Sweden and Norway provide more detailed information regarding damage origin and cause through dedicated organizations responsible for water-damage statistics, whereas Denmark and Finland mainly report damage occurrence within broader categories. As a result, the level of detail concerning where damage occurs and which technical systems are involved varies between countries. A common trend identified across all countries studied was an increasing emphasis on water-damage occurrence and associated reimbursement costs over time. Furthermore, increasing attention was directed towards water damage occurring in kitchens. Unlike wet rooms, kitchens generally lack waterproof membranes and floor drains, limiting their ability to contain and safely discharge leakage water. This trend is consistent with Swedish occurrence statistics, where kitchens represented the most frequently reported room and where a large proportion of damages originated from appliances such as dishwashers and refrigerators.

Although building regulations, insurance systems, and construction practices were generally similar throughout the Nordic region, differences were identified regarding regulatory requirements, functional demands, and insurance coverage. Furthermore, the building categories included in the existing Swedish insured residential building dataset, from the insurance industry organisation Svensk Försäkring differed between countries. For example, Danish statistics include a broader range of damage events and insured property types, while Swedish and Norwegian statistics primarily focus on indoor water-damage events and provide more detailed cause-specific reporting. These differences should be considered when comparing occurrence levels between countries and highlights the need for caution when interpreting international water-damage statistics.

3.2.2 Occurrence in Swedish Public Buildings

In addition to the residential sector, the Swedish building stock includes approximately 12 600 municipality buildings, comprising schools, nursing and care homes, offices and other premises, and culture and leisure buildings [68]. The distribution of these building categories is presented in Figure 14.

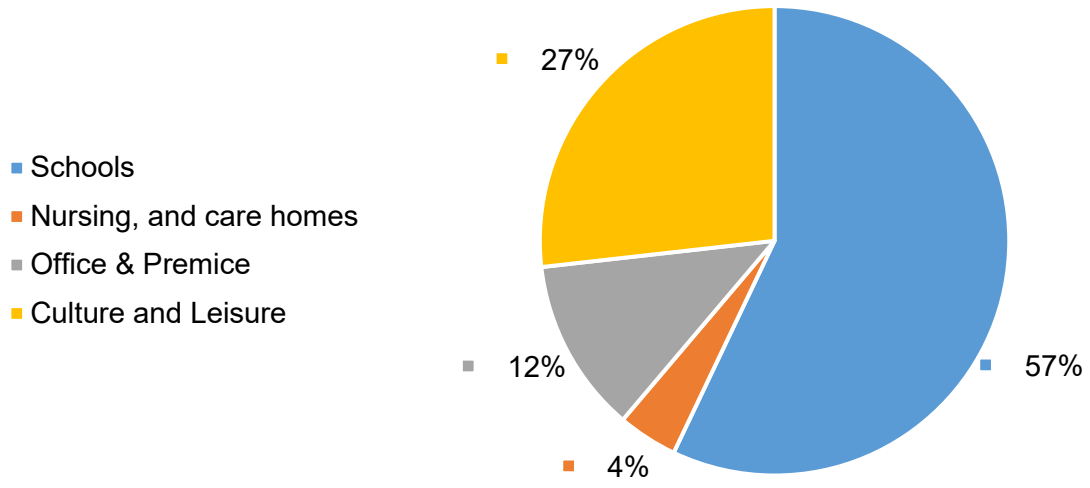


Figure 14. The distribution of non-residential Swedish municipal building stock is divided into 4 building categories [68].

These buildings are generally not included in detailed insurance-based water-damage statistics, resulting in limited knowledge of water-damage occurrence within large parts of the non-residential sector. Existing Swedish datasets of insured residential buildings, primarily maintained by the insurance industry organization Svensk Försäkring, mainly describe water damage occurrence in insured residential properties. In contrast, occurrence patterns in public and other non-residential buildings remain less well documented, despite the importance of these buildings as environments frequently occupied by children and other vulnerable population groups. To address this knowledge gap, water-damage occurrence was investigated in publicly owned and managed buildings. The analysis was based on a municipal building stock comprising 2 243 public buildings and approximately 18 000 building-year observations. The dataset originated from three Swedish municipalities and covered different study periods

depending on data availability: 2008-2021, 2015-2024, and 2017-2022. Following data screening, harmonization, and quality control, a total of 3 030 water-damage incidents were identified and verified for inclusion in the analysis (Paper VI). The dataset contained information on damage occurrence, causes, affected systems, building type, and, where available, repair costs. Although the dataset is extensive, the number of identified incidents should be regarded as a conservative estimate of the actual occurrence of water damage. Differences in reporting practices, maintenance systems, registration routines, and documentation procedures between municipalities may have resulted in some incidents not being recorded or identifiable as water-damage cases. The actual occurrence of water damage in the investigated building stock is therefore likely higher than the number of verified cases included in the analysis. Nevertheless, the verified dataset provides a robust empirical basis for analyzing occurrence patterns, causes, and costs of water damage in Swedish public buildings.

The investigated building stock consisted of 808 buildings in Municipality 1, 211 and in Municipality 2, and 1 224 buildings in Municipality 3, as presented in Paper VI. Together, the studied municipalities represented approximately 18% of the municipal public building stock registered in Sweden and were of the 10 largest municipalities in Sweden. The results show, as seen in Table 7, that water damage is a recurring problem across all public building categories investigated. In total, the datasets analysed corresponded to approximately 340 reported water-damage incidents annually within the studied building portfolios. On average, the annual number of reported water-damage cases corresponded to approximately 9 – 16% of the investigated building stock. Across the three municipalities, this equated to approximately one reported water-damage case annually for every 6 – 11 buildings. However, the reported occurrence should be interpreted as the ratio between reported damage cases and the number of buildings rather than the proportion of unique buildings affected, since multiple reported cases may occur within the same building.

Table 7. Distribution of building categories, total building stock, and average annual number of reported water-damage cases for the investigated municipal organizations (MU1-MU3). Percentages shown in parentheses represent the proportion of annual water-damage cases relative to the total number of buildings within each category during the respective study periods. **Note:** Costs are reported in current prices for the respective study period (2022 – 2025) and have not been adjusted for inflation.

	Building stock, number of buildings			**Average number of reported damage cases per year (ratio between average number of cases per year and number of total buildings in the category)**			
Building category	**MU1**	**MU2**	**MU3**	**MU1** 2017-2022	**MU2** 2008-2021	**MU3** 2015-2024	**Total**
Schools	175	148	500	47 (27%)	8 (5%)	95 (19%)	150 (18%)
Office	24	16	19	11 (46%)	3 (19%)	2 (11%)	16 (27%)
Nursing and care homes	129	6	80	47 (37%)	4 (67%)	39 (49%)	90 (42%)
Residential	400	-	440	5 (1%)	-	3 (1%)	8 (1%)
Leisure	48	20	185*	5 (10%)	1 (5%)	59 (32%)	65 (26%)
Culture	32	21		7 (20%)	4 (19%)		
Sum	**808**	**211**	**1 224**	**122 (15%)**	**20 (9%)**	**198 (16%)**	**340 (15%)**

*The building categories in municipality 3´s reporting system is combined.

Compared with statistics for insured Swedish single-family buildings from Swedish insurance companies, Svensk Försäkring [26], water damage occurrence in public buildings was higher. While these statistics indicate an annual occurrence of approximately 2.9% for the insured Swedish single-family building stock, the corresponding occurrence in the investigated municipal building portfolios was approximately 15% when using a building as the functional unit. It should be noted that this value was calculated as the total number of recorded water-damage events per year in building stock divided by the total number of buildings in the studied building category as an annual average over the studied year as presented in equation below.

$$\text{Ratio presented in \% in Table 7} = \frac{\text{Average number of damage cases per year in the building stock}}{\text{Number of total buildings in the studied building category}}$$

The reported 15% represents the annual frequency of water-damage events relative to the building stock rather than the proportion of unique buildings experiencing at least one water-damage event during a given year. Due to limitations in the available records, individual damage cases could not be consistently linked to unique buildings, and multiple damage events occurring in the same building were therefore treated as separate events in the analysis. Thus, the result should be interpreted as approximately 15 recorded water-damage events per 100 buildings and year. This corresponds to a two to four times higher occurrence compared to the

occurrence reported for the insurance-based single-family housing statistics. The results therefore indicate that water damage is a frequent event within the investigated public building stock. Furthermore, the compared building stocks differ in their characteristics, use, and occupancy patterns.

Municipal buildings, such as schools, offices, healthcare facilities, and cultural buildings, may accommodate substantially larger numbers of occupants than single-family dwellings, resulting in varying person loads between building types. The reported occurrence rates should be interpreted in relation to the functional unit used in the analysis, as a single public building may serve a considerably larger user population than a residential building. The results further revealed considerable variation between building categories. Nursing and care facilities exhibited the highest water-damage occurrence rates, with annual levels ranging from approximately 37% to 67% of the building stock across the investigated municipalities. Schools represented the second most affected building category in terms of the total number of reported cases, with annual occurrence rates ranging from 5% to 27% and an overall average of approximately 18%. Office buildings also exhibited relatively high occurrence rates, varying between 11% and 46%, although the number of office buildings included in the study was comparatively limited. In contrast, municipally owned residential buildings showed the lowest occurrence rates, with approximately 1% of buildings reporting water damage annually. Leisure and cultural buildings generally exhibited lower occurrence numbers than schools and nursing and care facilities; however, water damage remained a recurring issue across all investigated building categories.

3.2.3 Water-damage occurrence using floor area as the functional unit

The occurrence rates presented above were based on the number of buildings as the functional unit. However, public buildings vary substantially in size, and a comparison based solely on building count may therefore provide a limited perspective on the relative occurrence of water damage. To account for differences in building size, water-damage occurrence was also evaluated using gross floor area (m^2) as the functional unit. For Municipality 1, the investigated building stock comprised approximately 1.87 million m² of gross floor area and reported an average of 122 water-damage incidents annually during the study period. This corresponds to approximately 6.5 reported water-damage cases per 100 000 m² and year, or approximately 65 cases per million m² and year. As shown in Table 8, nursing and care homes exhibited the highest occurrence rate when normalized by floor area, with 21.4 cases per 100 000 m² and year. Leisure buildings showed the lowest occurrence rate, with 2.9 cases per 100 000 m² and year, while schools, offices, and cultural buildings exhibited similar levels ranging between 4.4 and 5.0 cases per 100 000 m² and year. The "Residential" category refers to municipally owned and managed residential properties rather than private dwellings or single-family houses. Therefore, the damage rates reported for this category should not be interpreted as representative of the general housing stock and are not directly comparable to detached houses.

Table 8. Water-damage occurrence per 100 000 m² of gross floor area and year for Municipality 1. The presented values correspond to the mean annual occurrence calculated from water-damage records collected between 2017 and 2022.

Building category	Gross floor area (m²)	Average annual damage cases	Cases per 100 000 m² and year	Floor area per case and year (m²)
Schools	1 079 054	47	4.4	22 959
Office	219 150	11	5.0	19 923
Nursing and care homes	219 527	47	21.4	4 671
Residential	30 392	5	16.5	6 078
Leisure	171 797	5	2.9	34 359
Culture	153 923	7	4.5	21 989
Total	**1 873 844**	**122**	**6.5**	**15 359**

To enable comparison with Swedish residential buildings, the occurrence rate was estimated using the mean annual number of water-damage claims in single-family houses reported to Svensk Försäkring [26] during the years 2015-2025 (on average 60 516 cases per year) and the national stock of approximately 2.1 million single-family houses reported by Statistics Sweden (SCB) [67]. This corresponds to an estimated annual occurrence rate of approximately 2.9% of the residential building stock experiencing at least one reported water-damage incident per year. However, this estimate is subject to several limitations. First, the claim statistics and building-stock data originate from different sources and may not cover identical populations. Secondly, the insurance statistics only include reported and insured claims from participating insurers, excluding uninsured buildings, unreported incidents, damages not exceeding insurance deductibles, and claims outside the Svensk Försäkring reporting system.

The reported occurrence rate should therefore be regarded as a lower-bound estimate of the actual annual incidence of water damage in Swedish single-family houses. A floor area of 122 m² was assumed, corresponding to the average size of a dwelling in one- or two-story dwellings buildings in Sweden, according to Statistics Sweden (SCB) [76, 77]. Using this average floor area, a stock of 100 000 m² corresponds to approximately 800 single-family houses. Based on an annual occurrence rate of 2.9% of the residential building stock, this corresponds to approximately 24 water-damage cases per 100 000 m² of gross floor area and year. When buildings are used as the functional unit, the investigated municipal building stock exhibits a higher occurrence rate than Swedish single-family houses. However, when gross floor area is used as the functional unit, the occurrence in Municipality 1 corresponds to approximately 6.5 cases per 100 000 m² and year, compared with approximately 24 cases per 100 000 m² and year for Swedish single-family houses. In other words, the area-normalized occurrence in the investigated municipal building stock is approximately 3.7 times lower than the corresponding value for Swedish single-family houses. This difference is likely explained by the substantially larger floor areas represented by individual public buildings. Although public buildings may experience water-damage incidents more frequently on a per-building basis, each building also represents a considerably larger floor area than a typical single-family house. The comparison should be interpreted with caution, as the municipal data represent registered water-damage

incidents, whereas the national residential statistics are based on insurance claims and may therefore be influenced by differences in reporting practices and claims.

3.3 Consequences of Water Damage

The results presented in the previous sections demonstrate that water damage is a frequent occurrence in buildings and that its development is influenced by a combination of technical, behavioural and organizational factors. However, the significance of water damage is determined not only by how often it occurs, but also by the consequences that follow once a damage event has developed. Water damage often initiates a sequence of activities including emergency response, moisture investigations, drying operations, material replacement and restoration work. These activities require substantial resources and may affect both building operation and long-term sustainability performance. The findings from this research indicate that water damage generates consequences that extend beyond the immediate repair of damaged building components (Paper VII). Economic costs, resource consumption and operational disruptions were identified across the building stock studied. Collectively, these consequences demonstrate that water damage should be viewed as more than a maintenance issue and instead as a challenge with implications for sustainable building management.

Although the health effects related to water damage were not explicitly investigated in this thesis, they were indirectly considered through the analysis of repair and restoration measures undertaken after water-damage events. The primary objective of these interventions is often to remove moisture-damaged materials, prevent microbial growth, and restore acceptable indoor environmental conditions. Potential health-related consequences associated with water damage, such as mold growth and moisture-related indoor environmental problems, were addressed through their influence on repair activities, resource use, and associated economic and environmental consequences. For this reason, the consequences examined in this thesis are primarily presented from economic and environmental perspectives, while acknowledging that improved indoor environmental quality is an important outcome of successful water-damage remediation.

3.3.1 Economic Consequences

The occurrence analyses presented in the previous sections demonstrated that water damage is a recurring challenge across residential and public buildings. However, the significance of water damage extends beyond its frequency of occurrence. Water-damage incidents generate costs through inspections, investigations, drying operations, repairs, renovation activities, and replacement of damaged materials and building components. In addition, building owners and users may incur indirect costs associated with operational disturbances, reduced building functionality, and temporary relocation of activities.

3.3.1.1 Costs of Water Damage

The economic analyses demonstrated that water damage constitutes a substantial financial burden across the Swedish building stock. The calculated costs were based on reported and reimbursed water-damage cases included in Swedish insurance statistics for single-family residential buildings [26]. These data were complemented by analyses of insurance policy terms related to deductibles, depreciation, and age-related reductions. Repair costs for multi-family residential buildings were estimated using data from housing companies, while water-damage

costs in public buildings were assessed through analyses of municipal damage reports. The economic analyses presented in this section are primarily based on findings from Paper III and Paper VI.

For single-family residential buildings, the average repair cost associated with a water-damage event was estimated at approximately 5 400 € per damage. The estimate was derived from reported and reimbursed water-damage claims recorded in Swedish insurance statistics over the most recent ten-year period and reflects average repair costs across variations in damage severity, repair requirements, and insurance compensation levels [26]. The repair cost estimates presented in Table 9 were compiled from multiple sources, including Swedish insurance statistics, industry reports, previous research, and documented repair projects involving water-damaged buildings [22, 43-45]. The estimates were derived from analyses of typical water-damage scenarios reported in Swedish residential buildings and included costs associated with damage investigation, demolition, drying, reconstruction, replacement of damaged materials, labor, transport, project management, taxes, and finishing works. The cost estimates therefore reflect complete repair processes rather than individual repair measures.

The analyzed repair costs were linked to the most common damage locations identified in Swedish insurance statistics, including bathrooms, kitchens, and other residential spaces. The results indicate substantial differences between damage locations. Waterproofing failures in tiled wet rooms generated average repair costs of approximately 8 300 € per damage event, whereas corresponding failures in wet rooms with plastic floor coverings were estimated at approximately 5 300 € per event. Kitchen-related water damage was associated with an average repair cost of approximately 2 700 € per event. The higher costs associated with wet-room failures primarily reflect the need for extensive demolition, drying, and reconstruction measures involving waterproofing systems and structural components [22].

Multi-family residential buildings exhibited higher average repair costs of approximately 9 500 € per damage event. The estimate was derived from documented repair projects, cost calculations, and damage records obtained from housing companies and supplemented by previous studies of water-damage repairs in residential buildings. Unlike single-family residential buildings, repair measures in multi-family buildings frequently involved shared building-service systems, common structures, and the potential for damage propagation to adjacent apartments. Repair interventions were often more extensive and complex, resulting in higher average costs. Table 9 compares the compiled average reimbursed repair-cost by the insurance with figures reported by Boverket [22] and demonstrates considerable variation between damage locations and building types, with the highest costs associated with waterproofing failures in tiled wet rooms and multi-family residential buildings.

Table 9. Estimation of repair costs of water damage in different rooms [22, 26, 78] **Note:** Costs are reported in current prices for the respective study period (2022 – 2025) and have not been adjusted for inflation.

Studied room for repair	Average repair costs**
Average reimbursted repair cost for insured single-family buildings 2015 - 2025	5 400 € (62 400 SEK)
Wet room with tiles – leakage through membrane	8 300 € (93 000 SEK)*
Wet room with a plastic mat - leakage through membrane	5 300 € (60 000 SEK)*
Kitchens – Water leakage from plumbing fixtures and supply pipes	2 700 € (30 500 SEK)*
Multifamily buildings	9 500 € (106 500 SEK)*

*Costs estimated by the Boverket reports [22]

** Values represent average estimates derived from the available datasets and should not be interpreted as representative for individual damage cases.

To further assess the economic significance of different damage mechanisms, the repair-cost estimates were combined with the relative occurrence of water-damage causes reported in Vattenskaderapporten 2020-2022 [43-45]. Figure 15 illustrates the distribution of repair costs across different water-damage causes by combining information on both damage frequency and repair severity. As a result, damage categories associated with high repair costs contribute disproportionately to the total cost burden, whereas frequently occurring damages with relatively low repair costs contribute less to the overall economic impact. The figure thereby provides an indication of the relative economic importance of different damage mechanisms and their contribution to the societal costs of water damage.

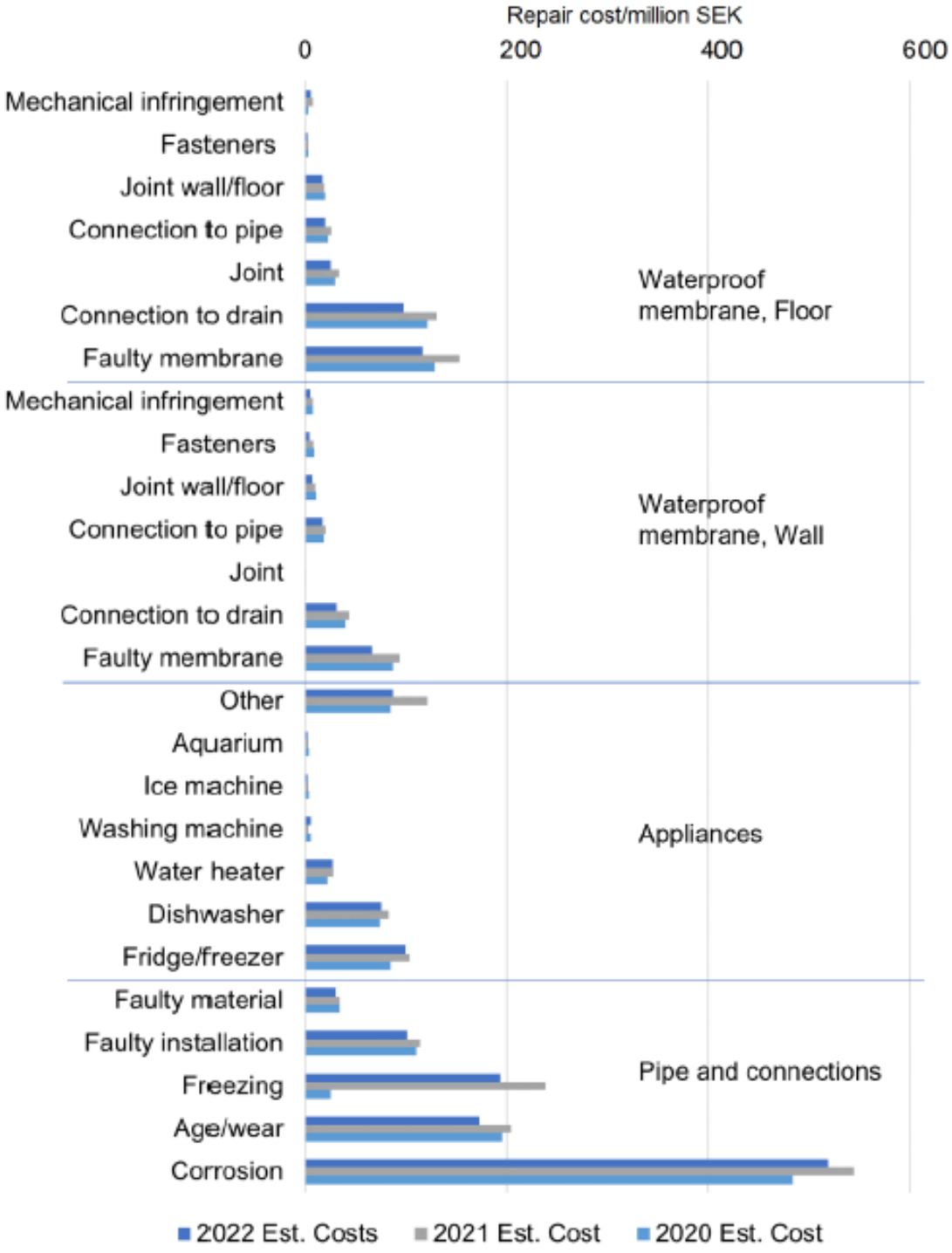


Figure 15.Repair costs, reimbursed by the insurance companies, allocated to different causes of water damage in insured Swedish single-family residential buildings, modelled using reported water-damage cases from *Vattenskaderapporten* 2020-2022 [43-45]. **Note:** Costs are reported in current prices for the respective study period (2022 – 2025) and have not been adjusted for inflation.

Figure 15 illustrates that the economic burden of water damage is unevenly distributed between damage causes. Although several damage categories contribute to the total costs, pipe and connection systems account for a substantial share of the estimated economic impact due to

their high occurrence. This finding is particularly important from a preventive perspective. Even small reductions in the occurrence of pipe- and connection-related damages may generate disproportionately large economic benefits because of their dominant contribution to the overall national cost burden. Waterproofing failures and appliance-related damages also contribute significantly, reflecting both their occurrence and the extensive repair measures that often are required when leakage remains undetected for a long period of time.

Repair, restoration, drying, and reconstruction activities accounted for the largest share of these costs. However, a substantial proportion of the financial burden was also borne directly by property owners through insurance deductibles, depreciation, and age-related reductions in compensation. Insurance deductibles refer to the amount paid by the policyholder before insurance compensation is provided, while depreciation and age-related reductions reflect reductions in reimbursement based on the age, condition, or expected service life of damaged building components.

The estimated owner-borne costs were derived from an analysis of policy conditions from five major Swedish insurance companies and consultations with insurance representatives. The analysis showed that deductible levels varied between insurers and claim sizes. For water-damage claims below approximately 9 653 € (100 000 SEK), an average deductible of 332 € per damage was estimated, whereas claims exceeding this threshold were assigned a deductible of 965 € per damage. Depreciation and age-related compensation reductions were estimated based on insurers' reimbursement policies for building components and installations and ranged from 936 to 1 722 € per damage event (Table 10). A calculation error in the depreciation estimate reported in Paper III was identified and corrected. The revised values are presented in Table 10 and do not affect the results or conclusions of either Paper III or this thesis.

As shown in Table 10, a substantial share of the economic consequences of water damage remains outside the formal insurance reimbursement system. While insurers cover a large proportion of direct repair and restoration costs, property owners frequently bear significant additional expenses through deductibles, depreciation, and age-related reductions in compensation. The actual economic impact of water damage is considerably greater than indicated by insurance reimbursement statistics alone, highlighting the importance of including both reimbursed and non-reimbursed costs when assessing the societal burden of water damage.

Table 10. Estimated deductible cost, depreciation, and age reduction cost per water damage in insured residential buildings, which is a direct cost that the homeowner/insurance claimant needs to cover. **Note**: Costs are reported in current prices for the respective study period (2022 – 2025) and have not been adjusted for inflation..

Deductible cost (€)	**Depreciation and the age reduction (€)**
332 – 965 per damage	936 – 1 722 per damage

The deductible and depreciation cost intervals established from the insurance policy review were extrapolated to the national level using Swedish insurance statistics on reported and reimbursed water-damage claims. The calculations were based on approximately 82 500

insured water-damage events, corresponding to the annual number of water-damage claims included in the insurance statistics. Estimated deductible and depreciation costs per damage event were multiplied by the observed number of claims to calculate aggregate owner-borne costs associated with water damage. The average depreciation cost was calculated using a weighted average of the low and high key factors. The weighting was based on the cost distribution reported by Boverket [22], where water-damage repair costs in multifamily buildings are described as typically ranging from approximately 8 000 € to 13 000 € per damage event [22]. Applying this distribution to the corresponding cost factors yielded an estimated average depreciation cost of approximately 726 € per damage event The resulting annual cost estimates were combined with reimbursement cost data for single-family and multi-family residential buildings to assess the total national economic cost of water damage. These estimates are presented in Table 11.

For multi-family residential buildings, annual costs were estimated using the cost key factors presented in Section 3.2.1. These factors were derived from annual water-damage repair costs reported by participating housing companies (60 000 € and 1.93 million € per year) and normalized by the number of apartments within the corresponding building portfolios (4 100 - 30 000 apartments), resulting in key factors ranging from approximately 24 € to 260 € per apartment and year. The factors were subsequently applied to the national stock of approximately 2.7 million apartments reported by SBC in 2022 [73] to estimate the annual repair-cost burden at the national level. For example, a cost factor of 170 €, derived from Boverket [22], per apartment and year corresponds to an estimated annual repair cost of approximately 455 million € when applied to the Swedish multi-family housing stock of 2.7 million apartments, SBC 2022 [73]. To account for uncertainties associated with water-damage occurrence, repair costs, building age, and insurance conditions, low-, medium-, and high-scenario estimates were developed. The medium scenario was considered the most representative estimate and was therefore adopted as the primary estimate in the national economic assessment. Whereas deductible and depreciation costs could be extrapolated directly using the annual number of insurance claims reported in the insurance statistics, repair costs for multi-family residential buildings required a separate extrapolation procedure based on building-stock data and the cost factors described above. The resulting values are presented in Table 11 and provide an estimate of the annual economic burden associated with water damage in Swedish residential buildings. An important note to Table 11 is that presented costs and estimates are covered by different actors.

- Reimbursement (single-family buildings): The share of water-damage repair costs compensated by the insurance company and paid to the homeowner.
- Deductible cost: The portion of the repair cost paid by the policyholder according to the insurance policy conditions.
- Depreciation (age reduction): The portion of the repair cost not reimbursed by the insurance company due to age-related deductions and therefore borne by the policyholder.
- Reimbursement (multifamily buildings): The share of water-damage repair costs borne by the building owner or property management company.

Table 11. Estimated annual cost of water damage in Swedish residential buildings. Key factors are expressed as Euro per apartment and year and were used to calculate the corresponding national annual costs under low, medium, and high scenarios. **Note:** Costs are reported in current prices for the respective study period (2022 – 2025) and have not been adjusted for inflation. Figures updated and corrected from the appended Paper II with building stock information as described above and not in method section in Paper II.

	Key factor (€) per apartment and year			**Estimated annual cost (€) of water damage in Swedish residential buildings**		
Cost-category	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
Reimburse-ment single-family buildings	-			395 000 000**		
Deductible cost	332	726	965	27 400 000	59 800 000*	79 500 000
Depreciation and the age reduction	936	-	1 722	77 100 000*	-	141 900 000
Reimburse-ment multifamily buildings	24	170 [22]	260	64 200 000	454 800 000*	695 600 000

***** Scenarios used as the estimate and applied in the national economic assessment.
** A cost key factor was not calculated for single-family buildings because insurance reimbursement statistics were only available in total cost in the insurance dataset. Therefore, only the national annual reimbursement cost is reported for this category.

The results indicate that insurance reimbursements constitute the largest share of the annual economic burden associated with water damage. Reimbursement costs were estimated at approximately 395 million € annually for single-family residential buildings and between 64.2 million € and 695.6 million € for multi-family residential buildings, with the medium scenario resulting in an estimated annual cost of 454.8 million €. In addition, property owners were estimated to incur annual deductible costs of 27.4 - 79.5 million € and depreciation together with age-related reductions of 77.1 – 141.9 million €. These findings demonstrate that a substantial proportion of water-damage costs is borne directly by property owners rather than insurers, indicating that insurance reimbursement statistics capture only part of the total economic burden associated with water damage. Overall, the results indicate that water damage constitutes a major recurring cost category within the Swedish residential building sector.

The estimates presented in this study should be interpreted as indicators of the overall magnitude of water-damage costs rather than precise representations of individual damage events. Overall, the results indicate that water damage represents a major recurring societal cost.

Depending on assumptions regarding insurance coverage, deductibles, age-related reductions, and building-stock characteristics, the total annual economic impact was estimated to range between approximately 564 million € and 1.31 billion €, while the most probable estimate was approximately €1 billion annually (i.e., on the order of one billion euros per year). The results demonstrate that the societal cost of water damage is driven not only by the frequency of different damage types but also by the severity and repair requirements associated with individual damage events. The financial consequences of water damage affect a broad range of stakeholders, including households, housing companies, municipalities, insurers, and property owners throughout the Swedish building stock. The presented cost estimates should be interpreted as indicative rather than exact values. Several cost categories, including operational disruptions, temporary relocation, administrative work, moisture investigations, reduced productivity, and indirect societal costs, were not included because consistent national data were unavailable. The estimates are therefore likely to underestimate the total economic burden of water damage.

Water damage was also shown to be a recurring challenge in public buildings, including schools, nursing and care facilities, offices, culture buildings, and leisure facilities. The repair costs associated with these building categories are presented in the following sections. Figure 16 illustrates the distribution of repair costs across the investigated building categories and highlights the considerable spread between individual damage cases. The skewed distribution in Figure 16 indicates that a relatively small number of high-cost events contribute disproportionately to the total economic burden. These findings demonstrate that both damage frequency and damage severity are important determinants of the economic consequences of water damage in municipal buildings.

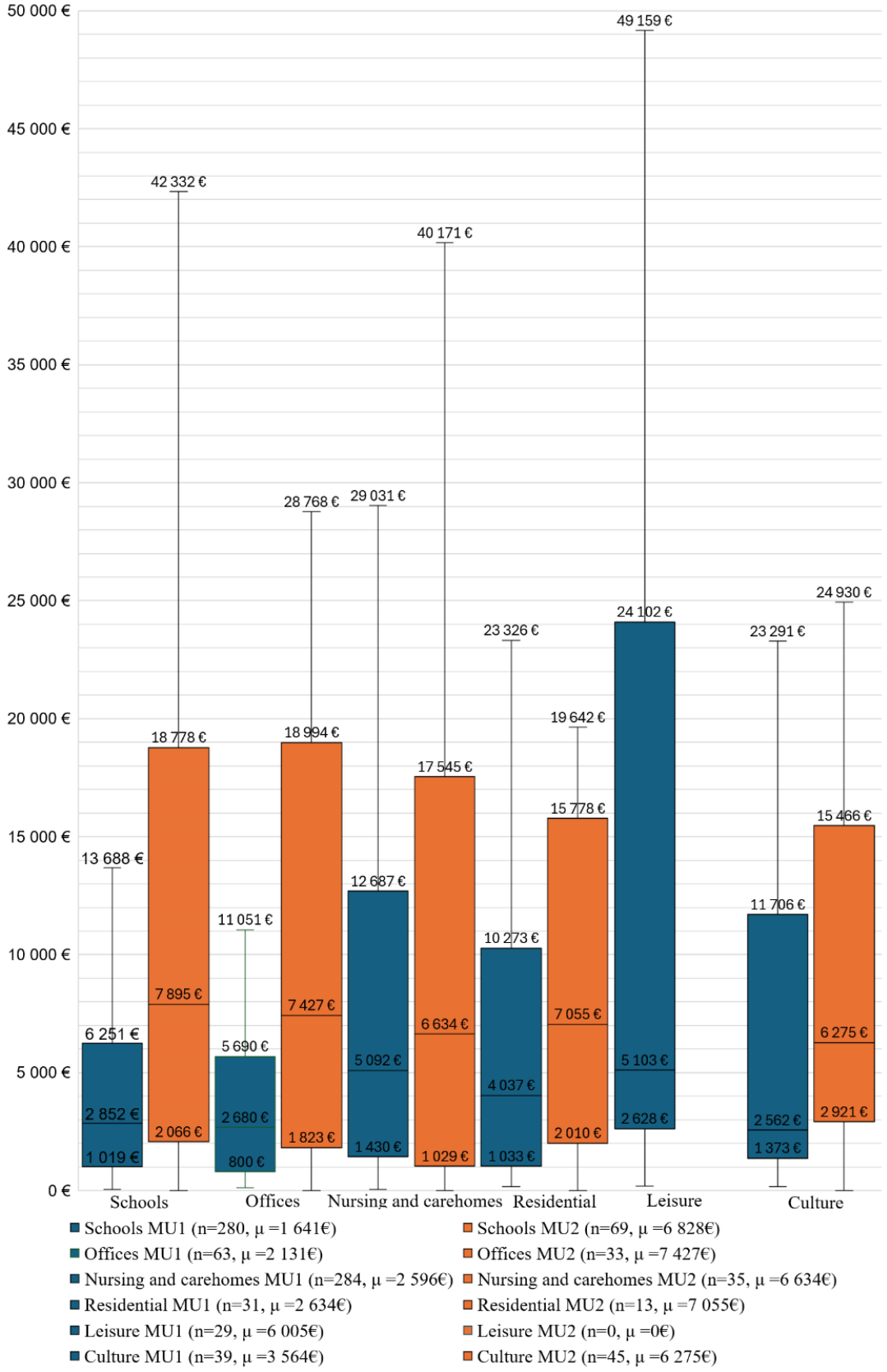


Figure 16. Total distribution of water damage repair costs for MU1 and MU2 are divided into different building categories. The number of cases (n), the geometric mean (μ), median (---), interquartile range and whiskers presented for the different building types. **Note:** Costs are reported in current prices for the respective study period (2022 – 2025) and have not been adjusted for inflation.

The results further revealed a large variation in repair costs within each building category. While many water-damage incidents resulted in relatively limited repair measures and costs, a smaller number of severe events generated substantially higher expenditures due to extensive drying, demolition, reconstruction, and replacement of damaged materials and installations.

The municipal building portfolios showed considerable variation in both number of cases (n) and repair costs between building categories and individual damage events. Average repair costs per damage case ranged from approximately 6 800 € in residential buildings to 10 400 € in culture buildings, with an overall average repair cost of approximately 9 200 € per damage case. The cost data were obtained from the municipalities' internal records of water-damage repairs and included all registered damage cases during the study period. For each building category, average repair costs were calculated by dividing the total recorded repair costs by the total number of reported water-damage events across all years and both municipalities. The reported averages represent aggregated values based on the complete dataset rather than individual incidents. Nursing and care homes, culture buildings, and leisure buildings were associated with the highest average repair costs, while schools and offices exhibited somewhat lower repair costs per event. Average repair costs should be interpreted as indicators of the overall magnitude of the problem rather than as representative values for individual damage events. The average repair cost per year spent by the municipalities on the different building types and the total repair costs are as presented in Table 12, which summarizes the average repair costs per year and the total repair costs for the two studied municipalities (MU1 and MU2).

Table 12. Summary of average repair costs per year and total repair costs for MU1 och MU2. **Note:** Costs are reported in current prices for the respective study period (2022 – 2025) and have not been adjusted for inflation.

	Average repair costs per year (€)	**Average repair costs per case** (€)	**Total repair costs** (€)	**Average repair costs per year** (€)	**Average repair costs per case** (€)	**Total repair costs** (€)	**Average repair cost per case** (€)
Building category	**MU1**	**MU1**	**MU1 (5 years)**	**MU2**	**MU2**	**MU2 (6 years)**	**MU1 and MU2**
Schools	385 000	6 900	1 926 200	229 800	13 100	1 378 700	8 600
Offices	63 000	5 000	314 300	89 700	14 200	538 000	8 400
Nursing and care homes	601 000	10 600	3 005 300	67 600	7 100	405 800	10 000
Residential	38 000	6 200	191 000	29 700	7 700	178 100	6 800
Leisure	84 000	14 400	418 800	-	-	-	9 300
Culture	65 000	8 300	323 500	104 500	12 100	627 200	10 400
Sum	**1 029 900**	**8 500**	**6 179 100**	**521 300**	**10 700**	**3 127 800**	**9 200**

The results indicate that schools dominate the total repair costs primarily because of their large representation within the public building stock combined with relatively high occurrence rates. In contrast, nursing and care homes exhibited the highest occurrence rates (42%) but

contributed a smaller share of the total costs due to the comparatively limited size of the national building stock as shown in Table 13.

Table 13. Occurrence and repair costs for the studied municipal-building dataset and calculated annual damage cases and repair costs (€). **Note:** Costs are reported in current prices for the respective study period (2022 – 2025) and have not been adjusted for inflation.

Building category	**Number of studied buildings**	**Average number of cases per year in the studied municipalities**	**Annual occurrence (MU1–MU3)** (number of damages/number of buildings)	**Average repair cost (MU1–MU2) (€)**	**Total costs (MU1-MU2) (€)**
Schools	823	150	18%	8 600	3 304 900
Nursing and care homes	215	90	42%	10 000	3 411 100
Offices and premises	59	16	27%	8 400	852 300
Leisure buildings	68	18	26%	9 300	418 800
Culture buildings	53	11	20%	10 400	950 700
Total	**2 243**	**340**	**15%**	**9 200**	**9 306 900**

By combining the occurrence rates identified in the public-building analysis with category-specific repair costs, annual repair costs for Swedish public buildings were estimated. If assuming that the occurrence and repair costs observed in the three investigated municipalities are representative of Swedish municipalities in general, the extrapolated national estimates indicate that schools accounted for the largest share of water-damage repair costs, corresponding to approximately 11.2 million € annually and an estimated 1 297 damage cases per year. Leisure buildings represent the second-largest cost category at approximately 4.5 million € annually, followed by offices and premises (3.4 million €), culture buildings (3.2 million €), and nursing and care homes (2.2 million €). The analyses were based on both observed (Table 13) and calculated values (Table 14). While the observed values were obtained directly from the municipal datasets, the calculated values were derived to enable comparisons between building categories, municipalities, and time periods presented in Table 13.

Table 14. Estimated annual number of water-damage incidents and associated repair costs in Swedish municipal building categories, based on occurrence rates derived from the investigated municipalities and extrapolated to the national municipal building stock. **Note:** Costs are reported in current prices for the respective study period (2022 – 2025) and have not been adjusted for inflation.

Building category	Municipal buildings in Sweden [67]	Estimated annual damages	Estimated annual repair cost (€)
Schools	7 206	1 297	11 200 000
Nursing and care homes	520	218	2 200 000
Offices and premises	1 518	410	3 400 000
Leisure buildings	1 862	484	4 500 000
Culture buildings	1 520	304	3 200 000
Total	**12 626**	**2 713**	**24 500 000**

In total, the extrapolation resulted in an estimated 2 713 annual moisture- and water-damage cases in Sweden across the investigated public-building categories, corresponding to annual repair costs of approximately 24.5 million € in Sweden per year as shown in Table 14. Although public buildings exhibited substantially higher occurrence rates than residential buildings, the total annual repair costs were lower because the public-building stock comprises significantly fewer buildings than the residential building stock. Taken together, the results demonstrate that the economic consequences of water damage are influenced by both damage frequency and repair costs. Building categories with moderate repair costs may generate substantial annual expenditures because of high occurrence rates or large building stocks, whereas categories with high repair costs may contribute more modestly to the national cost burden when the number of buildings is limited. These findings highlight the importance of considering both occurrence and repair costs when assessing the economic consequences of water damage. Compared with the residential building sector, public buildings accounted for a substantially smaller share of the total national economic burden, primarily because the municipal building stock is considerably smaller despite exhibiting higher occurrence rates.

3.3.2 Climate Impact of Water Damage

While the economic analyses demonstrated that water damage generates substantial repair costs, the results further show that water damage may also be associated with environmental consequences. Every repair activity requires additional materials, transportation, drying operations, and reconstruction, resulting in greenhouse-gas emissions that would not have occurred if the damage had been prevented. The climate impact of water damage was therefore assessed in this study by comparing the embodied emissions of a reference bathroom with the emissions associated with repair scenarios of increasing damage severity. The climate impact assessment presented in this section is based on the scenario analyses developed in Paper VIII.

3.3.2.1 Climate Impact of the Reference Construction

The embodied climate impact of the reference bathroom was analysed to establish a baseline for evaluating the environmental consequences of water-damage repairs. The analysed bathroom represented a typical sanitary room in a Swedish public building with a floor area of approximately 5 m² and a wall area of approximately 20 m². Four material configurations were assessed, combining ceramic or plastic flooring systems with ceramic tiled or painted wall surfaces. The results showed that the climate impact (A1-A3) of the reference bathroom varied substantially depending on material selection. Total embodied emissions ranged from approximately 215 $kgCO_2e$ for the configuration with plastic flooring and painted walls to approximately 510 $kgCO_2e$ for the configuration with ceramic flooring and ceramic wall systems, as shown in Table 15. Bathrooms with ceramic walls finish consistently exhibited the highest emissions due to the large wall area and the relatively high climate impact of ceramic materials. The difference between the highest and lowest impact scenarios exceeded 58%.

Table 15. Climate impact (A1–A3) of the analyzed bathroom configurations.

Scenarios of different surfces materials (Cases)	GWP (A1-A3) $kgCO_2e/m^2$	Area (m^2)	Total carbon emissions ($kgCO_2e$)
Case i			
Ceramic flooring	20	5	100
Ceramic wall systems	20.5	20	410
Sum			510
Case ii			
Ceramic flooring	20	5	100
Painted wall systems	8	20	160
Sum			260
Case iii			
Plastic flooring	11	5	55
Ceramic wall systems	20.5	20	410
Sum			465
Case iv			
Plastic flooring	11	5	55
Painted wall systems	8	20	160
Sum			215

3.3.2.2 Climate Impact of one Water Damage repair

The climate impact of water damage was evaluated through three repair scenarios representing increasing damage severity and leakage volumes of 50 l, 300 l, and 600 l, corresponding to leakage durations of approximately 5, 30, and 60 minutes, respectively. For the minor damage scenario (50l), repair activities were limited to localized replacement of approximately 1 m² of flooring combined with seven days of drying. The resulting climate impact ranged between 26 and 35 $kgCO_2e$, depending on the material configuration. For the moderate damage scenario (300l), moisture penetration extended beyond the floor surface and affected wall constructions. Repair activities included replacement of the complete floor system and approximately 5 m² of wall construction together with 21 days of drying. The resulting climate impact ranged between 140 and 247 $kgCO_2e$. The severe damage scenario (600 L) resulted in extensive moisture penetration affecting floor assemblies, wall systems, and supporting structures. Repairs involved near-complete reconstruction of the bathroom and 42 days of drying. The resulting climate impact ranged between 454 and 749 kg CO_2e depending on material configuration, as shown in Table 16. However, if replacement of supporting structural elements is not required and damage can be managed through drying and local repairs, the climate impact is reduced to

364-589 kg CO_2e. This highlights the significance of assumptions regarding structural replacement and duration time for the overall results.

Table 16. Estimated climate impact associated with the repair of water-damage cases affecting surface layers, expressed as $kgCO_2e$.

Leakage volume (l)	Range of climate impact ($kgCO_2e$) for surface layer cases i-iv
50	26 – 35
300	140 – 247
600	454 - 749

Comparison of the repair scenarios with the reference bathroom demonstrated a strongly non-linear relationship between leakage duration and climate impact. While minor damage generated only 26–35 $kgCO_2e$, moderate damage increased emissions to 140–247 $kgCO_2e$, and severe damage increased emissions further to 454–749 $kgCO_2e$. In several cases, the climate impact of a single severe water-damage event exceeded the embodied emissions associated with the original construction of the bathroom (215–510 $kgCO_2e$). The climate impacts associated with the repair and renovation of building service installations are not included in current Swedish regulations, which do not require building service installations to be included in building life cycle assessments (LCAs).

3.4 Causes and Contributing Factor

While the occurrence analysis demonstrated that water damage is a recurring challenge in public buildings, the available municipal datasets did not provide sufficient detail to enable a systematic analysis of the underlying causes of individual water-damage events. The findings presented in this section therefore combine evidence from several data sources. Particular emphasis is placed on the causes and contributing factors identified through the interviews conducted in Paper VII, while complementary insights are drawn from Papers I, II, and VI, including statistical analyses and broader sector-level data on water-damage occurrence. Together, these sources provide insight into both building-specific and more general causes of water damage.

Interviews conducted in Paper VII investigated the contributing factors and mechanisms associated with water-damage occurrence. The results showed that the underlying causes are rarely attributable to a single technical failure. Instead, water-damage events were found to arise through interactions between technical deficiencies, building-specific conditions, user behavior, and organizational practices. Across the interviewed municipalities, ageing pipe systems, installation defects, inadequate maintenance routines, and shortcomings in information transfer between operational and maintenance staff were repeatedly identified as contributing factors. In addition, user-related factors such as improper use, blocked drains, and intentional damage were highlighted as important contributors, particularly in school buildings. The results further showed that the development and severity of water damage depend not only on the initial cause of the leakage but also on how quickly the incident is detected and addressed.

Interview participants reported that leakage alarms, automatic shut-off devices, and structured inspection routines can facilitate earlier detection and response to water-damage events and were generally perceived as important measures for limiting damage extent.. However, the implementation of such preventive measures varied considerably between municipalities and building categories.

Four overarching themes emerged from the thematic analysis: Proactive maintenance and systematic control, technical system vulnerabilities, digital monitoring and early detection, and governance, standards and implementation barriers. Collectively, these themes, described in Table 17, indicate that water-damage occurrence in public buildings is shaped by the interaction between technical systems, organizational practices, user behavior, and the broader regulatory and operational context. Rather than being isolated, water-damage incidents were commonly described as the result of multiple interacting factors that influence both the likelihood of occurrence and the extent of the resulting damage.

Table 17. Themes identified in public municipal buildings

Theme	Main causes identified	Main effect
Proactive Maintenance & Systematic Control	Missing inspections, poor communication	Delayed detection
Technical System Vulnerabilities	Aging pipes, installation errors, sabotage	Increased occurrence
Digital Monitoring & Early Detection	Lack of sensors and alarms	Increased damage extent
Governance, Standards & Implementation Barriers	Budget constraints, unsuitable standards	Reduced implementation of preventive measures

3.4.1 Overview of Identified Causes

When considering the overall causes of water damage across both residential and public buildings, leakage from pipe and connection systems emerged as one of the dominant sources of reported damage. In residential buildings, pipe and connection systems were identified as the single most common source of water-damage incidents. The occurrence analyses showed that pipe and connection failures consistently accounted for the largest proportion of reported water-damage cases throughout the study period (Figure 5). Detailed analysis of the damage causes further demonstrated that corrosion and age-related deterioration were the most common underlying causes, representing approximately 57 % of all pipe- and connection-related cases. In addition, the results showed that kitchens were the most frequently affected room and that appliances such as dishwashers and refrigerators contributed substantially to the reported damage occurrence. Together, these findings indicate that ageing water installations and water-using appliances constitute key sources of water-damage occurrence in the Swedish residential building stock. Across both the literature review and empirical investigations, ageing, corrosion, wear, installation deficiencies, and inadequate maintenance were repeatedly identified as key contributors to leakage-related failures. These findings suggest that water

damage is not solely a consequence of component ageing, but rather the result of interacting technical, organizational, and operational factors throughout the building life cycle.

Consistent with these findings, the interviews revealed that water damage in public buildings should be understood as a multifactorial problem. Technical failures were frequently identified as the immediate cause of damage events, but respondents emphasized that organizational conditions, maintenance practices, user behaviour, and the ability to detect leaks before extensive damage occurs strongly influence both occurrence and damage severity. Across the studied municipalities, respondents consistently described water damage as a problem that develops through interactions between technical systems, building characteristics, organizational practices, and building use. Although technical failures often initiate damage events, the frequency, severity, and progression of water damage were found to depend on a broader range of conditions. As one participant in Paper VII noted:

"Preventive work only has effect if someone drives it. When engagement drops, we fall back into reacting to incidents instead of preventing them." (MU3-OM)

The identified causes and contributing factors could be grouped into three broad categories:

- Technical vulnerabilities
- Building-specific vulnerabilities
- Organizational vulnerabilities

Together, these categories encompass the full range of causes and contributing factors identified across the interviews, statistical analyses, and supporting data sources included in this thesis. While individual water-damage events may involve multiple interacting factors, all identified causes could be related to one or more of these categories.

These categories were found to interact rather than operate independently. For example, ageing installations may increase the probability of leakage, but the resulting damage often depends on inspection routines, maintenance priorities, communication between stakeholders and building operation and how the building is used. Taken together, the findings indicate that water damage should not be viewed as the result of isolated technical failures. Rather, water-damage occurrence and severity emerge from the combined influence of technical, organizational, and operational conditions throughout the building life cycle. This reinforces the holistic perspective adopted in this thesis and provides the foundation for the more detailed analyses of technical, building-specific, organizational, and monitoring-related vulnerabilities presented in the following sections.

3.4.2 Technical Vulnerabilities

Technical vulnerabilities were identified as one important contributor to water damage occurrence [2, 4, 19, 24]. The combined findings from the literature review, water-damage statistics, and stakeholder interviews indicate that failures in building service systems, ageing components, installation deficiencies, and waterproofing systems represent recurring sources of leakage-related damage. Respondents described municipal building portfolios containing

installations of varying ages, materials, and technical standards, creating a broad range of technical vulnerabilities throughout the building stock.

Ageing Systems and Components

Ageing pipe systems were repeatedly highlighted as a major source of water damage. Corrosion, wear, ageing joints, and deteriorated materials were frequently described as recurring causes of leakage. Cast-iron drainage systems, galvanized steel pipes, and older water installations were commonly identified as systems requiring increased attention due to their age and previous damage history. One respondent described how failures often occurred systematically rather than as isolated incidents:

"Galvanized pipes fail at the threads. Once they start, you often find three more in the same line." (MU3-OM)

The findings indicate that ageing infrastructure remains an important contributor to water damage occurrence. This observation is consistent with the national water-damage statistics presented in Section 3.2, where corrosion, ageing, and wear constituted some of the most frequently reported causes of damage in pipe and connection systems. The interviews further demonstrated that municipalities manage building stocks constructed over several decades, resulting in substantial variation in system condition and remaining service life.

Installation Deficiencies

Installation deficiencies were identified as another recurring contributor to water damage. Respondents described deficiencies related to inappropriate technical solutions, inaccessible installations, and design choices that complicated inspection, maintenance, and repair activities. Limited accessibility was repeatedly highlighted as a challenge. Technical systems located in confined shafts, service spaces, and concealed constructions often made inspections difficult and increased the risk that leakage remained undetected. One respondent explained:

"Shafts and rooms are tight, everything is stacked. Fixing one leak risks stressing another connection." (MU1-CL)

The interviews further revealed that installation-related vulnerabilities were not limited to older buildings. Inadequate design solutions, construction defects, and maintainability issues were also reported in relatively modern buildings. Respondents emphasized that technical systems are often designed with limited consideration of long-term maintenance and inspection requirements. As one participant stated:

"Standards are written with apartments in mind. Our usage patterns are different, more fittings, heavier wear." (MU3-OM)

These findings suggest that installation-related vulnerabilities originate not only from system age but also from decisions made during design, construction, and renovation processes.

Waterproofing Failures

Waterproofing systems constituted another important source of vulnerability. Bathrooms, dressing rooms, wet rooms, and other water-intensive spaces were identified as locations where failures in membranes, floor-drain connections, and waterproofing details could result in extensive damage. A recurring concern among respondents was the presence of hidden defects behind finished surfaces. Leakage originating within waterproofing systems often remained unnoticed until moisture had spread into surrounding building components. Damage was frequently detected only after it had been developed into more extensive repair projects.

Respondents further emphasized that water-intensive building environments require waterproofing solutions adapted to frequent use and continuous moisture exposure. This was particularly evident in healthcare and care facilities, where wet rooms are subjected to intensive daily use. As one participant explained:

"In 24/7 care environments, material specifications such as continuous vinyl flooring, coved skirting, and fittings, combined with localized shutoff functions, form the most feasible and least disruptive preventive package.*" (MU1-NC)
*(a sort of sealing between the membrane and the pipe)

Taken together, the results indicate that technical vulnerabilities are influenced by both the condition of building systems and the way these systems are designed, installed, maintained, and used throughout the building life cycle.

3.4.3 Building-Specific Vulnerabilities

The results indicate that vulnerability patterns differ significantly between building categories. Several participants emphasized that water damage prevention cannot be based solely on technical solutions, as building function strongly influences both occurrence and damage development.

Single-Family Buildings

Single-family buildings represent the building category for which the most comprehensive water-damage statistics are available. The results from the licentiate research showed that water damage in these buildings is dominated by failures in pipe and connection systems, appliances, and waterproofing systems. Corrosion, ageing, wear, freezing, and installation deficiencies were identified as recurring technical causes of damage. Kitchens and wet rooms accounted for a substantial proportion of reported water-damage incidents, reflecting the concentration of water-using installations in these areas. The results further indicate that appliance-related damage has become increasingly important within the single-family housing sector. Refrigerators, freezers, dishwashers, and other water-connected household appliances accounted for a growing proportion of reported incidents. In contrast to many public buildings, behavioral factors and intentional damage were rarely identified as dominant causes of water damage. Instead, the occurrence was primarily associated with ageing systems, component failures, and deficiencies in installations and waterproofing systems.

Multi-Family Residential Buildings

Multi-family residential buildings exhibited a different water-damage profile than single-family dwellings. While reported damage cases demonstrated that water damage occurs regularly within multi-family residential buildings, the availability of data regarding occurrence rates, damage distribution, and associated costs was considerably more limited. In contrast to single-family dwellings, where comprehensive insurance-based statistics are available, information for multi-family residential buildings was primarily obtained from individual housing companies and property owners, resulting in a less complete understanding of damage occurrence and economic consequences. Although detailed occurrence statistics for this building category are limited, the reviewed literature and industry reports indicate that water damage remains a recurring challenge throughout the sector [22, 48, 78]. The identified vulnerabilities were primarily associated with ageing building-service systems, corrosion, deferred maintenance, and failures in shared water-supply and drainage installations [22, 48, 78]. Unlike single-family dwellings, multi-family buildings contain technical systems that serve multiple apartments simultaneously. As a result, failures in distribution pipes, drainage systems, installation shafts, and other shared building-service systems have the potential to affect several dwellings and larger parts of the building. The literature further identifies concealed installations and inaccessible pipe systems within shafts as important challenges, as leakages may remain undetected for extended periods before becoming visible.

The factors associated with water-damage occurrence in multi-family residential buildings, described both in interviews, statistics and literature, were similar to those identified in public buildings and included technical systems, maintenance planning, inspection routines, organizational responsibilities, and preventive management activities. The three investigated housing organizations in Paper III reported annual water-damage costs of approximately 19.3 million €, 0.6 – 1.0 million €, and 1.0 million €, respectively, corresponding to cost factors of 64.4 €, 24 - 40 €, and 260 € per apartment and year. All organizations reported recurring water-damage incidents within their building stocks. However, compared with public buildings, considerably less statistical information was available regarding damage occurrence, distribution, and costs, as data were primarily maintained by individual property owners and housing companies. Water-damage occurrence in multi-family residential buildings was in the interviews associated with ageing infrastructure, shared technical systems, component failures, corrosion, waterproofing deficiencies, and maintenance-related conditions affecting repair and renewal activities. In public buildings, these factors were also present; however, the interviews further identified building function, occupancy characteristics, operational requirements, and user behavior as additional factors influencing water-damage occurrence and development.

Schools

Schools are particularly vulnerable to water damage due to their high user intensity and extensive daily occupancy (Paper VII). Unlike many other building categories, the respondents within this study frequently highlighted intentional damage, misuse, and vandalism as significant contributor to water damage occurrence. One interviewee described vandalism as the dominant cause of water damage in schools, stating:

"Intentional damage is our number one problem in schools, water drain trap pulled out, valves twisted open." (MU1-ES)

Examples of intentional damage described in the interviews included manipulation of sanitary installations, blocked drains, damaged fixtures, and deliberate release of water. The findings suggest that schools differ from many other building categories because technical systems are exposed not only to wear and ageing but also to behavioral and user interaction factors that increase the likelihood of damage.

Nursing and Care Facilities

Nursing and care facilities exhibited a different vulnerability profile. Interview participants described these buildings as highly water-intensive environments containing significant numbers of bathrooms, kitchens, laundry facilities, and healthcare-related installations. In addition to intensive water use, many facilities operate continuously throughout the day and night. This creates conditions where water systems are subjected to sustained loads and where even small technical failures may result in damage if not rapidly detected. As one respondent explained:

"*Watershutoff devices could help, but our facilities operate 24/7. We need solutions that isolate locally, kitchens or machines, without cutting essential supply to the unit."* (MU1-NC).

Respondents also noted that operational considerations can complicate repair activities, as maintenance interventions often must be coordinated with care activities and resident needs.

Other Building Categories

Offices, cultural buildings, sports facilities, and leisure buildings generally exhibited lower number of occurrence than schools and nursing facilities, but respondents nevertheless identified building-specific vulnerabilities. Examples included large water loads in swimming facilities, sports venues, and shower-intensive buildings, as well as intermittent occupancy patterns that can delay leak detection in buildings with limited daily use. Table 18 summarizes some of the influencing factors of the building specific vulnerabilities of the different building categories studied in this thesis.

Table 18. Summary of the principal factors influencing water-damage occurrence in different building categories, based on the findings from the investigated building stocks and interview studies.

Building category	**Influencing factors**
Single-family	Pipes, appliances, waterproofing
Multi-family	Shared systems, ageing infrastructure, maintenance
Schools	Vandalism, misuse, user behaviour and interaction
Nursing and care	Intensive water use, all day operation
Leisure/Sports	High water loads, delayed detection

3.4.4 Organizational Factors

Water damage was in this study found not only to be associated with failures in technical systems. Respondents repeatedly identified organizational conditions as factors influencing the occurrence and development of water-damage incidents. Communication and information transfer between different actors involved in property management were highlighted as recurring challenges. Information regarding previous repairs, recurring defects, and identified risk areas was not always systematically documented or transferred between operational units. Interview participants also questioned whether existing standards and guidelines adequately reflect the operational realities of public buildings. As one respondent stated:

"Public buildings are built according to industry rules made for single-family houses, but our buildings have completely different usage patterns…Each municipality has its own practice. There is not the same statistics as for residential buildings." (MU2-OA).

Decisions regarding replacement and renovation were reported to be influenced by competing operational demands and budgetary constraints. Several respondents described situations where known vulnerabilities remained in operation because planned renovation measures had been postponed. One respondent explained that maintenance decisions were sometimes limited by short-term financial considerations, resulting in partial interventions rather than comprehensive replacement measures:

"Politicians only see money. When we suggest renovating the entire building they say: can you just take this part? But then it will cost more later." (MU2-OA).

Organizational and communication-related factors were also identified as contributors to water-damage occurrence and development. Respondents reported that maintenance information was not always effectively transferred between departments, resulting in recurring failures and repeated reporting of the same issues. As described by one participant:

"We don't always get the maintenance notes back to operations. The result is that the same valve is reported again and again." (MU1-NC)

Access to affected premises was further identified in the interviews as an important factor influencing damage extent. Several respondents reported that delays in gaining access could allow leakages to continue for extended periods before mitigation measures could be implemented. One respondent noted that

"Access delays matter, by the time we enter, the flat may already be flooded." (MU1-NC)

Similar challenges were reported in nursing and care facilities, where water-damage incidents were often first detected by care personnel rather than residents. According to one participant,

"In many cases the incident is first noticed by the care staff, not the resident. If access is delayed, the water damage is already extensive when we arrive." (MU1-NC).

The interviews also identified organizational responsibilities and alarm-management procedures as factors affecting response effectiveness. In some cases, uncertainty regarding responsibilities for water-leak alarms delayed intervention measures. As described by one respondent:

"Alarms go to the burglar system in some sites; when that fails, nobody knows who should respond to a water alert." (MU3-OM).

The findings indicate that organizational vulnerabilities influence water-damage occurrence through deficiencies in communication, knowledge management, maintenance coordination, and the ability to translate technical information into preventive actions. Maintenance planning was identified as a particularly important factor, as respondents described how known technical weaknesses often remain unresolved for extended periods. This was attributed not only to long planning horizons and competing priorities, but also to financial constraints that limit the implementation of preventive measures. Available resources are frequently redirected towards responding to acute failures, repairs, and restoration activities, reducing the capacity to invest in proactive maintenance and system renewal. As a result, ageing installations, deteriorated components, and other known vulnerabilities may remain in operation long after they have been identified, increasing the risk of future water-damage events and reinforcing a reactive rather than preventive maintenance approach.

3.4.5 Synthesis of Identified Causes

Taken together, the results show that water damage rarely occurs because of a single failure. Instead, it is often the result of a combination of technical, building-related, and organizational factors. While leakage events may be caused by ageing systems, installation defects, or failures in waterproofing systems, their occurrence and consequences are also affected by building function, user behaviour, maintenance practices, communication, and organizational decision-making. Vulnerabilities can therefore be introduced throughout the building process, from planning and design to construction, operation, maintenance, and renovation. The decommissioning phase was not included in this research.

The analysis further shows that reducing water damage requires actions from several stakeholders. Clients, designers, contractors, manufacturers, property owners, facility managers, and occupants all influence the risk of water damage and therefore have different roles in its prevention. In addition to technical measures, the results highlight the importance of organizational aspects, such as communication, responsibilities, routines, competence, and decision-making. Based on the identified causes of water damage, a set of corresponding needs and preventive solutions was developed. These causes, needs, and solutions have subsequently been linked to the actors with direct influence over their implementation and structured according to the different phases of the building process. This makes it possible to identify where risks arise, which stakeholders are involved, and which measures can be implemented at each stage to reduce the occurrence and consequences of water damage. Figure 17a-b illustrates the relationships between causes, needs, stakeholders, and preventive measures across the building process. Decommissioning was not considered within the scope of this study and was therefore excluded from the framework.

1. DESIGN PHASE

Identified causes	Identified needs	Examples of possible solutions
Buildings not designed for actual use	Robustness and damage limitation in case of misuse	Moisture-resistant materials, protected installations, vandal-resistant design
Buildings with continuous operation where water supply cannot be shut off	Robustness and damage limitation in case of misuse	Moisture-resistant materials, protected installations, vandal-resistant design
Materials unsuitable for the building's environment or use	Limited water spread	Zone-specific shut-off, time-controlled water supply
Tight or complex installation spaces	Reduced vulnerability and improved accessibility	Simplified installation, clear and accessible shafts
Inaccessible installation shafts	Reduced vulnerability and improved accessibility	Simplified installation, clear and accessible shafts

2. CONSTRUCTION PHASE

Identified causes	Identified needs	Examples of possible solutions
Installation errors and poor workmanship	Reduced risk of early leaks	Quality assurance of installations, inspection of connections
Unsuitable material choices for the operation	Long-term moisture resistance	Robust, moisture-resistant materials adapted to use

3. ORGANIZATIONAL PART (GOVERNANCE AND MANAGEMENT)

Identified causes	Identified needs	Examples of possible solutions
Lack of structured inspection routines Irregular or no inspection of pipes Few or no preventive inspections	Predictable and recurring supervision	Scheduled inspections, checklists (based on water damage statistics), adapted construction industry regulations
Moisture issues (rain, humidity) confused with technical water leaks Maintenance notes are not fed back to the operations organization Lack of a shared reporting system	Feedback and learning	Shared reporting systems, feedback of maintenance data, adapted construction industry regulations
Communication gaps between property managers, technicians, and management Technical staff lack access to premises No designated responsibility for reducing water-related risks Different ownership and management structures Unclear responsibility for alarms and actions Delayed response to leaks	Clear allocation of responsibilities	Dedicated roles for supervision, clear alarm chains, adapted construction industry regulations
Preventive work lacks funding Budgets are consumed by emergency repairs	Ability for long-term planning	Use of water damage statistics for prioritization, Allocation of resources to preventive maintenance and responsibility from policymakers, adapted construction industry regulations

4. OPERATIONAL PHASE

Identified causes	Identified needs	Examples of possible solutions
Water traps physically removed Valves intentionally turned to open position Fixtures intentionally damaged Drains deliberately blocked with objects Manipulation of pipe and drainage components Incorrect objects flushed in toilets	Rapid limitation of damage in case of sudden leaks	Local shut-offs, fixed water traps Tamper-proof access panels (tool-required opening), recessed floor drains with lockable grates Sensor- and time-controlled mixers and water activation Leak alarms, clear alarm handling procedures Time-controlled water supply linked to lighting or alarms, adapted construction industry regulations
Taps left open by users Very long showers Users do not report minor leaks	Automatic limitation of water flow	Sensor- and time-controlled mixers Leak alarms and clear response routines, adapted construction industry regulations
Aging pipe materials Corrosion and wear	Control of installation systems and component lifespan	Camera inspections, planned relining, adapted construction industry regulations
Poor workmanship (insufficient tightening, faulty connections) Inaccessible pipe routing Systems sensitive to vibrations or mechanical impact Repeated failures in buildings with outdated piping systems Faulty equipment (dishwashers and washing machines)	Increased accessibility and controllability of pipe installations	Early detection and rapid action Camera inspections and planned relining Planning based on failure statistics Allocation of resources to preventive maintenance and responsibility from policymakers, adapted construction industry regulations

Figure 17. Identified causes, needs, and potential solutions across different stages of the building process, including organizational aspects.

3.5 Preventive Strategies

Reducing the occurrence and consequences of water damage requires the implementation of preventive measures throughout the building life cycle. The preventive strategies presented in this section synthesize findings from Papers I, III, IV, V, VII and VIII. While the causes and consequences of water damage have been examined in the preceding chapters, effective risk reduction ultimately depends on how this knowledge is translated into practical actions and management strategies. This section is therefore intentionally practice-oriented and is aimed at supporting stakeholders in the building and property sector, including property owners, municipalities, housing companies, facility managers, consultants, contractors, and policymakers. The ambition is to translate the research findings into actionable measures that can be implemented in practice to reduce both the occurrence and consequences of water damage. As a result, some overlap with previous chapters may occur; however, such repetition is intended to emphasize the practical relevance and importance of preventive actions identified throughout the thesis. This section therefore focuses on measures aimed at reducing both the probability of leakage occurrence and the extent of resulting damage. The section provides a structured overview of preventive strategies relevant to property owners, housing companies, municipalities, facility managers, consultants, and contractors. Several measures have been identified across multiple studies included in this thesis, reflecting their recurring importance for water-damage prevention. Figure 17 summarizes the preventive strategies identified in the research and illustrates how technical, organizational, and operational measures can contribute to reducing water-damage occurrence and consequences.

Across the investigated building categories, the identified preventive approaches included systematic inspections, condition assessments, planned replacement of ageing installations, leakage-detection systems, automatic shut-off devices, moisture sensors, and other monitoring technologies. Organizational measures, including improved maintenance planning, clearer communication procedures, defined responsibilities, and systematic knowledge management, were also highlighted. The findings further showed that the effectiveness of preventive measures depends on their adaptation to the technical and operational characteristics of individual building categories. Buildings with structured maintenance routines, regular inspections, and established follow-up procedures were reported to experience fewer recurring failures and improved opportunities for early intervention.

The results indicate that no single measure can eliminate water-damage risk. Instead, effective prevention requires a combination of technical solutions, maintenance activities, and organizational practices that support early detection, timely response, and long-term management of ageing building systems. The following sections describe the identified preventive measures and their contribution to reducing leakage occurrence, limiting damage propagation, and strengthening water-damage management.

3.5.1 Preventive Maintenance

A recurring finding across the studies was the importance of systematic maintenance in reducing water-damage risks. Interview participants consistently identified ageing systems, deteriorating components, and deferred maintenance as contributing factors behind many water-damage incidents. Preventive maintenance was perceived as one of the most important approaches for reducing future damage occurrence. Planned inspections and condition assessments were highlighted as particularly valuable for identifying deterioration before leakage occurs. Several municipalities described the use of systematic inspections to identify emerging risks and provide decision support for long-term maintenance planning and investment decisions. The findings are consistent with the licentiate research, which identified insufficient maintenance and delayed replacement of ageing systems as recurring contributors to water-damage occurrence.

Particular attention was directed in the results based on the interviews towards older pipe systems, drainage systems, and technical installations that have reached or exceeded their expected service life. Rather than relying solely on component age, respondents emphasized condition-based maintenance supported by inspections, documentation, and follow-up activities. Buildings with established routines for condition assessments and maintenance planning were generally perceived to have better opportunities to identify vulnerabilities before extensive damage occurred.

3.5.2 Technical Prevention Measures

Technical solutions constituted one of the most frequently discussed categories of preventive measures in the interviews. Respondents described a variety of technologies currently implemented or under consideration to reduce both the occurrence and extent of water damage. Leakage alarms and moisture sensors were identified as particularly important tools for improving the detection of hidden leaks. These systems can provide early warning of abnormal moisture conditions before significant damage develops, thereby reducing the time between leakage occurrence and intervention. Automatic shut-off systems were also highlighted as an effective measure for limiting water volumes during leakage events. Several respondents described successful implementations in schools and other public buildings where shut-off functions were connected to operational systems such as occupancy schedules, alarms, or lighting systems.

"Where we have leakage alarms and automatic shut-off, the damage is limited to a wet mat rather than a soaked floor." (MU3-OM)

By limiting the duration of uncontrolled water flow, these solutions were perceived as reducing the risk of extensive damage development. The interviews further identified monitoring technologies as an increasingly important component of modern property management. Digital systems capable of monitoring water consumption, leakage alarms, and abnormal operating conditions were described as providing improved opportunities for early intervention and damage prevention. Respondents consistently highlighted leakage alarms, moisture sensors,

monitoring systems, and automatic shut-off functions as promising measures for supporting water-damage prevention and management and improving response times.

In addition to monitoring and detection technologies, the interviews highlighted the importance of building and installation design in reducing water-damage risks. Several respondents emphasized that preventive measures should be incorporated during the design and renovation phases through the selection of robust and moisture-tolerant materials, accessible installation layouts, and technical solutions adapted to the intended building use. Examples included continuous waterproof flooring systems, durable fixtures, visible drainage solutions, tamper-resistant components, and localized shut-off functions in high-risk areas. The respondents also highlighted the importance of designing installation shafts and service spaces to facilitate inspection, maintenance, and rapid leak detection. In particular, the division of water systems into separate zones was identified as a preventive strategy, enabling affected sections to be isolated and the water supply to be shut off at an early stage without disrupting the operation of the entire building.

Building-specific adaptations were considered particularly important in schools, care facilities, and leisure buildings, where operational conditions and user behavior create different risk profiles. The interviews further indicated a need for technical systems and support services capable of automatically or remotely managing water shut-off functions while maintaining critical building operations. Such solutions were considered especially relevant in facilities where continuous operation, vulnerable occupants, or delayed access may complicate incident response. Consequently, the findings indicate that effective prevention depends not only on detecting leaks when they occur, but also on reducing underlying vulnerabilities through appropriate design, material selection, installation practices, system zoning, and the implementation of technologies that support rapid and controlled water isolation throughout the building life cycle.

3.5.3 Building-Specific Prevention

An important finding in this thesis was that prevention strategies should be adapted to the function and operational characteristics of different building categories. In schools, respondents frequently emphasized measures aimed at reducing vandalism and intentional damage. Robust fixtures, tamper-resistant installations, and automatic shut-off systems were identified as particularly relevant in environments where user interaction contributes significantly to water-damage occurrence. In nursing and care facilities, prevention efforts were focused on limiting the consequences of leakage while maintaining continuous operation. Local shut-off devices, moisture-resistant material selections, and monitoring systems were highlighted as suitable approaches for reducing disruption in buildings that operate around the clock. In sports facilities, leisure buildings, and other water-intensive environments, respondents emphasized the importance of waterproofing systems, drainage solutions, and regular inspections of highly exposed areas. These buildings require prevention measures capable of managing large water volumes and intensive daily use.

The findings indicate that prevention strategies should be tailored to building-specific risk profiles rather than applied uniformly across the building stock. Effective prevention must therefore consider not only the technical systems within a building, but also its operational conditions, occupancy patterns, and user influence.

3.5.4 Organizational Measures and Knowledge Management

While many preventive measures focused on technical systems, the interviews demonstrated that organizational practices play an equally important role in reducing water damage risks. Several respondents emphasized the importance of communication between property managers, operational staff, maintenance personnel and external contractors. Effective transfer of information regarding recurring problems, previous incidents and identified risk areas was described as essential for preventing repeated failures. Several respondents noted that recurring damage events often occurred in situations where lessons learned from previous incidents had not been systematically documented or communicated. Therefore, organizational learning was viewed as an important preventive measure in itself. Municipalities that systematically documented incidents and integrated lessons learned into maintenance and investment decisions were perceived to have greater opportunities to reduce future damage occurrence. In contrast, recurring problems were often associated with situations where information was lost between projects, departments or personnel changes.

Training and awareness among operational staff were similarly identified as important factors. Because many water damage incidents are first observed by building users, caretakers or operational personnel, the ability to recognize warning signs and initiate appropriate actions represents an important component of preventive work. The results therefore suggest that organizational capacity and knowledge management significantly influence the effectiveness of both technical and maintenance-related prevention measures. Budget constraints and investment priorities were repeatedly identified as factors influencing preventive work. Respondents reported that planned replacement and renovation measures were frequently postponed or reduced in scope due to competing municipal priorities. As a result, ageing installations and known vulnerabilities often remained in operation for extended periods.

3.5.5 Prevention as Risk Reduction Rather Than Risk Elimination

A recurring theme throughout the thesis was that water damage cannot be completely eliminated. Buildings contain water systems, users interact with these systems daily, and technical components deteriorate over time. Prevention should be viewed as a process of risk reduction rather than complete risk removal. Successful prevention combines measures aimed at reducing both leakage occurrence and damage consequences through maintenance, monitoring, building-specific risk management, and organizational learning. This perspective reinforces the holistic approach adopted in this thesis, where occurrence, causes, consequences, and prevention are closely interconnected.

4 Discussion

The following chapter presents a discussion of the presented results in this thesis and the appended papers. The major findings will be stated, explained, and discussed regarding the importance of them to the field and industry. The findings will be related to previous research and data in order to discuss the relevance of the findings and to further consider alternative explanations of the results presented in this thesis. Suggestions for further research contributions are made and gaps found which could benefit the research are presented and discussed throughout the chapter, together with the methods and limitations used throughout the thesis.

4.1.1 Water Damage as a Recurring Challenge in Buildings

The findings of this thesis demonstrate that water damage should be regarded as a recurring and persistent challenge throughout the building life cycle rather than as a series of isolated incidents. However, the reported occurrence rates, costs, and environmental impacts should be interpreted with caution, as many of the presented results are based on averages. Behind these average values lies a considerable variation in both occurrence and consequences. While some water-damage cases involve limited repairs and minor costs, a smaller number of incidents generate extensive reconstruction work, operational disruptions, and substantially higher economic and environmental impacts. Average values provide an overall description of the problem but do not fully capture the variability between individual damage events.

While insurance statistics and Swedish industry data from Vattenskadecentrum indicate that water damage is common in residential buildings, the occurrence analyses conducted in public buildings revealed even higher occurrence rates, particularly in schools and nursing and care facilities. On average, the annual number of recorded water-damage events corresponded to at least one water damage in average in 15% of the studied municipal building stock. However, this value represents recorded damage events rather than the share of unique buildings affected, as individual records could not be linked to specific buildings. In addition, unreported or undocumented incidents are not captured in the dataset, suggesting that the actual occurrence of water-damage events may be higher than indicated by the recorded statistics.

These findings suggest that water damage is influenced not only by the technical condition of building systems but also by factors related to building use, occupancy patterns, and operational requirements. The substantially higher occurrence rates observed in public buildings may partly be explained by their intensive use, larger numbers of occupants, extended operating hours, and more complex building-service systems compared with residential buildings. Since the available data did not contain information allowing individual records to be linked to unique buildings, repeated events in the same building could not be identified. All records were therefore treated as separate water-damage events. While this introduces some uncertainty regarding the proportion of buildings affected, it does not affect the total number of recorded damage events used in the analysis.

Schools and nursing and care facilities contain large numbers of water-using installations and are subject to intensive daily use, increasing both the exposure to leakage risks and the potential for damage development if leaks remain undetected. The interviews further demonstrated that user interaction plays an important role in water-damage occurrence. Respondents highlighted misuse, wear from intensive use, and deliberate damage to sanitary installations, valves, and water drain traps as recurring contributors to water-damage events, especially in school environments. These findings indicate that water-damage occurrence cannot be understood solely as a technical problem but must also be considered in relation to how buildings are used and occupied.

The higher occurrence rates observed in the municipal building stock should, however, be interpreted in relation to differences in reporting practices. The national residential statistics, SCB [67], are primarily based on insurance claims, meaning that smaller incidents and damages below the insurance deductible are often not included. In contrast, the municipal databases include all reported water-related incidents, regardless of severity, since faults and defects are typically reported through internal maintenance systems. As a result, the municipal datasets capture both major and minor water-damage events, whereas the insurance-based statistics mainly reflect damage that generate insurance claims. This suggests that part of the difference between the occurrence levels observed in public buildings and those reported for residential buildings may be explained by differences in reporting thresholds. The residential statistics likely contain a degree of underreporting of minor damage, while the municipal data provides a more complete picture of the actual number of incidents occurring in the building stock. The true occurrence of water damage in residential buildings may be higher than indicated by insurance statistics alone.

The climate assessment further demonstrated that the environmental consequences of water damage should not be overlooked. When the estimated greenhouse-gas emissions associated with a repair event are considered together with the observed occurrence rates, the cumulative impact over the service life of buildings becomes significant. Since approximately one in eight public buildings experienced a water-damage event annually, repair-related emissions represent a recurring contribution to the life-cycle environmental impact of buildings. These emissions should therefore be considered when assessing the long-term environmental performance of buildings and when evaluating design choices, maintenance strategies, and renovation decisions.

The results also raise questions regarding how building-service systems are considered in building design and life-cycle assessments. Current assessments often focus on the expected service life of individual components and installations. However, the findings indicate that water-damage events frequently occur during the operational phase long before the end of the theoretical service life of the building itself. This suggests that the practical performance of building-service systems should be evaluated not only in terms of durability, but also in terms of their probability of failure, associated repair needs, and resulting environmental consequences. From a life-cycle perspective, the occurrence of water damage represents an

important factor that should be considered when selecting and implementing technical systems in both new and existing buildings.

The results therefore support previous research describing water damage as one of the most common building-related defects. However, the findings also contribute new knowledge by demonstrating that occurrence varies considerably between building categories and that public buildings represent an important but previously understudied part of the building stock. The findings further highlight important limitations in existing insurance water-damage statistics. Detailed occurrence data remain largely restricted to insured single-family dwellings, while comprehensive data for multi-family residential buildings and public buildings are scarce. Current insurance statistics may underestimate both the occurrence and broader consequences of water damage across the Swedish building stock. The present research contributes to reducing this knowledge gap by providing empirical evidence from public buildings, a sector that has received comparatively limited research attention.

While future studies may benefit from investigating installation density as a potential explanatory variable, the principal finding remains that water-damage incidents occur at a substantial scale across both residential and public building stocks. Regardless of differences in building function, floor area, or the density of water-using installations, the results demonstrate that water damage remains a recurring phenomenon that affects a considerable number of buildings each year. From a preventive perspective, the objective should be to minimize the occurrence of such incidents as far as reasonably achievable. The continued frequency of reported water-damage events therefore indicates a need for further technical, organizational, and management-related interventions aimed at reducing both the likelihood and consequences of leakage-related failures.

4.1.2 Understanding Water Damage as a Multifactorial Problem

A key finding of this thesis is that water damage cannot be adequately explained through technical failures alone. Although ageing systems, corrosion, installation deficiencies, and waterproofing failures were frequently identified as direct causes of leakage events, the analyses demonstrate that the occurrence and severity of water damage are strongly influenced by organizational and behavioural conditions. An additional finding is the age distribution of reported damage events. A substantial proportion of water-damage cases occurred relatively early in the service life of installations, with approximately 43% of tap-water related damage in residential buildings occurring within the first ten years after installation. This finding challenges the assumption that water damage is primarily an ageing-related phenomenon. Instead, it suggests that design decisions, installation quality, workmanship, commissioning practices, and early operational conditions may play a more important role than previously assumed. Water-damage occurrence should therefore be understood as the result of multiple interacting factors throughout the building life cycle rather than as a consequence of system ageing alone.

The interviews showed that technical vulnerabilities often interact with maintenance practices, budget priorities, communication routines, and user behaviour. Identical technical systems may

exhibit very different levels of risk depending on the organizational context in which they operate. The findings also demonstrate that vulnerability profiles differ considerably between building categories. In schools, vandalism and misuse emerged as important contributors to water-damage occurrence, whereas nursing and care facilities were primarily characterized by intensive water use and continuous operation. These differences indicate that water-damage risks cannot be understood solely through the technical characteristics of buildings. Instead, building function and operational conditions must be considered when analysing why damage occurs. An important implication of these findings is that preventive measures targeting only technical deficiencies are unlikely to eliminate water-damage risks. Effective management requires a broader perspective that includes technical systems, organizational processes, building use, and user behaviour.

The interpretation of water-damage occurrence depends on the selected denominator. In this thesis, occurrence rates were analysed both in relation to the number of buildings and the total floor area. When expressed per building, the investigated public-building portfolios exhibited substantially higher water-damage occurrence rates than those reported for Swedish single-family houses. However, when normalized by floor area, the difference was smaller and, in some cases, lower than for the residential building stock. This apparent discrepancy reflects fundamental differences in building size and function. Public buildings are generally much larger than single-family houses, meaning that a single water-damage event is distributed over a considerably larger floor area when occurrence is expressed per square meter. Occurrence rates expressed per building and per unit floor area should be interpreted as complementary rather than directly comparable indicators. The per-building metric reflects the likelihood of encountering a water-damage event within a building portfolio, whereas the area-based metric reflects the frequency of events relative to the physical size of the building stock. Because the objective of this thesis was to assess water-damage occurrence, management needs, and consequences from a building-owner perspective, occurrence rates per building were primarily used in the analyses and conclusions.

4.1.3 Economic and Environmental Consequences of Water Damage

The results demonstrate that the consequences of water damage are determined primarily by damage severity rather than by leakage occurrence alone. While occurrence establishes how often damage events arise, the economic and environmental burden depends largely on the extent of reconstruction required following a leakage event.

The economic analyses showed that water damage generates substantial costs throughout the Swedish building stock, with an estimated annual societal cost of approximately 1.1 billion €. At the same time, the environmental assessment demonstrated that repair-related greenhouse-gas emissions increase rapidly as damage progresses. Severe damage scenarios, analysed in this study generated climate impacts comparable to, or exceeding, the embodied emissions associated with the original construction of the analysed bathroom. A limitation of the assessment is that impacts related to building service systems were excluded. Water damage frequently affects plumbing components and technical installations, and the repair or replacement of these systems may contribute substantially to the overall environmental burden.

The results are likely to underestimate the full environmental impacts of water damage remediation. Future studies should aim to include building service systems as more detailed LCA data becomes available. This is particularly relevant given ongoing developments in European building regulations, where building service systems are proposed to be included in whole-life carbon assessments, although sufficiently detailed and standardized data are not yet widely available.

The economic results presented in this thesis are based on nominal cost data reported in the original studies and datasets. To preserve transparency and consistency with the source material, no inflation or currency adjustments were applied in the individual figures. Direct comparisons of absolute costs across different years should be interpreted with caution, as changes may partly reflect inflationary developments rather than differences in damage occurrence or severity. Nevertheless, the findings consistently demonstrate that leakage-related water damage imposes substantial economic burdens on building owners and society. Considering recent inflationary trends, the present-day economic impact of water damage is likely higher than indicated by the historical cost figures presented in this thesis.

A particularly important finding is the non-linear relationship between damage development and consequences. Small increases in leakage duration may trigger disproportionate increases in both repair costs and climate impacts when critical damage thresholds are exceeded and extensive reconstruction becomes necessary. Similar patterns were observed in both the cost analyses and the climate-impact assessment. The results further indicate that material replacement, rather than leakage itself, is the dominant driver of both economic and environmental consequences. From a resource-efficiency perspective, water damage can be viewed as a form of premature material replacement. Building components that would otherwise have remained in service are removed and replaced before reaching their intended service life. This creates additional demand for construction materials, transportation, installation activities, and waste handling. Repair costs were largely associated with reconstruction activities, while greenhouse-gas emissions were driven primarily by replacement materials rather than drying operations. Preventing damage escalation appears to be more effective than focusing exclusively on reducing occurrence.

4.1.4 Prevention as the Link Between Causes and Consequences

One of the most important findings of this thesis is that prevention forms the connection between the identified causes of water damage and the resulting consequences. The same factors that contribute to water-damage occurrence also influence damage severity and therefore determine the magnitude of economic and environmental impacts. The analyses indicate that preventive measures should not be viewed solely as methods for reducing occurrence. Knowledge regarding recurring damage patterns, building-specific vulnerabilities, maintenance histories, and previous incidents enables more informed and proactive decision-making concerning inspections, maintenance planning, renovations, and investments.

Measures such as condition-based maintenance, leak-detection systems, automatic shut-off functions, and organizational learning influence both the probability of leakage events and the

extent of damage development after leakage occurs. This distinction is particularly important given the non-linear relationship identified between damage, severity and consequences. Even when leakage cannot be completely prevented, rapid detection and intervention may substantially reduce repair requirements and thereby lower both costs and greenhouse-gas emissions. he findings therefore support a risk-management perspective in which prevention is regarded as a continuous process aimed at limiting both the frequency and severity of damage events. This perspective is also consistent with previous moisture research, which emphasizes that moisture-related risks should be managed throughout the building life cycle rather than addressed only after failures have occurred. By combining assessment, monitoring, maintenance, and preventive interventions, building owners can reduce both the likelihood of moisture-related failures and the severity of their consequences. Preventive activities can therefore be viewed as part of a continuous process of reducing building vulnerability and improving long-term building performance [23]. From this perspective, prevention is not separate from occurrence or consequences but represents the mechanism through which both can be influenced simultaneously.

4.1.5 Towards a Holistic Framework for Water Damage Management

The findings presented in this thesis demonstrate that water damage should not be viewed as an isolated technical problem. Instead, water damage emerges through interactions between technical systems, building characteristics, organizational practices, and human behaviour. An important finding throughout the research was the close relationship between occurrence, causes, consequences, and prevention. The same factors that contribute to water-damage occurrence also influence damage severity and the resulting economic and environmental consequences. Similarly, preventive measures such as condition-based maintenance, leak-detection systems, automatic shut-off devices, organizational learning, and building-specific risk-management strategies were found to reduce both the probability of damage occurrence and the magnitude of resulting impacts. The results therefore support a holistic framework for water-damage management in which occurrence, causes, consequences, and prevention are viewed as interconnected rather than independent phenomena. Within such a framework, technical vulnerabilities, organizational practices, building function, and user behaviour influence the occurrence and development of water damage, while preventive measures act to reduce both damage frequency and damage escalation. The resulting reduction in repair requirements contributes simultaneously to lower economic costs, reduced resource consumption, and decreased greenhouse-gas emissions. The broader benefits may also include improved indoor environmental quality and reduced risk of building-related symptoms among occupants. Although health effects were not investigated directly in this thesis, previous research has demonstrated that moisture-related problems in buildings may negatively affect occupants through both physical and perceived indoor environmental conditions. Swedish studies have shown associations between dampness and increased risks of asthma and allergic symptoms among children [36], while more recent research has demonstrated that perceived indoor environmental problems, such as stuffy air and unpleasant odours, may be associated with reduced well-being and increased symptom reporting among building users [34]. Together, these findings suggest that the benefits of preventing water damage may extend beyond reduced repair costs and environmental impacts to also include improvements in indoor environmental

quality and occupant well-being. The findings indicate that effective water-damage management requires an integrated life-cycle perspective that addresses risk factors before damage occurs, limits damage development when leakage events arise and considers both economic and environmental consequences in decision-making. Such a perspective provides a basis for more resilient, resource-efficient, and sustainable management of buildings throughout their service life.

4.1.6 Methodological Considerations

The results presented in this thesis are based on a combination of complementary research methods, including literature review, statistical analyses of water-damage occurrence, stakeholder interviews, cost analyses, and life-cycle assessment. This mixed-methods approach enabled the investigation of water damage from multiple perspectives, including occurrence, causes, consequences, and prevention. By integrating quantitative and qualitative data, the research provides a broader understanding of water damage than would have been possible using a single methodological approach. The analyses of water-damage occurrence are primarily based on insurance statistics collected and compiled by external organizations and insurance companies rather than by the author. The analyses are subject to the limitations inherent in these datasets. As the statistics only include reported and insured water-damage events, both underreporting and overreporting may occur, and incidents not covered by insurance are not represented. However, insurance claims are generally supported by professional assessments conducted by claims adjusters and damage inspectors, which contributes to the consistency and reliability of the recorded information.

A major strength of the research is the combination of datasets covering different parts of the Swedish building stock. The occurrence analysis of public buildings included 3 030 reported water-damage incidents distributed across 2 243 buildings in three municipalities, corresponding to approximately 18% of the Swedish municipal public-building stock. This represents one of the most comprehensive datasets currently available for analysing water-damage occurrence in Swedish public buildings.

The national extrapolations of repair costs should be interpreted as indicative estimates rather than exact predictions. Nevertheless, the consistency of the findings across multiple datasets and methodological approaches strengthens confidence in the overall conclusions. The use of occurrence data, cost information, stakeholder perspectives, and environmental assessments in combination provides a robust basis for understanding water damage as a recurring technical, organizational, economic, and environmental challenge throughout the building life cycle.

At the same time, some limitations should be acknowledged. The studied municipalities used different property-management systems, reporting practices, and levels of detail in their documentation. Considerable effort was therefore required to harmonize the datasets and apply consistent inclusion criteria. In addition, the available records did not allow individual damage cases to be consistently linked to unique buildings over time. Consequently, repeated water-damage events occurring in the same building could not be identified and were treated as separate events in the analysis. The reported occurrence rates should therefore be interpreted as

frequencies of recorded water-damage events relative to the building stock rather than as the proportion of unique buildings experiencing at least one water-damage event annually. Another limitation is that the analyses rely on reported and documented incidents. Water-damage events that were handled internally, not formally registered, or lacked sufficient documentation could not be included. As a result, the recorded occurrence rates likely represent a conservative estimate of the true water-damage occurrence within the investigated building portfolios.

The research also benefited from combining occurrence data with stakeholder experiences obtained through interviews with property managers, operational staff, and technical specialists. These interviews provided insights into factors that cannot easily be identified through statistical data alone, such as organizational routines, maintenance practices, communication challenges, and specific building vulnerabilities. It should be noted that the interview study focused on stakeholder experiences, perceptions, and practical considerations related to water-damage prevention. The study identifies measures considered valuable and feasible by practitioners but does not quantify the effectiveness or cost-effectiveness of individual preventive measures. The qualitative findings therefore complemented the occurrence analyses and contributed to explaining why water damage occurs and develops differently across building categories. Additional limitations relate to the generalizability of the results. The occurrence analyses were based on data from three municipalities and may therefore not fully represent all Swedish municipalities or other building-owner organizations. Similarly, the climate-impact assessment was based on a reference bathroom and a set of predefined damage scenarios. Although these scenarios were designed to represent typical water-damage events, actual repair requirements and environmental impacts may vary depending on building type, construction system, material selection, and response time.

4.1.7 Implications for Research and Practice

The findings of this thesis have implications for both research and practice. From a practical perspective, the results demonstrate that water damage should be regarded as a recurring operational challenge rather than as a series of isolated technical failures. The occurrence analyses showed that water damage is common in both residential and public buildings, while the investigations of causes revealed that damage events develop through interactions between technical systems, organizational conditions, building characteristics, and user behaviour. Effective water-damage management requires coordinated strategies that address multiple aspects of the problem simultaneously.

For building owners and facility managers, the findings highlight the importance of systematic maintenance, condition-based replacement of ageing systems, leak-detection technologies, and organizational learning. The results further indicate that preventive measures should be adopted to build specific risk profiles. Schools, nursing and care facilities, offices, and leisure buildings exhibited different vulnerability patterns and therefore required different preventive approaches. This suggests that uniform prevention strategies are unlikely to be as effective as approaches tailored to building function and operational conditions. The analyses also demonstrate that prevention provides benefits beyond reducing damage occurrence. Both the economic and environmental assessments showed that limiting damage development can substantially reduce repair costs, material consumption, and greenhouse-gas emissions. The climate-impact analysis revealed that severe damage events may generate emissions comparable to, or exceeding, those associated with the original construction of a bathroom. These findings indicate that investments in early detection, rapid intervention, and risk reduction may contribute simultaneously to economic savings and improved environmental performance.

From a research perspective, the findings highlight the need for broader and more comprehensive datasets on water damage. National occurrence statistics remain largely focused on insured single-family dwellings, while detailed information for multi-family residential buildings and public buildings is limited. Future research would therefore benefit from more systematic national reporting systems capable of capturing occurrence, causes, repair requirements, and consequences across different building categories. Future research could also investigate how digital building-management systems, condition-monitoring technologies, and digital-twin approaches may be used to integrate occurrence data, service-life information, leak-detection technologies, and maintenance planning. Such approaches could support more proactive risk management by enabling building owners and facility managers to identify vulnerable systems before damage occurs.

The results also suggest opportunities for further research into the relationship between damage occurrence, repair costs, and environmental impacts. While this thesis demonstrates that water damage contributes to both economic losses and greenhouse-gas emissions, considerable uncertainty remains regarding the long-term lifecycle implications of repeated damage events. Future studies could therefore expand the analysis to additional building types, construction systems, and climate-impact categories, while also investigating how preventive measures influence lifecycle performance over time. The overall contribution of this thesis is the

integration of occurrence, causes, consequences, and prevention into a common analytical framework. Previous studies have typically examined these aspects separately, whereas the present research demonstrates how they interact throughout the building life cycle.

5 Conclusions

This thesis aimed to improve the understanding of leakage-related water damage in buildings from a sustainability perspective by examining its occurrence, consequences, causes and preventive measures to contribute to reducing water damage. The research was carried out by four research questions addressing where and why water damage occurs, what consequences it causes, and how it can be prevented. The results show that water damage should not be viewed solely as a technical defect, but as a recurring sustainability challenge affecting buildings throughout their service life.

RQ1: What is the occurrence and distribution of leakage-related water damage in buildings across different building types, activities, and building service systems?

The results demonstrate that water damage constitutes a recurring challenge across both residential and public buildings in Sweden. National insurance statistics recorded approximately 89 500 reported water-damage incidents in residential buildings during the year 2022. However, the insurance dataset available for information on water damage mainly covers insured residential properties and therefore does not fully represent the entire Swedish building stock. During the ten-year study period, the insurance statistics included approximately 60 615 reported water-damage cases in single-family dwellings, providing the primary basis for the residential-building analyses. To complement the national statistics, water-damage occurrence was investigated in municipal building portfolios from three of Sweden's largest municipalities. The analyses showed annual water-damage event frequencies ranging from approximately 9% to 16% relative to the examined building stock, corresponding to considerably higher occurrence levels than those observed in insured single-family dwellings. Across the investigated municipalities, the average annual frequency of recorded water-damage events was approximately 15% when using a building as the functional unit. This value was calculated as the total number of recorded water-damage events divided by the total number of buildings in the buildings stock and should therefore be interpreted as approximately 15 recorded water-damage events per 100 buildings and year, rather than the proportion of unique buildings experiencing at least one event. Due to the available data structure, individual damage records could not be consistently linked to unique buildings, and multiple events occurring within the same building may therefore be represented in the reported frequency. Substantial variation was also observed between different building categories.

The highest occurrence rates of water damage were identified in the evaluated nursing and care homes, where approximately 42% of the examined buildings experienced at least one water-damage incident annually, followed by offices and premises (27%), leisure buildings (26%), culture buildings (20%), and schools (18%). These results indicate that water damage is not evenly distributed throughout the public building stock and that certain building categories are particularly exposed. Direct comparisons between residential and public buildings should be interpreted with caution because the datasets originate from different sources and use different population definitions. The residential-building analysis was based primarily on insurance claims, whereas the municipal-building analysis was based on recorded repair and maintenance

cases from building owners. Nevertheless, the results consistently indicate substantially higher occurrence rates of water damage in public buildings than in single-family residential buildings. Pipe and connection systems represented the most common source of reported water damage across the analyzed building stock. At the same time, appliance-related damages have increased in importance within residential buildings, reflecting changes in household installations and water-using equipment. The findings further revealed important limitations in current national water-damage statistics. Large parts of the public-building stock, municipal properties, commercial premises, and many multi-family residential buildings are not systematically represented in the national insurance datasets. Existing insurance statistics are likely to underestimate both the true occurrence and the societal consequences of water damage in Sweden.

RQ2: What are the economic and environmental impacts of leakage-related water damage?

The economic analyses performed in this study demonstrated that water damage generates several types of costs for building owners. Direct repair and restoration costs constituted the largest cost category, while insurance deductibles, depreciation, and age-related reductions in compensation represented a substantial additional financial burden. The results showed that a considerable share of the total economic consequences of water damage is borne directly by property owners and therefore remains outside the formal insurance reimbursement system. For the studied single-family buildings, the average repair cost was approximately 5 400 € (62 400 SEK) per damage case. In municipal buildings, average repair costs varied between building categories, ranging from approximately 6 800 € per damage case in residential buildings to approximately 10 400 € in culture buildings, with an overall average repair cost of approximately 9 200 € per damage case. Nursing and care homes, culture buildings, and leisure buildings were associated with the highest average repair costs, while schools and offices generally exhibited somewhat lower repair costs per event.

The repair-cost distributions revealed substantial variations between individual damage cases. While many water-damage incidents resulted in relatively limited repair measures and costs, a relatively small number of severe events generated considerably higher expenditures due to extensive drying, demolition, reconstruction, and replacement of damaged materials and installations. The results demonstrate that the economic consequences of water damage are influenced not only by damage frequency but also by damage severity, with high-cost events contributing disproportionately to the overall economic burden.

The environmental assessment made in this study showed that water damage also generates considerable greenhouse-gas emissions through repair and reconstruction activities. Including the phases A1-A3 in a life cycle assessment, the calculated climate impacts increased non-linearly with damage severity, ranging from approximately 26 - 35 $kgCO_2e$ for minor repairs to 454 - 749 $kgCO_2e$ for severe damage events. In several cases, the calculated climate impact associated with repairing a severe water-damage event exceeded the embodied emissions of the original bathroom construction. Together, these findings demonstrate that water damage results

in substantial economic losses, premature material replacement, and avoidable resource consumption throughout the building life cycle.

RQ3: What are the primary causes and underlying mechanisms of leakage-related water damage?

The results demonstrate that water damage is a multifactorial problem. Ageing installations, corrosion, installation deficiencies, and failures in waterproofing systems were identified as important technical causes. However, the occurrence and development of water damage was also strongly influenced by organizational and behavioral factors. Maintenance practices, communication between stakeholders, operational conditions, and user interaction affected both the likelihood of leakage and the extent of the resulting damage. Building categories differed in their susceptibility to water damage due to variations in building characteristics, technical systems, usage patterns, organizational practices, and human behavior. Schools were particularly affected by vandalism and misuse, whereas nursing and care facilities were characterized by intensive water use and continuous operation. These findings highlight the need to consider the specific conditions of different building functions when developing preventive measures against water damage.

RQ4: Which technical and organizational measures can prevent leakage-related water damage or reduce its consequences to contribute to a more sustainable and resilient built environment?

No single preventive measure was found to be able to eliminate all water-damage risks. Instead, effective prevention requires a combination of technical, maintenance-related, and organizational measures. Stakeholders identified condition-based maintenance, systematic inspections, replacement of ageing systems, leak-detection technologies, moisture sensors, automatic shut-off systems, and digital monitoring as important measures for the prevention and management of water damage. Organizational factors such as communication, documentation, knowledge transfer, and clear responsibilities were also found to be critical. The findings suggest that preventive measures should be adapted to the operational conditions and risk profiles of different building categories, as the perceived challenges and vulnerabilities varied between building types.

Main Contribution of the Thesis

The main contribution of this thesis is the development and application of a holistic perspective on water damage in buildings. Previous studies have often examined occurrence, causes, consequences, or prevention separately. This thesis shows that these aspects are closely interconnected and should be considered together. Water-damage occurrence is influenced by technical, organizational, and behavioral factors; these same factors also influence the severity of damage and its resulting economic and environmental consequences.

Improving sustainability by reducing water damage requires more than repairing failures when they occur. It requires an integrated life-cycle approach that combines preventive design, robust installations, systematic maintenance, early detection, and effective organizational practices. By reducing both the frequency and severity of water-damage events, such an approach can contribute to lower costs, reduced greenhouse-gas emissions, improved resource efficiency, and a more sustainable and resilient built environment.

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7 Appended Papers

Paper I [redacted]

Check for updates

Review Paper

Indoor and Built Environment

Indoor and Built Environment
2024, Vol. 33(7) 1173–1189
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A quantitative and qualitative literature review of water damage in buildings occurring in building service systems, appliances and wet rooms

Christian Mattsson[1], Birgitta Nordquist[1], Dennis Johansson[1], Hans Bagge[2] and Petter Wallentén[2]

Abstract

Water damage affects both residents and buildings. Issues include moisture, climate impact and repair costs that amount to immense resources. Because of these, immense resources research is important to undertake to reduce and limit the extent and effects of water damage. This study aimed to compile and review the literature on water damage in buildings. Literature distribution, the status, consequences, effects, and strategies and methods for prevention of water damage were assessed by compiling and reviewing literature using quantitative and qualitative methods. Two scientific databases were searched to identify the relevant literature. Key findings of this study are that research conducted on water damage is embedded in the study of building defects and building pathology, and more specific research on water damage is needed depending on different rooms and buildings, the effect of moisture and sustainability. Informed and guided decisions, management and organizational structures have been internationally suggested as a part of the solution to reducing the amount and effect of defects and could have the possibility to reduce the amount and effect of water damage. However, there is a gap in research on water damage consequences, occurrence and costs in Nordic conditions.

Keywords

Water damage, wet rooms, indoor environment, defects, building pathology, building services

Accepted: 3 April 2024

Introduction

Water damage in buildings occurs for many reasons. Some examples are flooding, water infiltration through the building envelope, often rainwater and water vapour diffusion into walls and roofs. This paper is limited to water damage occurring indoors from building services systems such as tap water, sewage or heating systems including leaking pipes, connections or valves, as well as inadequate waterproof membranes, and appliances such as dishwashers, refrigerators or freezers in buildings. In Sweden, insurance companies in 2022 reported approximately 90,000 cases of water damage in approximately 6.7 million household and business property insurance.[1] This water damage was due to leakage or freezing in water pipes and connections that arose within the building envelope in residential buildings.[2,3] The reported cost in 2022 amounted to 4.9 billion SEK (approximately 434 million Euro) in

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insurance reimbursements for water damage in homes, dwellings, vacation homes and companies and property insurance, not including the sentimental value of damaged possessions and the unpleasantness of having to handle repairs and insurances issues.[2] Figure 1 illustrates the number of reported cases of insurance companies in Sweden, industry database,[2] between 2012 and 2022. Figure 2 illustrates the reimbursement amount of these insurance cases. The figures show the difference in both the number of reported cases and the reimbursements allocated for each damage category. Of all 17 insurance categories, two of them regard damage related to water in buildings,

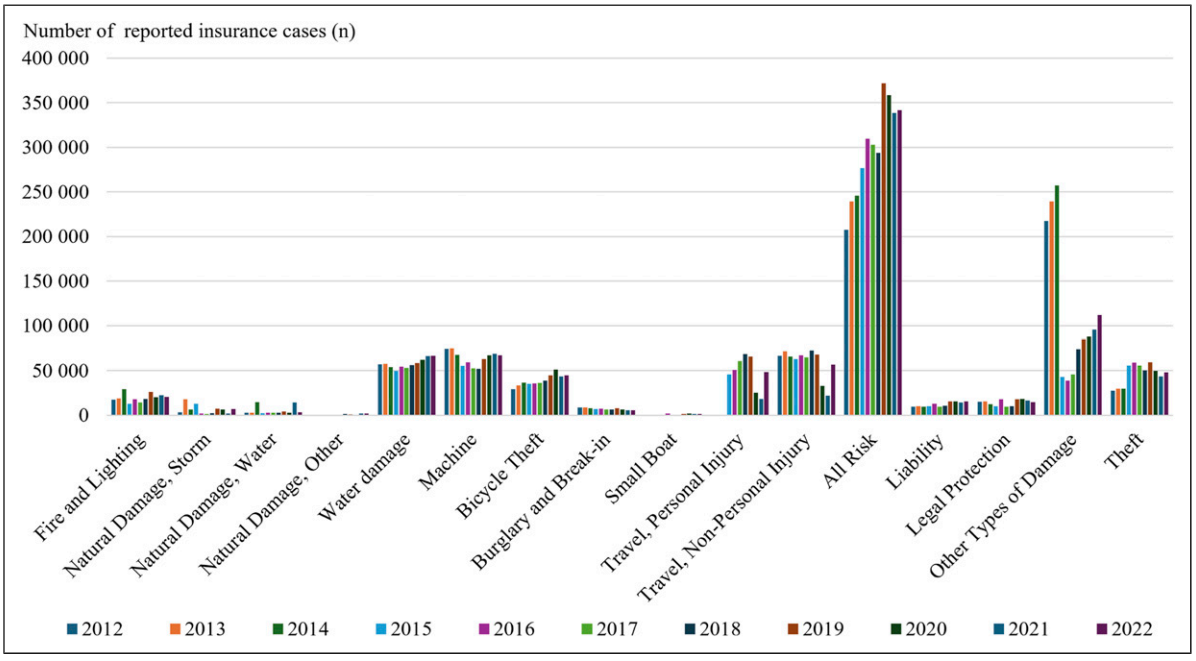


Figure 1. Number of reported insurance cases in Swedish buildings, 2012–2022.[1]

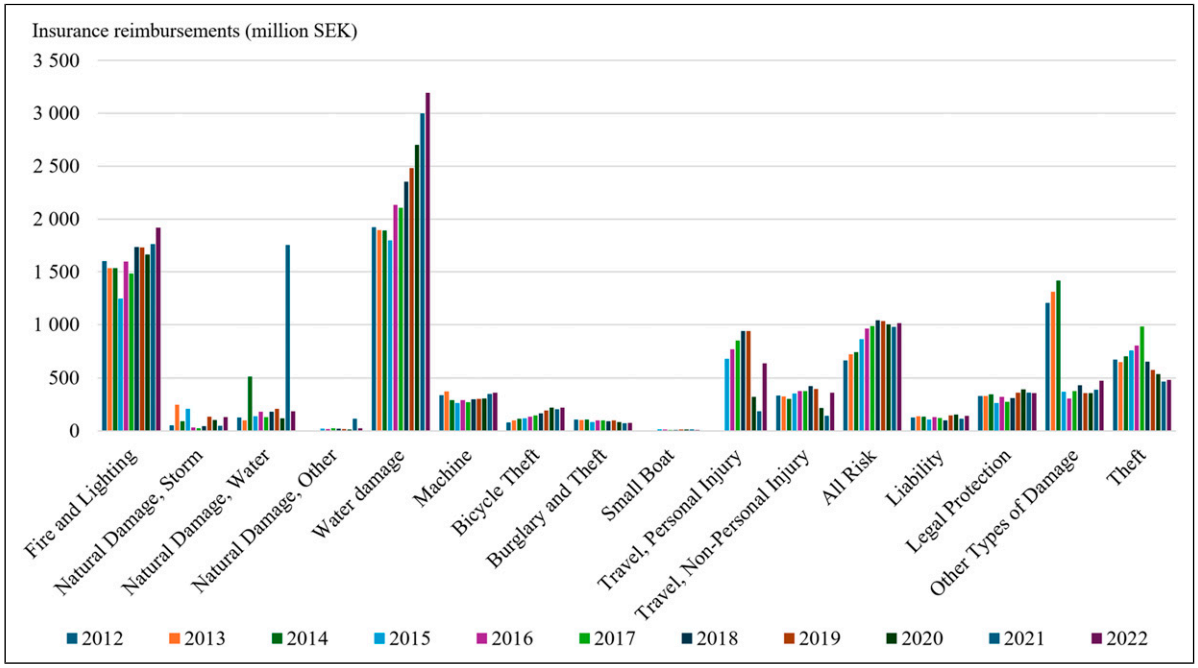


Figure 2. Insurance reimbursement (million SEK) in Swedish buildings, 2012–2022.[1]

'Water Damage' and 'Natural Damage, Water'.[1] The category 'Water damage' is such damage from leakage, moisture or freezing of water pipes or other causes unrelated to natural disasters (such as studied in this paper), and 'Nature Damage, Water' is damage cases caused by water resulting from heavy rainfall, snowmelt or rising lakes and watercourses, flowing from the surface or through the water supply system into buildings.[1] In terms of reimbursements paid by insurance companies, 'Water damage' (as focused upon in this study) represented the largest cost in Sweden in 2022.[1]

Figure 1 illustrates the reported number of insurance cases, where 'All risk' insurance cases constitute the largest category (approximately 38% of the total number of cases). Figure 2 illustrates the amount of insurance reimbursements which highlights that 'Water Damage' constitutes the largest category in terms of reimbursement (approximately 27% of the total reimbursements and 43% larger than the second largest, fire and lightning on average). This emphasizes the significance of water damage occurrence and costs on society and why it is important to research this topic to reduce the allocation of resources to the reparation of water damage cases. Approximately 40,000 water damage cases in insured buildings (from the insurance category water damage) in Sweden are annually analysed, where the occurrence and cause of the cases are documented. These statistics, comprised of data from 2002 to 2022, are presented in Figure 3 and divided into three categories of building service system (tap water, sewage or heating systems pipes and connections) and household appliances or waterproof membranes the damage was derived from. In Figure 3, the building services systems such as pipes and connections are the largest contributor to water damage occurrence in Sweden with approximately 60% of the annual cases. However, appliances have been increasing and have contributed to water damage in rooms without waterproof membranes, such as kitchens, which are the rooms where most water damage cases occur in Sweden.[4]

In Norway and Denmark, corresponding amounts of water damage and costs can be found, indicating that water damage is a problem across Nordic countries.[5–7] The number of water damage occurrences and the cost of water damage in residential buildings in Nordic countries is a cause for concern, one that leads to immense resources being used for reparation, renovation and restoration of water-damaged materials and buildings.[4,6–9] The similarities in construction and building methods could be a factor, but reports of water damage in buildings can also be found in Europe, Asia and North America, suggesting it is an international challenge.[10–14]

Moisture in homes from water damage and other sources has been associated with an increased likelihood of respiratory diseases and adverse health effects such as asthma, respiratory infections, allergic reactions and eczema.[15,16] Furthermore, discomfort for residents includes economic concerns such as whether the insurance company will cover the economic impact of the water damage. Moreover, the water damage could have consequences for the resident, such as absences from work or school. Environmental and cost concerns are likely to arise in a building where water damage has occurred. These include renovation measures to restore the buildings. A shortened life cycle for a building generates a higher carbon footprint and a waste of water-damaged material.[17] Such consequences contradict the

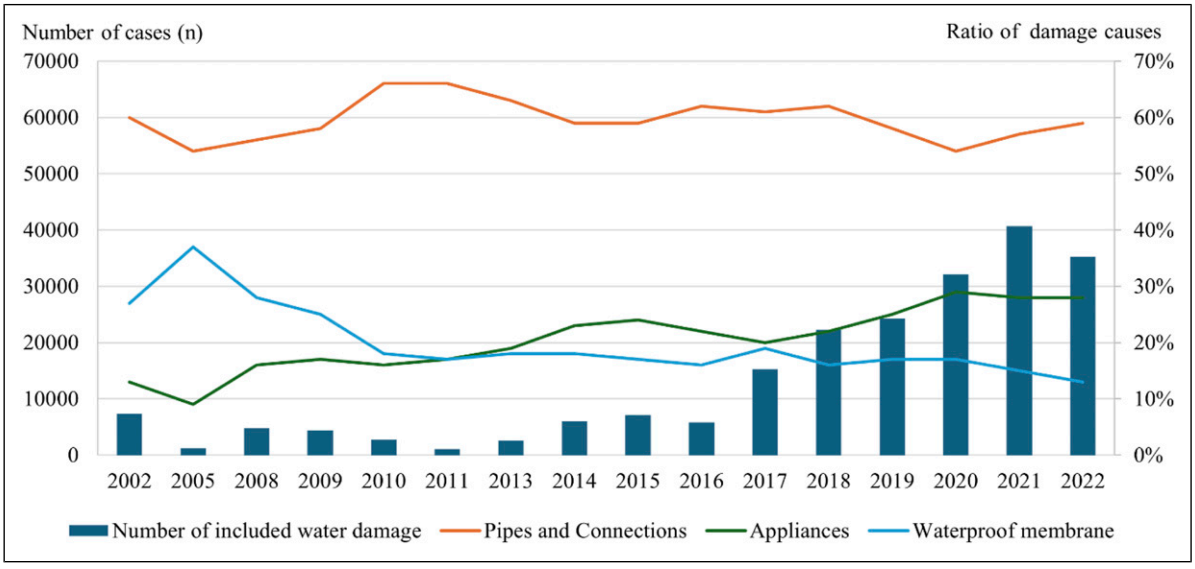


Figure 3. Water damage cases in the insurance category water damage evaluated in Sweden between 2002 and 2022 per cause.[4]

European Union's and the United Nations' goals for sustainability and increased efficiency of resources.[18,19]

The reimbursement cost of water damage has increased yearly in Sweden, from 1.8 billion SEK in 2000 to 4.9 billion SEK in 2022, an increase that, together with the increased efforts to promote sustainability in the built environment to decrease carbon emissions, demonstrates that water damage is an area that warrants more attention.[2] To address the problems and find ways to reduce the occurrences of water damage, the first step to take is a review of the current state, which will allow possible research gaps to be identified. Scientific publications and industry publications address various aspects of the problem, but systematic reviews are lacking and scientific research on water damage in building services systems seems to be limited. Research results, experience and outcomes from this research could also benefit the building industry.

To determine the current knowledge and the research performed in the water damage field, this study aimed to compile and review the literature on water damage in buildings to assess any gaps that exist in the research and determine where further research is needed. This study also aimed to review and assess measures used to reduce water damage in the field (such as methods for reducing water damage in the building sector) and those studied within the research community. Finally, the study aimed to further find research that could support industry and the scientific community in finding new methods and techniques for reducing the impact and consequences of water damage.

Method

The comprehensive examination of the field was undertaken through a literature review of both the scientific literature and literature from the governing industry organizations, commonly referred to as 'grey literature', the term used from here on. This study focused on water damage occurring in buildings due to the immense reimbursement (constitutes the largest category of all) costs that annually are reported (Figure 2). The water damage included in this study originated from building services systems such as leaking pipes, connections or valves in the tap water, sewage or heating systems (see example in Figure 4(a)). In addition, leakage from inadequate waterproof membranes in wet rooms was considered (see example in Figure 4(b)), as was leakage from appliances (see example in Figure 4(c)). Appliances are equipment that use water from the water system or could cause leakage, installed in a room without a drain, for example, dishwashers, refrigerators, freezers, coffee machines or ice machines. Figure 4 shows examples of typical causes and components for water damage occurrence studied in this paper, the same categories as described in Figure 3.

The review was conducted using both quantitative and qualitative analyses. To provide a comprehensive view of the research field, a quantitative analysis was conducted to try to identify significant parts in terms of quantitative measures such as the amount of articles being published. This was done to explore which fields and areas have been researched and which fields of research have been performed. However, the quantitative analysis does not reveal anything about the qualitative aspects as specific content, facts, which results and conclusions have been drawn, and methods used. Nor does it reveal what is known and has been established concerning this field or which areas have not been answered yet. A qualitative study/analysis has therefore also been undertaken to complement the quantitative one. Both aimed to contribute to being able to identify any possible research gaps that are valid to study in the

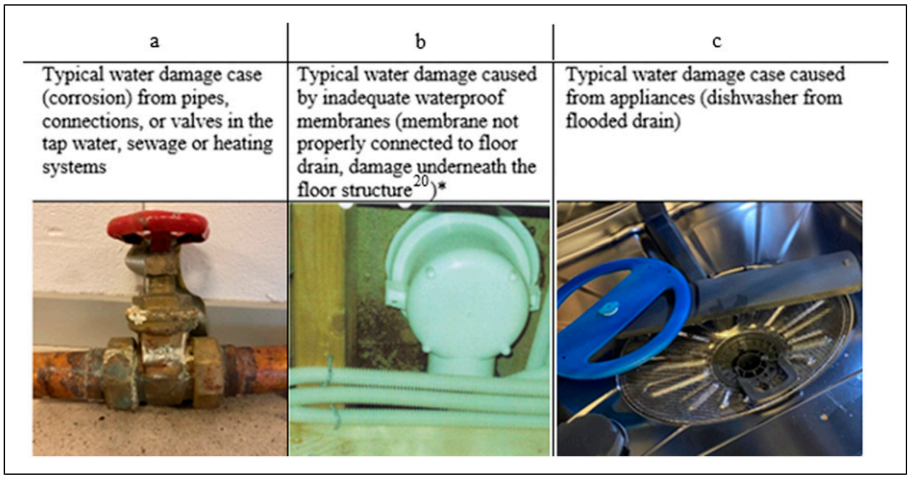


Figure 4. Examples of water damage cases studied in this paper. *Picture BKR.[20]

future. The papers found in the quantitative part were used in the qualitative section to analyse the field.

Quantitative analysis

The methodology used in the analysis follows the 10 steps of a literature review described by Säfsten and Gustavsson.[21] They are as follows:

(1) Specification of the purpose of the literature review.
(2) Identification of appropriate keywords.
(3) Formulation of criteria for inclusion and exclusion of literature.
(4) Selection of search tools and database.
(5) Formulation of the search strategy and the performance of searches.
(6) Brief analysis of identified literature.
(7) In-depth analysis of relevant literature.
(8) Extraction of data and creation of an overview.
(9) Analysis of results and content.
(10) Presentation of results – literature review.

The objective (1) of the study was to search for international and national literature to find different solutions on how the amount and effect of water damage could be reduced. Appropriate keywords were identified (2) by determining the words frequently used in studies of water damage as limited above. These keywords were also used to formulate a coherent search method and a structure between multiple searches. The search was limited to the bibliographic information of title, abstract, keywords and authors. Boolean operators of AND, OR and NOT were used together with truncations and parentheses to limit and specify the searches. Quotation marks were used to limit search results to the exact phrases given, for example, 'water damage'. An overview of the found literature was produced from their titles, abstracts and keywords, which together with a brief analysis of the identified literature (6) was used to compile the inclusion and exclusion criteria (3). The literature included in the study discussed water damage, its cost and its effect. Studies of the consequences of moisture in the building envelope, as defined by Hagentoft,[22] was also determined to be of interest even if the water did not originate from sources within the building.

The search strategy (5) used for this paper was developed to review literature by scientific information management. The strategy aimed to find scientific databases that included literature and relevant results for the study. The outcome of some preliminary searches conducted before this study determined the requirements for the databases. In this preliminary work, no international water damage-based database was found. Consequently, requirements for the databases used in this study were determined, namely, databases with international and multidisciplinary content that could offer a scientific library with peer-reviewed literature. The scientific databases chosen were Scopus and Web of Science (4). The Web of Science offers, according to Aghaei Chadegani et al.,[23] strong coverage of literature that dates back to 1990 written in English. Scopus, in contrast, offers a wider range of journals and literature.[23] This study did not exclude references due to the paper's publication date, but there was a sifting that determined the technical relevance of the paper, with publications closer to the present time deemed to be more relevant.

A brief analysis of the relevant literature (6) was carried out by analysing and scrutinizing the literature to determine the degree of relevance to the subject and in accordance with the aim of the paper. Papers of greatest relevance could then be analysed in more detail (7) using several key factors. First was whether the found literature was addressing water damage that occurred due to interior circumstances, for example, building service systems such as leaking pipes or connections from tap water, sewage, drainage, heating systems and inadequate waterproof membranes. Another decisive key factor was the building technique used, as different consequences and impacts of water damage would result, such as conditions for mould growth, depending on the materials used. Because of this study's objective, the climate and the building method were not decisive factors to exclude literature; rather climate and building method were factors in analysing the consequences and different effects of water damage.

The next step of the literature analysis was to extract data and create an overview of the found papers (8), which allowed the analysis of the found literature, also described as the analysis of the results and the contents (9). The literature was analysed by a quantitative method applied to the search results, using metrics from authors, publication field and country, and assessing the ratio between hits and relevant hits. Since the scope of this study was to study water damage in the indoor built environment, a limitation in the fields of engineering and construction building technology were made.

The presentation of the results (10) used several factors to describe the literature. These factors were the number of records found in total and by year of publication, the geographical distribution of the publications, the geographical distribution of the subject areas, literature distribution by methods used and publication type, the fields of science journals, and the found literature published within. In addition, the percentages of hits that were deemed to be relevant and therefore included in this study were also presented.

The relevant references were divided between Europe, South and North America, Asia, Australia and Africa to present the geographical distribution of the literature.

Furthermore, four categories of subject areas were defined, with the help of the categories mentioned in the databases, to explain what kind of research was conducted in certain parts of the world. They were construction defect analysis, automation in buildings, quality in construction and moisture analysis. Construction defect analysis included references that discussed or analysed defects within a wider narrative than just water damage, such as defects occurring in the construction or defects occurring due to the design of the building. The studies included were analyses of such defects. Automation in buildings included references that used/discussed methods and strategies using technology to automatically detect or prevent defects. Quality in construction included references that discussed or analysed factors such as quality during the different phases of the building's life cycle, and quality in terms of management, design, workmanship and building material. Moisture analysis included references that discussed the consequences and effects of moisture in buildings, and how it affects the occupants in terms of indoor air quality, indoor environment and building physics.

The governmental laws and regulations that were studied were the Swedish National Board of Housing, Building and Planning, the U.S. Department of Housing and Urban Development (HUD), and the UK Department for Levelling Up Housing and Communities. The included industry organizations are the National Board of Housing, Building and Planning (Boverket) in Sweden, the Danish Housing and Planning Authority (Bolig- og Planstyrelsen) and the Norwegian Building Authority (Direktoratet for byggkvalitet). The included research organizations and industry organizations are the Research Institutes of Sweden (RISE), SINTEF Norway, Säker Vatten (Safe water installation) and Vattenskadecentrum (Water damage centre). Technical manuscripts, theses and reports from projects were found by direct searches on industry organizations' webpages or indirectly through recommendations or communication with professionals working in the industry in Sweden, Norway or Denmark.

Qualitative analysis

The qualitative analysis was conducted using three topics. These topics are commonly used in evaluating water damage and were used to structure and to analyse the research field of water damage, allowing comparisons to be made and conclusions drawn. These three topics were chosen for this study to categorize the literature findings and to find what methods are used, what has been studied in the different topics, and what learnings could be learned regarding the different topics. Furthermore, in the analysis the topics were used to analyse the published papers in the field regarding each topic, to highlight where research has been done and what is needed to achieve the goal of decreasing water damage occurrence, cost and effects.

- *Status determination* – Causes and costs for water damage caused by leaking pipes or connections from tap water, sewage, drainage and heating systems and inadequate waterproof membranes in buildings.
- *Consequences and effects* – Factors that can be found in the literature about the consequences and effects of water damages in buildings.
- *Strategies and methods for prevention of water damage* –National and international strategies for approaches, methods and strategies, and technical solutions for preventing water damage in different stages of the building's lifecycle.

The status determination was carried out by analysing the literature that studied or presented conclusions on the causes of water damage from leaking pipes or connections from tap water, sewage, drainage and heating systems, and inadequate waterproof membranes in buildings. The title, the method used and the origin of the study were considered in light of the common causes found in the literature to determine any gaps in the published research.

The consequences and effects of water damage found in the literature, such as health impact, climate impact and costs were analysed to determine if there were any gaps in the literature and as a part of the determination. Health impact related to water damage is a complex issue, owing to the lack of scientific publications specific to health effects from water damage (within the limitations of this study as previously laid out). Hence, health impacts of water damage were analysed concerning water or moisture in buildings, regardless of the origin of the water.

Strategies and methods for the prevention of water damage were studied with a focus on solutions related to different phases of a building's life cycle, namely, design, construction and operation. The purpose of this approach was to distinguish the strategies and methods specific to the phase of the building's life cycle, thereby better capturing the current knowledge. Design phase studies described and/or analysed strategies and methods that could be implemented during the planning/design stage of the building. Construction phase studies described and/or analysed strategies and methods that could be implemented during the construction stage of the building. Solutions in the operation phase described and/or analysed strategies and methods that could be implemented during the operation stage of the building, meaning the time after construction by the occupants/residents or the building managers.

Results

In this section, the results of the quantitative and qualitative analysis are presented and discussed, including the literature

distribution, the status determination, strategies and methods for prevention of water damage and the consequences and effects of water damage.

Quantitative analysis

The combinations of search phrases (keywords) are presented in Table 1. Column 1 shows what was searched for, column 3 shows where the damage occurred, and column 5 shows how or why the damage occurred. Column 7 was used to include the economic effects of water damage. Columns 2, 4 and 6 give the Boolean operator used.

Literature distribution

Figures 5 and 6 present the number of records found using the chosen keywords and search method in the Scopus and Web of Science databases by year of publication. It also shows the number of hits that were relevant by year, with the percentage of relevant hits also shown. As can be seen, the number of records was increased. There was also a large increase in the percentage of relevant hits during the years 1997–2005. Furthermore, there was a rise in the number of records for the period 2009–2021, but there was not a corresponding rise in the number of relevant hits during that time. The relevant hits were determined using the 7th step in Säfsten and Gustavsson[21] method with an in-depth analysis of the hits to determine if they were within the scope of this study, for example, water damage from building services systems and building technique.

The searches resulted in a total of 451 hits of which 39 were deemed relevant for the study and within the study's limitations. Scopus resulted in 30 out of 336 and Web of Science resulted in 9 relevant hits out of 115. The

Table 1. Combinations of search phrases in the scientific literature search. Truncations, parentheses and quotation marks were used in addition to Boolean operators.

1	2	3	4	5	6	7
Water damage OR water-damage OR Water leakage OR water-leakage OR Defect* NOT Flood*	AND	Indoor OR Buil* OR Apartment* OR Dwelling*	AND	Tap water OR tap-water OR Sewage* OR Drainage OR Heat* OR system* OR Install*	AND	Cost* OR Amount* OR Worth*

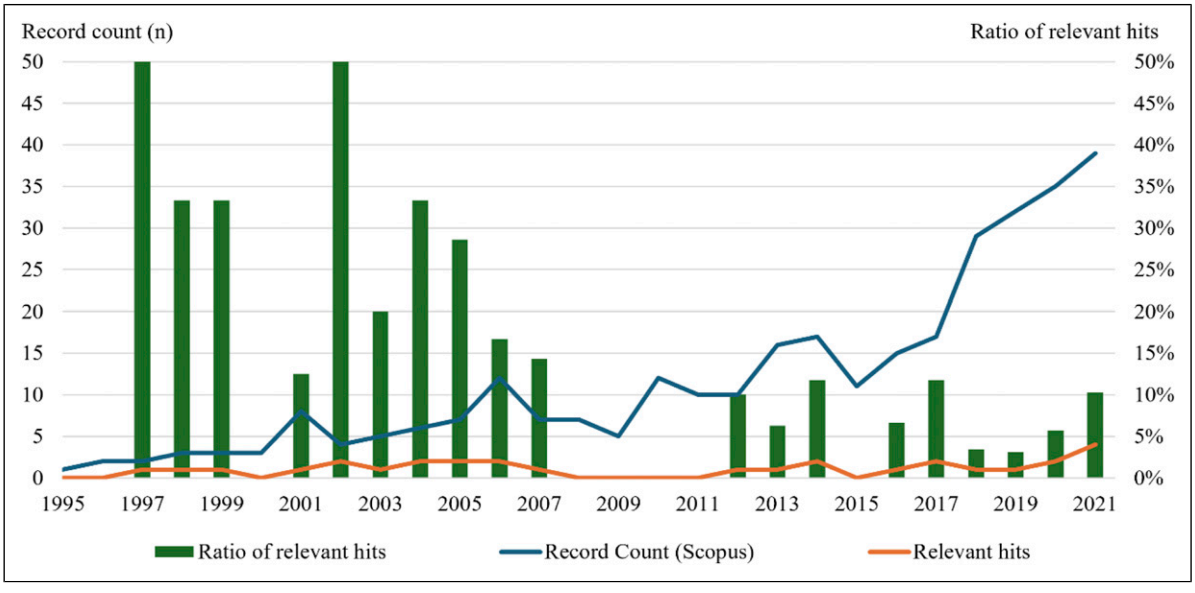


Figure 5. Number of records found and relevant hits in Scopus database.

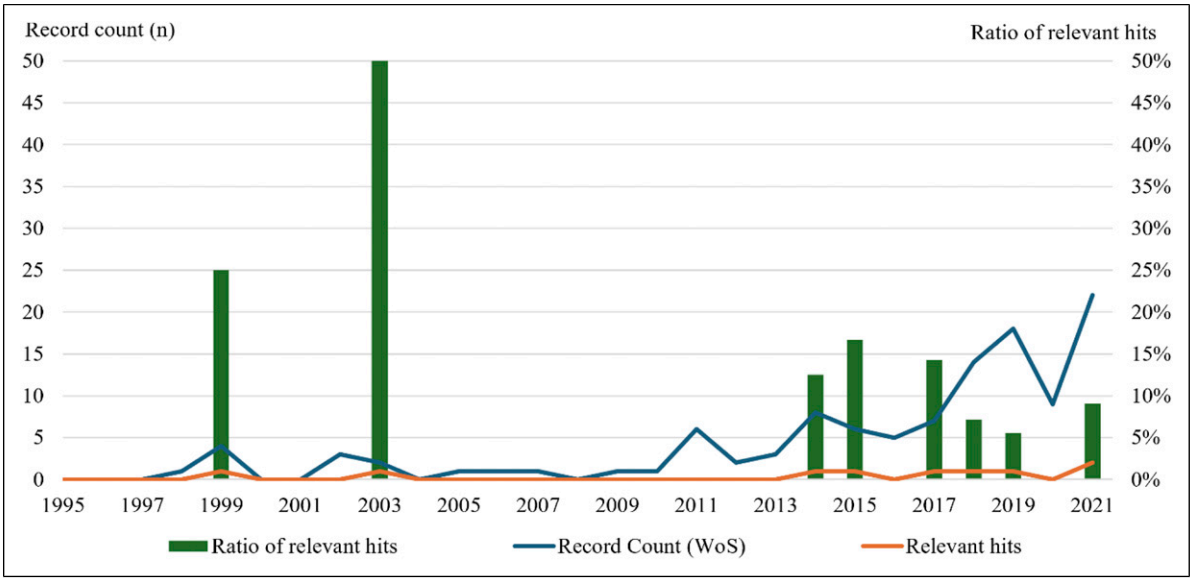


Figure 6. Number of records found and relevant hits in Web of Science (WoS) database.

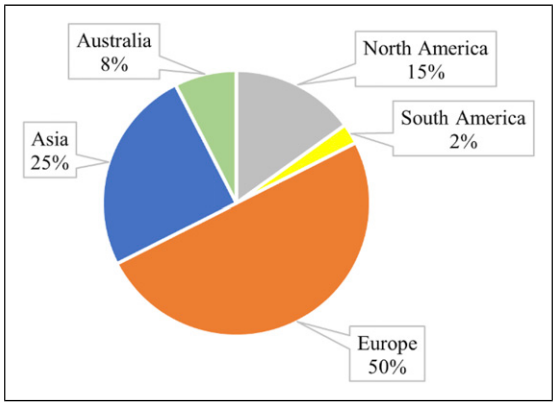


Figure 7. Geographical distribution of relevant records found in literature searches.

rate of relevant to non-relevant hits was from 9% to 7% in the individual databases and 8.6% when combining the search results. Scopus resulted in both more hits and relevant hits for the study. Many of the relevant records were found to be carried out between 1997 and 2007. The keywords that generated the most relevant hits were defect*, build* and cost*, which gave rise to a large number of records that were not relevant to this study, making the sifting to determine relevancy necessary. Figure 7 presents the geographical distribution of relevant hits in terms of the author's affiliation.

The geographical distribution relative to the subject areas – construction defect analysis, automation in buildings, quality in construction and moisture analysis – is presented in Figure 8, described as 8th and 9th step in Säfsten and Gustavsson[21] method.

Four methods used for studying water damage in the relevant hits were identified, namely, literature analysis or review, case study, statistical analysis or survey. Figure 9 shows the distribution of these methods across the papers. Three publication types were also identified, namely, conference papers, reviews and articles. Figure 10 shows the percentages represented in the relevant hits.

The number of journals and articles in the fields of building physics, sustainable buildings, social building science, architectural engineering, building services and machine learning is presented in Figure 11. The categories in the figure were defined from the databases.

A representative selection of relevant scientific articles is presented in Table 2, showing the main authors' names, country of residence, affiliation, along with number of publications and number of those publications that were relevant to this study. The table was compiled to identify the authors with the most scientific influence and impact in this study.

Qualitative analysis

The qualitative analysis was conducted to determine the research done with respect to three topics: status determination, consequences and effects, and strategies and methods for the prevention of water damage in buildings.

Status determination

The found literature was divided into different categories to represent the status of the field in this study and is presented in Table 3.

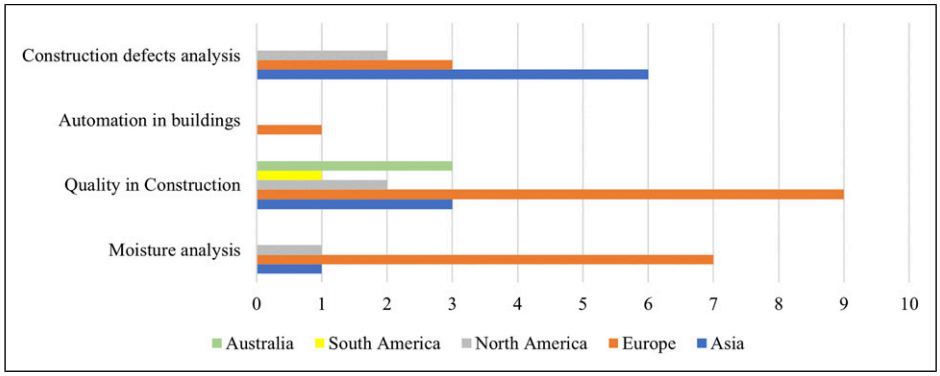


Figure 8. The geographical distribution of relevant records divided into the subject areas, construction defect analysis, automation in buildings, quality in construction and moisture analysis.

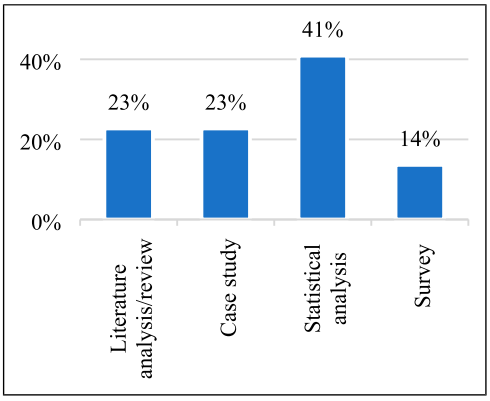


Figure 9. Literature distribution by method used in the relevant records.

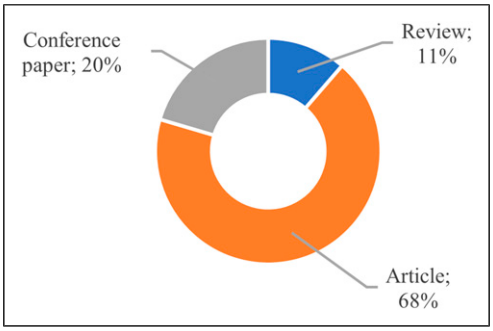


Figure 10. Literature distribution by publication type of the relevant records.

Residential buildings,[12,27,31,40,45] and affordable housing,[11,38] have been studied throughout the found literature, but defects and water damage in other buildings, such as offices, premises or public buildings have not been studied to the same extent. This gap is likewise found in the grey literature. One example is given by the Swedish statistics on water damage which contains data from dwellings and residential buildings but not from public buildings.[4] In Chew and De Silva's work,[12] the quality of wet areas was studied, and conclusions were drawn based on what could be improved and what factors caused reduced water tightness in the buildings. Studies on wet rooms and factors causing defects or water damage in wet rooms,[12,24,25,28,34] are more common than studies of defects and water damage in other areas of the building, for example, kitchens. Although water damage in kitchens is becoming more commonly reported in the Nordics,[4] there are only a few such studies, and more research should be done in the future.

Causes that are prominent and frequently mentioned are building design and construction quality.[11–13,24,25] Abdul-Rahman et al.[11] studied defects in affordable housing projects in Malaysia to identify and determine the causes and develop solutions to avoid defects in other projects. The most common defects identified were leaking water pipes and total failure of water supply systems; others mentioned were cracking concrete walls, faulty doorknobs and concrete walls dampness. Abdul-Rahman et al.[11] suggest that defects are correlated; once the concrete of the external walls has started to crack the pipes within, the walls are likely to leak as well, together with many other problems. The primary causes of the identified defects, according to the authors, are poor workmanship, inferior materials and poor supervision and monitoring routines. Chew[25] emphasizes that with respect to their study, construction quality played the most important role in controlling defects, followed by material performance in tropical environments, design and maintenance practices. The importance of design concerning water damage and leakages was also mentioned in studies of high-rise residential buildings in Singapore.[12,24] By assessing maintainability and the factors

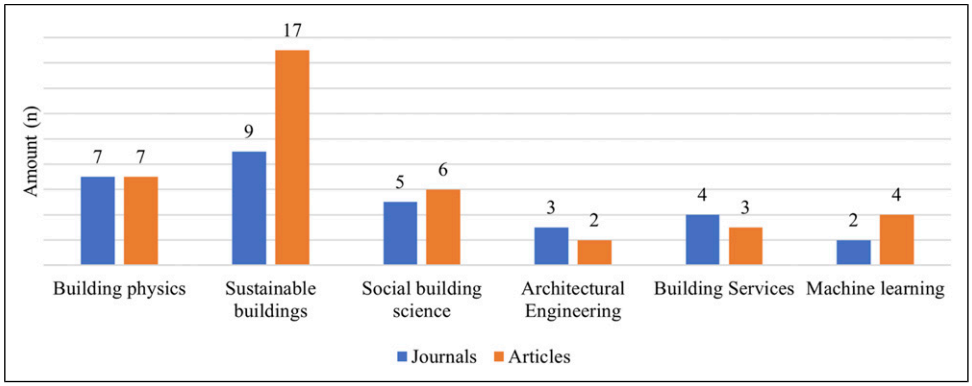


Figure 11. Scientific fields represented in the journals and the number of journals and articles in each field of the relevant records.

Table 2. Authors with scientific influence in the field of water damage (presented in no specific order) showing main author/s, number of publications and relevant hits, country of residence and affiliation.

Author(s)	Number of publications (relevant hits)	Country	Affiliation
Chew, Michael Yit Lin[12,24,25]	101 (3)	Singapore	National University of Singapore
Forcada, Núria[13,26,27]	72 (3)	Spain	Universitat Politècnica de Catalunya
Low, Sui Pheng[28,29]	195 (2)	Singapore	National University of Singapore
Lee, Sanghyo[30,31]	49 (2)	South Korea	Hanyang University
Faqih, Faisal[32]	5 (1)	Hong Kong	Hong Kong Polytechnic University
Zayed, Tarek[32]	348 (1)		
Abdul-Rahman, Hamzah[11]	105 (1)	Malaysia	Universiti Malaya
Chong, Wai Kiong Oswald [28]	67 (1)	US	Arizona state University
Becher, Rune[15]	62 (1)	Norway	Norwegian Institute of Public Health
Josephson, Per Erik Bertil[33]	22 (1)	Sweden	Chalmers University of Technology
Lee, Sanghoon[30]	21 (1)	South Korea	Hanyang University
Morelli, Martin[34]	15 (1)	Denmark	Aalborg University
Brandt, Erik[34]	18 (1)	US	Wiss, Janney, Elstner Associates, Inc.
Beasley, Kimball J[35]	18 (1)		
Hammarlund, Yngve[33]	7 (1)	Sweden	Chalmers University of Technology
Andersson, Johnny V.[36]	7 (1)	Sweden	Scandiaconsult International
Kaunisto, Tuija[37]	6 (1)	Finland	Satakunta University of Applied Sciences

affecting water tightness the authors underscore the importance of an integrated approach between designers and builders along with those responsible for maintenance and operation. Furthermore, in three studies carried out by Forcada et al.,[13,26,27] the influence of building types, sources and origins of construction defects in residential buildings and post-handover housing was assessed. The first study concluded that residents in multifamily buildings, flats or apartments detect more defects than in detached houses even though the gross floor area is smaller in flats. The authors suggest the following reason: 'The differences in contractors' and clients' perceptions of quality notwithstanding, contractors observe end-user needs more accurately in detached houses than in flats'.[26] The second study emphasized that the construction boom of the late 1990s led to a rise of inexperienced workers and that competition within the industry affected the quality of the construction of buildings. The study concluded that there is a strong correlation between post-handover housing defects and workmanship, inspection/checking

Table 3. Studies that examine the causes of water damages showing title, method used and the geographic origin of the study.

Title	Method used	Origin of the study
'Defects in Affordable Housing Projects in Klang Valley, Malaysia[11]	Survey, statistical analysis	Asia
'Defect analysis in wet areas of buildings' [25]	Survey	Asia
'Defect characterisations in the Malaysian affordable housing' [38]	Survey, statistical analysis	Asia
'Factors Affecting Water-Tightness in Wet Areas of High-Rise Residential Buildings' [12]	Statistical analysis	Asia
'LDA-Based Model for Defect Management in Residential Buildings' [30]	Statistical analysis	Asia
'Evaluating the Impact of Defect Risks in Residential Buildings at the Occupancy Phase' [31]	Review	Asia
'Water seepage in multi-storey buildings' [39]	Review, statistical analysis	Asia
'Posthandover Housing Defects: Sources and Origins' [13]	Statistical analysis	Europe
'Assessment of construction defects in residential buildings in Spain' [27]	Statistical analysis	Europe
'*Analysis of Defects in Residential Buildings Reported during the Warranty Period'* [40]	Statistical analysis	Europe
'Causes and costs of defects in construction a study of seven building projects' [33]	Statistical analysis	Europe
'Evaluation of defect influencing factors in public housing in the UK' [41]	Survey, statistical analysis	Europe
'Water damages in HVAC, tap water and sewage systems in cold climates' [5]	Review, statistical analysis	Europe
'Contemporary and traditional wall-system failures' [35]	Review	North America
'Latent building defects: Causes and design strategies to prevent them' [28]	Statistical analysis, review	North America
'Facility Defect and Cost Reduction by Incorporating Maintainability Knowledge Transfer Using Maintenance Management System Data' [42]	Review	North America
'Auditing the indirect consequences of rework in construction: a case based approach' [43]	Case study	Australia
'Building and construction quality: systematic literature review, thematic and gap analysis' [44]	Review	Asia, Australia, Europe, North America, South America

and responsibility.[13] The third study suggests that a quality management system can prevent and possibly eradicate construction defects. A quality management system in parallel with construction activities to minimize defects would be beneficial both in time and costs.[27] Statistics and data on the occurrence, causes, origins and costs of water damage were not found; these could have provided a comparative determination of different countries' status concerning water damage.

Consequences and effects

The literature that covers the health of residents or occupants, climate impact and consequences and effects on the building is presented in Table 4.

The health aspects of moisture and its effects and consequences have been studied by Becher and Høie,[15] Andersson,[47] Fisk, Lei-Gomez,[49] and Haverinen-Shaughnessy and Pekkanen,[48] amongst others. From these studies and others, it is well known that mould and damp indoor environments are associated with symptoms such as asthma and respiratory diseases[16] and that there is an approximately 30–50% increase in respiratory and asthma-related health issues in homes with dampness and mould.[49] Becher and Høie[15] concluded that crawl spaces, basements, insulated attics, cooling rooms and bathrooms, in that order, are most susceptible to moisture damage, and to prevent moisture damage from a leakage or water damage the damaged material/area must be removed, and the water must be dried out before the damage can be restored. However, although water damage, in most cases, could lead to moisture damage

Table 4. Studies that examine health, climate and building aspects of water damage showing title, method used and the origin of the study.

	Method used	Origin of the study
Health		
'Dampness and Moisture Problems in Norwegian Homes' [15]	Statistical analysis	Europe
'Drying behaviour and microbial load after water damage' [46]	Statistical analysis	Europe
'Humid Buildings – The Construction Remedy' [47]	Case study	Europe
'Estimating effects of moisture damage repairs on students' health—a long-term intervention study' [48]	Survey	Europe
'Meta-analysis of the associations of respiratory health effects with dampness and mould in homes' [49]	Statistical analysis, review	North America
Climate impact		
'Building rehabilitation versus demolition and new construction: Economic and environmental assessment' [50]	Case study	Europe
'CBA-Based Evaluation Method of the Impact of Defects in Residential Buildings: Assessing Risks towards Making Sustainable Decisions on Continuous Improvement Activities' [51]	Survey, statistical analysis	South America
Costs		
'A construction quality costs quantifying system for the building industry' [29]	Case study	Asia, North America
'Facility Defect and Cost Reduction by Incorporating Maintainability Knowledge Transfer Using Maintenance Management System Data' [42]	Review	North America
'Auditing the indirect consequences of rework in construction: a case based approach' [43]	Case study	Australia
'Water damages in HVAC, tap water and sewage systems in cold climates' [5]	Review, statistical analysis	Europe
'Hygrometric Moisture Measurements Based on Embedded Sensors to Determine the Mass of Moisture in Porous Building Material' [14]	Case study	Europe

it was not found to be studied as a specific cause or effect. Some examples of questions that arise are (1) How much water must leak from the water damage before it causes a risk of health issues to the occupant? (2) What kind of damage and in which area of the building pose the largest risk to the occupant? (3) Is there a difference in the health impact, and what would it be, depending on the source of the water, for example, sewage and heating water?

Studies that evaluated the climate impact of water damage were those by Alba-Rodríguez, Martínez-Rocamora,[50] and Milion and Alves.[51] They examined various renovation measures and how to make educated decisions in the operation of a building. However, these studies did not directly analyse water damage but rather the effect of the damage. Thus, the grey literature was used to assess the climate impact of water damage. Petrovic et al.[52] studied the carbon impact of the repair of water damage in a Swedish dwelling, which they concluded amounted to emissions of approximately 250–430 $kgCO_2e$, depending on the extent of the damage.[52] Water damage in a bathroom in a Swedish dwelling amounts to emissions of approximately 250–700 $kgCO_2e$, depending on the extent of the damage and the amount of material that needs to be restored.[52] Notwithstanding these estimations, more research is needed to understand the climate impact of water damage in different kinds of buildings – such as dwellings, multi-family buildings and public buildings – and for different building materials – such as wood and concrete. Furthermore, more needs to be known about the climate impact of various causes and origins of water damage to further understand the consequences and effects.

The costs of water damage are commonly studied by defects (in the quality of construction, for instance) and the costs of correcting defects at different stages, such as quality costs, prevention, appraisal and failure costs.[29] Also considered are the correlations between preventative maintenance, corrective maintenance, emergency work[42] and the consequences in terms of cost of rework.[43] The cost of defects for an organization or building project in terms of delays, rework and economic losses are described well in the literature, but the costs of the water damage to the occupants, insurance companies and society, such as sick leave, health costs and uninsured buildings, are not as adequately covered. The costs of water damage in insured

buildings, mostly dwellings, are kept track of by statistics or insurance companies for example,[2,6,7,53] but a holistic approach, one that covers multiple cost categories in different building types, such as multifamily buildings and premises and offices, is lacking.

Strategies and methods for prevention of water damage

The studies that describe various strategies and methods for the prevention of water damage are presented in Table 5, divided into the design, construction and operation phases of the building.

Design phase strategies and methods are the following: additional waterproofing and changing traditional building methods, as described by Morelli and Brandt;[34] moisture trapping zones and leakage-stopping systems to prevent leaks flowing into dry areas, as described by Chong and Low;[28] and methods to support the decision-makers in sustainable choices, described by Milion et al.[51] Current solutions that could be implemented in the construction phase include detecting defects using sensors, and during the construction phase inspection and analysis together with follow-up actions[54] and methods for assessing building components during inspection.[32] In the operation phase, strategies and methods to prevent water damage are mapping the building structure to make water leakages and other defects visible[55] and designing buildings that allow and facilitate maintenance.[42]

The strategies and methods for the prevention of water damage focus on decision-makers, inspection and building techniques. Proven and tested solutions for active water damage prevention are fewer, even though some studies were found[34,54] that could be implemented in the design and operation phases. Studies of measures that actively stop water from flowing or indicate when leakage occurs, which studied the performance of such measures were not found, even though such measures are available on the market. Studies that discuss wet rooms and ways to limit moisture from reaching moisture-sensitive material in the structure were found. The water damage problem is not limited to wet rooms, however, but can affect all areas in the building. For example, approximately 33% of the water damage in Sweden occurs in the kitchens of which the residents have a large influence.[4]

Discussion

This study has demonstrated that water damage in buildings is an international issue. Research on water damage was not found to focus specifically on water damage in buildings but on defects, as a part of the building pathology field, in the built environment, with water damage being one source of many defects. Often, however, water damage-related problems, such as leaking pipes[28] and water leakage,[25] were the most common defects studied or the defect with the highest impact on the results of the study. In total 39 studies were found to be relevant in this review. The

Table 5. Studies about strategies and methods for the prevention of water damage show strategies are divided into the design, construction and operation phases of the building's life cycle.

	Method used	Origin of the study
Solutions in the design phase		
'Performance of Lightweight Wet-Room Floor with Two Waterproof Membranes' [34]	Statistical analysis	Europe
'Latent building defects: Causes and design strategies to prevent them' [28]	Statistical analysis	North America
'CBA-Based Evaluation Method of the Impact of Defects in Residential Buildings: Assessing Risks towards Making Sustainable Decisions on Continuous Improvement Activities' [51]	Survey, statistical analysis	South America
Solutions in the construction phase		
'A formalism for utilization of sensor systems and integrated project models for active construction quality control' [54]	Case study	North America
'A comparative review of building component rating systems' [32]	Review	Asia
Solutions in the operation phase		
'Revolutionising building inspection techniques to meet large-scale energy demands: A review of the state-of-the-art' [55]	Review	Europe
'Use of a surface emissions trap for improving the indoor air quality by efficient exposure reduction' [56]	Case study	Europe
'Facility Defect and Cost Reduction by Incorporating Maintainability Knowledge Transfer Using Maintenance Management System Data' [42]	Review	North America

periods between 1997 and 2007 and 2017 and 2021 stand out with the earlier period showing a large percentage of relevant hits, but not a large number of records being found. The later period showed a large increase in records but not as high a percentage of relevant records. These findings could indicate that the focus on water damage is continuous throughout the years, but the focus on defects or building pathology has increased in the later period. Research was largely conducted in Europe and Asia, 45% and 30%, respectively. A distinction related to geographical distribution was also noted, namely, that studies conducted in Europe had a stronger emphasis on subjects such as construction quality and moisture analysis while studies conducted in Asia had a stronger emphasis on construction defect analysis. One explanation could be differences in building codes or methods, warm or cold climates and economic incentives.

The amount of water damage and, in particular, the costs of water damage are contributing to inefficient use of resources, both in economic terms and sustainability terms. Economic parameters were studied in construction defects and construction quality. These studies primarily aimed to make the building process more efficient for the building company and to improve the quality of the construction and the design phase. Studies of the economic impact arising from defects or water damage on occupants or residents in the finished building, during its operation phase, were fewer; more studies could be beneficial. It should be noted that this topic was partially covered in the grey literature, for example, in Nordic countries,[4,6,7] but additional research could have an impact on reducing the costs of water damage. Furthermore, the articles found in this study were selected to represent the research in the field where they did reveal that the field of water damage was embedded in other research fields, of which sustainability and building physics were the most common. Sustainability in buildings is a major concern, possibly connected to climate goals in place, such as the UN's 2030 Agenda for sustainable development and the European Union's goal for reducing energy dependency and greenhouse gas emissions.[18,19] Thus, the number of articles and journals related to sustainability is not surprising. Literature that focuses on sustainability related to or directly connected to water damage was not found. A pertinent topic, for example, would be the climate impact of water damage and what measures could be done to reduce the climate impact that water damage brings due to the repair and restoration of the building and additional use of material. There were case studies of construction projects,[28,32,44] in which the causes of defects and the costs allocated to them were analysed and suggestions were made in design and construction; similar studies could benefit the field if they were primarily about water damage from leaking pipes, connections or values in the tap water, sewage or heating system, from inadequate waterproof membranes and appliances.

In the operation phase, usually the longest period of a building, it is the residents/occupants or building owner who are responsible for the building and its installations, services and systems. However, in contrast to the designer, constructor and building manager, they typically have less education, experience and knowledge on how to maintain the building and how to prevent damage. Thus, strategies and methods in this phase could have a vast effect, and the fact that the literature on this subject is more sparse than on others indicates a gap that, if filled, could have a large impact on the amount and cost of water damage.

Studies of water damage were often published in building physics and social science, suggesting that the consequences of moisture for both the residents and the building itself have been studied to some extent. Examples of moisture affecting the social aspects of the building have been reported[47,49] and examples of water damage affecting the building physics are recorded.[25,44] Surprisingly, fields such as building services, machine learning and architectural engineering were not as frequently found in the literature using the search strategy chosen for this study, indicating a gap, as previously mentioned, in the distinction between defects and water damage. More multidisciplinary research, for example, design, architecture and machine learning, could benefit the field of water damage in buildings. Water damage from building services in heating systems and household appliances is not covered by the literature to the same extent as water damage from leaking pipes in the tap water system. The rising trend of water damage from household appliances and in rooms other than wet rooms, as could be seen in Sweden and through the qualitative analysis, emphasizes the importance of research in such fields where architecture, social science, building physics and building services are integrated and where both defects and water damage are considered, such studies were not found in this review.

The qualitative analysis furthermore determined that residential buildings and affordable housing are studied to a greater extent than other buildings, such as offices, schools, preschools and publicly owned buildings. The design of the building and the quality of the construction in the construction phase were the prominent causes of water damage identified. Improved management systems and inspection routines were common solutions proposed. However, studies that emphasize the importance of designing and building to avoid or prevent water damage were few, though some coverage could be found in the grey literature.[57,58] Furthermore, it was determined that methods, mostly passive, to prevent water damage have been studied but active methods and solutions that could be installed and added to

decrease the risk of water damage have not been studied and evaluated to the same extent. Negative effects on humans living or spending longer periods in buildings with moisture and mould growth have been shown in several studies.[15,16,47,49] Thus, studies with a focus on reducing its causes are important to improve factors such as indoor air quality and to reduce the possibility of mould growth in buildings. In addition, such studies could reduce the immense costs that annually are allocated to water damage and contribute to fewer repairs and unnecessary use of resources.

Conclusions

Through quantitative and qualitative analyses this paper can conclude that water damage in building services systems such as leaking pipes, connections or valves in the tap water, sewage or heating system, inadequate waterproof membranes and appliances has been studied to some extent. However, the research is heavily weighted toward the unifying concept of defects within the field of building pathology. In total 39 scientific studies and 16 studies and reports conducted by industry, government or other institutions between 1997 and 2021 were studied to determine the status, consequences, effects and strategies and methods for the prevention of water damage in buildings. The findings of this study are summarized as follows:

- Water damage occurring in buildings is being studied, embedded in the larger field of defects. However, more specific research and statistics are needed to reduce the causes, costs and effects of water damage in all areas of a building.
- Areas not commonly covered with waterproof membranes, such as kitchens, were not found to be studied to a great extent, even though the number of reported damages from appliances in these areas is increasing.
- Informed and guided design, management and organizational structures to reduce defects in the early stage of the building and/or construction phase were found to be part of the suggested solution of reducing the amount, cost and effects of defects, including water damage. These shortcomings were found to be the most studied causes of defects.
- There is a lack of research and statistics on water damage occurring in public buildings, such as schools and multifamily buildings, which are needed for a comprehensive analysis of the entire building stock.
- Sustainability factors, such as emissions and climate impact of the repair caused by water damage in buildings, have not been comprehensively studied in the research identified in this study. Sustainable solutions for water damage could potentially reduce costs for residents, building owners, and management and insurance companies, and reduce the climate impact of the building sector. Even though the topic of sustainability had the most articles published, few were found on emissions and climate impact related to water damage.
- Inclusion of fields such as social science, building physics and building services is needed to fully understand the consequences of water damage to the building, occupants and the indoor air.
- Moisture in homes and its consequences have been studied with little or no regard for the water's origin. It is important to understand the effects and consequences of mould growth and effects on indoor air quality, but the effects of water from specific sources, such as sewage, heating and hot tap water could have other consequences which are not yet studied. Therefore, there should be further studies on the consequences and effects of water damage from various origins.
- Water damage was found to be an international problem, but different aspects of water damage are emphasized depending on the broader building problems occurring in the different regions of the world, for example, analysis of construction defects, quality in construction and moisture analysis.

Authors' contribution

All authors contributed equally in the preparation of this manuscript.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the FORMAS (the Swedish Research Council for Sustainable Development) under Grant 2019-00649. The funding source had no involvement in writing this paper or the study.

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Paper II [redacted]

Water damages in HVAC, tap water and sewage systems in cold climates

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Abstract. Water damages in buildings in the Nordic countries results in costs amounting to several billion Euros each year as well as a great deal of unpleasantness. The vast majority of the water damages cost in Sweden is caused by leaks from buildings services in the form of piping such as tap water, sewage, drainage and heating, as well as through insufficiently waterproof layers in wet rooms. The economic potential for making measures to prevent water damages on building services and wet rooms is enormous and savings could be used for other sustainability measures in the built environment. The aim of this paper is to review statistics of damages caused in cold outdoor climates. This is done by an analyse of empirical damage statistics by a literature review of both scientific literature and in retrievable cases from practical experience. The result will be a help to focus on the right damage types in colder climate and will make a foundation for future research on how to prevent water damages. The cold climate in the Nordic countries seems to be a factor for the number of water damages due to freezing that are described in the statistics and it could be established that the impact of the climate should be considered and that it need to be constructed and designed for in a larger extent.

1 Introduction

Water damage in buildings in the Nordic countries is a problematic area and amounts to a cost to society of some 1 billion EUR for homeowners and insurance companies each year [1]. In Sweden, the cost for just homeowners 2019 amounted to some 3,9 billion SEK (approximately 0.39 billion EUR) in insurance reimbursements from water damages in buildings [2]. In Denmark, the cost amounted to some 2,2 billion DDK (approximately 0.22 billion EUR) in insurance reimbursements [3]. In Norway, the cost amounted to some 3,4 billion NOK (approximately 0,34 billion EUR) in insurance reimbursements [3]. Water damages in buildings also contributes to other problems than cost related issues. It brings the homeowners discomfort and time-consuming work to restore the buildings to good shape. To reduce the amount of water damages in the Nordic countries, there are ongoing projects and incentives to educate builders and to stipulate rules and codes to build buildings with less water damages. These incentives have probably had a positive effect on the number of water damages in buildings in the years prior to this study [1]. The occurrence of water damages in buildings shows a positive trend and are decreasing for every year, but the problematic area is that the costs for the damages are increasing and shows a negative trend [2]. In Sweden, the cases of water damages were, according to Svensk Försäkring [2], in 1985 approximately 110 000 and 2019 were the cases 75 000 and a similar trend could be found in Norway and Denmark but in a shorter time span. However, considering the still large-scale amount of cases and the vast costs more knowledge is needed.

Causes for water damages in buildings in Sweden according to Vattenskadecentrum [1] are bursting or leaking pipes in wet-rooms and kitchens, which causes approximately 58 % of the water damages in Sweden [1]. Other causes for water damages in buildings are appliances which stands for 25 % of the water damages in Sweden and the last 17 % of water damages could be derived from inadequate waterproof membranes in wet rooms with a floor drain [1]. Bursting and leaking pipes from tap water, sewage, drainage, and heating and damages in the waterproof membrane in the interior environment of the building is covered by this paper. This study aims to review statistics on water damages and costs in cold climates such as in the Nordic countries and add research about damages that could be related to cold climates; freezing damages and to examine to what extent cold climates do impact the number and costs of water damages.

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2 Research methodology

A literary review and analysis of water damages with focus on cold climates in the Nordic countries was conducted in this study. The Nordic countries that were analysed were Sweden, Norway, and Denmark (due to the similarities in construction methods and climate). Because of similarities and that the climate are similar but with a slight difference between the most northern country (Norway) and the most southern country (Denmark) it allowed for the study to analyse water damages due to freezing in water pipes in buildings with same preconditions. An empirical statistical review of water damages was conducted based on actual cases and costs of water damages in buildings in the studied countries.

The international perspective was taken in consideration in the literary review by analysing literature on water damages in warmer climates. The literature review was based on the reasons for defects and flaws in the building sector that could lead to water damages. A scientific database search was used to conduct the searches. The scientific databases that were used in the study were Elsevier´s Scopus, Engineering Village and the scientific database Web of Science. The defects that the literary review focused on were not limited to damages in the Nordic countries but to general defects and flaws in the building sector that could lead to water damages in the indoor environment. Both scientific literature and grey literature, such as governmental papers, was used in the review. The study aimed to answer the question of where and if there was a gap in the research on water damages, mostly focused on water damages due to freezing and cold climate.

An empirical statistic review of water damage cases and cost were conducted by gathering statistics of actual cases and costs for reimbursement from insurance companies. The gathering of cases and cost for damages was conducted from the different country's statistic gathering company. The data that was gathered in the study was the number of water damages that has occurred in each country during a timespan between 2000 and 2019. This timespan included buildings of any stage of its lifecycle. Measurements of occurrence and cost for water damages in Sweden, Norway and Denmark are carried out by the insurance companies. The insurance companies documents and inspects the water damage and could offer a reimbursement to the homeowner to cover the cost for the restoration of the damage. The costs for reimbursements and the number of cases are documented by the different insurance companies. The damage does only appear in the statistics if the homeowners report the damage to the insurance companies and if the deductible cost is lower than the cost of the restoration of the damage. The deductible cost is a number decided by the insurance company which the homeowner has to pay themselves. The part of the renovation cost that is not covered in the reimbursement. An area that has a lower coverage of water damages in the statistics are apartment blocks. Damages in apartment blocks could have a higher deductible cost than dwellings and most often a common property manager that could restore the damage to a lower cost than the deductible cost from the insurance company and therefore the damages does not appear in the statistics. Another part of the building stock that is not covered by the statistics from the insurance companies are the buildings that does not have a coverage of insurance, e.g., building owned by the government or state. Hence the costs and the number of cases that occur in these kinds of buildings are not included in the statistics presented by the insurance companies. The buildings studied were the buildings covered by the insurance company´s statistics, which are mostly represented by single-family houses. Building types that are not covered by the statistic, at the same extent as single-family houses, are apartment blocks, offices and uninsured buildings, for example, public buildings and schools. This is a problematic area by itself and will not be covered by this paper, still the quantity of water damages in buildings covered by the statistics is large and it is assumed to be a representative selection of the water damages that occurs in buildings in the Nordic countries.

Water damages occurs due to a vast number of reasons, this paper covers the water damages in the indoor environment. Water damages are categorized in different systems depending on the country. The Swedish water damage statistics by Svensk Försäkring [4] are categorized in pipes and appliances, and damages in the waterproof membrane of wet rooms. The categorization and the subcategories used in Sweden are described in Table 1.

Table 1. *Categories used in Sweden for describing water damages [1].*

Causes	**Subcategory**
Pipe system	Corrosion
	Age or wear
	Defect products
	Wrongful installation
	Freezing
Service and appliances	Hoses
	Machines
Waterproof membrane	Walls
	Floors

The categorization of the water damages are organized by insurance companies and are carried out by an authorised damage investigator and in some case by an inquiry document, for example, the inquiry document by Vattenskadecentrum [4].

The Norwegian statistics by Finans Norge [3] are being categorized depending on the cause of the water damage, e.g., failure of the product, corrosion and freezing. The categorization for water damages used in Norway are described in Table 2.

***Table 2**. Categories used in Norway for describing water damages [3].*

Causes
Defect product
Faulty design
Wrongful installation
User fault
Tear or older than 30 years
Corrosion
Stop in sewages
Freezing

The danish water damage statistics by Forsikring & Pension [5] is categorized in a system based on the cause of the water damage, e.g., water damages which originates due to hidden pipes and connections and water damages that originates due to other reasons than hidden pipes and connection and exterior influence. The categories used in Denmark are described in Table 3.

***Table 3**. Categories used in Denmark for describing water damages [6].*

Causes
Water damages that originates from defect pipes or connections
Water damages that originated from other reasons than pipes, connections, storm, rain or snow
Cold or freezing

The empirical damage statistics will also be analysed in an aspect of water damages due to freezing and to what extent the cold climate in the Nordic countries in this aspect affects number of water damages in buildings. The water damages that have been categorised by the insurance companies due to freezing were evaluated in a percentage of reported cases in the chosen timespan and compared to the yearly winter mean temperature deviation for each studied country.

3 Results

3.1 Literature review

From the literature review of water damages and defects in buildings was structured in two parts, the grey literature form governmental institutes and industry organizations in the Nordic countries and the scientific literature within the subject.

National board of housing, building and planning in Sweden, Boverket, carried out a compilation of defects and damages in the Swedish building industry. The aim was to investigate and evaluate solutions to reduce the number of defects and systematic building failures in the industry by conducting a study with interviews, surveys and gathering of statistics of defects [7]. The study resulted in a conclusion that most of the defects in the Swedish building sector occurs in effect of water and moisture in buildings and that the number of the most common defects was constant during the latest 10-year period. This, Boverket finds worrying because of the increasing number of buildings that are being build each year. Boverket states that this could lead to an increase of damages and defects. Boverket determined that the most common defects that occurred was due to shortage of time, lack of competence or resources, and the deficiency in communication and experience feedback within the own organisation.

A comprehensive compilation of Swedish water damage cases has been carried out before and the recent follow-up study was conducted 2015 based on the VASKA-project in Umeå 1987. The VASKA-project in 1987 was aimed to minimize risk for water damages with a thorough project descriptions and a control of the building process [8]. The study 2015 showed that VASKA-project succeed in the aim to reduce the risks of water damages in both apartments and single-family houses [9]. With the strategic work and the control of execution they found that the building within the VASKA-project had less defects in the building process and with the accurate and thorough monitoring the risk for water damages could be reduced significantly within the buildings in the VASKA-project.[9].

A study of seven building projects in Sweden carried out by Josephson and Hammarlund [10] had the focus on various defects in the building sector. The study was carried out in two parts, the first aimed to evaluate the different defects and costs that occurs in Swedish buildings and the second one aimed to evaluate the cause for the defects. By monitoring the building site and the production phase of seven building projects the study determined, in resemblance with Boverket, that many of the causes of defects occurred because of organisational aspects. The lack of motivation, e.g., forgetfulness and carelessness, and lack of information or knowledge was also common aspects that lead to defects in the building.

The international perspective of water damages in the indoor environment in buildings are limited and focuses on most of the same aspects of the problem as Josephson and Hammarlund [10], defects in buildings. Studies on defects has the focus of various defects in buildings but the ones of interest for this study are the literature that focuses on water damages caused by bursting pipes and inadequate installations and utilities. Chew and De Silva [11] identified 14 important risk factors in wet areas by assessing 56 high-rise non-residential buildings. The study were conducted of interviews with keypersons in the building organisations and site surveys. Results indicated that water leakages were the defect that occurred most frequently in the studied buildings. The causes were located to deficient construction, material, design and maintenance practice. Similar problems and solutions were found in the study

for Defects in affordable housing projects in Klang Valley, Malaysia by Abdul-Rahman, et al. [12]. The authors studied different kinds of buildings in this study and found similar problems and defects.

That the most common reason for that defects occurs seems likely to be because of organisational and design aspects. Several of the studied building projects in the literature review assess this as the main problematic area [13-15]. Whether water damages and water damages due to freezing could be related to defects in the entire building sector as described in the literature could be questioned but since the problematic area seems to be in the design and the organisation phase of the building it does seem likely that the problematic areas also occur in the damage categories this study treats. One aspect that was not clearly specified in the literature was the differences in location of the water pipes that are more exposed to the outdoor climate. One example of this are the water faucet that are placed outside of the building and have pipes that reaches though the insulation and are therefore exposed to the colder climate. If this part of the water system is not designed for being exposed to a colder climate, it could become a part that leads to water damages in the building. Hence causes for defects in the literature are most likely to be similar for the water damages due to freezing that are not covered by the scientific literature found in this study. In the Nordic countries there are examples of literature that cover this possible risk. For example, the industry rules from Säker Vatten [16], is one set of rules and instructions on how the buildings should be built to reduce the amount of water damages. However, these kinds of regulations seems to be missing on an international basis.

3.2 Statistic review

The empirical statistical review of water damages in the Nordic countries are presented as the statistical data of water damage from the different companies with both number of damages and costs of reimbursements from the insurance companies. The results were divided in three parts, with each part representing one of the studied countries. The separation of the statistics are made because of the different categories that each county describes the water damages that occurs. To not compare different water damage categories for each county the statistics are divided with each country´s specific input to the water damage statistics as described in the research methodology.

Water damages in Sweden from Svensk Försäkring are presented as damages from water in different kinds of insurance principles. Damages from water were described as a damage that has occurred due to leakage, moisture or freezing from waterpipe or another reason that is not a natural damage [2]. The statistical data is gathered each year and dates to 1985. As a complement to the statistics from Svensk Försäkring publish Vattenskadecentrum each year a water damages investigation, Vattenskadeundersökningen, with more descriptive information and in-depth analysis of the causes for the water damages in Sweden.

The number of water damages and cost between 1985 and 2019 in Sweden is presented in Figure 1. No specific costs for freezing damages are presented in the statistics and therefore in opposite of Norway and Denmark the cost for the freezing damages are not presented.

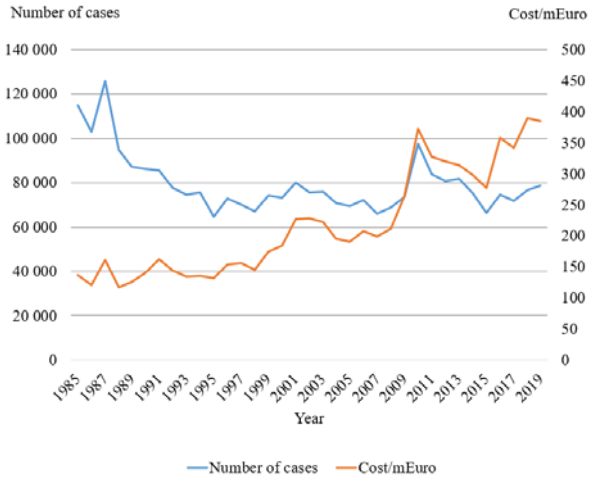


***Figure 1**. Number and cost of water damage cases in Sweden between 1985 and 2019 [2].*

The Norwegian water damage statistics are gathered from the Norwegian financial organization, Finans Norge, which are responsible for the presentation of statistics from the insurance market. The water damages are sorted in different categories that describes where the water damages occurred. The categories chosen for this study are the ones that occurred in the indoor environment. These were, leakage in pipes and sewage, utilities that are connected to the water supply, heating distribution and installations in wet rooms. The timespan of the statistic were between 2008 and 2019 [3]. The number of water damage cases, cost and cost for freezing damages between 2008 and 2019 in Norway is presented in Figure 2.

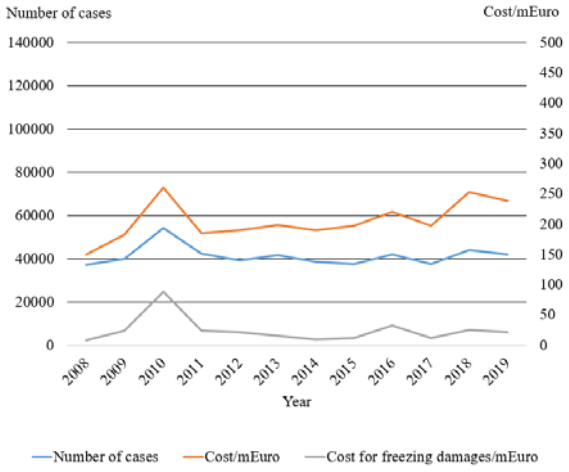


***Figure 2**. Number and cost of water damages cases in Norway between 2008 and 2019 [3].*

The statistics of water damages in Denmark are gathered by the Danish building industry body, Forsikring & Pension, for insurance- and pension companies. The water damage statistic was presented in different damage cause categories. The categories included in this study were water damages cause by inadequate pipes and connections, water damages caused by all other reasons but inadequate pipes and connections, weather and external causes, utilities and installations that are not related to weather and cold and freezing caused damages [5]. The number of reported cases, cost and cost for freezing damages in Denmark between the years 2006 and 2019 are presented in Figure 3.

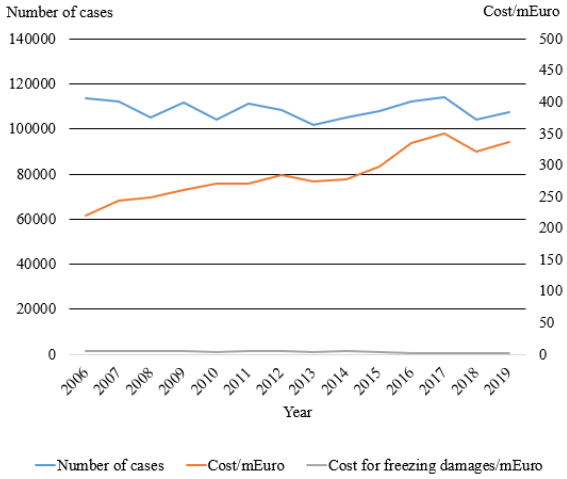


Figure 3. *Number and cost of water damage cases in Denmark between 2006 and 2019 [6].*

3.3 Climate impact on freezing damages

Water damages due to freezing each year in the Nordic countries are presented as a percentage of number of water damage cases and in relation to the mean winter temperature deviation in Figure 4. The mean winter temperature deviation are the factor that determine how much the mean winter temperature a year is deviating from the mean winter temperature for the country. The mean winter temperature is defined as the mean temperature between December, January and February and the deviation from the mean temperature for the climatological normal period 1961-1990. In Sweden, the mean winter temperature are – 4.8 °C [17] and in Norway the mean winter temperature are – 6.8 °C [18]. The y-axis in Figure 4 are presented with an inverted scale to illustrate the deviation of mean winter years with a mean winter temperature that are colder than the mean winter temperature.

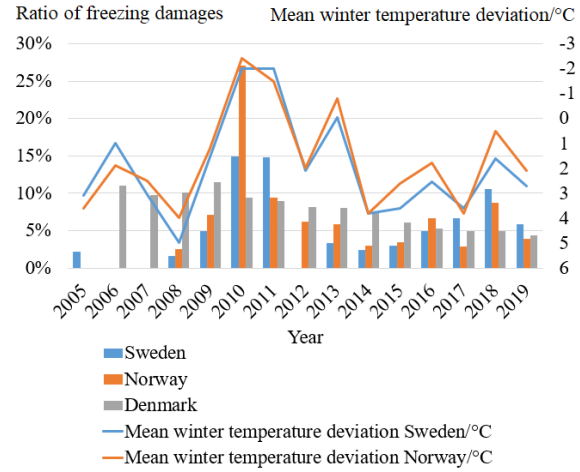


Figure 4. *Ratio of water damages due to freezing in relation to the mean winter temperature deviation for the Nordic countries between 2005 and 2019[1, 3, 6, 17, 18].*

The occurrence of water damages due to freezing in the Nordic countries was extracted from the different statistic gathering companies as the number of water damage cases. Since the number of studied cases varied between the counties and because of the different categorisation of water damages the occurrence of freezing damages was presented as percentage of all damages covered by the statistics. The figure shows the water damages that are reported to the insurance companies as a water damage due to freezing. The gaps of data from the years 2005, 2006, 2007 and 2012 are year that there was not published statistics in some countries and therefore there are no data for these years.

The impact of the climate to the statistics are an important aspect to evaluate to reduce the number of water damages due to freezing. The parameter evaluated in this study was the yearly temperature within the timespan. According to SMHI [17], the Swedish Meteorological and Hydrological Institute, the timespan studied was mostly consistent of years with a mean temperature higher than the normal mean temperature of the reference period between 1961 and 1990. The year 2010 was an exception to this relation. The statistic showed that the mean temperature this year was significantly lower than the other years studied. According to SMHI [19] the winter of 2010/11 was the coldest in since 1987 which also could be seen in the yearly winter mean temperature deviation in Figure 4.

The water damages due to freezing are presented in Figure 4 next to the yearly winter mean temperature deviation for each county according to each county's meteorology institute [17, 18, 20]. The yearly mean winter temperature deviation is an important factor to evaluate in relation to the number of freezing damage cases because of the potential impact of the climate in the cold part of the year. Hence a year with a colder winter than the mean winter temperature could show that the climate could be a factor that affects the number of freezing damages. The correlation between the

climate and the number of freezing damages are therefore evaluated. The Figure 5 present this potential correlation.

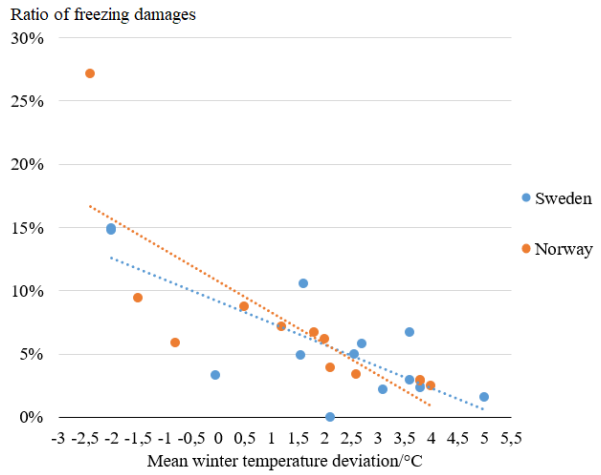


***Figure 5**. Correlation between the mean winter temperature deviation and the percentage of freezing damages.*

The coefficient of determination (R^2) between two parameters are in this case 0.59 for freezing damages that occurred in Sweden and 0.61 for freezing damages that occurred in Norway. This indicates that the climate does have an impact on the number of freezing damages in the Nordic countries. However, the coefficient was not high enough to exclude the fact that other reasons than the cold climate could have an impact on the number of freezing damages.

4 Discussion

From the literature studied in this paper, it could be established that the impact of the climate in relation to water damages are not as well covered as defects in the general aspect of the building sector by the international studies. More research on the subject could be beneficial to reduce the number of freezing damages in cold climate. Researching the causes could be given more focus in the future as only limited facts of the reasons for the damages could be found in the review. However, it could also be established that the organisations and the design and construction of the buildings that have been found in the literature seems to be one of the main problems and it could also be regarded as the one of main problems for water damages. A solution to reduce the amount of water damages that occurs because of freezing could be the organisational, communication and design problems that should be solved in first-hand. This would most likely not only affect the amount of water damages due to freezing but also the whole amount of water damages in the building industry, but since the climate is not a factor that can be controlled it seems most likely that a solution for minimising the risk of freezing damages are to solve these kinds of problems that are mentioned by the studied literature.

The number of water damage cases during the latest 15-year period seems to be constant but the costs are starting to rise which could be indicating that the complexity of building methods could be a reason for that the cost of the water damages are increasing. The empirical statistic review of water damages that occurs in the Nordic counties did also result in the statistic foundation for the study to evaluate the reported cases of water damages due to freezing in the Nordic countries. The study established that freezing damage is not an unusual damage and that it could have correlation to the cold climate in Sweden and Norway, however it seems to not be the only reason for the number of freezing damages. Other reasons that could be factors are the way that buildings are being constructed and designed but also, as mentioned in the literature review, organisational and communication problems in the building process. Some construction and design choices that could affect the buildings resistance against water damages due to cold climate are pipe insulation, building accordingly to building standards against water damage and planning of placement of pipes and connections in the building at an early stage of the building process.

The water damage statistics shows that the years 2010 and 2011 are two years with remarkable higher numbers of freezing damages. This could indicate that the cold climate of 2010 was one reason for the high amount water damages due to freezing in the Nordic counties. In a comparison between the statistics from a country with warmer climate, Denmark, and a country with colder climate, Norway, the same cold year 2010 showed that the percentage of water damages due to freezing was significantly higher in the country with the colder climate.

The coverage and the different categorization for different countries for water damages in the statistics are a problem that could be investigated further. The coverage of single-family houses are high in the Swedish statistic, but the coverage of the apartment blocks are not at the same standard. Hence, the statistic could be an overwhelming representation of damages that occurs in single-family buildings but not in apartment blocks.

5 Conclusion

Water damages in the Nordic countries that are covered by the statistics indicates on a decreasing amount but are still considerable with about 225 000 reported cases in 2019 in the three studied counties, Denmark, Norway and Sweden. The gathered statistics shows that the percentages of water damages due to freezing constitutes between 2-27% of all the reported water damages cases in the three studied Nordic Countries Denmark, Norway and Sweden during the recent 15 years. It could be concluded, based on the results in the study, that there could be correlation between the impact of the cold climate and the number of water damages due to freezing. The number of damages due to freezing do increase a year with a winter

with colder temperature than the mean temperature, this implies that the impact of the climate should be considered and that it need to be constructed and designed for in a larger extent.

The water damages in the studied Nordic countries amount to some 610 – 965 million Euros in insurance reimbursements each year and considering the vast amount and considering the fact of the rising costs it could be justified to establish more risk reducing actions to reduce the amount and cost of water damages that occurs each year. The water damages that occurs due to the cold climate are of importance to address due to the fact that the climate is one factor that cannot be affected by any other methods and therefore the buildings should be designed and constructed to be able to in a sustainable way endure a cold climate.

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Paper III [redacted]

Cost performance analysis of water damage for sustainable prevention measures.

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SUMMARY
Water damage in homes and buildings can cause moisture problems such as mold growth and negative health effects for residents. The water damage from building services not only affects the indoor environment but leads to costs for society both in Sweden and other countries. This paper aims to make a cost analysis to attain an estimate of the cost of water damage to society. The analysis is based on insurance reimbursements, deductibles, depreciation, and age reduction costs for water damage in both residential and non-residential buildings. The results showed that the estimated cost in Sweden amounts to 955 M€ annually. The economic impact that originates from water damage is shown to be immense meaning, there is economic potential for sustainable prevention measures to reduce the amount and cost of water damage.

KEYWORDS
Water damage, IEQ, sustainability, cost analysis, healthy buildings.

1 INTRODUCTION

The indoor conditions for a good indoor climate are affected by factors such as moisture, air quality, and temperature. To achieve good standards on factors, such as these, the buildings should not be affected by moisture problems that could be caused by water damage from installations and systems in the indoor environment. Water damage in the indoor environment that don't get noticed or repaired causes moisture in the buildings that could cause problems in the indoor environment quality, IEQ, and the indoor air. Problems such as respiratory diseases and adverse health effects, such as asthma, respiratory infections, allergic reactions, and eczema have been shown to have a higher likelihood to happen in a building where moisture problems have occurred [1, 2]. Furthermore, aspects such as absence from work due to illness caused by these kinds of problems in the indoor environment and the resident's overall life quality will be affected. Water damage are, therefore, an important factor to give attention to, with the overall aim to ensure good IEQ.

Another sustainable factor is the cost the water damage may lead to. Water damage in buildings are shown to raise in cost and slightly reduce in numbers over time [3-7]. By evaluating the cost and examining the underlying sub-cost categories that make up the actual cost to the society, a comprehensive analysis of water damage costs, could be used as a variable in further research to reduce the amount, cost, and consequences of water damage.

Increased knowledge about the cost of water damage could be used as motivation and further justification to act on measures that could reduce the amount, cost, and impact of water damage. This could also improve the indoor air and the IEQ as a result of reducing the risks of water damage and moisture problems in homes and buildings.

The objective of this paper is to describe the different cost categories that are included when water damage occurs in the indoor building environment, both residential buildings and non-residential buildings. By examining these cost categories in detail, calculations on each

category could be executed and an extensive analysis of the different costs that are derived from water damage could be developed and further researched. This study is based on data that originates from the Swedish construction and insurance industry, but it doesn't exclude other counties to use these calculations for a similar purpose as in this study.

2 METHODS

The aim of this study was to examine and conduct a comprehensive analysis of the water damage costs in the indoor environment. To represent the overall problem of water damage cost, as many buildings as possible, both residential and non-residential buildings should be involved. To be able to make conclusions on the cost of water damage, statistical data that describes water damage had to be obtained. Data that could be analyzed in such a way, that it was only water damage that have occurred in the indoor environment was included. There had to be a clear connection between the origin of the water damage and the cost of the damage. To reach that requirement, the data had to be accessible and described to the extent that the cause and origin could be determined. The data includes damage from tap water, sewage, drainage, household appliances, heating systems, and inadequate waterproof membranes.

Buildings included in this study are residential buildings with the form of the lease as tenancy, condominium, or ownership. Non-residential buildings that are included are premises and offices. The residential building included are single-family buildings, such as dwellings, villas, and holiday homes, multi-family buildings (buildings with more than 2 apartments), such as residential owned multi-family apartments, and apartment buildings with tenancy leases.

The included buildings were specified due to the different insurance categorizations that are in use and that was the main contributor to water damage statistics. In cases, e.g., multi-family apartments, where the insurance companies weren't the contributor to statistics the residential owner, the managing company, or the caretaker were contacted. A good example of this is the multi-family buildings where the statistics often are gathered in-house and not by an insurance company. This was examined during the pre-study for this study. This is according to the multi-family buildings companies, which were contacted during this study, because the deductible cost in multi-family buildings often is larger than the cost for the actual water damage cost, hence the damage is not reported to the insurance company.

In the cases of statistics gathered from the insurance companies, there was one main source of water damage statistics for single-family buildings, the Swedish insurance companies' industry body, Svensk Försäkring [8]. Svensk Försäkring used categorization of damage that occurred including leakage, moisture, or freezing from a water pipe respectively other reasons that weren't caused by nature-related damage [8]. They have gathered statistics yearly between 1985 - 2020 and presented both the number of damage, cost, and what kind of insurance category it occurred in. The included insurance categories were home insurance, insurance of dwellings, leisure home insurance, corporate and real estate insurance inclusive agriculture, and other insurances for single-family buildings. In this study, the number of total damage and costs was used. Due to the large coverage of the statistics and due to that Svensk Försäkring is an industry body that gathers statistics from many different separate insurance companies this gave good coverage over the cost of water damage that occurred in single-family buildings.

The first costs that were evaluated were the reimbursement cost which covers the estimated amount of money that the damage has caused. This was evaluated both for single-family buildings and multi-family buildings. The type of building matters due to whether the damage is reported to the insurance companies and entered in the statistics or as in the case of the multi-family building where the norm is the opposite, as mentioned earlier. The cost of water damage in multi-family buildings is hence evaluated from communication with three, both small and

large, building managing companies in larger Swedish cities. Apartments that were owned by residents, as well as tenancy apartments, were examined. The collection of data was carried out by first asking the companies about their cost for water damage yearly and how many apartments are included in the company´s building stock and asking them about their data to make sure that the damage are within the limitation of this study. Secondly, a water damage cost interval per year and apartment was determined and weight in relation to the building stock. The building stock was estimated by Statistics Sweden [9] and since the key factors are calculated from different years the mean value of multi-family buildings during the last 10 years was calculated, approximately 2 480 000 apartments both in the form of homes owned by the resident, tenancies, and tenant-ownership.

A report is done as an assignment from the Swedish National Board of Housing, Building, and Planning was used as a complement to the communication with the building managing companies [10]. The report describes water damage and costs where companies got to answer and estimate the cost of water damage in their housing stock. An estimation of the cost of water damage in multi-family buildings, based on the gathered data from the three companies questioned and the report by the Swedish National Board of Housing, Building, and Planning, was used. The report is based on 88 building managing companies of varied sizes and over 417 000 apartments together.

Furthermore, the deductible cost of water damage was evaluated by conducting a discussion with insurance companies and analyzing terms and conditions in housing insurance by 5 different companies. The deductible cost for water damage is the cost beyond the reimbursement of the repair or renovation of damage. The insurance categories that were analyzed were leakage, moisture, or freezing from water pipes and household appliances. Since the terms and conditions were constructed differently by the different insurance companies an interval between the highest and the lowest deductible cost was used. Another cost category that was added to the study was the cost of the depreciation and the age reduction on the damaged material. The method used for analyzing this category was, as the deductible cost, searching through home insurance terms and conditions.

The deductible cost and depreciation and the age reduction were either described as a percentage of the reimbursement for the damage or an interval of the cost of the specific cost category. Hence the number of total water damage and the number of buildings in Sweden were needed. The building stock was gathered from the Swedish statistics company [9]. The building stock was divided into what kind of residential home it was, tenancy form, and yearly sectioning.

The last part of the buildings that could have been involved in this study is the uninsured building, such as public buildings owned and managed by the municipality or the state. In these buildings, there were damage statistics found, and it was reasonable to include this in the study but due to the limited quality of the statistics and because the data received did include a vast number of damage that occurred due to exterior circumstances in public buildings owned and managed by the municipality or the state are not included. Therefore, this study was limited to only drawing conclusions based on the other cost categories, insurance reimbursement for single- and multi-family buildings, deductible cost and depreciation, and age reduction.

The total cost estimated in this study is the cost of reimbursements of water damage that the insurance companies pay´s the homeowner in case of the occurrence of water damage, a cost that the homeowner pays for in case of water damage is the deductible, depreciation, and the age reduction cost which is determined by the terms and conditions of the insurance for the home or resident. Calculation of this cost is described in equation 1, where the estimated cost

is the summarized cost of the different cost categories, the reimbursements are the estimated cost of reimbursements for single- and multi-family buildings. The deductible cost is the estimated cost of deductible for home and residential owners. The depreciation and age reduction are the estimated cost that the home and residential owners pay based on the age of their residents.

$$\text{Estimated cost} = \text{Reimburstments} + \text{deductible cost} + \text{depreciation and age reduction} \quad (1)$$

3 RESULTS

Single-family buildings

In Figure 1 the yearly number and cost of reimbursements for water damage in single-family buildings are presented between the years 1985 – 2020 [8]. The statistics showed that the cost of reimbursement for single-family buildings was 2020 approximately 395 000 000 euro in paid reimbursements for water damage by insurance companies and approximately 82 400 cases of water damage in Sweden.

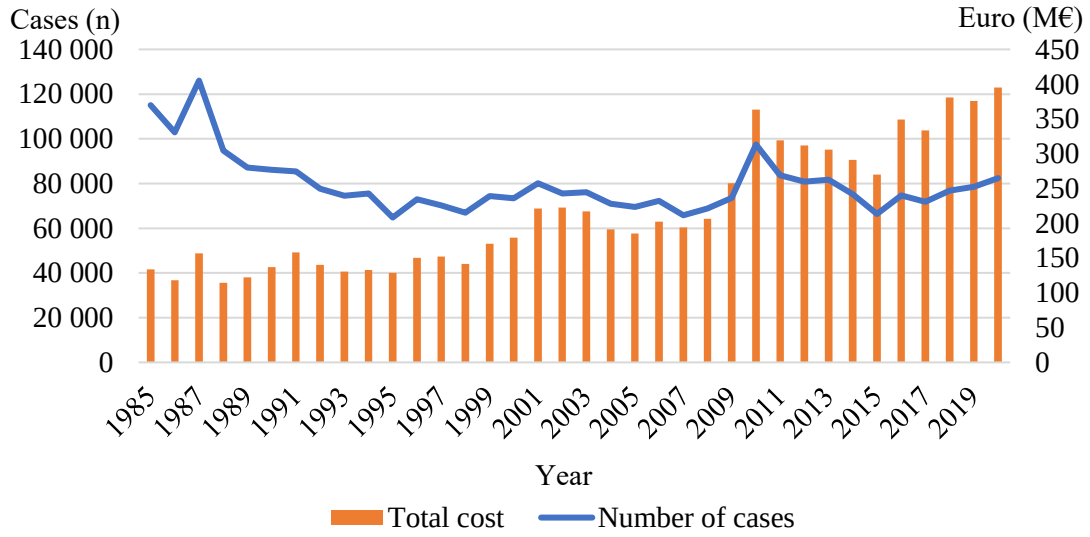


Figure 1 Number and reimbursement cost of water damage that occurred in the indoor environment between the years 1985-2020. The left axis describes the number of cases (n), right axis cost (M€) bottom axis years [8].

Multi-family buildings

The cost of water damage in multi-family buildings, such as apartments owned by residents and tenancy apartments, was estimated by communication with building managing companies. The building stock in each of the building managing companies is presented next to the company. The three companies will be referred to as 1,2,3 to withhold anonymity. The building companies' key factors, approximate cost, and main form of the lease are described in Table 1.

Table 1. Answers from building managing companies of cost for water damage.

Building managing company	Building stock	Main form of lease	approx. cost	Key factor (€ per apartment and year)
1	30 000	tenancy	19,3 M€	64,4
2	25 800	tenancy, residential owned apartments	0,6 - 1 M€	24 - 40
3	4 100	tenancy	1 M€	260

In the Swedish National Board of Housing, Building, and Planning´s report on water damage in residential buildings, the authors assessed the cost for isolated water damage in the interval of 7 700 – 12 800 euros per water damage but mention that it could be higher. Furthermore, they assess a cost of 170 euros per apartment and year for water damage [10].

Deductible cost and depreciation and the age reduction

The cost for deductible costs based on the 5 Swedish insurance companies resulted in different costs depending on the size of the reimbursement of the water damage. In all the studied 5 companies, the deductible cost would be as highest at 965 € per occurred water damage (10 000 SEK) since there was a 10 % limit on the damage cost. A damage cost below this threshold would result in a cost of 10 % of the damage cost unless it is below a certain value described in the terms and conditions of the insurance company. The average value of these costs is described in Table 2.

Table 2. Deductible cost of leakage and freezing damage. Lower and higher limits are presented (€) [11-15].

Interval of deductible cost	Lower limit (€)		Higher limit (€)
Leakage	193	483	965
Freezing damage	193	290	

The lower limit was, in this study, valued at 332 € by weighing the shares of damage that occurred due to water damage related to leakage in pipe systems, equipment, and waterproof membranes, approximate 94 %, and freezing damage approximate 6 % described by Vattenskadecentrum [3-5]. By weighting the lower limit of leakage, 193 €, and 483 €, and freezing damage, 193 € and 290 €, by the respective percentage of occurrence the value of 193 € and 471 € was determined. The lower limit of deductible is thereafter estimated to be the mean value of these values, 332 €. With this value of an approximate interval of a deductible cost of 332 € for damage below the threshold of 9 653 € and a deductible cost of 965 € for damage above the threshold, the deductible cost could be estimated.

The cost of depreciation and the age reduction was calculated by the 5 studied insurance companies that had similar terms for depreciation which are described in Table 3. The Swedish National Board of Housing, Building, and Planning´s report on water damage in residential buildings did also cover this subject but estimated the cost of depreciation and the age reduction to a cost described in Table 4.

Table 3. Terms for depreciation from the 5 studied insurance companies. Cause of damage, number of years without depreciation (n), and value reduction due to age per started year (%) are described [11-15].

Cause of damage	Number of years without depreciation (n)	Value reduction due to age per started year (%)
Pipe and connections, installations, and sanitary equipment (WC, washer, underfloor heating)	10	5
Other installations and appliances	5	8

Table 4. The Swedish National Board of Housing, Building and Planning´s estimation of the cost of depreciation and the age reduction cost [10]. The age of the building and the cost of depreciation and the age reduction (€) are described.

Age of the building (years)	Cost of depreciation and the age reduction (€)
below 10	only deductible cost
10-15	866
over 15	1 922

The calculations were heavily dependent on the age of the building. According to Vattenskadecentrum [5], the number of damage that occurred in buildings built between 2010-2019 was 6 % of the occurred water damage and 8 % for the buildings built between 2000-2009. The key factors for depreciation and age reduction were calculated. The threshold from the insurance companies was 965 € and years without depreciation are described in Table 3. Hence, the lower limit is calculated to the value of 936 € by weighing the number of damage that occurred in 94 % of the building with water damage built before 2010 which had a cost of 965 €. The building built between 2010 – 2019 amounts to 6 % of the water damage, the costs of these damage vary up to the threshold of 965 €. Therefore, the cost used in the calculations is the weighted value of 482 €.

The high key factor was estimated to 2 520 € by using the Swedish National Board of Housing, Building and Planning are presented values, where those damage in building with an age below 10 years are given a cost of 0 €, the 8 % of the buildings within the span of 10-15 are given the cost of 866 € and the remaining 86 % are given the cost of 1 922 €. Hence the weighted key factors for depreciation and the age reduction are 936 € and 2 520 € per occurred water damage.

Total cost estimation of water damage in the indoor environment.

The estimation of the cost of water damage in the indoor environment is based on the key factors that were described earlier. Table 5 describes the cost category, the key factors divided into low, medium, and high because of the different key factors described in the study, the cost of each cost category. To calculate the water damage cost for multi-family apartments the number of apartments in Sweden had to be taken into consideration. The total amount of multi-family apartments in Sweden was estimated to be 2 480 000 [9]. The weight of the building stock for the deductible cost and depreciation and the age reduction was the number of actual occurred water damage used, approximate 82 500 [8]. The medium cost for deductible cost is an estimation of the Swedish National Board of Housing, Building and Planning´s interval of the cost of damage, between 7 700 – 12 800 € where the threshold of 9 653 € is weighted with the low and high key factors because of the large number of apartments that the report is based upon.

Table 5. Key factors are described in low, medium, and high values gathered from results (the reimbursement key factors have the unit per apartment and year). The calculated cost is described in low, medium, and high values.

	Key factor (€)				Cost (M€)			
Cost-category	Low		Medium	High	Low		Medium	High
Reimbursement single-family buildings	-				395*			
Reimbursement multi-family buildings	24	64	170	260	59,5	159,6	421,4*	644,5
Deductible cost	332		-	965	27,4		59,8*	79,5
Depreciation and the age reduction	936		-	2 520	77,1*		-	207,5

*The costs are based on the highest number of coverages in the statistics, these were used to estimate the most probable cost of water damage.

The estimated cost of water damage in the studied categories is calculated between the interval of 559 M€ and 1 327 M€. The estimated cost of the water damage studied (marked * in Table 5) is the most probable because the key factors are based on the largest building stocks and statistics are estimated to be 953 M€.

4 DISCUSSION

A contribution to the field of indoor air, like this study, shows the immense amount of resources that are spent on water damage to uphold a building in good condition both in building physics, building services, and environmental perspectives. Resources that, rather than repair or renovation cost, material, and time, could be used in other projects or be used to develop the field to reduce the amount and cost of water damage in new construction and building projects. This could also contribute to better indoor air quality and environment due to the fact that the moisture in buildings is reduced and that the risks of long-term leakages are noticed earlier as shown in articles [1, 2]. The presented cost does not include all the societal costs as the possible health costs, e.g., sick leave and unpleasantries for residents. The extensive costs however substantiate, especially considering the health impacts, that actions reducing the amount and costs of water damage must be given attention. The comprehensive analysis of the water damage costs, covered by this paper, could be used as a variable in further research to reduce the amount, cost, and consequences of water damage in the indoor building envelope and a holistic perspective to find the best solutions to improve the indoor environment. Costs that both affect the homeowner, such as deductible cost and depreciation, and the insurance companies, such as reimbursements, could be used for measures to improve the indoor air quality.

The estimations of costs presented in this paper are based on assumptions and approximations, hence the results are not given in an exact number. Factors that must be considered when doing a calculation such as this are the impacts of the quality and the quantity of the data. The result is an estimation based on actual statistics and is assumed and considered representative of the building stock. The most probable alternative is therefore based on the key factors with the statistics with the largest building stock [9]. Water damage are dependent on several different aspects, but the age of the building is one aspect that is shown to affect the probability of the occurrence of water damage [4, 5].

5 CONCLUSIONS

The reimbursement cost for water damage in single- and multi-family buildings in Sweden amount to a cost between 455 – 1 040 million euro each year. The deductible cost caused by water damage is between 27,4 - 79,5 million euros each year. The depreciation and age reduction are between 77,1 - 207,5 million euros each year. The estimated cost figure: reimbursement, depreciation, and deductible, for the studied Swedish building stock, can be estimated between 559 – 1 327 million euro per year with a probable figure of 955 million euro per year, assuming the costs reported by the studied companies and reports are valid for all Swedish buildings. This estimated cost doesn't include the cost of water damage in the uninsured buildings. This study shows that large costs are paid due to water damage in buildings and shows the importance to address these kinds of issues possibly being able to instead use the money to improve and add resources to the indoor environment and the indoor air.

ACKNOWLEDGMENT

Formas, The Swedish research council for sustainable development is acknowledged for funding for this study 201900649. Further acknowledged are the Swedish water damage center (Vattenskadecentrum) and the Swedish industry organization for secure water installations (Säker Vatten) for their help with providing statistics.

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Paper IV [redacted]

Examination of Water Damage Statistics in the Nordic Countries to Identify and Suggest Preventive Cost-effective and Sustainable Measures during the Maintenance and Operation Phase

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ABSTRACT

Water damage in the indoor environment is a rising issue within Nordic countries with about 90 000 cases in appx. 6.5 million insurance is reported annually in Sweden, and corresponding numbers are in Denmark and Norway. The question then becomes what type of measures residents, building managers, and insurance companies can take in the maintenance and operation phase to decrease the impact of the water damage. Another question is how the effects, cost, and extent of the water damage are affected if the measures were executed in this phase as preventive measures. This was done by selecting actions and measures that could reduce the impact and cost of water damage, examining the action and measures, and finally analyzing the payback time of the investment of the actions and measures. The study shows average payback times for the actions and measures studied, for passive investments between 10 months and 8 years, and longer for investments that actively shutting off the water in case of a leakage, between 18 years and 30 years on average. The study demonstrates the potential benefit of implementing cost-effective measures, such as waterproof underlays beneath the fridge and the dishwasher. This suggests that introducing effective measures in the maintenance and operation phase will reduce the effect of water damage and also reduce the effect of water damage in a large portion of the existing buildings and therefore also reduce the immense amount of resources annually spent on water damage (approximately 1 billion USD each year in Sweden).

INTRODUCTION

Water damage occurring from leaking pipes or connections, and inadequate membranes from building services, installations, or appliances are annually causing vast costs for building owners, managers, and insurance companies. In Sweden, the reported costs of 90 000 cases amounted to 4.4 billion SEK (0.39 billion USD) in 2021, which in terms of value is the largest damage that occurred in buildings covered by home insurance (Svensk Försäkring, 2022a, 2022b). In other Nordic countries, similar reports could be found (Finans Norge, 2022; Forsikring & Pension, 2022). Actions that are effective,

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sustainable, inexpensive, and applicable actions are desirable in all building industry fields and if the actions are proven to be easy to install and be able to prevent future costs, they are even more desirable.

Water damage tends to occur in specific rooms, of which kitchens have become a more common candidate in recent years. In 2019, it surpassed bathrooms with the most damage in Swedish resident buildings (Vattenskadecentrum, 2020, 2021, 2022). An explanation for this tendency could be the decrease in the expected time for kitchen appliances before they cause a leakage. A majority of the water damage in Swedish kitchens comes from dishwashers, fridges, and freezers, of which 65-70% of the damage comes from appliances installed during the last 10-year period (Vattenskadecentrum, 2022).

The positive outcome of the actions and measures could contribute to increasing sustainable solutions in terms of economic, technological, and health factors. Factors such as indoor air quality, moisture damage, and reducing the climate impact due to fewer damage repairs could be improved upon. Regarding indoor climate and moisture damage, earlier detection of leaking water and less water damage can be a means to reduce moisture in homes, which has been related to respiratory diseases and discomfort (Becher, Høie, Bakke, Holøs, & Øvrevik, 2017; Institute of Medicine, 2004). Further, regarding climate impact, the estimated carbon emission of water damage repair in Swedish buildings is estimated at approximately 250 – 700kgCO_2e, which could be reduced if the water damage is noticed and repaired earlier (Petrovic, Lindkvist, Pettersson, & Apel, 2022). This emphasizes the importance of research on actions to reduce the effect, cost, and amount of damage.

This paper presents actions and measures for reducing water damage that could be implemented, or advocated for, in the maintenance and operation phase of the building by the building owner, manager, or insurance company. The study presents a potential solution to minimize the effects of water damage. By using technology that indicates when water is flowing in undesired places or membranes that direct the leakage to a visible area. Further, the study evaluates the potential economic benefit of installing said actions and measures based on the potential and statistical risk of water damage derived from water damage statistics in Nordic countries. It is proposed that if awareness of the potential cost-reducing actions and measures are increased, the effect and costs of water damage could be reduced; however, it should also be pointed out that solutions merely indicating the water leakage or damage are not the whole solution, but that they could be a vital part of a strategy to reduce the currently vast costs of water damage.

PREVIOUS FINDINGS

In Sweden, Vattenskadecentrum (2022) reports that approximately 33% of water damage in 2021 occurred in the kitchen, and approximately half occurred because of leaking or faulty appliances. In other words, 17% of the water damage in Swedish residential buildings can be derived from faulty appliances or the installation of them. The prominent causes are fridges/freezers and dishwashers which account for 30% and 24% of appliance damage, respectively (Vattenskadecentrum, 2022). Even though there is a demand stated in the industry rules that waterproof underlays should be installed beneath a fridge/freezer and a dishwasher, it´s reported that 15% and 7%, respectively, of the damage occurring due to a fridge/freezer and a dishwasher, lacks a waterproof underlay (Vattenskadecentrum, 2022). However, the majority of damage (57%) occurs due to corrosion, freezing, age/wear, or faulty pipe system installation. Where approximately 53% of the damage occurs in the tap water system (Vattenskadecentrum, 2022). The Swedish insurance industry organization reported that insurance reimbursement in residential buildings from water damage is in terms of value the largest category, approximately 4.4 billion SEK (0.39 billion USD) annually (Svensk Försäkring, 2022a, 2022b).

In other Nordic countries, comparable trends in water damage statistics could be found. In Norway, appliances account for 16% of the total number of damage and 11% of the total reported costs. Where appliances connected to the water distribution system account for 7% of all reported damage (Finans Norge, 2022). In Denmark, approximately 67% of the reported water damage that occurred in 2021 was due to faulty pipes and connections.

The cost of water damage in residential buildings has been investigated and found to vary depending on the examined buildings and the matter of materials that are damaged. Björk, Lind, Kling, and Larsson (2018) studied the damage costs in wet rooms, kitchens, and multi-family residential buildings in Sweden. The study evaluated the cost of typical water damage in wet rooms with tiles or plastic mats as surface layers on the floor and walls, where water has entered the joist through the connection between the membrane and the drain. The studied repair consists of replacing the waterproof membrane and the surface layers, which also involves material costs, transport, taxes, and installation. In wet rooms with tiles of 8 -12 m^2 (86 – 130 sq ft), the total cost was estimated to be 85 000 – 101 000 SEK (7 500 – 9 000 USD). In a wet room with a plastic mat as a surface layer, with the size of 8 – 12 m^2 (86 – 130 sq ft) the total cost was estimated to 56 000 – 64 000 SEK (5 000 – 5 700 USD).

Furthermore, the study evaluated the costs of water damage in kitchens, where the damage studied was a leakage beneath the sink that arose from the tap water faucet. The repair consisted of replacing parts of the floor surface layer and parts of the supporting structure. The cost of water damage in the studied kitchen of 14 m^2 (150sq ft) was estimated to be 30 500 SEK (2 700 USD) (Björk et al., 2018). Other estimations of costs found for this study are not specified depending on in which specific room the damage occurred but are derived from the overall water damage statistics. For multi-family buildings, the cost has been estimated to 80 000 – 133 000 SEK (7 100 – 12 000 USD) per damage in a multi-family building (Björk et al., 2018; Mattsson, Nordquist, Johansson, Bagge, & Wallentén, 2022). The Nordic country's insurance companies cover statistics on water damage and total reimbursement paid out for the damage. The method for gathering and presenting statistics is different between the countries but the average reimbursement for damage is 49 000 SEK (4 400 USD) in Sweden, in Norway 76 500 NOK (7 300 USD), and in Denmark 19 600 DDK (2 550 USD) (Finans Norge, 2022; Svensk Försäkring, 2022a).

METHOD

This section describes how the selection, examination, and analysis of different actions and measures were conducted to determine which and where in the buildings actions and measures are of the most efficiency. Firstly, the selection of which actions and measures to include in the study was done by searching the market for different actions and measures. The actions and measures included in this study were required to be installed by the homeowner, building manager, or contractor without any larger impact on the existing building. For example, adding extensions to existing pipes to indicate leaks, or temporarily moving appliances to add waterproof membranes beneath the appliance. The selection criteria did also include the demand that the actions and the measures should be implemented, used, and available. Secondly, an examination of actions and measures was made, where the selected actions and measures are examined in terms of cost, functionality, and what kind of damage they could prevent or minimize the effect of. The exchange rate used throughout this study was 1 SEK to 0.089 USD (InforEuro, 2022). Thirdly the analysis of the actions and measures was done by an estimation of the payback time in years that an investment in the actions and measures would have. By analyzing the actions/measures by a payback estimation the owners, residents, or building manager receives a reference to decide upon. Furthermore, the payback method is commonly used to assess investments (Yard, 2000). The actions and measures were analyzed in the matter of the potential economic savings due to the reduction of water damage and early prevention measures that could save resources, both in economical and sustainable terms. The selection of actions and measures was carried out by the problem areas where water damage could be prevented, and actions and measures selected to be included in the study were made based on the current market and what kinds of actions and measures were available (Vattenskadecentrum, 2022). The actions and measures that fulfilled the requirements of the study were waterproof underlays for appliances, water monitoring devices, water leak switches, and water leak alarms. These actions and measures have been implemented in projects, have been used, and are available on the market (Säker Vatten, 2020; Ömsen Försäkringar, 2022).

The waterproof underlays for appliances selected for the study are such underlays that if leakage from an appliance occurs the water flows out from beneath (usually hidden) the appliance to a visible area where the water leakage could be stopped. The measure is a passive way to indicate leakage from a dishwasher, fridge, freezer, or water-connected appliance and could also be used in a kitchen cabinet beneath the sink to indicate leakage. It is assumed to be installed by the resident or the building manager without any contractor costs. The waterproof underlay does not stop the flow of water in case of a leakage, but it limits the time that it takes to notice the leakage and therefore take action to stop it, which could reduce the effect of the damage. The damage costs categories that the device is assumed to prevent are kitchens, other spaces (average reimbursement for water damage in Sweden), and damage in multifamily buildings (Björk et al., 2018; Mattsson et al., 2022; Svensk Försäkring, 2022a). The waterproof underlay is used and available on the Nordic market and is a demand in the building regulations for new buildings and renovation in Sweden for example Säker Vatten (2020). The payback of the investment is calculated from the damage that occurred due to 15% of the faulty appliances that are reported missing water-proof underlays (Vattenskadecentrum, 2022). By comparing the reported damage where the water damage that the underlays could reduce or prevent the damage and the building stock, the probability that a building annually has water damage could be estimated to 1 out of 1225 dwellings in Sweden (SCB, 2022; Vattenskadecentrum, 2022).

The water monitoring device is a device that is installed at the inlet pipes of a building most commonly after the water meter. The device is constructed to, varies in performance and execution depending on the brand, monitoring the water flow and creating an overview of the system and the resident's water usage habits. It should be able to automatically shut off the

water flow for the building if a leakage, small or large, is discovered. The damage that the water monitoring device could prevent are smaller leakages inside the structure that aren't visible and that could cause immense damage and even such damage that is the most common in the Nordics, such as leakages due to corrosion in the water tap-water system (Finans Norge, 2022; Forsikring & Pension, 2022; Vattenskadecentrum, 2022). Damage caused by sudden breakage of parts of the system is few but could also be prevented (Nordling & Månsson, 2020). In short, the device could prevent and make the resident or building manager aware of various kinds of unwanted leakages or unwanted flow both in visible and hidden pipes. Water monitoring devices are assumed for this study to be able to reduce and/or prevent the water damage that occurs due to faults in the tap-water system both for the pipes, connections, and appliances, which accounted for approximately 33% of the damage in 2021 in Sweden (Vattenskadecentrum, 2022). With this motivation, the damage costs categories that the device is assumed to prevent are wet rooms with tiles, wet rooms with plastic mats, kitchens, other spaces (average reimbursement for water damage in Sweden), and damage in multifamily buildings (Björk et al., 2018; Mattsson et al., 2022; Svensk Försäkring, 2022a). The devices are not a demand in the Nordic building codes but are available in the market and have been included in independent testing conducted by RISE (2022) (Nordling & Månsson, 2020). In estimation, the water damage that could be reduced or prevented occurs in approximately 1 out of 155 dwellings in Sweden (SCB, 2022; Vattenskadecentrum, 2022).

The water leak switches with switches are devices that are installed locally to detect and stop water leakages from e.g., appliances. In contrast to water monitoring devices, the water leak switches stop the water from a single or pair of pipes that feeds a single unit. That, most commonly, consists of a switch and a water-sensitive sensor. The switch is connected between the appliance's main pipe and the distribution pipe. For example, the water-sensitive sensor is placed where the water would flow if leakage appears, which could be wired and wireless to the switch. These devices are most common in kitchens and rooms without a drain, it is also in these rooms the device could stop the leakages with the most damage, due to that these rooms usually don't have a waterproof membrane, as a wet room usually has, whereas a small but continuous unnoticed leakage could cause large damage to water sensitive material. With this motivation, the damage costs categories that the device is assumed to prevent are kitchens, other spaces (average reimbursement for water damage in Sweden), and damage in multifamily buildings (Björk et al., 2018; Mattsson et al., 2022; Svensk Försäkring, 2022a). These devices are a demand in some installations in Swedish regulations and the product could be widely found in the Nordic market (Säker Vatten, 2020). Water leak switches are assumed for this study to reduce and/or prevent the water damage that occurs due to appliances, accounting for approximately 28% of the damage in 2021 (Vattenskadecentrum, 2022). In estimation, the water damage that could be reduced or prevented occurred in approximately 1 out of every 185 dwellings in Sweden (SCB, 2022; Vattenskadecentrum, 2022).

The water leak alarms are devices that are placed, usually by the resident, in areas where water could leak, the alarm is designed to indicate this, usually with a loud sound, light, or a message to the resident's phone or a combination of the three. These devices are available on the Nordic market but are not demanded by the regulations (Säker Vatten, 2020). The alarms have a similar area of application as the water leak switches, except that the alarms don't shut off the water flow in case of a leakage. The damage costs categories that the device is assumed to prevent and therefore studied are kitchens, other spaces (average reimbursement for water damage in Sweden), and damage in multifamily buildings (Björk et al., 2018; Mattsson et al., 2022; Svensk Försäkring, 2022a). Water leak alarms have a similar area of application as the water leak switches therefore, the estimation of water damage that could be reduced or prevented is the same as earlier, 1 out of 185 (SCB, 2022; Vattenskadecentrum, 2022).

These actions and measures were then examined in terms of cost, functionality, and what kind of damage they could prevent or minimize the effect of. The retail price of the different actions and measures was obtained from a search of different distributors within the Nordic market. Together with the retail price the installation cost and the vat of the product needed to be added. The vat was added according to regulations in Sweden and the installation was added by half a day's work (4h) or a whole day's work (8h) conducted by a contractor with 500 SEK per hour (44.5 USD/h) estimated to 2 000 SEK (178 USD) and 4 000 SEK (356 USD). The measure that required a full day of a contractor that conducted the installation was water monitoring devices since that measure requires encroachment of the pipes and could even demand rebuilding the piping which could take more time but 8 hours for a contractor was deemed sufficient. Water leak switches with switches were considered to require a contractor for 4 hours since is action requires smaller if any, encroachment of the existing pipes. The water-proof underlays and the water leak alarms were not allocated any cost for installation since it was considered, for this study, not to require any contractor for installing such equipment, the installations require no encroachment of the existing pipes and are only to place the device or underlay where water could leak. This is most often written in the installation instructions.

The investment costs of the studied actions and measures were examined at the time of the study. This was done in the Swedish market. In case of any variation of the retail price of the actions/measures, an average price was calculated, as in the case of water monitoring devices, where 7 different devices were studied, and water leak alarms, where 8 different devices were studied. The retail price was one factor that could affect the payback time but since the differences in the found actions and measures within the category were not the function of stopping or reducing water damage but rather other features and additional functions that didn´t affect the inclusion or exclusion of the action/measure in this study. The differences in retail price were therefore reduced to the average price of the included actions/measures. The investment cost included the retail price, the cost of the installation of those actions/measures that were considered to require an installation by a contractor, and the vat. The investment cost for the different actions and measures, whether the action/measure is passive or active the prevention of leakage, the percentage of dwellings estimated to have damage per year, and the estimated damage costs that the action/measure prevents, chosen for the study, are presented in table 1. The estimated damage cost categories are presented in the table for each action/measure, where kitchens, wet rooms with tiles, wet rooms with plastic mats, and multifamily buildings are derived from the study conducted by Björk et al. (2018). Other spaces have an estimated damage cost calculated by the average reimbursement costs in Sweden in 2021 (Svensk Försäkring, 2022a). The rooms, kitchens, other spaces, and wet rooms or buildings allocated to the cost of the water damage were used in this study to describe the difference between water damage occurring in the different spaces and buildings.

Table 1. Average investment cost of studied action/measures (includes retail price, an installation by a contractor, and VAT), if the action/measure has an active or passive way of indicating a leakage, the percentage of dwellings estimated to have damage per year, and the estimated damage cost that the actions/measures could prevent.

Underlays (3 units) *	**Water monitoring devices (7 units) ***	**Water leak switch (2 units) ***	**Water leak alarms (8 units) ***
300 SEK (27 USD)	10 500 SEK (930 USD)	4 700 SEK (420 USD)	460 SEK (41 USD)
Passive**	Active**	Active**	Passive**
0.03%	0.58%	0.54%	0.54%
	Kitchens 30 500 SEK (2 700 USD)		
Kitchens 30 500 SEK (2 700 USD)	Other Spaces 49 000 SEK (4 400 USD)	Kitchens 30 500 SEK (2 700 USD)	Kitchens 30 500 SEK (2 700 USD)
Other Spaces 49 000 SEK (4 400 USD)	Multifamily buildings 106 500 SEK (9 500 USD)	Other Spaces 49 000 SEK (4 400 USD)	Other Spaces 49 000 SEK (4 400 USD)
Multifamily buildings 106 500 SEK (9 500 USD)	Wet room with tiles 93 000 SEK (8 300 USD)	Multifamily buildings 106 500 SEK (9 500 USD)	Multifamily buildings 106 500 SEK (9 500 USD)
	Wet room with a plastic mat 60 000 SEK (5 300 USD)		

* Number of units studied for the different actions and measures.
** Passive and active prevention describe whether the action/measure stops the flow of water or not when leakage is noticed.

The analysis of whether the actions and measures are considered to be cost-effective is conducted with a payback calculation of the investment of the action/measure, which describes, within the limitations of the study, how many years the initial investment of the action/measure is expected to be earned back. The calculation doesn't take inflation and economic speculation into consideration. The payback calculation was done by an estimation, based on the statistics provided by Vattenskadecentrum (2022), on the risk of water damage by the number of occurring damage within the specific water damage that the action/measure is assumed to prevent (room of the building, water damage statistics describing the problem that the actions/measures are assumed to prevent). Furthermore, the probable damage cost was calculated by multiplying the percentage of dwellings with damage per year and the estimated damage costs, and finally, the payback calculation is estimated by dividing the investment cost by the probable damage cost per year. For example, the water leak switch where damage due to appliances is investigated. 11 386 damage were reported in 2021 which approximately corresponds to 0.54% of the dwellings in Sweden reported damage. This corresponds to 1 out of 185 dwellings in Sweden, calculated by comparing the reported damage where a water leak switch could reduce or prevent water damage and the building stock. This estimation of buildings corresponds to the probability that a building annually has water damage. The cost of the damage could, for this study, be in kitchens, other spaces, and multi-family buildings. These costs are divided by the corresponding amount of dwellings with damage per year

(0.54 multiplied by the cost of the damage in this example). This cost corresponds to the annual cost that the resident would have if the investment wasn´t made, these costs are presented in table 2. If the investment was made the payback time is calculated by dividing the investment cost by the probable damage cost if the investment wasn´t made. Then the result is calculated which describes the number of years needed for the investment before it starts paying off in relation to the estimated cost that water damage would cause.

Table 2. Estimated probable water damage cost per year without any measure taken varying due to different expected costs of water damage and what the water damage the action/measures act to reduce/prevent

The expected cost of water damage	Underlays (3 units)	Water monitoring devices (7 units)	Water leak switch (2 units)	Water alarms (8 units)
Kitchens 30 500 SEK (2 700 USD)	10 SEK/year (1 USD/year)	200 SEK/year (18 USD/year)	165 SEK/year (15 USD/year)	166 SEK/year (15 USD/year)
Other spaces 49 000 SEK (4 400 USD)	16 SEK/year (1.5 USD/year)	320 SEK/year (28 USD/year)	266 SEK/year (24 USD/year)	267 SEK/year (24 USD/year)
Multifamily buildings 106 500 SEK (9 500 USD)	36 SEK/year (3 USD/year)	690 SEK/year (61 USD/year)	576 SEK/year (51 USD/year)	577 SEK/year (51 USD/year)
Wet room with tiles 93 000 SEK (8 300 USD)	-	600 SEK/year (54 USD/year)	-	-
Wet room with plastic mat 60 000 SEK (5 300 USD)	-	390 SEK/year (34 USD/year)	-	-

LIMITATIONS

Specific manufacturers and companies of studied actions and measures are not presented, the action and measures are only presented within the 4 chosen groups presented in the previous section. The cost is presented as an average value of the found actions/measures that is chosen to represent the cost of the product if it was bought on the market in Sweden at the time of the study. The function of the different actions and measures within the specific cost categories is considered to fill the same basic functions. The water damage costs are assumed to reflect the different damage types that are occurring in buildings in Sweden but could also reflect buildings in countries with the same cold climate. The expected costs studied are complex and could vary in extent and therefore also size but they reflect common and documented water damage in buildings constructed in cold climates, e.g., with the demands of insulation and structures built in moisture-sensitive material. Another assumption made for the study was that the water damage statistics by Vattenskadecentrum (2022) corresponded to the entire building stock of homes in Sweden.

RESULTS

The examination of actions and measures included the assumptions of what kind of damage they are designed to reduce and/or prevent, and the estimated cost that the water damage would cause which resulted in an estimation of the payback time in years of the investment. Figure 1 presents the estimated payback times for the action measures investigated, calculated with the investment costs provided in table 1. For water alarms, the payback was estimated to be an average of 10 months. For waterproof underlays, the payback was estimated to be an average of 8 years. For the water leak switch, the payback was estimated to be 18 years on average, but with a 10 year-variation in each direction (Figure 1). For water monitoring devices the expected payback time is an average of 30 years.

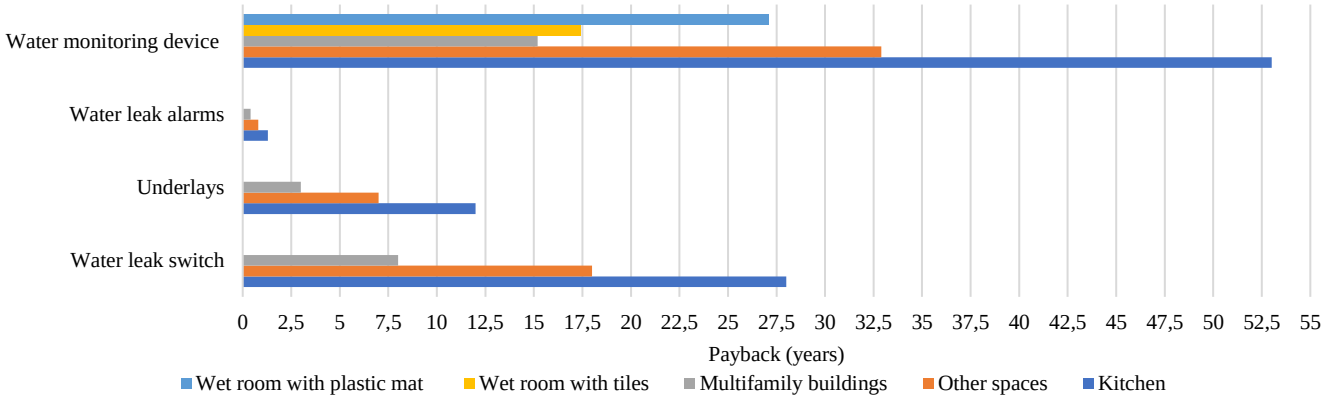


Figure 1 The estimated payback time of water monitoring devices, water leak alarms, underlays, and water leak switch investments divided by the different water damage cost categories (table 1).

DISCUSSION

Constructions built for cold climates pose a number of challenges related to water damage. For one, In the Nordic countries, these constructions are often built with wood or timber, which are vulnerable to moisture, and the constructions also contain considerable amounts of built-in materials, which if exposed to water likely causes expensive moisture damage. The building codes additionally demand that buildings should withstand the climate and the moisture that they must endure in construction and during the building's lifetime both from the indoor and outdoor climate. Furthermore, the Nordic countries have problems with the freezing of pipes and connections that causes leakages, which has increased in recent years (Mattsson, Nordquist, Johansson, Wallentén, & Bagge, 2021). Taken together, it is clear that measures must be taken to reduce the increasing trend of water damage, and actions have been taken regarding building regulations, industry rules, and insurance policies. However, few measures have been taken in the maintenance and operation phase. As a background to this study, then, it is assumed that actions and measures could have a large impact on the total amount and cost of damage since a large portion of the damage occurs in buildings with an age of 30 years or more (Vattenskadecentrum, 2022). This could be because the expected lifespan of the installed products is coming to an end but if products that monitor the water system or indicate that damage has occurred, are installed and if these investments have a payback time that is relatively short of the expected lifetime of the building a vast amount of the water damage and the cost of these could be reduced.

The study shows that water leak alarms have the shortest payback time, approximately 10 months after the installation even though the costs of these devices are for the most part higher than the waterproof underlays, for example, but since the action was estimated to reduce or prevent a higher number of cases the payback time was shorter. A further advantage is that the water leak alarms have a wide area of application and could be used in existing buildings with an underlay already installed, whilst the waterproof underlays are used in 85% of the reported damage cases (Vattenskadecentrum, 2022). However, the combination of actions and measures could be studied in more detail to evaluate how the different measures complement each other. With the method used in this study a higher investment cost, as a combination of multiple actions would imply, would lead to a longer payback time, but that is not certain to be accurate. If the start of the leakage and the time of the leakage detection, by the occupant, building manager, or the device, are reduced the cost could be significantly reduced. For example, the combination of a waterproof underlay and a water leak switch with a switch does limit the leaking water to reach places where moisture-sensitive construction material could be, and the water leak switch turns off the flow of water that would otherwise continue the flow and the actions would not be effective in reducing the water damage if the leaking water would not be stopped manually by a resident. The active actions and solutions are therefore preferable, even though they have a longer payback time because they stop the flow of water from the source without any physical action that needs to be taken by the occupant, building manager, or anyone else. But the passive actions/measures are still better than no action since they make the water damage visible and easier to notice and could also be a way of reducing the time between the leakage and the turning

off of the water flow. Furthermore, it could be installed on more than one device and different devices in a building could have an effect, not only on the water damage security but on the payback time as well, due to more damage could be prevented/reduced. Not studied in this study but will be regarded in studies further on in the project. Additionally, when installing actions and measures the insurance companies could have incentives such as a reduction in the insurance premium due to the installation of the studied actions and measures, which could reduce the payback time as well.

The study is subject to certain limitations, mainly to do with the dataset. First, the study was conducted based on actions and measures used and available in the Swedish market. The damage that the studied actions and measures could have an impact on did not include all the reported damage in that study. Certain water damage types were therefore not included in the study. Specifically, approximately 58% of the reported damage in Sweden has been studied, which implies that the studied actions and measures, even though they could have an impact on the number and cost of water damage, still needs other actions and measures to impact all the reported damage. For example, the results show that water damage occurs from sewage pipes, waterproof membranes in wet rooms, and water-based heating and cooling systems. The results presented in this study are based on statistics where the majority of the reported damage is from dwellings, due to the quality of the insurance coverage and the lack of reporting of damage in other building types in Sweden and the Nordics (not covered by the damage report) but since the statistics are based on a large selection of damage cases (approximate 40 000 cases) in Swedish dwellings it was deemed to represent the entire building stock in Sweden and it could also be applicable in other Nordic countries with similar construction techniques and climate.

Another assumption was the number of dwellings estimated to have damage per year, which the different actions and measures were assumed to be able to prevent. This was done by estimating, from the water damage statistics, the annual risk of one water damage occurring per household. This method accounts for the estimation of water damage to be able to conduct the payback calculation but does not account for multiple units leaking in the same home in the same year. The payback times presented in this study represent the time that the studied investments installed, with the statistics used, would pay back if the studied action/measure was conducted with no relation to other factors such as the size of the building, the number of appliances, usage, and the number of residents. Factors such as these are not included in the statistics and could therefore not be considered. A limitation not related to the dataset is, the total costs of water damage are not only reimbursements from the insurance companies. Costs such as deductible, age reduction of the damaged material that the homeowner needs to cover to get the reimbursement from the insurance company, and costs due to the effects of the water damage, such as sick leave due to moisture in the indoor environment, were not included in this study (Mattsson et al., 2022). The payback times can therefore be assumed to be overestimated in this study. Further research in payback time for a combination of the studied investments together with other measures to reduce or limit water damage would be beneficial to further develop the field and provide decision-makers with more information to reduce the effects of water damage.

CONCLUSION

The study demonstrated that passive actions and measures, such as waterproof underlays for fridges, freezers, and dishwashers and water leak alarms have an average payback time of 10 months (alarms) and 8 years (underlays) depending on the estimation of the damage repair cost. Active actions and measures, such as water leak switches and water monitoring devices have, as an investment an average payback time of 18 years (water leak switches) and 30 years (water monitor device) depending on the estimation of the damage repair cost. Further, the study concludes that the actions and measures investigated would have a substantially shorter payback time if the repair cost were higher. If the studied actions and measures are installed in buildings where the residents/owner are aware that water damage could be costly and if the building is built before 1990 the actions/measures investigated could be used with a shorter payback time to prevent and/or reduce the economic impact water damage but also improve sustainable aspects regarding material usage and indoor air quality and residents' well-being. Lastly, the study recommends a number of actions and measures that can be implemented in the maintenance and operation phase of the building to reduce water damage, without major renovation or encroachments to the specific building.

ACKNOWLEDGMENTS

Formas, The Swedish research council for sustainable development is acknowledged for funding for this study 2019-00649. Further acknowledged are the Swedish water damage center (Vattenskadecentrum) and the Swedish industry organization for secure water installations (Säker Vatten) for their help with providing statistics.

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Paper V [redacted]

Similarities, differences, and tendencies of water damage in the Nordic countries

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Abstract

This extended abstract compiles statistics and information regarding the process of gathering water damage statistics. A questionnaire was used to determine similarities, differences, and tendencies in the water damage statistics, in the Nordic countries Sweden, Norway, Denmark, Finland and Iceland. The study aimed to answer what lessons were learned and what knowledge could be shared between the Nordic countries to reduce water damage. Several suggestions and tendencies between the counties are introduced and what obstacles are hindering a deepened cooperation, based on the answers from the statistic-gathering companies acting in the five countries, such as insurance- and industry organizations. A first step should be to increase the number of buildings included in the statistics, such as multi-family and public.

Peer-review under the responsibility of the organizing committee of the ICMB23.

Keywords: water damage; insurance companies; statistics; Nordic countries; built environment; indoor environment.

1. Introduction

Moisture in buildings occurs because of a vast number of reasons. One common and costly reason is water damage from building services that supply the residents/occupants with tap water, drainage, or heating [1]. Water damage is likely to cause mold growth and in effect worsen the indoor environment [2, 3]. To limit this, buildings and their installations need to be designed to limit moisture and water to reach sensitive materials which could be a breeding ground for mold growth. By annually gathering statistics on water damage and categorizing the occurring damage in such a way that problems could be found, mapped, and used to make educated and informed decisions the aim is to reduce the amount, cost and effect of water damage. Which could limit and reduce the sources of moisture in buildings. This extended abstract composes similar statistics from the 5 Nordic countries, Sweden, Norway, Denmark, Finland, and Iceland, to distinguish and determine key figures and determine approaches aiming at the reduction of water damage in buildings. This is done by a questionnaire answered by the statistic-gathering companies, such as insurance- and industry organizations, in the 5 countries to find and describe the learnings that could be found in countries with similar building cultures, and climates. The goal of the study was to compile and review what statistic is available and what is gathered in the different countries. In doing so, this paper offers data to build further upon in future studies that could show statistical correlations between countries to give guidance on what measures are in need to reduce the amount, cost and effects of water damage.

2. Method

A questionnaire was electronically sent out to industry organizations, insurance companies and universities in Nordic countries to gather information about water damage statistics. The information searched for, concerning documentation, gathering, reporting, extent, and presentation of water damage statistics, was used to determine what kinds of water damage are occurring, what is the costs, why are they occurring, and how is the water damage statistics carried out. Answers from the questionnaire in combination with the estimated reimbursement (cost) per inhabitant in each studied country constitute the basis for the analysis of similarities, differences, and tendencies. The average water damage reimbursement (cost) per inhabitant was chosen as a key figure to relate to the answers received in the questionnaire. It was calculated by dividing the reported reimbursement costs and the number of inhabitants in the country. It should be mentioned that the cost per inhabitant should not be used as a comparison of the different countries as the single parameter alone because of the differences in the reporting of water damage and different categorization of what to include as water damage in each country, other factors could be differences in building code and usage of different technical equipment e.g., monitors. The results presented in this study are based on the latest published statistics gathered in 2020 and 2021, and the questionnaire was carried out in early 2022.

3. Results/discussion

Water damage statistics, population, estimated cost per inhabitant, and the most common cause are presented (Table 1). From the results, it could be distinguished that Norway has the highest cost per inhabitant of the studied countries, followed

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by Denmark and Iceland, even though Norway doesn't have the highest number of damage reported. The main obstacle, as of writing this extended abstract, that was found was the differences in the categorization of statistics and the inclusion and exclusion of different buildings, such as multi-family buildings and public buildings.

Table 1 Comparison of the Nordic countries, based on questionnaire and public statistics.

	Sweden [4, 5]	Denmark [6, 7]	Norway [8, 9]	Finland [10, 11]	Iceland [12]
Reported water damage	90 000	125 000	104 000	31 000	7 000
Reported reimbursement cost	420 000 000 €	360 000 000 €	510 000 000 €	170 000 000 €	20 000 000 €
Population	10 400 000	5 800 000	5 400 000	5 500 000	400 000
Cost per inhabitant per year	40 €	62 €	94 €	31 €	50 €
Most common cause	Corrosion of pipes	Hidden pipes	Wear and age of pipes	Corrosion if pipes	Damaged pipes

The key findings from the responses are (1) Causes and costs are reported comparably but there are important differences in the process of gathering statistics, namely in the categories in which the statistics are presented. For example, Sweden and Norway have separate organizations that gather data which is presented in origin-specific detail whilst Denmark and Finland present statistics in general categories similar to the Swedish insurance industry organization but the details and follow-up of where damage occurs were lacking in the public statistics. (2) The tendency of increasing the number of damage and total reimbursements (costs) was found in all studied countries [4, 6, 8, 10]. (3) The process of reporting damage and the insurance companies' role in collection statistics is similar across all studied countries. (4) Tendencies of increasing emphasis on water damage in kitchens from the insurance industry could be found particularly in rooms without waterproof membranes and floor drains. One explanation for this tendency could be that kitchens in Sweden are the room in dwellings with the largest percentage of damage, where most damage occurs from appliances, such as dishwashers and refrigerators. (5) Building regulations, codes, and insurance policies in the countries are similar from a large perspective but some differences could be found in the way they are intended to regulate, the number of mandatory rules explicitly stated in the rules, or if they are stated as a functional demand differs depending on the country. The differences in rules could account for some differences in the water damage statistics. (6) Differences in which buildings are included in the statistics and what the insurance covers were found. Denmark for example includes personal property and water damage from other sources, e.g., weather, in the statistics, approximately 60% (76 000) of the reported damages originate from water pipes and connections. Sweden and Norway have more detailed coverage of origins and causes and do only include damages occurring within the indoor environment. (7) Similarities in reimbursement cost per inhabitant can be seen in the studied countries, even with varying types and amounts of included buildings; 31 – 94 €. Even though, the result is a subset of the total water damage costs and buildings included in the water damage statistics.

4. Conclusion

Similarities in reporting and in documenting water damage together with the tendencies of number, cost and effects of water damage in the Nordic countries are indicating that the problems with water damage that each country is facing could be shared to a further extent. But if lessons learned and further cooperation between the countries were introduced, it could potentially be beneficial in finding solutions to reduce the amount, cost and effects of water damage in the Nordic countries. The effects of further cooperation, in finding solutions to reduce water damage, could also generate a decline in moisture levels due to water from tap water, drainage, or heating which could potentially improve the indoor environment in homes and buildings in the Nordic countries.

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Paper VI [redacted]

Journal of Building Pathology and Rehabilitation (2026) 11:159
https://doi.org/10.1007/s41024-026-00828-4

RESEARCH ARTICLE

Water damage occurrence in Swedish public buildings

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Received: 3 February 2026 / Revised: 8 April 2026 / Accepted: 13 April 2026 / Published online: 13 May 2026
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Abstract
Water-related damage represents a major challenge in the built environment, with consequences for building performance and occupant health. While external factors can contribute, this study focuses on damage originating from internal sources. Deficiencies and failures in building service systems, water supply, sewage, and technical installations, constitute a substantial problem, leading to repair costs, operational disruptions, material degradation, and health risks linked to mold and poor indoor air quality. Publicly owned buildings in Sweden lack centralized data on such incidents, limiting understanding of their frequency, causes, and economic impact. This study analyzes more than 3000 reported cases of water-related damage across three Swedish municipalities. Causes were categorized at the system level, occurrence was normalized by building category, and repair cost distributions were examined where cost data were available. Results show recurrent water damage across all public building categories. Schools and nursing and care facilities display the widest spread of repair costs, including outliers exceeding 400 000 €. Appliance and membranerelated incidents are less common but sometimes highly cost intensive. Inconsistent reporting and many uncategorized cases limit crossmunicipal comparisons. On average, 13% of buildings had a reported case each year. A standardized, systemspecific reporting scheme would support prevention, risk prioritization, and management.

Keywords Water damage · Cost · Building service systems · Tap water · Sewage · Heating · Moisture · Public buildings

1 Introduction

Water damage occurs in buildings and represents one of the most common types of buildingrelated defects [1–3]. Building defects and especially water damage affects both the performance of the structure and the well-being of its users. Among these, water leakage and the resulting damage are particularly common and resource demanding [2, 4]. Water leakage may originate from external sources such as rainwater intrusion or flooding, as well as from internal sources, including moisture transport within structures or unintended leakage from installations and building service systems. Such damage may arise in various parts of the building envelope or technical systems and often results in significant repair and maintenance costs, operational disruptions, and longterm deterioration of building components. In addition to direct repair and material costs, water damage can lead to secondary problems such as mold growth, reduced indoor air quality, and increased health risks for occupants. Moisture resulting from such water damage has been associated with increased risks of respiratory diseases and other adverse health effects, including asthma, infections, allergic reactions, and eczema [5–7]. Beyond the health implications, residents may also face financial uncertainty regarding insurance coverage and indirect consequences such as absence from work or school. Water damage also entails economic, environmental, and sustainability concerns. Repair and renovation activities increase resource consumption and carbon emissions, while a shortened building lifespan contributes to greater overall environmental impact [8]. Defects in residential buildings and housing projects have been studied to a further extent internationally [2], such

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as single-family buildings in studies such as [4, 9–12] and empirical data from such buildings also exist in Sweden for example [13]. However, studies of water damage or defect data from buildings not for residential use, e.g., schools, offices and premises, were not found to the same extent [2].In Scandinavian countries, systems exist for collecting statistics on water damage, primarily limited to residential and single-family buildings. Despite this limitation, these statistics provide an overview of water damage occurrence and trends in frequency and repair costs, and show that most water damage is caused by faulty pipes and connections, often due to corrosion or ageing [13, 15, 16].

Previous studies indicate that water damage in residential buildings is associated with substantial repair costs, with average expenses of several thousand euros per incident. In 2024, approximately 57 000 water damage incidents were reported in Sweden, leading to insurance reimbursements totaling 4,2 billion SEK (about 440 million €) across roughly 2.4 million single-family buildings [31]. This corresponds to an average reimbursement of 78 000 SEK (around 7 150 €) per incident. Single-family homes account for about 41% of Sweden's total building stock, and nearly all are covered by home insurance. Uninsured homeowners must cover all repair costs themselves, creating a strong incentive for full insurance coverage. Consequently, insurancebased defect data for single-family buildings are considered highly reliable and representative, covering approximately 41% of the national residential building stock. In contrast, no comparable nationwide data collection exists for or publicly owned or multi-family buildings, making single-family statistics uniquely comprehensive.

In Sweden, detailed insurance-based statistics on residential water damage are available primarily through the Swedish Water Damage Centre, while no equivalent reporting system exists for publicly owned buildings [21]. The Swedish residential building stock includes single- and multi-family dwellings and vacation homes [23]. When insured buildings experience defects requiring repair, cases are reported to insurance companies, enabling detailed statistical analyses of causes and costs. Data collection for residential buildings, primarily single-family homes, is conducted by industry organizations and insurers that publish annual summaries. Although insurance coverage rates are not disclosed, the available data indicate that most reported damage cases concern single-family dwellings [13].

In contrast, national statistics for public buildings such as schools, healthcare facilities, offices, and cultural institutions are largely absent due to the lack of a centralized reporting system and uninsured buildings. This results in a knowledge gap, despite these buildings' societal importance and public funding. Municipalities manage extensive building portfolios, yet documentation of water damage remains fragmented across internal systems with varying data quality. Consequently, comprehensive assessments and preventive strategies are difficult to establish. According to the BETSI study by the Swedish National Board of Housing, Building and Planning [24], approximately one-third of Swedish buildings show signs of moisture damage, often linked to health problems from mold and poor indoor air quality.

Previous research has often assumed that the extent and cost of water damage in publicly owned buildings are similar to those in residential buildings, or these have been omitted altogether [1, 25, 26]. In a previous comprehensive cost analysis [25], buildings owned or managed by municipalities, regions, or the state were excluded, while large parts of the residential building stock were included. Accounting for insurance costs, deductibles, depreciation, and age reduction, the total annual repair cost of water damage in single- and multi-family buildings was estimated at approximately 875 million € using the 2025 rate (1 SEK = 0.091 €) [26, 27]. Sweden's residential building stock comprises approximately 2.13 million single-family dwellings, 2.68 million dwellings in multi-family buildings, 278 000 in special housing, and 80 000 in other residential types [23]. The non-residential building stock, including schools, care homes, and offices, consists of about 12 600 buildings owned by the municipalities [28]. In total, 137 500 buildings serve essential societal functions [23], however only about 12 600 buildings are included in this study, as they are owned, managed, and operated by Swedish municipalities and registered as such in the Swedish Real Property Register [28].

Instead, buildings managed and operated by municipalities, regions, or the state, along with private real estate owners, which were not part of the present study. The municipalities often report the defects and water damage cases in their own systems, often separate from the damage reporting system conducted by collaboration between the insurance companies and the SWDC. For the municipalities studied, water damage cases are reported through internal systems that record repair costs and, in most cases, brief comments describing the cause of the damage. These reporting systems are not part of any official or national registry but are instead used internally by the municipalities for operational tracking and follow-up. The structure and level of detail in the documentation may vary between municipalities, and the information is primarily intended for internal use rather than external reporting.

Informed and guided decisions during the design- and construction phases together with management structures are often mentioned as one of the most important solutions to reduce the number of defects and water damage [2, 4, 9, 11, 29]. To be able to conduct and make such informed and guided decisions the knowledge and empirical data

on the causes, occurrence and costs needs to be developed [2]. Therefore, this study aims to examine water damage in Swedish municipalities, focusing on the occurrence, causes, and repair costs of cases related to technical systems such as piping, installations, and waterproof membranes. These buildings are usually not covered by insurance which excludes them from the national insurance company's comprehensive statistical gathering about water damage in buildings [13]. With few sources and limited studies on water damage occurrence and repair costs in publicly owned buildings and with most existing research focused on insured single-family homes there may be significant differences in the types of solutions required to reduce the frequency and cost of water damage incidents. The first important step in increasing this knowledge is to study the buildings not included in the published statistics. This paper aims to contribute to this buildup of knowledge by studying water damage occurring in publicly owned and managed buildings. The research questions that were addressed and analyzed in this paper were:

i. What is the frequency of water damage incidents in publicly owned and managed buildings, and how does this occurrence vary across different building categories, schools, nursing homes, offices, residential, cultural and leisure buildings? Furthermore, how does the observed occurrence compare to the frequency reported for residential buildings in national insurance statistics?
ii. What are the predominant causes and origin of water damage cases in buildings operated and managed by the studied municipalities in Sweden?
iii. How much monetary resources are spent on water damage from installations and systems in public buildings?

Water damage studied in this paper is limited to the unexpected flow of water in undesirable areas within the building, occurring from the building's services, installations, or appliances inside a building. Water leakage from pipes, connections, and valves in the tap water-, sewage, or heating system, and water damage occurring from inadequate waterproof membranes and appliances, such as refrigerators or dishwashers causing damage are all studied in this paper. This categorization of water damage is also commonly used in the statistic gathering companies in the Nordic countries [13, 15, 16, 18]. This paper will use this categorization to be able to compare the results found with the existing statistics in other buildings, such as residential single-family buildings, with larger coverage in the statistics and other studies. This paper does not cover water damage caused by rain, flooding or other nature related water damage cases.

2 Methods

This study compiled data on water damage incidents, associated repairs and costs for the repairs collected by several municipalities in Sweden. The data was extracted from each municipality's internal fault reporting system, where cases related to water damage in municipally operated and managed buildings were documented. To obtain data, six large municipalities, among the 10 largest in Sweden were contacted regarding statistics or records on repairs of defects and damages caused by water leakage. To determine if the quality of data was sufficient for the study, following requirements were used. Data gathered in buildings managed, operated or owned by the municipality.

- Data gathered in buildings managed, operated or owned by the municipality.
- The data had to allow for a clear distinction between damage caused by undesired water flow from distribution pipe systems, appliances, or inadequate waterproof membranes in wet rooms opposed to naturerelated water damage.
- Costs of repairs was an added feature to determine the extent of the damage.
- The municipalities needed to have a size of inhabitants of more than 1,000 and be among the 10 largest municipalities in Sweden.

Three of six municipalities achieved these requirements and were therefore included in the study. The data was gathered from the three different municipalities in Sweden with more than 2243 buildings operated and managed by the municipalities. The studied municipalities were located in the south and middle part of Sweden, where the main part of Swedish inhabitants is located. The data studied in this study was gathered by the municipalities during the years 2017–2022 by first municipality, between 2008 and 2021 for the second municipality. and between 2015 and 2022 for the third municipality. The buildings studied in this paper were publicly owned, managed, and operated buildings in Sweden under the responsibility and ownership of the municipalities. There are also residential buildings, such as apartments that are either owned or rented by private occupants, but where the municipality remains the ultimate owner. However, because the municipalities' records lack operational data for this type of property, these buildings were excluded from the analysis. Furthermore, the allocation of data of this paper coincided with a system transition in one of the municipalities' subsidiary companies for data collection.

Municipality 1, a southern Swedish municipality hereafter referred to as MU1, provided data from repair reports and facility management records, including entries on

maintenance and damage costs. Information on building properties, including names, addresses, and internal accounting units used for allocating costs, was also included. These records were complemented by contextual notes provided by operational personnel, describing individual cases.

Municipality 2, also located in southern Sweden hereafter referred to as MU2, contributed detailed damage reports and facility management documentation. Each record included standardized fields such as case number, object number, contractor, property name, date and time of incident, building part, type of damage, and associated preventive measures, along with information on repair costs. Together, these reports provided a systematic account of propertyrelated incidents, their causes, and the municipal responses implemented.

Municipality 3, a west Swedish municipality hereafter referred to as MU3. Data were drawn from service and maintenance records, encompassing both routine and incident-based reports. Each entry contained structured fields such as service request ID, description, creation date, management object ID and name, financial category, and responsible management area. These records enabled systematic analysis of municipal resource allocation, operational workflows, and responses to maintenance and damage events.

This study used a mixed-methods approach combining quantitative and qualitative analyses to investigate the occurrence, causes, and economic impact of water damage in municipally owned, operated and managed buildings the three Swedish municipalities. The methodology is structured into three main components: occurrence analysis, cause categorization, and water damage repair cost evaluation.

3 Occurrence analysis

Water damage case data were collected from three municipalities (MU1, MU2, and MU3), with a total of 3 030 reported cases. The selection of cases for analyzing the occurrence of water damage was based on a set of predefined criteria, as described below, applied in each municipality. The criteria were each case includes metadata such as the year of occurrence, building type, and, where available, repair cost and cause of damage, as recorded in the municipality's own system. For this study, the data was provided by the municipalities, who extracted water damage cases from their internal reporting systems. The dataset initially included a variety of water damage cases, some of which fell outside the scope of this study. Therefore, the metadata was carefully analyzed to identify and exclude cases not relevant to the study. Only cases with sufficient detail were retained, allowing a clear distinction between damage caused by unintended water flow, such as leaks from distribution pipe systems, appliances, or inadequate waterproof membranes in wet rooms, and those resulting from external, nature-related events not analyzed in this study. This was done for MU1 and MU2 since the metadata included information about the water damage cases that allowed for this sort of exclusion of the cases not within the scope of this study. Regarding municipality 3 (MU3), the analysis of water damage cases was conducted using a keyword-based filtering approach due to limitations in the structure and categorization of the reporting system. Specifically, all cases containing the term waterleak* "vattenläck" (including variations such as "vattenläcka", "vattenläckage", etc.) were extracted and included in the analyzed data. This method enables the identification of relevant cases where water leakage is explicitly mentioned in the incident description. However, it also introduces certain limitations, such as ambiguity in context: The presence of the chosen keyword does not guarantee that the damage falls within the defined scope of this study, i.e., damage caused by internal systems such as tap water, sewage, heating, or appliances. Without structured fields for cause or system type, it was not possible to distinguish between the different sources of water damage or to perform any detailed cause or repair cost analysis. Despite these limitations, the keyword-based approach provided a method for identifying water damage cases in MU3 and allows for a comparative analysis with municipalities that have more structured reporting systems.

The data were collected over different periods depending on the municipality: between the years 2017–2022 for the first municipality, 2008–2021 for the second, and 2015–2024 for the third. After sorting the cases by municipality and building type according to the Swedish building stock register [28], the average number of reported damage cases per year was calculated for each building category. All of buildings in the Swedish building stock register [28] is divided into the building categories, which were applied for this study.

- Schools, including preschools, elementary schools, high schools, and universities.
- Nursing, and Care homes, including care centers, hospitals and animal hospitals.
- Municipality-owned residential buildings.
- Offices and Premises, including fire- and police stations, correctional facilities, bus stations, municipal building.
- Culture buildings, including buildings for cultural activities.
- Leisure buildings, indoor aquatic center, societal and community buildings, sports buildings.

The buildings included in this study are managed, operated, and owned by the municipalities. The analyzed cases cover

a range of building types, including schools, offices, nursing and care homes, residential buildings, leisure facilities, and cultural institutions. The data from all municipalities were compiled and sorted into the six building categories. The building categories were sorted from the municipality internal accounting system which reported the damage to the municipality and were therefore used in this study and sorted into the categories of the Swedish building stock register.

To analyze the building stock in the municipality and the occurrence of water damage, it was first necessary to identify the buildings associated with reported cases. While additional buildings of these categories could exist within each municipality, Table 1 presents the subset of the building stock included in this study, for which corresponding water-damage records were collected and analyzed. Of the total 18 282 reported cases, 3 030 could be confirmed as falling within the scope of this study. The remaining cases were attributable to external factors such as precipitation, flooding, and other nature-related events. It is possible that additional cases within the approximately 15 000 excluded reports also met the study's inclusion criteria; however, due to the sampling methodology and limitations inherent in the reporting system, these cases could not be reliably classified for inclusion.

To further examine the occurrence of water damage by building category, the dataset was analyzed to determine the number of reported cases within each category. These results were presented as a heatmap, showing both the absolute number of reported cases per building type and the number of water damage cases in each category per year. While the data allows identification of whether a building has experienced water damage, it is not possible to verify whether multiple records with the same building name correspond to the same event. Therefore, the analysis focuses on the total number of reported cases within the municipal building stock rather than individual damage cases. This approach enables a comparative view of water damage occurrence across building categories while accounting for differences in the size of the building stock in each municipality.

4 Cause categorization

The damage categorized as water damage is such damage that occurred in the municipality's property through undesired water flow from distribution pipe systems, appliances, or water from inadequate waterproof membranes in wet rooms. To identify the underlying factors behind water damage, the data can be divided into categories that indicate the system in which the damage occurred rather than the exact root cause. In this study, 'cause' refers to the affected

Table 1 Municipal building stock in Sweden, from Swedish building stock register, divided by building category

Number of buildings	Munici-pality 1 number of buildings (ratio of buildings in category in relation to total in MU)	Munici-pality 2 number of buildings (ratio of buildings in category in relation to total in MU)	Munici-pality 3 number of buildings (ratio of buildings in category in relation to total in MU)	Sum of buildings in the studied municipalies number of buildings (ratio of buildings in the studied MUs in relation to total in Sweden)	Total buildings owned by municipalities in Sweden (2023) [28]
Schools	175 (22%)	148 (70%)	500 (41%)	823 (11%)	7 206
Nursing and care homes	129* (16%)	6 (3%)	80* (7%)	215 (41%*)	520
Residential	400 (50%)	Not known	440 (36%)	840	Not known
Offices	24 (3%)	16 (8%)	19 (2%)	59 (4%)	1 518
Leisure	48 (6%)	20 (9%)	143 (12%)	211 (11%)	1 862
Culture	32 (4%)	21 (10%)	42 (3%)	95 (6%)	1 520
Sum	**808**	**211**	**1 224**	**2 243 (18%)**	**12 626**

The table includes only the buildings managed, operated, and owned by municipalities [28].

*Numbers retrieved from the municipalty, not from the swedish property register, due to different owner structure and that the buildings are not included in the register, hence the ratio of the buildings in MUs in relation to Sweden is so high, there are probably more nursing and care homes in Sweden than registered in the national property register

system, such as tap water, sewage, heating, appliances, or waterproof membranes, since detailed trigger points (e.g., corrosion, material failure) are not consistently available in the municipal datasets. Categorizing by system enables a structured analysis of where failures happen and supports comparisons with national statistics for residential buildings. The categorization of water damage causes is divided into a system used by the Swedish industry organization for water damage [21]. These categories are unexpected flow of water in undesirable areas within the building, occurring from the building's services, installations, or appliances inside a building as this is the same distiction as the Swedish water damage center, SWDC, are using analyze water damage cases in single-family residential buildings. The following categories was used:

- *Pipes and connections*, e.g. water leakage from pipes, connections, and valves in the tap water, sewage, or heating system.
- *Appliances* and installations where the appliance or the connection to the pipe system has failed, including appliances without any connection to the tapwater, sewage or heating system e.g. refrigerators or dishwashers, and other utilities in buildings with any water source.
- *Waterproof membranes*, penetration of water or moisture through waterproof membranes or joints in wet rooms [21].

The municipalites have developed their own reporting system. This means that the structure differs and for some municipalities it was easier to divide the water damage cases into the categories applied by the Swedish Industry organisation and for others it was more difficult. Data points with sufficiently detailed descriptions to enable categorization were manually reviewed and classified according to the definitions outlined above. Each record was evaluated based on its textual description and accompanying metadata, such as type of repair, location, and damage notes, provided by the municipalities. In cases where the wording or terminology in the metadata suggested a likely connection to one of the SWDC categories (for example, references to leaking pipes, faulty appliances, or damaged waterproof membranes) but lacked the level of detail required for a confident classification, such as confirmation of the leakage source, the exact location of the damage, or a clear description of the repair work, the data point was considered uncertain and therefore assigned to one of the residual categories described below.

- *Unknown* cause of the water leakage or damage, these datapoints could be water damage cases without any additional information in the municipality´s data.
- *Other* water damage or moisture damage, such as sabotage, and treatment of mould growth, without any description of the origin of the water damage. E.g. water damage cases not in the scope and limitations of this study.

Furthermore, the reported damage cases were categorized according to the damage type classifications used by the SWDC [21]. While the SWDC framework distinguishes between several underlying causes of pipe and connection failures, the available dataset in this study did not contain sufficient metadata to determine the specific cause of each damage event. Instead, the classification was limited to identifying the system in which the damage occurred. The pipe and connecions systems presented in this study included the following three categories following the categiries defined in SWDC.

- *Tapwater*: Tap water systems of pipes and connections that deliver water in buildings. These systems include main distribution pipes and connections in buildings, connections and joints between the pipes. Common issues in these systems include corrosion, freezing, and material degradation due to age and wear.
- *Sewage*: Sewage systems consist of pipes and connections that transport wastewater from buildings to treatment facilities. These systems include main sewer pipes, building branch pipes, and the connections and joints between pipes.
- *Heating systems*: Heating systems consist of pipes, radiators, and connections that distribute heat within buildings. These systems include main supply and return pipes, distribution pipes in rooms, and the connections and joints between components.

The appliance-related water damage cases identified in this study were categorized into specific subtypes based on the source of leakage or malfunction, listed below. Unlike the SWDC data, which commonly features damage from household appliances such as refrigerators and freezers, the appliances in public buildings were more varied and often part of larger, centralized systems.

- *Refrigerator/Freezer*: Leakage from the appliance, whether connected to the main water supply or not. The leakage could occur from condensation over longer periods which cause damage.
- *Dishwasher*: Leakage from the appliance, its connection to the main water supply, sewage or the appliance causing water damage from other reasons.

- *Heat pump and HVAC*: Leakage from the appliance, its connection to the main water supply, sewage or the appliance causing water damage from other reasons.
- *Other*: Any damage or issue that does not fit into the above categories.
- *Unknown*: Damage or problems where the cause cannot be determined.

The waterproof membrane-related water damage cases identified in this study were categorized into specific failure types based on the location and nature of the leakage, listed below.

- *Connection Floor Drain*: Leakage occurring due to penetration of water between the floor drain connection to the floor waterproofing system.
- *Waterproofing Layer*: Leakage through the waterproofing layer or membrane applied to floors or walls to prevent water from penetrating into the structure.
- *Joint/Seam*: Leakage through joints and seams in the waterproofing layer or membrane applied to floors or walls to prevent water from penetrating into the structure.
- *Pipe or other penetrations*: Leakage through penetrations, pipes, fastenings, etc. in the waterproofing layer or membrane applied to floors or walls to prevent water from penetrating into the structure.

5 Water damage repair cost evaluation

In the municipalities' reporting systems, the costs of repair are registered alongside the reported water damage cases in two of three studied muncipalies. These cost entries are recorded as part of the municipalities' internal property management and maintenance systems and therefore provide a direct link between reported damage events and their financial consequences. This makes it possible not only to track the frequency and type of damage, but also to quantify the economic impact associated with them.

Repair cost data were available for MU1 and MU2. MU3 was excluded from cost analysis due to lack of avaliable repair cost data in the data gathering phase. For MU1, all 726 damage cases included cost information, while 173 out of 291 cases in MU2 had reported costs. Costs were converted from SEK to EUR using the exchange rate of 1 SEK = 0,091 € [18]. Boxplots were generated for each cause category, showing the cost distribution across different building types. The boxplots include median, interquartile range, whiskers, and outliers. These visualizations help to identify both typical and extreme cost outcomes and provide insights into the variability and skewness of the data. The geometric mean (μ) was calculated for each category to account for skewed distributions. To address the skewed distribution of repair cost data, the geometric mean (μ) was calculated for each category. Unlike the arithmetic mean, which can be heavily influenced by extreme outliers, the geometric mean provides a more representative central value for datasets with large variations. This approach is particularly relevant because water damage costs vary widely, from minor surface repairs to full-scale renovations, resulting in a right-skewed distribution. By using the geometric mean, the analysis reduces the impact of exceptionally high-cost cases and offers a more balanced comparison across building types and damage categories. Inflation adjustments were also considered to ensure comparability of costs reported over different years, these adjustments where of data from the Swedish Statistic organisation (SCB) [30]. The formula used for geometric mean is:

$$\mu = \sqrt[n]{x_1 * x_2 \ldots * x_n}$$

where x_1 represents the individual water damage cost values and n is the number of cases with reported repair costs. Scatterplots and boxplots were used to identify patterns and outliers in the cost data. These visualizations helped highlight building types and damage causes associated with particularly high or variable repair costs. The analysis also considered the skewness of the data and the presence of extreme outliers, which significantly influence average water damage cost metrics.

6 Results

This chapter presents the number of water damage cases identified in the municipalities included in the study, with the results divided into three sections. The first section presents the occurrence of water damage cases across the studied municipalities, including frequency and distribution by building category. The second section analyzes the categorization of damage based on the affected system, such as tap water, sewage, heating, appliances, or waterproof membranes, rather than detailed root causes. The third section examines the economic impact by evaluating repair costs, highlighting variations between building types and identifying patterns such as extreme outliers and skewed distributions. The term "studied cases" refers to the data points analyzed in this research. The study focused on water damage caused by internal sources, such as failures in tap water, sewage, and heating systems, as well as appliances and waterproof membranes. External sources of water damage, including rain, flooding, and groundwater, were excluded, along with general moisture issues not directly linked to leakage.

Table 2 Summary of the number of buildings, reported damage cases, and the subset of cases included in the analysis for each municipality, along with how many cases could be categorized and how many included repair cost data

MU1	Building stock [28]	Total number of reported cases	Occurrence (Number of cases within the scope of this study)	Detailed cause description (Number of cases within the scope of this study)	Number of datapoints with costs (Number of cases within the scope of this study)
	808	1 232	726	90	726
MU2	211	544	291	231	173
MU3	1 224	16 506	2 013	0	0
Sum	2 243	18 282	3 030	321	899

Table 3 Number of total reported cases and number of studied cases in municipalities

	MU1		MU2		MU3	
	Total reported cases (*n*)	Studied cases (Ratio of total and studied cases)	Total reported cases (*n*)	Studied cases (Ratio of total and studied cases)	Total reported cases (*n*)	Studied cases (Ratio of total and studied cases)
2008	-	-	13	2 (15%)	-	-
2009	-	-	49	46 (94%)	-	-
2010	-	-	73	36 (49%)	-	-
2011	-	-	69	41 (59%)	-	-
2012	-	-	59	35 (59%)	-	-
2013	-	-	35	18 (51%)	-	-
2014	-	-	45	22 (49%)	-	-
2015	-	-	48	20 (42%)	1460	223 (15%)
2016	-	-	16	5 (31%)	1492	211 (14%)
2017	155	91 (59%)	18	9 (50%)	1387	195 (14%)
2018	104	59 (57%)	31	11 (35%)	1444	157 (11%)
2019	155	109 (70%)	15	11 (73%)	1421	213 (15%)
2020	174	104 (60%)	28	11 (39%)	1705	198 (12%)
2021	260	163 (63%)	45	24 (53%)	1912	233 (12%)
2022	384	200 (52%)	-	-	1895	156 (8%)
2023	-	-	-	-	1835	192 (10%)
2024	-	-	-	-	1678	198 (12%)
2025*	-	-	-	-	277	37 (13%)
SUM	**1 232**	**726 (59%)**	**544**	**291 (53%)**	**16 506**	**2013 (12%)**
Building stock	808		211		1 224	

*Until 27 of Feb 2025. Data after this date is not analyzed further due to the gathering of data occurred during 2025.

After applying the exclusion criteria mentioned above in the method to remove irrelevant or incomplete entries, 1017 cases from MU1 and MU2 were selected for detailed analysis. For MU1, 726 cases were included in the occurrence analysis, all directly related to water damage as defined in this study. However, only 90 cases could be categorized by cause, all of which were related to heating systems under the "pipes and connections" category. MU2 provided more detailed data, with a total of 291 cases within the scope of this study, allowing cause categorization of 231 cases and further sub-classification by affected system (e.g., tap water, sewage, heating systems) and appliance type (e.g., dishwasher, HVAC). Table 2 summarises the number of studied buildings, total reported damage cases, and the subset of cases included in the analysis for each municipality. The table also shows the number of cases for which a detailed cause could be identified, as well as the number of records with available repair cost data. As shown, MU1 and MU2 provided structured datasets that enabled both cause categorisation and cost analysis, while MU3 reported a large number of incidents but lacked the metadata required for further classification. In total, 3 030 cases across 2 243 municipal buildings were included in the occurrence analysis, with 321 cases allowing detailed cause categorisation and 899 cases containing repair cost information.

7 Occurrence analysis

The total number of cases analyzed in the first municipality (MU1), Table 3, was 726 water damage cases out of 1 232 cases reported by the municipality in 808 buildings managed and operated by the municipality between the years 2017 and 2022. The total number of cases analyzed in in the

second municipality (MU2), Table 3, was 291 water damage cases out of 544 cases reported by the municipality in 211 buildings managed and operated by the municipality between the yers 2008 and 2021. The total number of cases analyzed in the third municipality (MU3), Table 3, was 2,013 water damage cases out of 16 506 cases reported by the municipality in 1 224 buildings managed and operated by the municipality between the years 2015 and 2024. These cases were selected for analysis based on predefined inclusion criteria, where the criteria excluded cases that were incomplete, irrelevant, or outside the scope of the study, such as moisture issues not linked to internal water leakage or damage caused by external sources like rain or flooding.

It is important to note that the number of analyzed cases in each municipality does not necessarily reflect the total number of water damage incidents that may have occurred. The selection was based on predefined methodological criteria, which excluded cases that were incomplete, lacked sufficient detail, or fell outside the scope of the study. As a result, while additional relevant cases may exist within the municipal reporting systems, they were not included in the analysis due to limitations in data structure, categorization, or documentation quality.

For each municipality, the average number of reported damage cases per year and the ratio between the number of damage cases per year in relation to the total number of buildings in each buildings category was calculated and presented in Table 4. While additional relevant cases may exist, the selection was limited by the scope and structure of the available data.

The average number of damage cases per year divided with the number of buildings varies between 9 and 16% for the three studied municipalities. This means that on average 1 of 6,5 (15%) of buildings have a damage reported each year. In this study, the average annual share of buildings with reported water damage was 15% in MU1, 9% in MU2, and 16% in MU3. The portion is very similar for the three municipalities. In a comprehensive review of the studied cases across the three municipalities, MU2 shows a somewhat lower average percentage of water damage incidents in municipally operated buildings.

When compared to the residential building stock reported by the Swedish insurance industry [13], where approximately 4% of privately owned single-family homes experience water damage annually [1], the percentage in the municipalities (9–16%) is much higher. The figures shows that a noteworthy higher amount of water damages occurs in building types owned and managed by the municipalities compared to private single-family homes.

When comparing only the residential buildings owned by the municiplaties the occurrence of such incidents in municipally owned, operated, or managed residential buildings appears to be lower. However, these figures reflect the studied public building types, and the proportion of residential buildings specifically affected was notably lower, suggesting either reduced occurrence or underreporting in the municipal sector.

The categories schools, offices and nursing and care homes have the highest number of water damage cases per year related to the building stock within each category. Nursing and care homes have the portion, varying between 37% −67% of the building stock. For offices, however having a limited number of building in total, the corresponding portion is 11% −46%. For schools the portion varies between 5 and 27% or on average calculated for all three municipalities 18%. In municipality 1 the portion 27% means that on average more than 1 of 4 schools buildings have a water damage reported each year. As the number of school building constitute a rather large portion of the municipalities building stock this amounts to high number of buildings. It can also be mentioned that the analysis is based only on cases that were verified and reported as actual water damage

Table 4 The average number of reported damage cases per year between the studied years

Building category	Building stock			Average number of reported damage cases per year (ratio between average number of cases per year and number of total buildings in the category)			
	MU1	MU2	MU3	MU1 (2017–2022)	MU2 (2008–2021)	MU3 (2015–2024)	Total
Schools	175	148	500	47 (27%)	8 (5%)	95 (19%)	150 (18%)
Office	24	16	19	11 (46%)	3 (19%)	2 (11%)	16 (27%)
Nursing and care homes	129	6	80	47 (37%)	4 (67%)	39 (49%)	90 (42%)
Residential	400	-	440	5 (1%)	-	3 (1%)	8 (1%)
Leisure	48	20	185*	5 (10%)	1 (5%)	59 (32%)	65 (26%)
Culture	32	21		7 (20%)	4 (19%)		
Sum	808	211	1 224	122 (15%)	20 (9%)	198 (16%)	340 (15%)

*The building categories in municipality 3´s reporting system is combined.

in the database, meaning that additional cases may exist that were not included due to the study's delimitations. Consequently, the real number, and thus the true proportion, is likely higher than the percentage reported. To further examine water damage occurrence by building category, Fig. 1 further presents the number of studied cases in each category presented in a heatmap. Figure 1 present the number of water damage cases in relation to the total number of buildings in the municipality MU1 per year. The dataset enables identification of whether a building, in the differernt building categories, has experienced water damage; however, it does not allow verification of whether two records with the same building name refer to the same event. Consequently, the data are expressed as the number of reported damage cases within the total municipal building stock. When comparing the reported number of water damage cases over the years the schools and nursing homes are standing out with high number of cases for municipality 1 in the years 2021 and 2022. A somewhat increasing number of damage cases seems to be the trend for municipality 1.

The number of studied buildings in municipaliy 2 was 211 buildings [23]. In the following Figs. (3–4), the same analysis is applied to MU2 as in 1, enabling comparison between the three municipalities water damage data. Figure 3 presents the number of studied cases in each category presented in a heatmap. Figure 4 present with the ratio of buildings with water damage cases in relation to the total number of buildings in each category in the municipality per year. For municipality 2 the reported cases seems to be rather similar over the years. Nursing and care homes have a high ratio of cases in regards to the number of buildings.

The number of studied buildings in municipaliy 3 was 2 013 buildings [23]. In the following Figs. (5–6), the same analysis is applied to MU3 as in 1, enabling comparison between the three municipalities water damage data. Figure 5 presents the number of studied cases in each category reported each year presented in a heatmap. Figure 6 present the number of buildings with water damage cases to the total number of buildings in each category in the municipality per year.

In municipality 3 the schools have a high amout of damage cases per year and as seen in Fig. 6 the ratio of building with a water damage and number of buildings is mostly constant at 20%. However, the nursing and care homes maintain a consistently high ratio of water damage cases across all studied years, indicating that these facilities are particularly

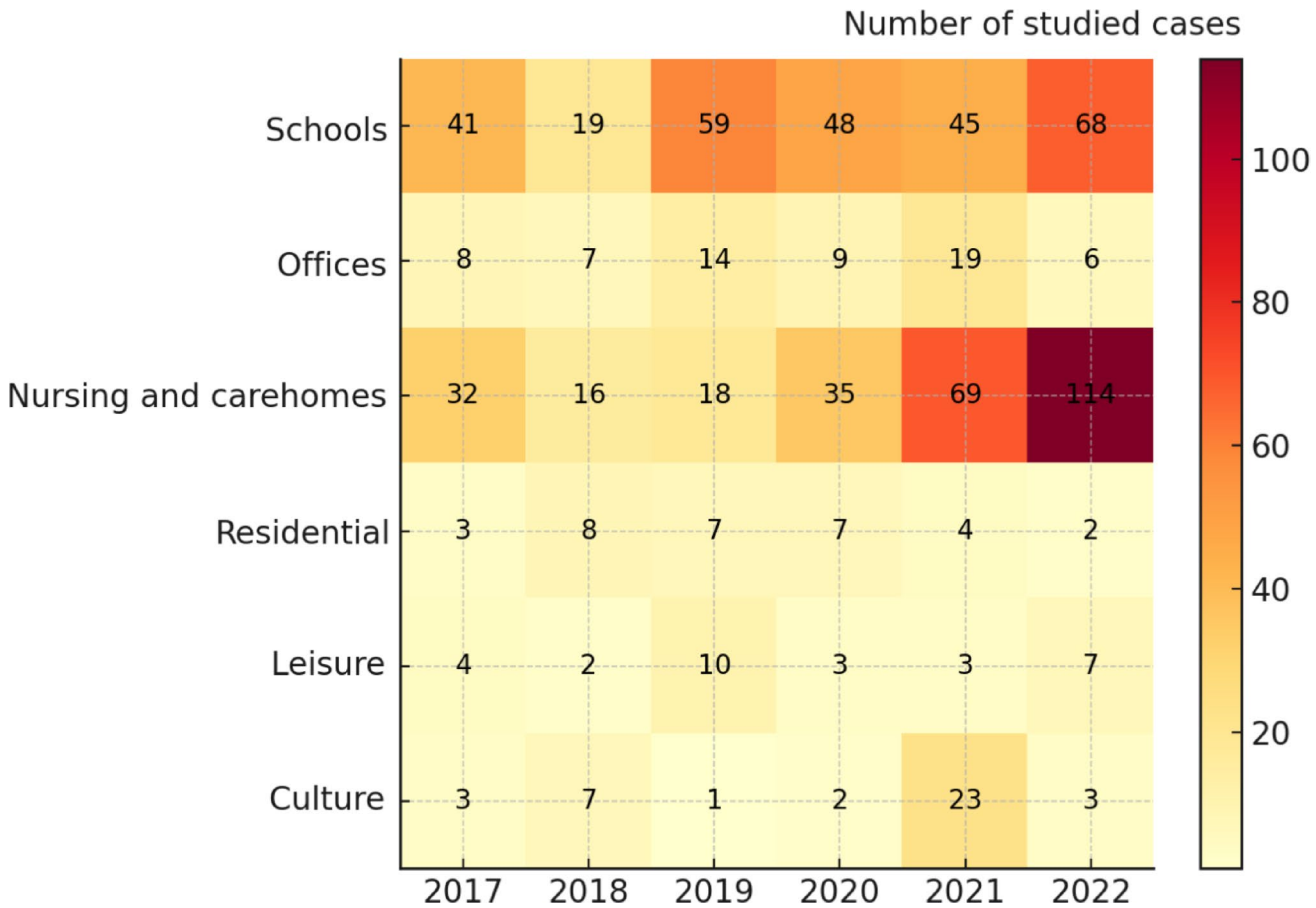


Fig. 1 Heatmap of the number of studied cases per building category and year in MU1, Darker yellow/red indicating more cases per year

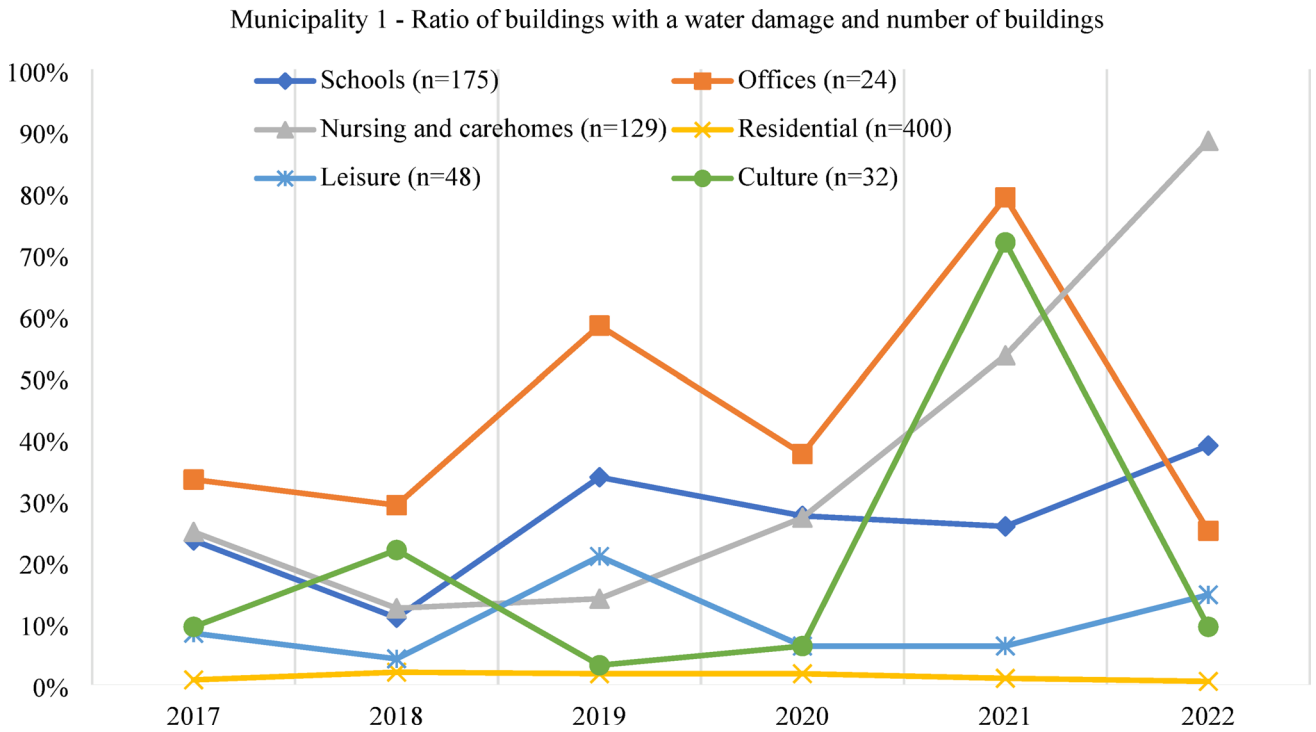


Fig. 2 Ratio of building with water damage in MU1 and in relation to the number of buildings in each category in the municipality

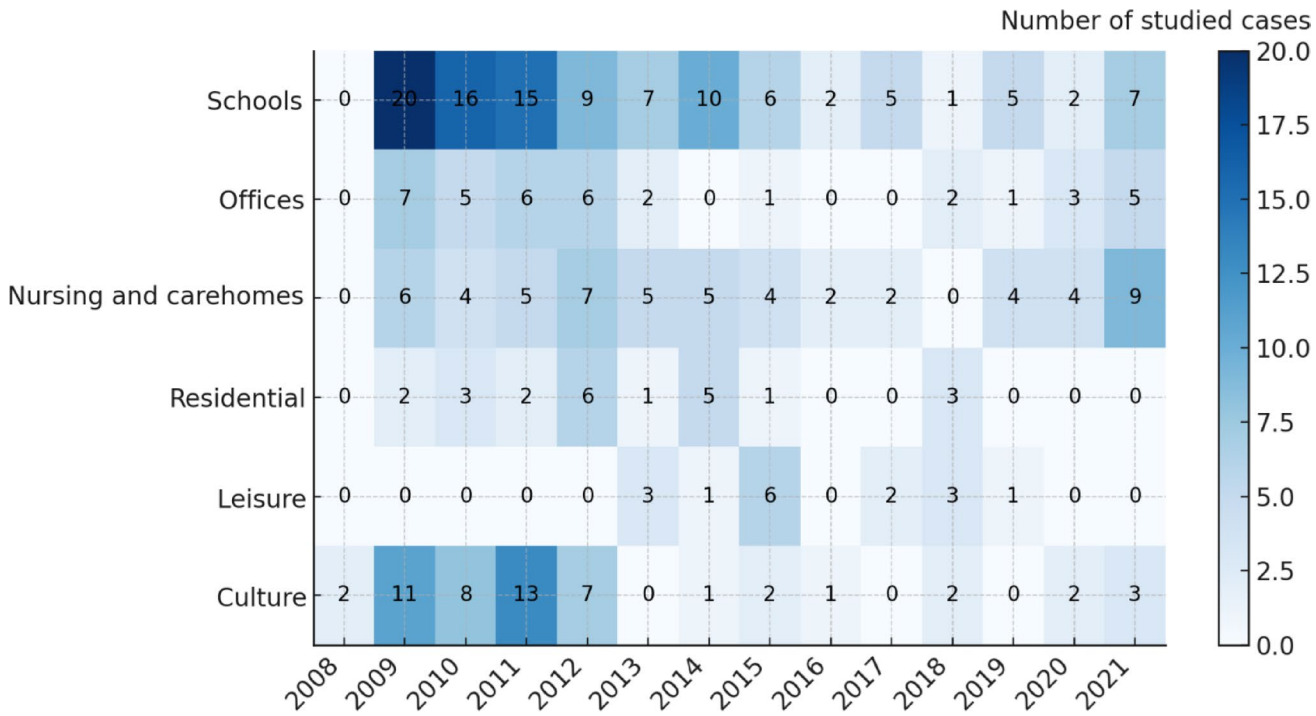


Fig. 3 Heatmap of the number of studied cases per building category and year in MU2. Darker blue indicating more case per year

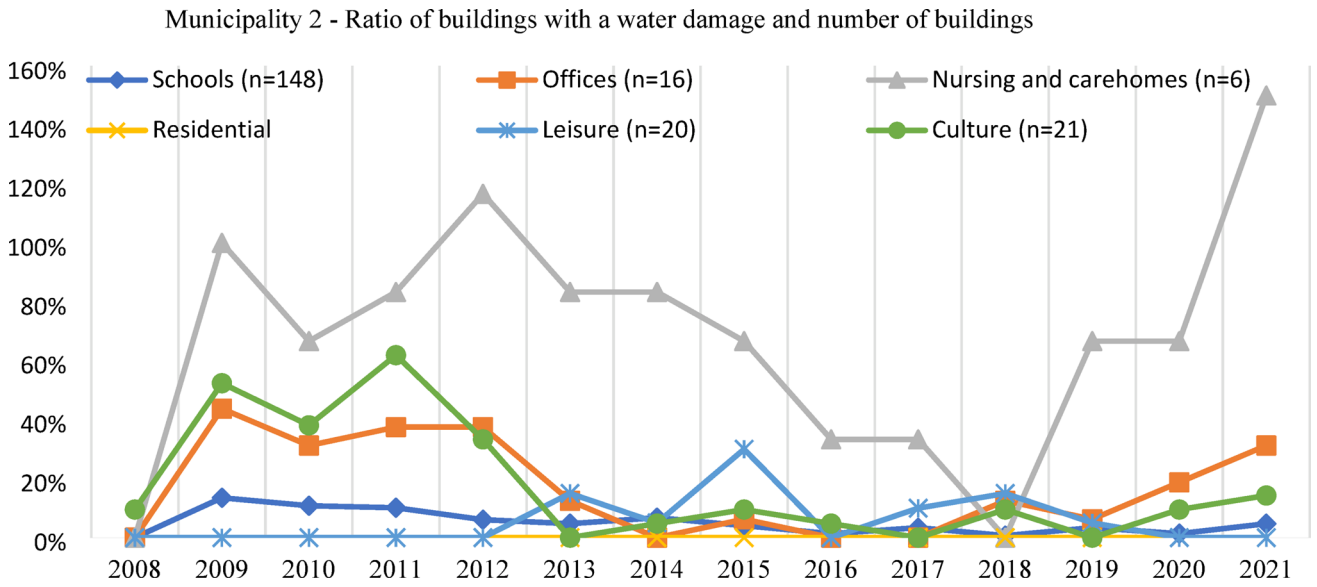


Fig. 4 Ratio of building with water damage in MU2 and number of buildings and in relation to the number of buildings in each category in the municipality.(note that some years the ratio is above 100%, this can occur since the municipality have reported damage cases in the same buildings or when the cases have been reported as several cases)

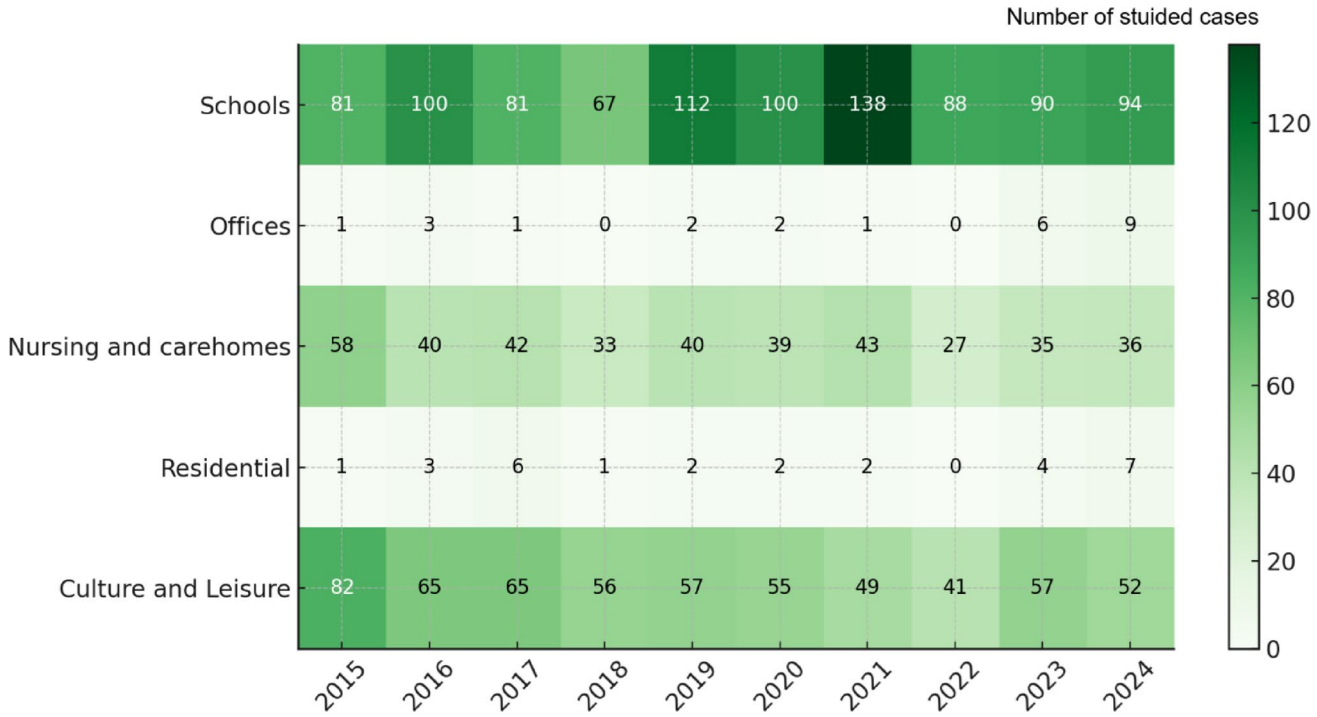


Fig. 5 Heatmap of the number of studied cases per building category and year in MU3.Darker green indicating more cases per year

vulnerable to recurrent incidents. Offices also seem to have an increase after 2022.

8 Cause categorization

Furthermore, the data were categorized according to the reported cause of water damage, determined by the building system or component in which the damage originated. In this study, cause refers to the building system in which the water damage occurred, rather than the specific technical

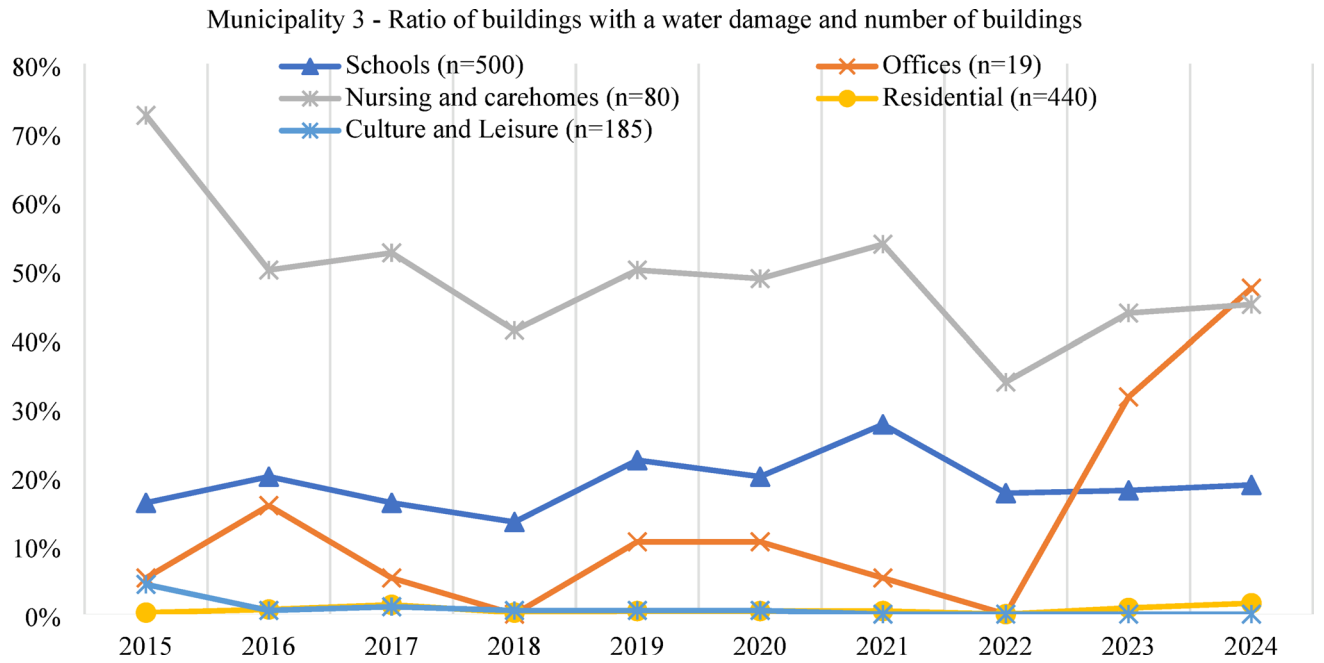


Fig. 6 Ratio of buildings with water damage in MU3 and number of buildings and in relation to the number of buildings in each category in the municipality

trigger. Since detailed failure mechanisms were not consistently available in the municipal datasets, the analysis categorizes cases according to the affected system. This categorization included five groups: pipes and connections, appliances, waterproof membranes, other causes, and unknown. The categorization and analysis were based on the information provided by the municipalities. In MU1, out of a total of 726 reported damage cases, only 90 could be categorized by cause, all of which were related to heating systems under the "pipes and connections" category. This limitation was primarily due to the structure and level of detail in the municipal reporting system. In contrast, MU2 provided more comprehensive documentation, allowing for categorization of 231 out of 291 cases, including sub-classification by affected system (e.g., tap water, sewage, heating) and appliance type (e.g., dishwasher, HVAC). These differences in categorization capacity reflect the variation in how municipalities record and report damage events, which directly influenced the analytical depth of this study. Several other cases were classified as having an unknown cause due to limitations in the raw data and incomplete descriptions that prevented further categorization. Table 5 presents the distribution of reported water damage cases by cause category for the two municipalities, covering the periods 2017–2022 for MU1 and 2008–2021 for MU2. The table also includes the relative proportion of reported damages per building and year, illustrating both the frequency and nature of water damage within the municipals building stock. As shown, damage cases associated with pipe and connection systems dominate the categorized cases, particularly within heating and tap water systems, whereas cases linked to appliances and waterproof membranes are less frequent. In total, 636 cases in MU1 and 60 cases in MU2 were categorized as "unknown," as the available metadata did not contain sufficient information to determine the cause of the water damage. For municipality 2, of a total of 291 damage cases 231 cases could be categorized with an direct cause for MU2 and occurred in buildings. More information was given in the municipality´s report structure, hence the more detailed description of data.

The studied damage cases were also divided into the same three categories that are used for single-family homes in which the damages occurs: pipes and connections, appliances respectively waterproof membrane. Due to the different reporting systems, retreived information and chosen caracterisation in the municipalities this was not possible to do for municipality 3. For municipality 1 the vast majority of the damages (636 cases) could not be divided into the three categories. A valid divide could only be made for municipality 2 in which only 60 cases classified as unknown.

The data were further divided into categories based on the type of damage, including pipes and connections, appliances, and waterproof membranes, as presented in Table 6. In comparison to data from insured single-family residential buildings in Sweden, as reported by the Swedish Water Damage Centre (SWDC), the distribution of water damage causes shows both similarities and differences. The SWDC database, based on approximately 35

Table 5 Categorization of studied water damage cases by cause for MU1 (2017–2022) and MU2 (2008–2021)

Building type	Pipes and connections		Appliances		Waterproof membrane		Unknown		Sum	
	MU1	MU2	MU1	MU2	MU1	MU2	MU1	MU2	MU1	MU2
Schools	53	78	-	8	-	4	227	15	**280**	**105**
MU1, $n=175$	x̄: 8,8	x̄: 5,6		x̄: 0,6		x̄: 0,3	x̄: 38	x̄: 1,1	x̄: 46,7	x̄: 7,5
MU2, $n=148$	(5%)	(4%)		(0%)		(0%)	(22%)	(1%)	(27%)	(5%)
Offices	21	27	-	3	-	0	42	8	**63**	**38**
MU1, $n=24$	x̄: 3,5	x̄: 1,9		x̄: 0,2			x̄: 7	x̄: 0,6	x̄: 10,5	x̄: 2,7
MU2, $n=16$	(15%)	(12%)		(1%)			(29%)	(4%)	(44%)	(17%)
Nursing and	6	36	-	7	-	3	278	11	**284**	**57**
care homes	x̄: 1	x̄: 2,6		x̄: 0,5		x̄: 0,2	x̄: 46	x̄: 0,8	x̄: 47	x̄: 4,1
MU1, $n=129$	(1%)	(43%)		(8%)		(4%)	(36%)	(13%)	(37%)	(68%)
MU2, $n=6$										
Residential	3	13	-	1	-	2	28	7	**31**	**23**
MU1, $n=400$	x̄: 0,5	x̄: 0,9		x̄: 0,1		x̄: 0,1	x̄: 4,7	x̄: 0,5	x̄: 5	x̄: 1,6
MU2, n=NA	(0%)	(0%)		(0%)		(0%)	(1%)	(0%)	(1%)	(0%)
Leisure	6	5	-	2	-	2	23	7	**29**	**16**
MU1, $n=48$	x̄: 1	x̄: 0,4		x̄:0,1		x̄: 0,1	x̄: 3,8	x̄: 0,5	x̄: 4,8	x̄: 1,1
MU2, $n=20$	(2%)	(2%)		(1%)		(1%)	(8%)	(3%)	(10%)	(6%)
Culture	1	38	-	1	-	1	38	12	**39**	**52**
MU1, $n=32$	x̄: 0,17	x̄: 2,7		x̄: 0,1		x̄: 0,1	x̄: 6,3	x̄: 0,9	x̄: 6,5	x̄: 3,7
MU2, $n=20$	(1%)	(15%)		(0%)		(0%)	(20%)	(4%)	(20%)	(19%)
Sum	**90**	**197**	-	**22**	-	**12**	**636**	**60**	**726**	**291**
MU1, $n=808$	x̄: 15	x̄: 14		x̄: 1,6		x̄: 0,9	x̄: 106	x̄: 4,3	x̄: 121	x̄: 20,8
MU2, $n=211$	**(2%)**	**(7%)**		**(1%)**		**(0%)**	**(13%)**	**(2%)**	**(15%)**	**(10%)**

The table presents the number of cases in each category, along with the average number (x̄) of damage cases per year and the corresponding percentage of average cases relative to the total number of buildings in each building category per year in each municipality

Table 6 The distribution of reported water damage causes across different building types

The columns show the number of damage cases and their percentage share within each category. The column "Sum" represents the total number of identified causes, while "Unknown" indicates cases where the cause of damage was not specified

Building type n=number of buildings	Cause of damage				
	Pipes and connections	Appliances	Waterproof membrane	Sum	Unknown
Schools ($n=148$)	78 (87%)	8 (9%)	4 (4%)	**90**	15
Offices ($n=16$)	27 (90%)	3 (10%)	-	**30**	8
Nursing and carehomes ($n=6$)	36 (78%)	7 (15%)	3 (7%)	**46**	11
Residential (n=NA)	13 (81%)	1 (6%)	2 (13%)	**16**	7
Leisure ($n=20$)	5 (56%)	2 (22%)	2 (22%)	**9**	7
Culture ($n=20$)	38 (95%)	1 (3%)	1 (3%)	**40**	12
Sum ($n=211$)	**197 (85%)**	**22 (10%)**	**12 (5%)**	**231**	**60**
SWDC [21] Single-family buildings	**62%**	**26%**	**12%**	**100%**	**-**

000 reported cases from insured single-family homes, indicates that 62% of all water damage incidents were caused by failures in pipes and connections. Appliances such as refrigerators, freezers, and dishwashers accounted for 26% of the cases, while 12% were attributed to failures in waterproof membranes in wet rooms. The water damage cases involving pipes and connections in MU2 were reported by the municipality using a systematic structure, allowing the data to be analyzed and categorized according to the affected building system, presented in Table 6 with comparison to SWDC data. Cases with clear descriptions of both the cause of damage and the water system involved were extracted and classified.

The distribution for municipality 2 is 85% occurs in pipes and connections, 10% in appliances and 5% in waterproof membranes. The corresponding number for single-family home are 62%, 26% and 12% respectively. A larger portion of the damages occurs in pipes and connections in municipality 2 compared to single-family homes. When pipes and connections were futher divided into tapwater, sewage and heating system the share were 43%, 41% and 16% respectively as can be seen in Table 7. This distribution is rather similar to single-family homes where the corresponding numbers are 59%, 26% and 14%. However 39% of the damages occuring in pipes and connections could not be divided further which implies an uncertainty in the distribution.

Table 7 System in which the reported damage cases occurred in for pipes and connections for MU2 in tatal 85% of the studied cases in MU2

Building type *n*=number of buildings	Pipe and connections				
	Tapwater	Sewage	Heat-ing-system	Sum	Unknown
Schools (*n*=148)	18 (46%)	13 (33%)	8 (21%)	**39**	39
Offices (*n*=16)	11 (53%)	7 (33%)	3 (14%)	**21**	6
Nursing and carehomes (*n*=6)	11 (38%)	14 (48%)	4 (14%)	**29**	7
Residential (n=NA)	1 (17%)	4 (67%)	1 (17%)	**6**	7
Leisure (*n*=20)	2 (100%)	-	-	**2**	3
Culture (*n*=20)	9 (39%)	11 (48%)	3 (13%)	**23**	15
Sum (*n*=211)	**52 (43%)**	**49 (41%)**	**19 (16%)**	**120**	77
SWDC [21] (Single family buildings)	**59%**	**26%**	**14%**	**100%**	-

The 197 cases in MU2 attributed to pipe and connection-related causes represent approximately 85% of all investigated cases (*n*=231) within MU2. The comparison with SWDC data shows that tap water and sewage systems are also the most common causes of water damage in public buildings, although their proportions are lower than in single-family dwellings. In contrast, damages related to heating systems occur less frequently in public buildings, while a considerably higher share of cases remains classified as unknown compared with residential buildings.

The 22 cases in MU2 attributed to appliance-related causes represent approximately 10% of all investigated cases (*n*=231) within MU2. According to SWDC, appliances, in kitchens and building services systems, accounted for 26% of all studied water damage cases, however there are a differences in number of units and what kind of units used in public buildings and residential buildings. Residential buildings typically contain multiple individual appliances with direct water connections and public buildings often have larger kitchens and more complex systems, such as HVAC. In the municipal dataset (Table 8), dishwashers were the most frequently reported appliance-related source of water damage, accounting for 50% of cases. No incidents involving refrigerators or freezers were recorded, which contrasts sharply with SWDC data where these appliances are among the most common causes. Additionally, the municipal data included cases involving HVAC systems and heat pumps, which are rarely present in single-family homes but are common in public buildings and included in the other category.

Table 9 presents water damage cases in municipality 2 (MU2) caused by failures in waterproof membranes. The 12 cases in MU2 attributed to waterproof memebrane-related causes represent approximately 5% of all investigated cases (*n*=231) within MU2. Compared to data from SWDC, which reports that 13% of water damage cases in insured single-family homes are caused by waterproofing failures in wet rooms, the proportion in MU2 is notably lower. In MU2, drain connection failures accounted for 58% of waterproofing-related water damage cases, significantly higher than the 29% reported in insured single-family homes by SWDC. Membrane layer failures were the most common in residential buildings at 44%, while they represented only 33% in MU2.

Table 8 Number of reported cases that occurred in appliances in MU2 in total 10% of the studied cases in MU2

Building type *n*=number of buildings	Appliances					
	Refridgirator /Freezer	Dish-washer	Heat-pump	Other	Sum	Un-known
Schools (*n*=148)	-	3 (60%)	1 (20%)	1 (20%)	**5**	3
Offices (*n*=16)	-	1 (50%)	-	1 (50%)	**2**	1
Nursing and carehomes (*n*=6)	-	3 (60%)	-	2 (40%)	**5**	2
Residential (n=NA)	-	1 (100%)	-	-	**1**	-
Leisure (*n*=20)	-	-	-	2 (100%)	**2**	-
Culture (*n*=20)	-	-	-	1 (100%)	**1**	
Sum (*n*=211)	-	**8 (50%)**	**1 (6%)**	**7 (44%)**	**16**	6
SWDC [21] (Single-family buildings)	**36%**	**30%**	**9%**	**22%**	-	-

Table 9 Number of reported cases that occurred in waterproof membranes in MU2, in total 5% of all studied cases in MU2

Building type *n* = number of buildings	Waterproof membrane				
	Connection Floor Drain	Waterproofing Layer	Joint/Seam	Pipe or other penetrations	Sum
Schools (*n* = 148)	2 (50%)	2 (50%)	-	-	**4**
Offices (*n* = 16)	-	-	-	-	-
Nursing and carehomes (*n* = 6)	2 (67%)	-	1 (33%)	-	**3**
Residential (n = NA)	1 (50%)	1 (50%)	-	-	**2**
Leisure (*n* = 20)	1 (50%)	1 (50%)	-	-	**2**
Culture (*n* = 20)	1 (100%)	-	-	-	**1**
Sum (*n* = 211)	**7 (58%)**	**4 (33%)**	**1 (8%)**	-	**12**
SWDC [21] (Single-family buildings)	**29%**	**44%**	**9%**	**7%**	

9 Water damage repair cost evaluation

To better understand the economic impact of damages to technical systems, the average repair costs per damage case were calculated and categorized by building type for Municipalities 1 and 2, considering only cases where repair costs were recorded. Table 10 presents the data used for the cost analysis in the studied municipalities, with the number of total studied cases, number of cases with reported costs average costs, min and max values in the datasets. As shown in Tables 10 and 30% of the total studied cases include data on repair costs, which form the basis of this analysis. The cases with available repair cost information come from MU1 and MU2.

The average cost allocated for repair was calculated to 10 105 €. For municipality 1 was the average cost 8 500 € and for municipality 2 it was 18 100 €. Costs from municipality 3 could not be retrieved (as this was reported in another system and not connected to each reported damage). The repair cost for the individual damages varied between 47 and 409 600 €. Both datasets from these municipalities contain properties that will be examined in this chapter. MU1 provides a large dataset of water damage repair costs; however, as previously discussed, information on the causes of damage in MU1 is limited, restricting the scope of analysis to water damage repair costs in heating systems, since all of the reported cases in MU1 that could be categorized with a damage cause occurred heating systems. The repair costs from MU1 is presented in a scatterplot in Fig. 7. The large variation or spread of repair costs can be seen for all studied building categories.

From the scatterplot it´s shown that schools have the largest variation and spread across the datapoints, followed by nursing and carehomes. These outliers include a school building with a repair cost of approximately 56 900 € and a leisure building with a repair cost of 62 200 €, both of which substantially influence the overall cost distribution.

In contrast, MU2 offers a more detailed categorization and description of the causes of damage, enabling a deeper analysis of both repair costs and their underlying causes. The total repair costs in MU2 in each building category and cause of damage category is presented in Table 11 and all of the datapoints analyzed in a scatter plot in Fig. 8.

For municipality 2 the repair costs could be divided into the three subcategories and the average repair cost were 16 028 € for pipes and connections and 42 570 € for appliances and 7 818 € for waterproof membranes. The total cost for MU2 amounted to 3 128 000 € for the studied damages reported over 13 years.

The scatterplot for MU2 present the datapoints scattered for the different building types. There are similarities between the municipalities especially in the large varation of high and low costs in school buildings. The data presented show a significant span which the damage costs falls inbetween. However, more analysis is needed to understand what the costs are caused by.

Table 10 The number of datapoints with an associated repair costs in the three municipalities, number of cases and average costs, minimal and maximal valvues in the datasets are presented

Number of datapoints with an associated repair costs	Total number of stuided cases	Number of cases with reported cost	Average cost	Mini-mum value	Maximum value	Average repair cost per year	Total repair costs of the studied years
MU1	726	726	8 500 €	47 €	245 500 €	1 240 000 €	6 180 000 €
MU2	291	173	18 100 €	113 €	409 600 €	520 000 €	3 127 000 €
MU3	2 013	-	-	-	-	-	-
SUM	**3 030**	**899**	10 105 €	47 €	409 600 €	846 100€	9 307 000 €

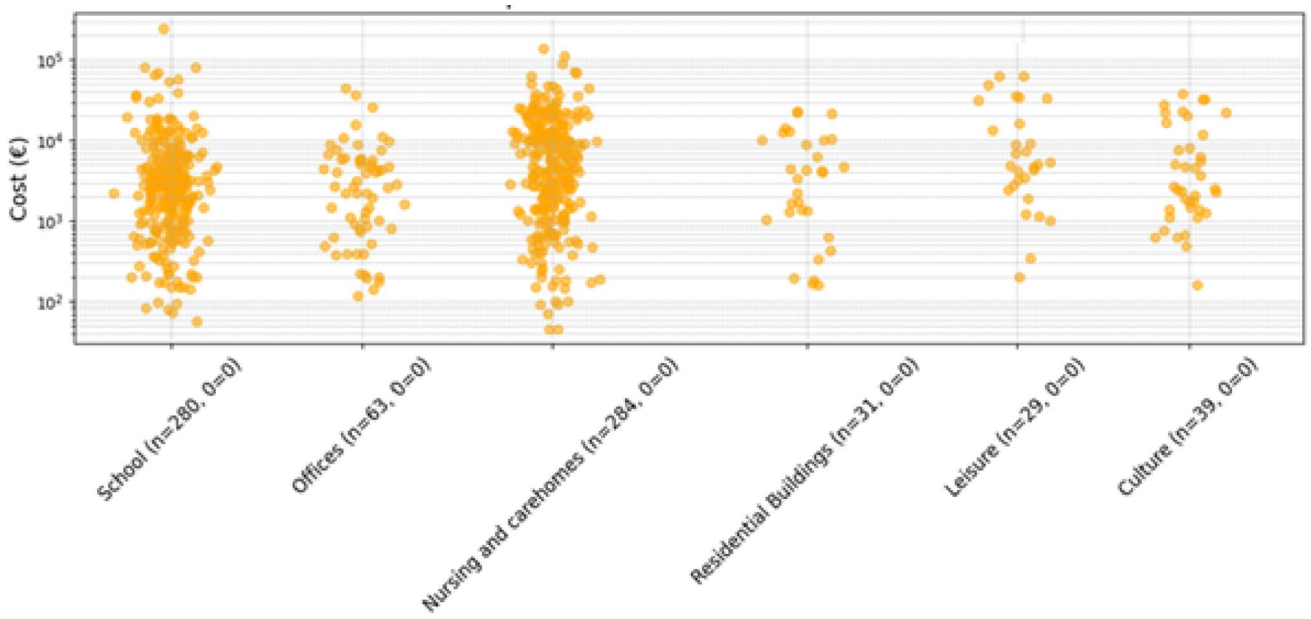


Fig. 7 Scatterplot of cost by Building type in MU1, (n is the total amount of cases with a reported cost)

Table 11 Total repair costs of studied water damage in MU2 sorted by building typ and cause of damage

Building type *n* = number of buildings	Cause of damage (*n* = number of water damage cases)				
	Pipes and connections (*n* = 197)	Appliances (*n* = 22)	Waterproof membrane (*n* = 12)	Unknown (*n* = 60)	Sum (*n* = 291)
Schools (*n* = 148)	936 000 €	420 000 €	-	22 000 €	**1 378 000 €**
Offices (*n* = 16)	319 000 €	22 000 €	-	196 000 €	**537 000 €**
Nursing and carehomes (*n* = 6)	342 000 €	13 000 €	29 000 €	22 000 €	**406 000 €**
Residential (n = not known)	65 000 €	16 000 €	8 000 €	90 000 €	**179 000 €**
Leisure (*n* = 20)	-	-	-	-	-
Culture (*n* = 20)	559 000 €	-	2 000 €	66 000 €	**627 000 €**
Sum (*n* = 211)	**2 221 000 €**	**472 000 €**	**39 000 €**	**396 000 €**	**3 128 000 €**

Figure 9 is included to provide a clearer visual representation of the highly skewed cost distributions, illustrating how a small number of extreme outliers significantly increase the spread and influence the overall interpretation of repair cost variability across building types. The distribution of water damage repair costs within each building type is highly skewed. A few particularly costly damage cases, especially in leisure and culture buildings, drive the maximum values far above the interquartile range, as illustrated in the corresponding boxplot in Fig. 9. Although not displayed in the figures, extreme outliers are present, including leisure buildings exceeding 49 159 € and culture buildings above 20 942 €, which substantially influence the overall cost distribution. This variability underscores the need to consider both central tendencies and outliers when interpreting the dataset. In total the distribution of water damage repair costs in MU1 and MU2 is illustrated in Fig. 9, which displays boxplots for the studied municipal buildings. As seen in the figure, the median repair costs are relatively low compared to the maximum values, highlighting the presence of a small number of very costly incidents. The outliers represent rare but significant repair events that can heavily affect municipal water damage costs on a annual basis. The dataset also shows several intermediate high-cost repairs ranging from 10 000 € to 50 000 €, which, although less extreme than the top outliers, still have a considerable impact on the average repair cost per buildings. In Fig. 9, repair cost data from MU1 and MU2 are combined and presented next to each other, and each boxplot presents the standard statistical components: the median (50th percentile), the interquartile range spanning the 25th to 75th percentiles, whiskers extending to the most extreme data points within 1,5 times the interquartile range, and any values beyond these limits are outliers,

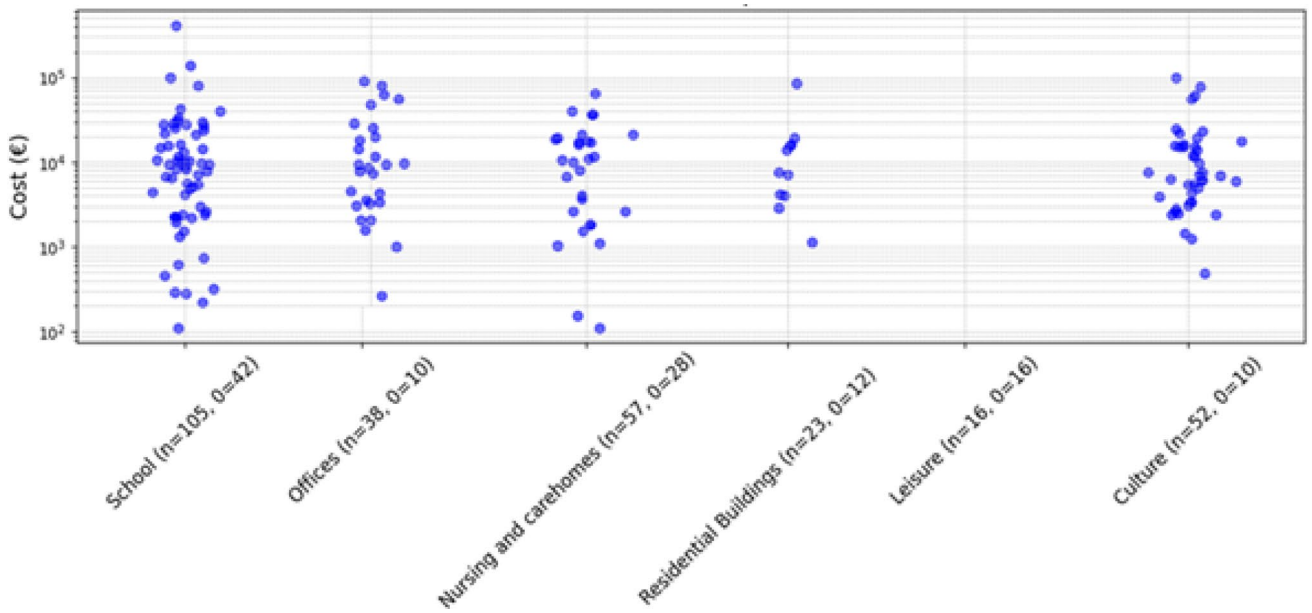


Fig. 8 Scatterplot of cost by Building type in MU2, (n is the total amount of cases with a reported cost)

which are not shown in these figure due to space limitations, but still exists.

Across the building categories, the results show clear differences between MU1 and MU2 cases. In schools, MU1 cases have an average cost of 1 641 € while MU2 cases are considerably higher at 6 828 €, with maximum values reaching around 42 332 €. Offices exhibit a similar pattern, where MU1 averages 2 131 € compared to 7 427 € for MU2, with MU2 cases rising to approximately 18 994 €. Nursing and care homes show MU1 cases at an average of 2 596 €, whereas MU2 cases reach 6 634 €, with the highest values around 17 565 €. Residential buildings follow the same trend, with MU1 averaging 2 634 € and MU2 7 055 €, and maximum costs of about 15 778 €. Leisure buildings display the highest MU1 average at 6 005 €, with individual cases reaching 24 902 €, while no MU2 cases were recorded for repair cost. In culture buildings, MU1 cases average 3 564 € and MU2 6 275 €, with upper values around 15 466 €.

The analysis of the water damage caused in pipes and connections shows that tap water-related damages generally result in the highest average costs, particularly in nursing and care facilities and schools. Sewage system damages display greater variation between building types, while heating system damages, although less frequent, can lead to significant costs in specific categories, such as cultural buildings. The different repair costs in tapwater, sewage, heating for MU1 and MU2 systemes is presented Fig. 10.

Across the different types of buildings, the results show substantial variation between MU1 and MU2 cases and between the three damage types: tapwater, sewage, and heating. In schools, tapwater MU2 cases have an average cost of 7 063 €, while sewage MU2 cases average 1 963 €, and heating MU2 cases 4 798 €. Offices show lower values overall, with tapwater MU2 averaging 1 198 €, sewage MU2 5 833 €, and heating MU2 3 315 €. Nursing and care homes display the highest MU2 variability, where tapwater MU2 reaches an average of 14 130 €, sewage MU2 averages 5 297 €, and heating MU2 shows lower values at 154 €. For residential buildings, tapwater MU2 averages 705 €, sewage MU2 6 767 €, and heating MU2 0 €, reflecting limited MU2 cases. Leisure buildings show only heating MU1 cases, averaging 3 747 €, with no MU2 values reported. In culture buildings, tapwater MU2 averages 518 €, sewage in MU2 averages 6 858 €, and heating MU2 presents the highest MU2 average across all categories at 6 700 €, with heating MU1 cases also reaching high values at 3 120 € and 7 580 € in some instances.

The repair costs for tapwater shows a considerable variation in size across building types and represent the majority of data points in MU2: 197 out of 291 cases (68%) with an associated cost. To further examine the remaining building types and the costs associated with water damage in MU2, two additional categories are considered: appliances (22 cases) and waterproof membranes (12 cases). The observed trends are summarized below.

Appliances MU2 (22 cases, 9 with reported repair costs):

- *Schools*: A leakage from a WC in 2021 caused the single most expensive damage in the dataset, amounting to approximately 450 000 €.
- *Nursing and care homes*: In 2 out of 3 cases with a reported cost, leakage from a dishwasher required repairs

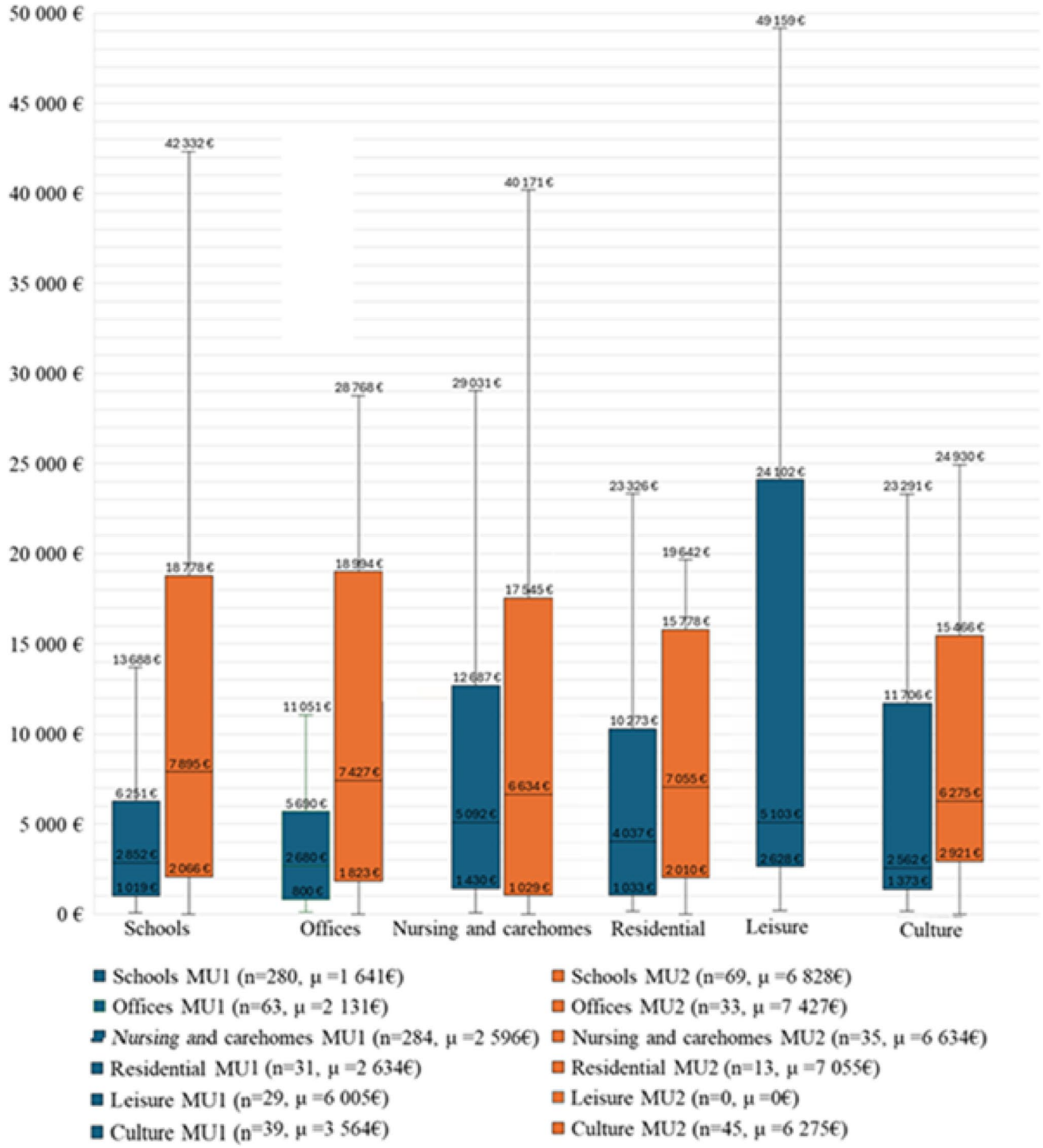


Fig. 9 Total distribution of water damage repair costs for MU1 and MU2. The number of cases (n), the geometric mean (μ), median (---), interquarile range and whiskers presented for the different building types

of 1 000–2 000 €. The third case involved resident-caused flooring damage, with repair costs of about 10 000 €.

- *Offices*: All 3 reported cases involved repair costs: a toilet stoppage (10 000 €), a kitchen water leak (10 000 €), and a malfunctioning showerhead (~3 700 €).
- *Residential buildings*: One case involved a leaking dishwasher, resulting in repair costs of 17 000 €.
- *Leisure and culture buildings*: No cases with reported costs.

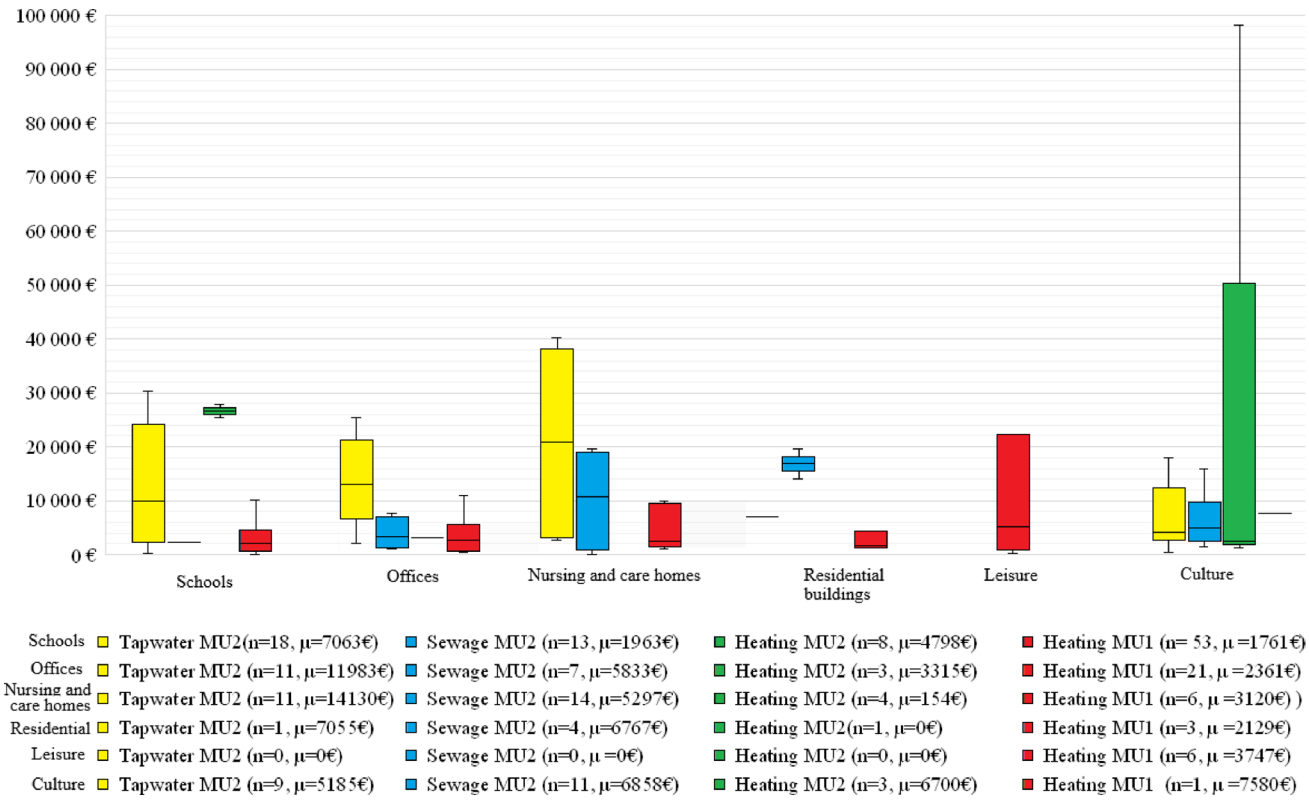


Fig. 10 Boxplot of repair costs in MU1 and MU2 that occurred in tapwater system, sewage, heating systems. The number of cases (n), the geometric mean (μ), median (---), interquarile range and whiskers presented for the different building types

Waterproof membranes MU2 (12 cases, 4 with reported repair costs):

- *Schools*: No cases with reported costs.
- *Nursing and care homes*: In 2 out of 3 cases with reported costs, membrane failures occurred in the shower area: at a joint (13 000 €) and at a drain connection (20 000 €).
- *Offices*: No cases with reported costs.
- *Residential buildings*: In 1 out of 2 cases, water leakage beneath the membrane caused repair costs of 8 500 €.
- *Leisure buildings*: No cases with reported costs.
- *Culture buildings*: 1 case with a reported cost of 2 700 € due to a faulty drain.

In summary, tap water systems account for the majority of the studied repair cases in MU2 (197 cases), but appliances (22 cases) and waterproof membranes (12 cases) also represent noteworthy sources of damage. Among appliances, 41% of cases (9 out of 22) had reported costs, ranging from 1 000 € to 450 000 €, with the most costly incidents occurring in schools and offices. For waterproof membranes, one-third of cases (4 out of 12) involved reported costs, typically in bathrooms, with expenses between 2 700 € and 20 000 €. Although less frequent than failures related to pipes and connections, both categories demonstrate the potential for severe and costly damage, particularly in schools and nursing homes. Offices and schools account for the highest expenses, with extreme outliers exceeding 90 000 € and 135 000 € respectively, while most other building types have far lower costs. Nursing and care homes, as well as culture buildings, show moderate expenses, though occasional outliers raise the upper cost range significantly. In contrast, residential, leisure, and smaller categories often involve zero or minimal repair costs. Overall, the cost distributions are right-skewed, meaning that a small number of cases account for the majority of expenses. Median repair costs per damage remain comparatively moderate across building types, ranging between 6 275 € – 7 895 € for the studied building types. However, the average repair cost per year spent by the municipalities on the different building types and the total repair costs are as presented in Table 12, which summarizes the average repair costs per year and the total repair costs for the two studied municipalities (MU1 and MU2).

MU3 has not been analyzed with respect to repair costs due to the absence of cost data in its dataset.

Table 12 Summary of average repair costs per year and total repair costs for MU1 och MU2

Building category	Average repair costs per year	Average repair costs per case	Total repair costs	Average repair costs per year	Average repair costs per case	Total repair costs	Average repair cost per case
	MU1	MU1	MU1 (5 years)	MU2	MU2	MU2 (6 years)	MU1 and MU2
Schools	385 000 €	6 900 €	1 926 200 €	229 800 €	13 100 €	1 378 700 €	8 600 €
Offices	63 000 €	5 000 €	314 300 €	89 700 €	14 200 €	538 000 €	8 400 €
Nursing and care homes	601 000 €	10 600 €	3 005 300 €	67 600 €	7 100 €	405 800 €	10 000 €
Residential	38 000 €	6 200 €	191 000 €	29 700 €	7 700 €	178 100 €	6 800 €
Leisure	84 000 €	14 400 €	418 800 €	-	-	-	9 300 €
Culture	65 000 €	8 300 €	323 500 €	104 500 €	12 100 €	627 200 €	10 400 €
SUM	**1 029 900 €**	**8 500 €**	**6 179 100 €**	**521 300 €**	**10 700 €**	**3 127 800 €**	**9 200 €**

10 Discussion

This study investigated and gathered data about the occurrence, causes, and repair costs of water damage in publicly owned, operated and managed buildings in Sweden, focusing on technical systems such as building services systems for piping for tapwater, sewage and heating systemes, appliances, and waterproof membranes. It addresses a knowledge gap, as previous statistics have primarily covered insured single-family houses.

The further analysis of over 3 030 cases from the three Swedish municiplaities across 2 243 municipal buildings revealed that water damage in public buildings, such as schools, nursing and carehomes, offices, leisure- and culture buildings, is both frequent in number of occurrence and economically significant. The number of reported cases varied between municipalities. MU3 recorded the highest total of cases (with an average of 198 cases, 16% of the building stock had in average a damage case per year), followed by MU1 (with an average 122 cases, 15% of the building stock had in average a damage case per year) and MU2 (with an average 20 cases, 9% of the building stock had in average a damage case per year). The variations between the municipalites may relate to differences in building stock, reporting routines, or maintenance practices. The three municipalities has each developed an individual report system since no standard is avaliable. The chosen categories, concepts, and individual approaches to categorization differ. In order to make a valid comparison, a selection of damages that were verified and reported as actual water-related incidents in the database had to be made. These limitations in reporting structure also influence how the distribution of identified damage causes should be interpreted.

As shown in the results, cases attributed to pipe and connection systems dominate the categorized incidents, particularly within heating and tap water systems, while damages linked to appliances and waterproof membranes occur far less frequently. This pattern is partly a reflection of the technical characteristics of public buildings but also of the large number of cases, 636 in MU1 and 60 in MU2, that could not be assigned a specific cause due to insufficient metadata. Such gaps indicate that the apparent dominance of pipe-related damages may, to some extent, be shaped by documentation practices rather than the true distribution of underlying failures. In order to make a valid comparison a selection of confirmed reported damage cases were needed to be made. This means that valid conclusions can be drawn for the studied cases. However, the design of the individual systems limits which damages could be included in the analysis. The number of studied cases does not represent the real number of damages. This means that the total number of actual water damages is larger. The structure of the individual systems also limits the possibility of making a fully valid comparison, especially for the sub-categories used for single-family homes. Even though only one municipality provided sufficiently detailed data for full cause categorisation, the results still demonstrate qualitatively that all major types of water-related failures, pipes and connections, appliances, and waterproof membranes, occur across municipal building stocks. This indicates that the range of damage types observed in the structured dataset is not unique to a single municipality but instead reflects the broader reality of public buildings. Even with large proportions of uncategorised cases in MU1 and MU2, the presence of all main damage categories underscores that diverse system failures are a recurring issue in publicly owned buildings. This strengthens the validity of the findings and highlights the need for more consistent reporting routines to capture this full variety of damage mechanisms more accurately. Municipalities with large populations (one of the ten largest in Sweden) were targeted for inclusion to ensure a sufficient volume of reported damage cases. As a result, smaller municipalities are not represented in the dataset. Their smaller organisational structures, including fewer building managers, may influence both their maintenance capacity and available

competence. The magnitude and direction of this potential difference remain unknown.

Out of the studied buildings categories schools and nursing homes was found as the most affected building categories, both in terms of frequency and repair cost variability, with significant high repair cost on outliers. This indicates that the some of the cases are causing immence repair cost. Furthermore, the median of the analyzed buildings categories and analyzed causes is substantially lower than the mean value, suggesting that the distribution of costs is highly skewed and that a limited number of very costly damages disproportionately influence the average. Although the majority of cases fall below 50 000 €, the presence of several extreme outliers highlights the importance of considering both the cause and frequency of the outliers.

One conclusion that can be drawn is that it would be valuable to implement a common reporting system in order to ensure consistent data quality, allowing reliable comparisons between building types, and support more precise analyses in future studies.

The extent of each reported damage can vary significantly, as some cases may involve only minor surface repairs while others require complete renovation. This variation is not directly visible in the database except through the repair cost, but this does not diminish the validity of the results. Each water damage incident has the potential to escalate into a major problem, and damages originating from system failures often lead to secondary issues. Furthermore, the time factor is critical: if a water leak is not detected promptly, it can cause a chain of consequential problems, increasing both the complexity and cost of repairs.

To intrepret the results of the study the distribution of the reported damage cases and repair costs is really important to consider. However, the boxplots and the scatterplotts presented highlights the trends that could be observed throughout the building categories and be determined from the dataset.

- Schools exhibit the greatest repair cost variation, with several high outliers indicating that damages in this category can be particularly severe.
- Nursing and care facilities also show substantial variability, though with a slightly lower median than schools, suggesting different underlying risk profiles.
- Offices present fewer cases but include instances of costly damages, highlighting that even less frequent incidents can have significant financial implications.
- Residential, leisure, and cultural buildings generally display lower costs, yet isolated cases deviate sharply from the overall trend, emphasizing the need to account for outliers when assessing risk across all building types.

The analysis showed that the studied data from schools have a large variation in water damage repair costs compared to other building types. This could be due to several reasons such as the complexity of the systems, the high level of daily use, and the differences in maintenance from users interactions and municipality. Schools do often also include several water-intensive spaces, like large kitchens, labs, and restrooms. Nursing and care homes also show a lot of cost variation. These facilities are in constant use, often with sensitive environments where damage has to be addressed quickly and thoroughly. The presence of vulnerable residents and specialized equipment makes the consequences of water damage even more significant, both operationally and financially. Overall, the findings point to schools and care facilities as building types where targeted preventive measures and prioritized maintenance are especially important, helping reduce both the frequency and impact of water damage. When compared to the frequency of damage cases reported in SWDC which is based on approximately 35 000 cases in insured single-family homes, the categorization of water damage causes in the studied municipalities (MU1 and MU2) shows both similarities and differences.

- Pipes and connections were the most common cause in both datasets, accounting for 85% of categorized cases in MU2 and 62% in SWDC.
- Appliances caused 9,5% of cases in MU2, compared to 26% in SWDC. Notably, MU2 reported no cases involving refrigerators or freezers, which are common in residential buildings.
- Waterproof membranes accounted for 5% of cases in MU2, while SWDC reported 12%. MU2 had a higher proportion of failures in drain connections (58%) compared to SWDC (29%).

These differences reflect the distinct characteristics of public versus residential buildings. Public buildings often have centralized systems and fewer individual appliances, whereas residential buildings typically contain multiple water-connected units. The data also suggest that public buildings may have more complex HVAC and heating systems, which are less prevalent in single-family homes. Differences in building size and function further contribute to varying operational and technical requirements. Buildings such as schools and care homes often have extensive water systems with multiple wet rooms and technical installations requiring regular inspection, while preschools and offices typically have simpler systems with fewer water connections.

Understanding these differences in building usage and system complexity is essential when planning preventive maintenance and conducting risk assessments. Buildings

with complex technical systems and intensive daily use, such as schools and nursing and care facilities, require more robust maintenance strategies and, in many cases, advanced technical solutions such as automated water shut-off systems to reduce the consequences of leaks. Smaller and less complex buildings, by contrast, may benefit sufficiently from simpler routines, regular inspections, and clear user instructions.

Given the high frequency of water damage identified in this study, it becomes evident that the current level of reactive maintenance in many municipalities is insufficient. Allocating more resources to facility management would enable a shift from predominantly reactive, problem-driven actions to more proactive and preventive measures. Such a shift would allow earlier identification of failures, shorter leakage durations, and timely replacement of aging components. The substantial repair costs observed in MU1 and MU2 demonstrate that investments in preventive maintenance could reduce both the occurrence and severity of damage events, thereby lowering long-term costs while improving the reliability and resilience of public buildings. To reduce repair costs and mitigate the potential negative effects of human presence in buildings related to water damage, the study highlights that high-risk buildings, such as schools and care homes, require further analysis and evaluation of possible solutions. The high variability observed in the repair-cost data can be utilized during the operational phase to identify critical building components and to prioritize preventive maintenance efforts. It may also be important to actively follow up on maintenance plans and to educate building users on appropriate actions when a leakage is detected, in order to reduce the duration of the event. Another possible measure is the implementation of automatic water-flow shut-off systems that engage when abnormal flow conditions occur. Moreover, policymakers and other decision makers can facilitate risk reduction by establishing regulatory frameworks and funding mechanisms that support systematic preventive maintenance and the adoption of proven mitigation technologies.

The predominance of tapwater and pipe and connections-related, damage cases aligns with previous studies on residential buildings [1, 26]. For public buildings, municipalities are responsible for managing and financing water damage, which makes a data collection on a national level more challenging. This differs from the residential sector, where insurance records provide a basis for consistent monitoring and prevention efforts [21, 31]. The findings underscore the need for improved preventive maintenance and standardized reporting systems within municipal property management.

While residential water damage has been well documented through insurance statistics [13, 21], comparable data for public buildings has not been found in the literature. This study bridges that gap by providing empirical evidence from municipal reporting systems. The results correlate with earlier findings regarding the dominance of pipe and connections related damage cases [1, 32], but also highlight differences in repair cost structures and reporting structures. The BETSI study by Boverket [24], found that, together with several other sources [5, 6, 33] that have reported similar trends, found that one-third of Swedish buildings suffer from moisture damage, often with health implications due to mold and poor indoor air quality. These findings are consistent with the current study's findings that water damage in schools and nursing and care facilities may pose risks beyond financial costs, including occupant health and operational disruptions. Highligting the importance of reducing water damage occurrence in such buildings. the comparison to SWDC reveals that public buildings show a higher proportion of pipes and connections related damage cases and a lower proportion of appliance-related damage than residential buildings. This may reflect differences in building usage, maintenance routines, and the types of equipment installed. For example, public buildings often have centralized heating and plumbing systems, which may be more prone to age-related failures, while residential buildings have more water-connected appliances per unit. Moreover, the repair costs in public buildings, especially in schools and care facilities, can be significantly higher than in residential buildings, despite the latter being covered by insurance. This underscores the economic vulnerability of municipalities, which often bear the full cost of repairs without insurance reimbursement. The findings highlight the need for standardized reporting systems in the public sector, similar to those used by insurance companies, to enable better risk assessment and preventive maintenance planning.

The high frequency of water damage identified across the three municipalities clearly highlights the need to allocate more resources to municipal property management. During the studied years, the two municipalities spent on average 1,2 million € (12 million SEK) per year in MU1 and 520 000 € (5 million SEK) per year in MU2 on water-related damage. These substantial annual costs suggest that increased investment in maintenance, such as hiring an additional staff member and implementing more proactive measures, may be economically beneficial for the municipalities. The responsibility for this ultimately lies with politicians, who allocate resources to the municipalities, underscoring the need for strengthened accountability mechanisms. The people who control the municipality; the politicians must acnowledge the need. With 9–16% of the public building stock reporting at least one water damage incident per year, the current level of reactive, problem-driven maintenance practices

is insufficient to limit long-term costs or prevent repeated failures. Enhanced resources would enable the transition from predominantly reactive responses to more proactive and preventive strategies, such as systematic inspections, early detection technologies, and timely renewal of aging components. The substantial repair costs observed in MU1 and MU2, where individual cases reached up to 409,600 €, further illustrate that investing in preventive management could reduce both the occurrence and severity of damages. Strengthening the operational capacity of municipal facility management teams is therefore essential, not only to reduce repair costs but also to ensure safer and more resilient public buildings.

The study is limited by the variation of the municipal reporting systems, which affected the consistency and the level of detail of the data. Only two municipalities provided detailed cost information, and categorization of damage causes was not always possible due to incomplete descriptions. Furthermore, the absence of national-level data for public buildings restricts the generalizability of the findings. Future studies should aim to develop a standardized national framework for reporting water damage in public buildings, similar to the systems used by insurance companies for residential properties. Expanding the dataset to include more municipalities and integrating building-specific variables such as age, usage intensity, and maintenance history would enhance the analytical depth. Comparative studies between publicly and privately owned non-residential buildings could also yield valuable insights. The causes of the damage cases should also be researched further, to underline and understand to prodominant trigger points and failures that lead to water damage repairs in the studied buildings.

11 Conclusions

Water damage in publicly owned buildings represents a substantial and underrecognized challenge for Swedish municipalities. The findings demonstrate that technical system failures are occurring in a large extent, with significant financial problems. Addressng this issue requires improved data collection, targeted preventive measures, and policy-level initiatives to support municipalities in managing and mitigating water dam-age risks. This study is a first step to analyze these water damage cases, comparing sever-al larger municipalities in Sweden. The main findings of the study are the following:

The analysis shows that water damage occurs frequently in publicly owned and managed buildings, with 9–16% of the building stock on average reporting on average at least one incident per year across the three studied municipalities. The occurrence of re-ported water-related damage varies substantially between building categories. Schools, nursing and care homes, and offices exhibit the highest annual ratios, defined as the pro-portion of buildings within each category with at least one reported damage case per year on average. The corresponding shares reach up to 27% for schools, up to 46% for offices, and between 37% and 67% for nursing and care homes, depending on municipality. Residential buildings, cultural buildings, and leisure facilities show significantly lower frequencies. When compared to national insurance statistics for privately owned single family homes, where approximately 4% experience water damage annually, the occurrence in public buildings is considerably higher, indicating that municipally managed buildings face a disproportionately large water damage burden relative to residential properties.

The analysis shows that the predominant causes of water damage in publicly owned and managed buildings are failures in pipes and connections, which account for the vast majority of all categorized cases, particularly in heating, tap water, and sewage systems. In MU2, 85% of all cases with an identified cause originated in pipe and connection systems, while only 10% were related to appliances and 5% to waterproof membranes. MU1 showed a similar pattern, although with more limited categorization, with all identifiable cases originating from heating system failures. A substantial share of cases, 636 in MU1 and 60 in MU2, could not be categorized due to insufficient metadata, indicating that the dominance of pipe related incidents may partly reflect limitations in reporting structure rather than the full underlying failure distribution. Compared with national statistics for single family homes, where 62% of water damage is linked to pipes and connections, public buildings appear, based on the identified cases, even more strongly dominated by system level failures, underscoring the vulnerability of aging or heavily loaded municipal plumbing and heating systems.

The analysis shows that water damage in publicly owned buildings results in sub-stantial and highly variable repair costs than in single-family buildings. In total, 899 cases across MU1 and MU2 included cost data, with average repair costs of 8 500 € in MU1 and 18 100 € in MU2, and individual cases ranging from minor repairs of 47 € to extreme events exceeding 409 600 €. For both the studied municipalities the average repair costs are 10 105 €. Schools, offices, and nursing and care homes consistently account for the highest total repair costs and exhibit the largest cost variation, with several severe outliers driving up annual expenses. MU2 in particular showed significant cost burdens, with to-tal repair costs of 3,13 million € over the studied period and markedly

higher catego-ry specific costs than MU1. The strong right skew in the cost distributions indicates that a small number of major incidents contribute disproportionately to municipal repair budg-ets, highlighting the financial vulnerability of public building portfolios and the potential value of proactive maintenance strategies to prevent high impact failures.

Taken together, the results demonstrate that water damage represents a significant and recurring challenge in publicly owned and managed buildings. Across municipali-ties, the data reveal clear patterns: certain building types, primarily schools, nursing and care facilities, and offices, show consistently elevated vulnerability, both in terms of incident frequency and cost variability. The underlying causes point toward system level fail-ures within building services, particularly in tap water, sewage, and heating systems, highlighting the sensitivity of aging or heavily used buildings. Although the specific dis-tribution of causes is partly shaped by differences in municipal reporting practices, the dominant role of these technical systems is evident across the datasets.

The economic analysis further underscores the impact of these incidents. Repair costs are highly skewed, with a small number of severe cases driving a substantial share of total costs. This cost structure emphasizes the financial risks faced by municipalities that lack insurance coverage for many types of public buildings. The study therefore makes clear that there is considerable potential to reduce both the frequency and severity of water damage through more proactive maintenance strategies, improved reporting routines, and earlier detection of failures. Overall, the findings highlight the need for strengthened management practices, allocated resources to conduct proactive actions and coordinated data collection to support more effective prevention efforts across the public building stock and that actions and practices like this could be cost effective.

Acknowledgements The project is a collaboration between industry partners Säker Vatten AB and AB Rörläggaren and LTH, Lund University. The authors report there are no competing interests to declare. The authors would like to express gratitude to the studied municipalities for the contribution of the data and their work of retriveing and compiling data.

Author contributions All authors contributed equally in the preparation of this manuscript.

Funding Open access funding provided by Lund University. The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the SBUF (the Development Fund of the Swedish Construction Industry) under Grant 14360. The funding source had no involvement in writing this paper or the study.

Data availability Data are available upon request.

Declarations

Conflict of interest The author(s) declared no potential conflicts of interest concerning the research, authorship, and/or publication of this article. All authors contributed equally in the preparation of this manuscript.

Ethical standards No ethical approval was required and this article does not contain any studies with human or animal participants.

Consent for publication Not applicable.

Consent to participate Not applicable.

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Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Paper VII [redacted]

Water Damage in Public Buildings: Causes, Vulnerabilities, and Preventive Strategies

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Abstract

Purpose

This study explores the underlying causes of water damage in public buildings and identifies preventive strategies adapted to different municipal building types. Despite the substantial economic and operational consequences of water damage, knowledge of its causation and prevention within the public sector remains limited.

Design/Methodology/approach

A qualitative, exploratory research design was adopted. Empirical data comprised municipal water-damage reports and semi-structured interviews with facility managers, technical specialists and operational staff from three Swedish municipalities. The interview data were analysed using reflexive thematic analysis to identify recurring mechanisms contributing to water-damage occurrence and prevention.

Findings

Water damage was found to result from the interaction of user behaviour, ageing or vulnerable building service systems, workmanship deficiencies, inaccessible installation environments and organisational routines that delay detection. Schools were particularly affected by sabotage and intentional misuse, while nursing and care facilities experienced challenges associated with continuous water demand and moisture exposure. Four overarching themes emerged: Proactive Maintenance and Systematic Control; Technical System Vulnerabilities; Digital Monitoring and Early Detection; and Governance, Standards and Implementation Barriers. Effective prevention requires building-specific combinations of technical, organisational and monitoring measures, supported by procurement practices and governance frameworks tailored to public buildings.

Originality/value

This study provides a holistic understanding of how water damage develops in public buildings and highlights how prevention strategies should be adapted to different operational contexts. The findings contribute empirical knowledge to an under-researched area and offer practical guidance for improving resilience and reducing water-damage risks in municipal property management.

Keywords: water damage, public buildings, municipal property management, prevention strategies, facility management, building services, resilience.

Article classification: Research paper.

Introduction

Water damage in public buildings represents a substantial challenge, both economically and operationally. These damages not only lead to costly repairs and disruptions in essential services but also pose risks to occupant health and long-term building performance. Schools, nursing homes, offices, and cultural buildings are particularly vulnerable due to their intensive use, complex technical systems, and the societal importance of their functions (Mattsson et al., 2026, Mattsson, 2023).

Internationally, water damage is often studied within the broader context of building defects, with residential buildings receiving the most attention (Mattsson et al., 2026, Mattsson, 2023, Mundt-Petersen et al., 2026, Josephson and Hammarlund, 1999, Sassu and De Falco, 2014, Olanrewaju et al., 2018, Chew, 2005, Zegowitz et al., 2016, Forcada et al., 2013). Nationally, Sweden has developed systems for tracking water damage in residential buildings through insurance data and centralized reporting initiatives such as the Swedish Water Damage Centre (SWDC). However, publicly owned buildings are typically excluded from these datasets, resulting in a substantial knowledge gap. Swedish municipalities manage approximately 12 600 public buildings. However, their internal reporting systems regarding water damage and related measures vary widely, making it difficult to consistently assess its frequency, causes, and costs (Mattsson et al., 2026). Previous research on building defects, has shown that water-related damage in buildings is often dominated by moisture problems linked to external sources such as rainwater intrusion and flooding rather than failures in internal installations (Mattsson et al., 2026, Mattsson et al., 2023, Mattsson, 2023, Mundt-Petersen et al., 2026, Mundt-Petersen et al., 2023, Gustavsson et al., 2022, Josephson and Hammarlund, 1999, Chong and Low, 2006, Low and Yeo, 1998, Kim et al., 2019, Lee et al., 2018, Faqih and Zayed, 2021). These studies typically classify water damage broadly and highlight the significant impact of precipitation-related defects on building envelopes and structural components. Within this wider building defect literature, unintended water flow from technical systems, such as tap-water, sewage, heating installations, or indoor appliances, receives comparatively less attention, even though such failures can also lead to substantial repair costs, operational disruptions, and long-term material degradation (Mattsson et al., 2026, Mattsson, 2023) In contrast, this study focuses specifically on internally occured water damage, excluding rain, flooding, and other nature-related events. Failures in piping systems, waterproof membranes, and appliances are among common causes of water damage in municipally owned buildings (Mattsson et al., 2026). On average 13% of buildings in three studied municipalities report at least one water-damage incident per year, corresponding to approximately 1 of 8 buildings (Mattsson et al., 2026). Schools and nursing and care facilities showed the highest proportions, with certain municipalities reporting annual incident rates exceeding 25% in school buildings and up to 68% in care homes. These findings highlight not only the scale of the problem but also the substantial variation between building categories, underscoring the need for a deeper understanding of the underlying causes driving these patterns.

Recent research has also highlighted the importance of facility management and maintenance practices for building performance and damage prevention during the operation phase. Mundt-Petersen et al. (2026) found that almost one-quarter of investigated building damages were linked to deficiencies in building management and maintenance, demonstrating that operational and organisational practices can substantially influence damage occurrence. Similarly, research on predictive maintenance, machine-learning-based risk assessment, and sensor-based leakage detection has expanded rapidly in recent years, highlighting new opportunities for more proactive management of building assets. However, existing research has largely focused on moisture damage, defect prediction, or technical detection technologies rather than the actual occurrence of leakage-related water damage in building service systems. Limited knowledge exists regarding how facility management practices, maintenance strategies, inspection routines, and organisational structures influence the occurrence and consequences of water damage in publicly owned buildings (Mundt-Petersen et al., 2026, Mundt-Petersen et al., 2023, Mohd Yussof and Ho, 2022).

Water damage in public buildings not only leads to high repair costs but also pose risks to health, service continuity, and the long-term durability of facilities that are essential for societal functions. Despite these challenges, knowledge about damage frequency, underlying causes, and effective mitigation strategies remains limited, particularly for municipally owned buildings. The analysis revealed a similar pattern between the municipalities. In MU1, an average of 15% of the buildings in the building stock that reported at least one water-damage case per year, while MU2 showed a lower annual proportion of 9%, and MU3 reported 12%. In residential single-family buildings the average is approximately 2,6% (Mattsson, 2023, Vattenskadecentrum, 2025). Schools and nursing and care homes were consistently

among the most affected categories. For example, the share of school buildings experiencing water damage each year ranged from 5% to 27% across the municipalities, and for nursing and care homes the proportion ranged from 37% to 68%. These results indicate not only substantial variation in occurrence patterns but also that certain building types are disproportionately exposed to recurrent water-damage incidents. Cases were filtered to include only those with sufficient detail to allow categorization by cause and affected system, as well as those linked to a specific building category and operational context. Cases lacking adequate metadata or falling outside the defined scope, such as nature-related water damage, were excluded in the following analysis. After applying these criteria, 1 017 cases from MU1 and MU2 were selected for detailed analysis, while MU3 contributed 2 013 cases for occurrence trends. Of the total 18 282 reported cases, 3 030 could be confirmed as falling within the scope of this study. The remaining cases were attributable to external factors such as precipitation, flooding, and other nature-related events. It is possible that additional cases within the approximately 15 000 excluded reports also met the study's inclusion criteria; however, due to the sampling methodology and limitations inherent in the reporting system, these cases could not be reliably classified for inclusion (Mattsson et al., 2026).

The quantitative results provide an overview of how frequently water damage occurs across building categories, but also reveal substantial variation that cannot be fully explained by the statistics alone. High rates in schools and nursing and care facilities, along with differences between municipalities, suggest that underlying causes are more complex than system type and frequency indicate. However, the specific causes could not be identified due to limitations in the reporting system. A large share of cases (696 out of 1 017) were classified as unknown, and the dataset lacked sufficient detail to determine the cause of each individual event. As a result, the classification was limited to identifying the system in which the damage occurred. This study address this gap by combining quantitative analysis of municipal water damage data with qualitative insights from stakeholder interviews conducted in Swedish municipalities. Furthermore, this study builds on the previous statistical foundations (Mattsson et al., 2026), where in addition this article aims to find the causes of the studied water damage cases and suggest technical solutions based on the found causes that can reduce both future occurrence and impact of water damages in public buildings. The study aims to identify the underlying causes of water damage in public buildings, evaluate preventive measures and technical solutions, and explore stakeholder perspectives regarding their feasibility and effectiveness. By combining statistical patterns with operational experiences, the study seeks to support more resilient and proactive management of public buildings.

To address these challenges, the study combines quantitative municipal water-damage data with qualitative interviews with facility managers and technical staff. The aim is to identify the underlying causes of water damage, evaluate preventive measures and technical solutions, and explore stakeholder perspectives regarding their feasibility and effectiveness. Together, these approaches provide a foundation for more resilient and proactive management of public buildings. The research questions that were addressed and analyzed in this study were:

i. Which types of water damage occur most frequently in municipally owned buildings, and what underlying causes can be identified from the statistical data developed in previous study (Mattsson et al., 2026)?
ii. How can technical solutions that address the identified causes, such as building and installation measures, sensors, and leakage indicators, be adapted to different building types and operational contexts to reduce the occurrence and extent of water damage and what are the state-of-the-art of these solutions in the studied buildings?
iii. How do stakeholders perceive the feasibility and cost-effectiveness of implementing preventive and reparative measures in both existing and new buildings, in light of previous findings on the extent and costs of water damage (1), where the underlying causes could not be established and therefore warrant further investigation in this study?

In this study, technical solutions refer to preventive and reparative measures intended to reduce the occurrence, extent, or consequences of water damage in building service systems, including design choices, maintenance practices, monitoring systems, and leakage detection technologies.

Water damage studied in this paper is limited to the unexpected flow of water in undesirable areas within the building occurring from the building's services, installations, or appliances inside a building. Water leakage from pipes, connections, and valves in the tap water-, sewage, or heating system, and water damage occurring from inadequate waterproof membranes and appliances, such as refrigerators or dishwashers, causing damage are all studied in this paper. This categorization of water damage is also commonly used in the statistic-gathering companies in the Nordic countries (Vattenskadecentrum, 2025, Forsikring & Pension, 2022, Finans Norge, 2022, Svensk Försäkring, 2022). This paper does not cover water damage caused by rain, flooding or other nature-related water damage cases. The interviews complement the quantitative data by providing insights into operational practices, perceived challenges and the feasibility of preventive measures.

Method

The methodology combined results from quantitative analysis of water damage statistics, in a previous study (Mattsson et al., 2026), with qualitative insights from stakeholder interviews, carried out in this study. Statistical data from municipal water damage reports were used in the previous study (Mattsson et al., 2026) to identify the extent and patterns of water damage across different building categories, including schools, care homes, offices, cultural buildings, and leisure buildings from three municipalies. In this study, following the previous study, the municipal building stock is divided into five main categories; schools, nursing and care facilities, office buildings, cultural buildings, and leisure and sports facilities. Schools include preschools, elementary schools and high schools, representing a diverse group of educational facilities with high occupancy and intensive use of sanitary areas. Nursing and care homes comprise elderly care facilities, health-care centers, support- and servicehousing, such as special residential care, for people with significant and long-term disabilities, all of which operate with continuous water use and sensitive environments. In this category, buildings with specially adapted housing for support and services for people with mental or physical disabilities are included. These buildings are designed to provide security, independence and a meaningful everyday life. Residential buildings refer to municipality-owned housing units, such as apartments or supported living units, although these are sometimes inconsistently registered in municipal systems. Offices and premises include administrative buildings, fire and police stations, bus stations, and other municipal service buildings. Cultural buildings cover facilities used for cultural activities, such as libraries, museums, exhibition venues, and community cultural centers. Leisure buildings include indoor aquatic centers, public swimming facilities, sports halls, and various community or recreational buildings with high water exposure requirements.

The analysis and interviews were based on a dataset of 3 030 reported water damage cases collected from municipal damage reporting systems in three Swedish municipalities. These cases were categorized by building type, schools, care homes, offices, cultural and leisure buildings, and by location of the damage, including pipes and connections, appliances, and waterproof membranes. Repair cost data were available for two municipalities (MU1 and MU2), while MU3 provided occurrence data only.

A qualitative interview study was conducted with facility managers and technical staff from three Swedish municipalities, referred to as MU1, MU2 and MU3. The aim of the interviews was to gain deeper insights into the analyzed water damage data and to understand the operational practices, perceived challenges, and potential solutions related to water damage prevention and management that the studied muncipalies use.

Participants were selected based on their professional roles and responsibilities within municipal property management, ensuring representation from individuals with direct insight in the previous

studied data set and experience in building maintenance, water damage incidents, and decision-making related to technical systems and repairs. The three municipalities included in this study were the same as those examined in the previous quantitative analysis of water-damage occurrence in publicly owned buildings (Mattsson et al., 2026), forming an established foundation for the present investigation. These municipalities were selected based on predefined criteria requiring that they be among the 10 largest municipalities in Sweden, ensuring sufficiently large building portfolios, diverse building categories, and comprehensive reporting structures suitable for both quantitative and qualitative analysis. In total, interviews were conducted individually with 7 individuals from the studied municipalities, 5 from MU1, 1 from MU2 and 1 from MU3. This distribution reflected differences in the organisational structures of the studied municipalities, where the division of responsibilities varied between them, explaining the variation in the number of interviews conducted across the municipalities. Participants were selected based on their professional expertise and operational responsibilities within specific building categories, schools, offices, nursing and carehomes, culture and leisure buildings. The muncipalites where contacted and then the municipalites identified and assigned suitable personnel within their divisions to be included in the interviews, such as facility managers, technical specialists, and operational staff, who possessed direct knowledge of maintenance routines, incident actions, and the technical systems in the municipal buildings. The selection aimed to ensure representation from individuals with in-depth knowledge of maintenance and damage management and interviewees who oversee multiple buildings and have broad operational experience in the different municipalities. All participants were informed about the purpose of the study, their right to withdraw at any time, and how the data would be used. Anonymity was ensured by removing identifiable information from transcripts and reporting findings in aggregated form.

A semi-structured interview guide was developed to ensure consistency across interviews while allowing for open-ended responses. The interviews were guided by a semi-structured set of questions designed to capture both the strategic and operational dimensions of water-damage management in municipal buildings. Participants were first asked to describe the types of buildings they were responsible for and their specific roles in maintenance and damage response. The conversation then turned to the frequency and nature of water-damage incidents, including their perceptions of common causes, the extent to which service requests and technical failures occurred, and how internal processes unfold from the moment a leak is detected to the completion of repairs. Further questions explored proactive practices, such as routine inspections, preventive maintenance planning, and the use of digital tools for monitoring and documentation. To understand constraints and long-term risks, interviewees were also asked about challenges in older buildings. Finally, the interviews included open reflections on why certain incidents lead to disproportionately high costs, which weaknesses in current practices they considered most critical, and what changes would most effectively reduce future water-damage occurrence in their municipal context. The structure was used in all interviews and the thematic sections covered:

- Background and responsibilities (e.g., types of buildings managed, role in maintenance and damage response)
- Water damage experience (e.g., frequency, causes, internal processes, collaboration with insurers)
- Most common causes of water damage in the building stock
- Maintenance routines (e.g., inspection practices, use of digital systems, prioritization strategies)
- Challenges and innovations (e.g., issues in older buildings, new technologies, staff training)
- Cost and impact (e.g., reasons for high repair costs, material choices, restoration methods)
- Recommendations and reflections (e.g., desired changes, perceived weak points, future needs)

Each interview was conducted via Microsoft Teams, lasted approximately 45–60 minutes, and was audio-recorded and transcribed with participants' consent. Transcripts were reviewed and translated from Swedish to English with emphasis on preserving meaning and context.

The interview transcripts were analysed using reflexive thematic analysis following Braun and Clarke's six-phase framework (Braun et al., 2024, Braun and Clarke, 2006). The method was selected because it provides a systematic approach for identifying patterns of meaning in qualitative data and is well suited for semi-structured interviews. The analysis involved familiarisation with the data, generation of initial inductive codes, construction of preliminary themes, review and refinement of themes, and the final definition and naming of themes. The process was iterative, involving continuous movement between transcripts, codes and emerging interpretations. Reflexive notes were maintained throughout the analysis to document analytical decisions and enhance transparency. The first author conducted the analysis iteratively through coding, theme development and refinement. Themes were continuously reviewed against the original transcripts, and representative quotations were translated from Swedish to English while preserving their intended meaning.

The analysis focused on identifying recurring patterns and concepts related to water damage causes, preventive strategies, and organizational practices. This thematic structure provided insights into how statistical evidence can inform practical decision-making and highlighted opportunities for aligning technical solutions with operational realities. Both reparative and preventive measures were examined, including building design, planning, installation techniques, and digital monitoring systems. Parameters such as material selection, extent of leakage, and building type were considered in the intervieews answers in order to assess the influence and how it affect on damage frequency, cost, and climate impact of the buildings. The findings aim to support tailored solutions for different operational contexts in buildings such as schools, nursing and care homes, cultural facilities, offices, and leisure buildings, thereby contributing to sustainable building management.

Results

This section presents the results from the interviews conducted with municipal building managers and technical staff responsible for the operation and maintenance of public buildings in the studied municipalies. These professionals manage water damage incidents and implement preventive measures both in planing and designing and in the operation phase of the buildings, making their insights essential for understanding the practical conditions behind technical and organizational strategies aimed at reducing the occurrence, casues and consequences of water damage from building services systems. The interviews provide an in-depth perspective on how municipalities currently address water damage risks, the challenges encountered in the operation and management of public buildings, and the solutions considered most effective for reducing both the occurnace and the impact of water damages. Previous studies have documented economic consequences and technical causes in mostly single-family buildings (Mattsson, 2023, Vattenskadecentrum, 2025, Carretero-Ayuso et al., 2020).

Interviews

The interviews included seven participants from three municipal property organisations, comprising facility managers, technical specialists and operational staff, thereby providing both strategic and operational perspectives on water-damage management. To ensure confidentiality, participants were anonymised using role-based codes reflecting municipality and building category. Personal names were removed during transcription, and only these codes are used when presenting quotations in the results. The anonymisation scheme is shown in Table 1.

Table 1. Overview of interview participants and anonymisation codes. The codes MU1 stands for the municipality and the last two letters are short for the building category/role.

Building category / Role	**Municipality**	**Code**
Preschool – Facility Management	MU1	**MU1-PS**
Elementary School – Facility Management	MU1	**MU1-ES**

Culture & Leisure Buildings – Operations/Technical Staff	MU1	**MU1-CL**
Nursing and Care Facilities – Facility Management	MU1	**MU1-NC**
Residential Buildings – Technical Specialist	MU1	**MU1-RB**
Overall Operations and Building Mangement	MU2	**MU2-OA**
Operations & Management	MU3	**MU3-OM**

These codes were applied consistently throughout the coding process and during thematic development. When quotations are included in the results, only the anonymised participant code (e.g., *MU1-ES* or *MU3-OM*) is shown. Together, these roles represent the key functions involved in preventing, detecting, and managing water-damage incidents in public buildings. The interview material therefore reflects experiences from both decision-making levels and practical site-based operations, forming the empirical basis for the thematic analysis presented in the following section.

Consolidated interview responses

This section presents the consolidated interview findings sorted by interview participant. Each subsection present the key perspectives, experiences, causes and selected quotes provided by the interviewees. The structure follows the anonymisation codes described in the methodology.

MU1-PS – Preschool, Facility Management

The respondent emphasized that water damage often escalates because of gaps in routine inspections and delayed technical action. Daily caretakers act as "eyes" in the buildings, but piping-related issues are frequently postponed or overlooked. The interviewee highlighted that communication gaps between maintenance and operations lead to repeated failures of the same components. Older piping systems and inaccessible service areas were presented as persistent risk factors.

"We have our property caretakers out there as our eyes… but when it comes to piping, things often get postponed. We don't really have a good system for that."

MU1-ES – Elementary School, Facility Management

This interviewee stressed that intentional damage (sabotage) is the single most dominant cause of water-related incidents in schools. Deliberate removal of traps, manipulation of valves, and damage to fixtures lead to rapid water release with large consequences. These acts often target technically vulnerable components, compounding existing weaknesses in older installations.

"Intentional damage is our number one problem in schools, water traps pulled out, valves twisted open."

MU1-CL – Culture & Leisure Buildings, Operations/Technical Staff

The respondent described high technical vulnerability due to tight installation spaces in cultural and sports facilities. Large wet zones, high humidity, and complex water-use patterns increase the difficulty of both prevention and remediation. Failures in routine inspections, particularly in heavily used public shower and locker areas, were noted as drivers of repeated incidents.

"When inspections slip, we pay for it later. Leaks that could have been caught early turn into big clean-ups."

"Shafts and rooms are tight, everything is stacked. Fixing one leak risks stressing another connection."

“It doesn’t feel great that something has to break before we act… but that’s really how we discover it today.”

MU1-NC – Nursing and Care Facilities, Facility Management

This interviewee highlighted that all day and night (24/7) operational requirements significantly limit the feasibility of common technical solutions such as whole-building shutoff systems. Many incidents arise from user-related behaviors, such as long unsupervised showers, obstructed drains, or taps left running. The respondent stressed the need for robust, moisture-resistant materials, and emphasized cost-effective design choices such as continuous vinyl flooring and non-absorbent fixtures.

“We don’t always get the maintenance notes back to operations. The result is that the same valve is reported again and again.”

“Access delays matter, by the time we enter, the flat may already be flooded.”

“Camera inspections and scheduled relining keep us ahead, if the plan is up to date.”

“Watershutoff devices could help, but our facilities operate 24/7. We need solutions that isolate locally, kitchens or machines, without cutting essential supply to the unit.”

“In many cases the incident is first noticed by the care staff, not the resident. If access is delayed, the water damage is already extensive when we arrive.”

“That sewage components are clogged in care units is a daily occurrence; objects that should not be there are often flushed into the system”

“In 24/7 care environments, material specifications such as continuous vinyl flooring, coved skirting (a sort of sealing between the membrane and the pipe), and fittings, combined with localised shutoff functions, form the most feasible and least disruptive preventive package.”

“Design choices (such as material choises, fixtures, visible draines for example) were sometimes driven by aesthetics rather than the realities of care environments.”

MU1-RB – Residential Buildings, Technical Specialist

This interviewee discussed the challenges linked to aging infrastructure and the need for vandal-resistant materials in certain residential environments.The interviewee noted frequent failures in galvanized or aging piping as well as inconsistent reporting flows between caretakers, tenants, and maintenance teams.

“For high-risk tenants we’ve specified more robust fixtures, even all-steel bathrooms in some supported housing appartments, for people with mental disabilities, because replacing porcelain weekly isn’t feasible.”

“Immediate mitigation is prioritised, but the lack of clear ownership for digital monitoring and the negotiation of costs create barriers to systematic prevention.”

MU2-OA – Overall Operations and Building Management

This interviewee highlighted that vandalism-related incidents are a central driver of water damage in schools and that automated shut-off solutions have proven highly effective in limiting the extent of such events. The respondent also emphasized significant challenges in older buildings with cast-iron piping, where monitoring and preventive measures are difficult to implement. Budget constraints and outdated standards further complicate long-term planning, underscoring the need for preventive technologies and building practices better adapted to public-sector usage.

"Intentional damage… often we have had to close the toilet for several days for the pupils to understand the consequence."

"Elementry school (approximatly age 6 to 15) is where a lot of vandalism happens. But it is also very much in pre-school (approximatly age 3 to 5). And that is perhaps the most frightening thing."

"We have connected the water shut-off device to the lighting. When you enter the building, the light turns on and then the water is activated, and after five minutes it shuts off…this means that if a leakage occurs, maybe 50 liters run out, and that is easy to clean up. It does not become a cubic meter that leaks through the whole building…before, it could run for two hours. Ten liters per minute… that becomes a lot of water…this solution costs around 10 000 SEK, but it often stops the escalation of vandalism."

"Where I have installed it, there is no leakage, because when it happens, the water shuts off after five minutes…At the schools where I have installed it, they are extremely satisfied…The cost is not that big. Installation is the large part, but afterwards you don't have these problems."

"I absolutely believe you can implement the same solution in other buildings…We have also installed it in housing units where people cannot really live independently… you press a button on the outside and then the water turns on, and then you press another button and it shuts off again."

"All buildings from the 1960s and 1970s with cast iron pipes are extremely difficult. You don't know where to place a sensor strip…These old buildings are a problem and will be as long as they exist."

"Politicians only see money. When we suggest renovating the entire building they say: can you just take this part? But then it will cost more later…Maintenance plans have not really been done properly until last year…I had a period when I had a water damage every week, you get quite fed up."

"Public buildings are built according to industry rules made for single-family houses, but our buildings have completely different usage patterns…Each municipality has its own practice. There is not the same statistics as for residential buildings."

MU3-OM – Operations & Management

This interview respondent stressed the importance of structured maintenance inspections and how dedicating personnel to systematic building assessments improved risk management. The interviewee also noted that digital monitoring is highly effective when implemented but suffers from fragmented routines and unclear response structures. The interviewee focused on digital alarm integration problems, where water alarms are sometimes linked directly to burglar systems. The respondent emphasized the need for clearer protocols and accountability regarding alarm response, as well as more consistent deployment of sensors across the municipal portfolio.

"Galvanized pipes fail at the threads. Once they start, you often find three more in the same line."

"Where we have leakage alarms and automatic shutoff, the damage is limited to a wet mat rather than a soaked floor."

"In several schools we link the water supply to the burglar alarm. When the alarm activates for the weekend, the water shuts off, preventing taps left on from flooding the building."

A few years ago, we introduced dedicated maintenance-inspection roles. They assess entire buildings room by room. Their reports now guide most of our risk and maintenance planning."

"Standards are written with apartments in mind. Our usage patterns are different, more fittings, heavier wear."

"Alarms go to the burglar system in some sites; when that fails, nobody knows who should respond to a water alert."

"Preventive work only has effect if someone drives it. When engagement drops, we fall back into reacting to incidents instead of preventing them."

Familiarization with the data

The first step of the thematic analysis was that all interview transcripts were read multiple times to achieve deep familiarity with the gathered material. Early impressions were documented in reflexive notes, highlighting recurring mentions of technical system failures, preventive routines, and cost-related concerns. A particularly strong pattern that emerged during this stage was the role of sabotage as a major contributor to water damage. All interviews referenced sabotage, especially in schools, as a significant cause of incidents. This finding positions sabotage as a critical factor alongside aging systems and technical vulnerabilities.

Generating intial codes

In this step, all transcripts were systematically reviewed line by line to identify meaningful units of text related to the research questions. Each segment was assigned an code summarizing its core idea. The preliminary observations that emerged at this stage was:

- **Frequent references to aging piping systems and material degradation** were identified, particularly concerning galvanized steel pipes and older installations, which were repeatedly described as common sources of leakage.
- **Preventive measures such as leakage alarms, shut-off valves, and systematic inspections** were mentioned across interviews, although their implementation was inconsistent between municipalities and building types. This inconsistency highlighted variations in organisational capacity and prioritisation of preventive work.
- **Substantial variability in repair costs** was noted, with several participants emphasising the financial costs associated with severe or large-scale water damage incidents. These high-impact cases were described as particularly influential in shaping maintenance strategies and risk perception.
- **Concerns regarding the municipality's reporting structure** emerged, particularly the lack of distinction between water damage from installations and buildings services and moisture-related issues from external sources, such as rain and flooding. Interviewees described how a wide range of incidents are routinely categorised as "water damage," regardless of underlying cause, potentially obscuring important causal differences.
- **The functional design of public buildings**, including cultural facilities, sports complexes, and leisure buildings, such buildings with indoor swimming pools, was highlighted as introducing highly specialised technical environments. These buildings contain large wet areas, such as public showers, high-capacity water systems, and sensitive materials, all of which require adaptations in both design and maintenance practices.
- **User behaviour and vandalism** were identified as recurring contributors to water damage across multiple building categories. Participants described deliberate tampering with fixtures, misuse of facilities, and other forms of user-induced damage, underscoring the behavioural dimension of risk.

This process resulted in a coding scheme that captured recurring concepts across interviews. These codes provided a structured foundation for clustering the segments into broader themes. The codes that emerged are presented in Table 2.

Table 2. Overview of the initial codes generated during the first phase of the thematic analysis. The table summarizes the inductive codes derived from the interview material.

Code	Description
Lack of systematic control	Absence of structured routines for inspections, follow-up, and preventive maintenance.
Information transfer and operations	Gaps in communication and feedback between operations, caretakers, technicians, and maintenance teams.

High frequency and cost	Repeated incidents and large variations in repair costs, including high-impact outlier events.
Aging pipes and installation errors	Failures linked to old piping, corrosion, poor workmanship, or inaccessible installation spaces.
Sabotage and intentional damage	Deliberate manipulation of valves, traps, or fixtures. Improper use, leaving taps running, blocking drains, or intentional damage.
Digital monitoring and alarms	Use or absence of leakage sensors, alarms, and automatic shutoff solutions.
Alarm handling and response workflows	Unclear routines for who receives, evaluates, and responds to alarms; varying alarm routes and leakage responce
Industry standards and regulations	Unclear building standards and guidelines in public buildings
Prioritization and funding	Budget limitations that favor reactive repairs over preventive investments.
Preventive measures (leakage alarms, shut-off valves, inspections)	Identified practical preventive actions and tools.
Concerns regarding the municipality's reporting structure	Reporting systems that merge different types of damage, making analysis and categorisation difficult.
The design of public buildings	Complex building types (e.g., schools, cultural buildings, leisure facilities, building for service and special needs) that affect vulnerability and detection of water damage and prevention
User behaviour	The use of the buildings and their requirements to operate as the intended function.

Searching for themes

Relationships between codes were examined with respect to the research questions.This iterative grouping produced four overarching themes that integrate the full code set. The first grouping of the codes where the codes including statements that repeatedly pointed to missing or uneven inspection routines, limited feedback loops between operations and maintenance, and unclear responsibilities between municipality, user, employees and residents. Participants linked these gaps to higher incident rates and escalating repair costs. Consolidating these the codes, listed below, under one theme captures the operational preconditions for prevention and the importance of structured processes (e.g., scheduled inspections, checklists, and clear escalation paths).

- *Lack of systematic control*
- *Information transfer and operations*
- *High frequency and cost*, as a consequence highlighting the need for preventive routines.
- *Preventive measures*
- *Alarm handling and response workflows*

The second grouping of the codes reflected how the interviewees consistently described weaknesses in the building services systems, including issues such as galvanized pipes, aging connections, and cramped installation shafts. Within this grouping, sabotage emerged as a reinforcing mechanism: intentional damage by users often targets already vulnerable points, such as traps, valves, and fittings, thereby magnifying the overall failure risk.

- *Aging pipes and installation errors*
- *High frequency and cost*, when tied to failure-prone systems and materials

- *Sabotage and intentional damage*, as an exacerbating factor stressing fixtures and connections
- *User behaviour*
- *Lack of systematic control*

The third clustering of codes emerged when participants described the partial implementation of leakage alarms and water shut-off devices, alongside the overall uneven coverage and integration of these systems across the building stock. In several cases, alarms were tied to burglar alarm systems, creating additional variation in how signals were managed.

- *Digital monitoring and alarms*
- *Information transfer and operations*, regarding alarm handling and response workflows
- *The design of public buildings*
- *Alarm handling and response workflows*

The final grouping of codes reflected interviewees' emphasis that existing guidelines and industry norms are largely derived from residential building contexts and therefore do not correspond well to the operational realities of public buildings such as schools and care facilities. Participants also highlighted budget constraints and the complexity of retrofitting existing buildings as recurring barriers to scaling up preventive technologies.

- *Current regulations based on residential statistics*
- *High frequency and cost*, as a driver for reconsidering prioritization and funding
- *Digital monitoring and alarms*, when constrained by budgets or procurement practices
- *Prioritization and funding*
- *Concerns regarding the municipality's reporting structure*

Reviewing Themes

During the fourth phase of the thematic analysis, the preliminary themes generated in the earlier coding stages were systematically reviewed and refined to ensure that they provided a coherent representation of the interview material.

Theme 1

Preventive routines and structured inspections emerged as critical factors for reducing water damage. Gaps in information flow between maintenance and operations often lead to repeated failures as mentioned by the interviewees.

"When inspections slip, we pay for it later. Leaks that could have been caught early turn into big clean-ups." – MU1-CL

"We don't always get the maintenance notes back to operations. The result is that the same valve is reported again and again." – MU1-NC

These insights highlight the need for scheduled inspections, clear checklists, and effective communication channels to prevent recurring issues.

Theme 2

Aging infrastructure and installation errors were consistently identified as major risk factors. Importantly, sabotage was mentioned in every interview as a dominant cause of water damage in schools,

often targeting vulnerable components such as water traps in the water drain and valves in the pipes and water systems.

"Galvanized pipes fail at the threads. Once they start, you often find three more in the same line." - MU3-OM

"*Intentional damage is our number one problem in schools, water traps pulled out, valves twisted open."* - MU1-ES

This theme underscores the combined effect of technical weaknesses and deliberate tampering, which significantly amplifies risk.

Theme 3
Digital solutions such as leakage alarms and water shut-off devices were viewed as effective in limiting damage, but their implementation is uneven. Some buildings have advanced monitoring systems, while others lack coverage entirely. Integration with other systems, such as burglar alarms, was reported as problematic, creating confusion about responsibility for responding to alerts.

"*Where we have leakage alarms and automatic shut-off, the damage is limited to a wet mat rather than a soaked floor."* – MU3-OM

"Alarms go to the burglar system in some sites; when that fails, nobody knows who should respond to a water alert."– MU3-OM

This theme highlights both the potential benefits of early detection and the operational challenges of alarm handling.

Theme 4
Participants stressed that current regulations and standards are primarily based on residential building statistics, making them poorly suited for public facilities such as schools and care homes. Budget constraints and procurement practices further limit the adoption of preventive technologies and tamper-resistant fixtures.

"Standards are written with apartments in mind. Our usage patterns are different, more fittings, heavier wear." MU3-OM

"Budgets prioritize acute repairs over prevention. It's hard to argue for sensors when last year's claims were already overspent." MU1-NC

This theme reflects systemic barriers that hinder proactive investment and long-term resilience.

Defining and naming themes
After reviewing the preliminary themes, each theme was namned and defined to capture its central concept and scope. Below are the four themes with concise definitions:

Theme 1: Proactive Maintenance & Systematic Control
This theme includes preventive routines, structured inspection practices, and effective information flow between maintenance and operations. It reflects the importance of systematic control in reducing the frequency and repair costs of water-damage incidents. The theme was named Proactive Maintenance & Systematic Control because the interview findings consistently showed that the most influential factors behind reduced damage occurrence were organisational rather than technical, specifically the presence of clear routines, predictable inspections, and functional communication pathways.

Theme 2: Technical System Vulnerabilities
This theme addresses weaknesses in building service systems, including aging materials, installation errors, and spatial constraints. It also incorporates sabotage as a reinforcing mechanism that targets

vulnerable points, particularly in schools. The results highlight that actions to reduce the effect of the frequent sabotage must be taken. Interview findings consistently showed that the sabotage and material condition of building service systems form the underlying infrastructural risk landscape in which water-damage incidents occur. Aging pipes, corroded connections, cramped shafts, and workmanship deficiencies were repeatedly identified as structural weak points that both increase the likelihood of failures and worsen their consequences.

Theme 3: Digital Monitoring & Early Detection

This theme focuses on the role of technology in detecting and mitigating water damage, including leakage alarms, water shut-off devices, and sensor systems. It also considers the operational challenges of alarm handling and response workflows. This theme includes the varying coverage of sensor systems and the degree of integration between digital monitoring and existing building management infrastructures, as well as the operational challenges associated with alarm handling, response routines, and system reliability.

Theme 4: Governance, Standards & Implementation Barriers

This theme captures factors that influence the usage and implementation of preventive measures, such as frameworks, budgeting priorities, and operation practices. It highlights the mismatch between current standards (mostly based on residential buildings) and the construction, design, and operation of public facilities. Interview findings consistently showed that structural, policy-level conditions, rather than technical limitations, play a decisive role in shaping what preventive measures can realistically be implemented.

Analyzis

Taken together, the four themes show that water-damage risks in public buildings do not arise from isolated technical failures, but from the interaction of organisational practices, system vulnerabilities, technological limitations, and structural governance conditions. Each theme represents a distinct dimension, yet the analysis reveals strong interdependencies that shape both the frequency and severity of incidents across the municipalities.

The theme Proactive Maintenance & Systematic Control demonstrates how weak routines, unclear responsibilities, and fragmented information flows enable minor issues to escalate into major water-damage events. Small leaks may remain unnoticed due to insufficient inspections or unclear task delegation, while preventive work is often overshadowed by acute repairs. In contrast, structured inspections, preventive maintenance, and effective communication contribute to fewer incidents and lower costs. The theme Technical System Vulnerabilities shows how ageing materials, installation faults, spatial constraints, and user behaviour contribute to water-damage incidents. Failures in ageing pipe systems, workmanship deficiencies, and intentional tampering, particularly in schools, were identified as important drivers of damage occurrence and severity. The theme Digital Monitoring & Early Detection highlights both the potential and limitations of sensor-based technologies. Leakage alarms and automated shut-off systems can substantially reduce damage, but implementation remains uneven and is often constrained by building conditions, organisational routines, and unclear alarm-response responsibilities. The theme Governance, Standards & Implementation Barriers shows how regulations, procurement practices, and budget constraints influence municipalities' ability to adopt preventive measures. Existing standards are largely based on residential buildings and do not adequately reflect the operational requirements of public facilities, limiting the implementation of preventive technologies and long-term risk-reduction strategies.

Across the themes, a clear pattern emerges: water-damage risk is co-produced by technical, organisational, behavioural, and structural factors. Weaknesses in one domain reinforce vulnerabilities in others, for example, ageing infrastructure increases dependence on preventive routines and digital detection, while unclear procurement structures hinder the implementation of those measures.

Conversely, well-functioning organisational processes, tailored standards, and appropriate technologies can compensate for underlying vulnerabilities and reduce damage extent.

The findings therefore emphasise that reducing water-damage risk in public buildings requires a holistic approach in which maintenance practices, system design, user behaviour, digital tools, and governance frameworks are aligned. Without coordinated action across these areas, municipalities risk recurring incidents, high repair costs, and continued reactive management cycles. The substantial repair costs, ranging between 521 300 € in MU2 and 1 029 900 € in MU1 on average per year, associated with these incidents, as shown in the previous study (Mattsson et al., 2026), further strengthen the incentive to prioritise preventive measures and targeted interventions in these areas, both from the government and municipalities. However, the findings in this study show that human and organisational factors strongly influence daily practices and provide important insights into the current state of water-damage prevention in municipally owned public buildings.

Producing the Results of the Interviews - Identified causes and solutions

The thematic analysis of interviews with municipal facility managers and technical staff resulted in four distinct themes that explain recurring patterns in water damage causes, preventive strategies, and implementation challenges. Analysing the causes and solutions it becomes evident that several actors have influence over and are needed in the quest to reduce the occurence of water damages in buildings as well as actions are need to be taken in all phases of the bulding´s lifecycle. The identified causes and solutions have therefore been divided into the different phases of a building´s life cycle to emphasize and clarify that several actors in different phases must adress the problem, presented in Figure 1.

1. DESIGN PHASE

Identified causes	Identified needs	Examples of possible solutions
Buildings not designed for actual use	Robustness and damage limitation in case of misuse	Moisture-resistant materials, protected installations, vandal-resistant design
Buildings with continuous operation where water supply cannot be shut off	Robustness and damage limitation in case of misuse	Moisture-resistant materials, protected installations, vandal-resistant design
Materials unsuitable for the building's environment or use	Limited water spread	Zone-specific shut-off, time-controlled water supply
Tight or complex installation spaces	Reduced vulnerability and improved accessibility	Simplified installation, clear and accessible shafts
Inaccessible installation shafts	Reduced vulnerability and improved accessibility	Simplified installation, clear and accessible shafts

2. CONSTRUCTION PHASE

Identified causes	Identified needs	Examples of possible solutions
Installation errors and poor workmanship	Reduced risk of early leaks	Quality assurance of installations, inspection of connections
Unsuitable material choices for the operation	Long-term moisture resistance	Robust, moisture-resistant materials adapted to use

3. ORGANIZATIONAL PHASE (GOVERNANCE AND MANAGEMENT)

Identified causes	Identified needs	Examples of possible solutions
Lack of structured inspection routines Irregular or no inspection of pipes Few or no preventive inspections	Predictable and recurring supervision	Scheduled inspections, checklists (based on water damage statistics), adapted construction industry regulations
Moisture issues (rain, humidity) confused with technical water leaks Maintenance notes are not fed back to the operations organization Lack of a shared reporting system	Feedback and learning	Shared reporting systems, feedback of maintenance data, adapted construction industry regulations
Communication gaps between property managers, technicians, and management Technical staff lack access to premises No designated responsibility for reducing water-related risks Different ownership and management structures Unclear responsibility for alarms and actions Delayed response to leaks	Clear allocation of responsibilities	Dedicated roles for supervision, clear alarm chains, adapted construction industry regulations
Preventive work lacks funding Budgets are consumed by emergency repairs	Ability for long-term planning	Use of water damage statistics for prioritization, Allocation of resources to preventive maintenance and responsibility from policymakers, adapted construction industry regulations

4. OPERATIONAL PHASE

Identified causes	Identified needs	Examples of possible solutions
Water traps physically removed Valves intentionally turned to open position Fixtures intentionally damaged Drains deliberately blocked with objects Manipulation of pipe and drainage components Incorrect objects flushed in toilets	Rapid limitation of damage in case of sudden leaks	Local shut-offs, fixed water traps Tamper-proof access panels (tool-required opening), recessed floor drains with lockable grates Sensor- and time-controlled mixers and water activation Leak alarms, clear alarm handling procedures Time-controlled water supply linked to lighting or alarms, adapted construction industry regulations
Taps left open by users Very long showers Users do not report minor leaks	Automatic limitation of water flow	Sensor- and time-controlled mixers Leak alarms and clear response routines, adapted construction industry regulations
Aging pipe materials Corrosion and wear	Control of installation systems and component lifespan	Camera inspections, planned relining, adapted construction industry regulations
Poor workmanship (insufficient tightening, faulty connections) Inaccessible pipe routing Systems sensitive to vibrations or mechanical impact Repeated failures in buildings with outdated piping systems Faulty equipment (dishwashers and washing machines)	Increased accessibility and controllability of pipe installations	Early detection and rapid action Camera inspections and planned relining Planning based on failure statistics Allocation of resources to preventive maintenance and responsibility from policymakers, adapted construction industry regulations

Figure 1. Identified causes of damage, needs, and possible solutions at the different stages of the building's lifecycle

Discussion

The findings of this study indicate that water damage in municipally owned public buildings occurs from an interaction between technical vulnerabilities, operational practices, and building-specific usage patterns. Although failures in pipes and installations still occurs in public buildings similar to the residential buildings, the underlying mechanisms and causes differ substantially. Instead, water damage risk is shaped by reinforcing factors such as high usage intensity, limited preventive maintenance, and delayed detection of leakage. These dynamics are particularly evident in schools and nursing and care facilities, which consistently exhibit the highest number of cases, largest costs and are most frequently mentioned in the interviews.

The causes of water damage in public buildings can be grouped into four main categories. First, user-related actions and sabotage, such as removed water traps, deliberately opened valves, blocked drains and unreported leaks, create sudden or prolonged leakages of water. Second, material degradation and installation errors contribute significantly, including corrosion in aging galvanized pipes, worn fittings and valves, poor workmanship, and tightly packed or inaccessible installation shafts where leaks remain undetected. Third, failures in appliances and technical systems, for example dishwashers, washing machines, refrigerators, heating pipes, and floor drains, constitute additional points of vulnerability. Finally, organisational and design-related weaknesses, such as irregular inspections, communication gaps, unclear alarm responsibilities, inadequate waterproofing, and buildings not designed for their actual usage patterns, increase both the likelihood of incidents and the time until they are discovered. Together, these factors show that water-damage risks arise from the interaction of behaviour, aging infrastructure, technical complexity, and insufficient preventive routines.

A key insight from this study is that water damage development is closely linked to how buildings are used in practice. In schools, repeated incidents are often associated with user behaviour, including intentional tampering and heavy wear on fixtures, which amplify existing vulnerabilities in ageing piping systems and delayed maintaince and inspections. The interview with MU2-OA further reinforces these findings by illustrating how vandalism-related incidents in schools and the limitations of aging pipe systems interact with organisational and financial constraints. The respondent highlighted that automated shut-off solutions can significantly reduce the extent of water-damage events, yet implementation remains uneven due to budget priorities and outdated standards. Their perspective also underscores the systemic challenges faced by municipalities, where buildings constructed according to residential norms and lacking modern monitoring systems create additional barriers to prevention. This interview therefore emphasizes the need for both updated technical specifications and long-term planning frameworks that support preventive rather than reactive maintenance.

In contrast, care facilities operate under conditions of continuous water demand, where conventional preventive measures such as full shut-off strategies are often impractical. Instead, these environments require localised solutions and robust, moisture-tolerant materials to reduce the consequences of inevitable incidents. This highlights that technical solutions cannot be evaluated independently of their operational context but must be adapted to the functional requirements of each building category. Cultural and leisure buildings highlighed another problem and design complexity. High humidity levels, such as in indoor swimming facilities, combined with continuous water usage, limit the effectiveness of standard sensor-based solutions and instead require targeted monitoring and rapid response routines to sudden leakages.

Across the studied building types, the results clearly demonstrate that usage patterns shape both the causes of water damage and the feasibility of preventive measures. In schools and leisure buildings its shown in this study that vandalism and deliberate manipulation of fixtures could benefit of tamper-resistant components, protected installations, and automated shut-off systems to reduce the water damage problematic. Nursing and care environments, however, present a different risk profile, where prevention cannot rely on behavioural control or supervision alone but the solutions could be embedded

in design, material and system design. These conditions indicate that prevention strategies must move beyond uniform approaches. Nursing and care facilities, for example, require moisture-tolerant flooring and wall systems capable of withstanding continuous wetting, as well as localised shut-off valves and sensors that prevent escalation without interrupting essential services. Similarly, public leisure facilities, museums, and sports buildings demand solutions that function reliably under conditions of high humidity, large wet areas, and constant water demand.

The results further show that effective prevention methods should include a combination of technical, organisational, and policy-level measures. From a technical perspective, buildings require more robust and moisture-tolerant materials in high-risk areas, as well as tamper-resistant fixtures in environments such as schools. Localised shut-off valves are critical in care facilities, where they enable isolation of small zones without disrupting essential operations. In addition, digital monitoring systems need to be expanded and made more reliable, supported by clearly defined alarm routines to ensure early detection and rapid response. Further studies are needed to evaluate how alarms, sensors, and leakage indicators can be effectively applied in public buildings, where operational demands and spatial conditions differ significantly from single-family houses. As highlighted in the MU2 interview, current sensor solutions are largely designed for residential units, such as dwellings, and future development must therefore adapt these technologies to larger buildings with multiple units, shared spaces, and more complex installation environments to be able to be adapted to such buildings.

From an organisational perspective, stronger inspection routines, clearer handovers between operations and maintenance, and systematic follow-up procedures are necessary to prevent recurring incidents. Many of the observed failures are not caused by isolated technical issues but by repeated breakdowns in processes and communication. At the policy level, current standards and procurement frameworks were frequently identified as barriers. These frameworks are often based on residential building models and do not adequately support preventive, durable, or tamper-resistant solutions in public buildings. As a result, municipalities face structural constraints that limit their ability to implement effective long-term strategies.

Stakeholder perceptions of feasibility are closely linked to practical, organisational, and financial considerations. While there is broad agreement that sensors, leakage detection systems, and local shut-off solutions are effective when combined with rapid response mechanisms, their implementation is often constrained by existing budget structures and governance models. In particular, funding mechanisms tend to prioritise reactive repairs over preventive investments. In addition, unclear responsibilities and contractual boundaries between actors can hinder long-term implementation, even when the technical potential of solutions is widely recognised. The findings also demonstrate significant potential to reduce both economic and environmental impacts. Preventive measures not only reduce the frequency of incidents but also limit their severity, thereby decreasing the need for drying, demolition, and material replacement. Since total costs are often driven by a small number of extreme events, targeted measures addressing these high-impact cases can substantially reduce long-term costs.

At a systemic level, water damage risk can be understood as the outcome of interactions between technical systems, user behaviour, organisational routines, and governance structures. Technical solutions include measures applied during construction or renovation, such as material selection, installation quality, and tamper-resistant fixtures, as well as operational strategies, including digital monitoring systems, localised shut-off valves, leakage alarms, and maintenance-oriented design features. In this context, technical solutions are not limited to advanced technologies but also include practical, low-tech or procedural improvements that enhance the performance and reliability of water-carrying systems in buildings. Weak inspection practices, incomplete reporting flows, and unclear responsibilities contribute to recurring incidents. At the same time, existing standards and procurement systems are not designed to meet the specific demands of public buildings, limiting the adoption of more robust and digitally integrated solutions.

Overall, the findings suggest that the most effective improvements arise from combining robust technical measures, early detection systems, durable materials, systematic inspections, and clearly defined organisational procedures. Achieving this requires aligning building standards, procurement frameworks, and maintenance practices with the operational realities of public buildings. The challenge faced by municipalities is therefore primarily structural rather than managerial. Finally, it is important to emphasise that the identified challenges are not solely a consequence of municipal mismanagement but are rooted in broader systemic conditions. Municipal property organisations operate within national standards, procurement regulations, and budget frameworks that are not adapted to the complexity of public building use. Without structural and political changes, there is a significant risk that maintenance practices will remain reactive, leading to recurring large-scale and costly repairs despite competent and well-functioning organisations.

Conclusions

The findings of this study demonstrate that water damage incidents in municipally owned public buildings are primarily driven by the combined effects of high building use intensity, ageing and vulnerable water systems, and long detection times of leakages. Schools and nursing and care buildings account for the highest proportion of cases, reflecting demanding operational environments, high water use, and increased exposure to user-related stresses. While appliances and waterproofing failures contribute to the damage profile, their influence is comparatively limited, according to the interviews. Overall, water damage development is shaped less by isolated technical faults and more by the interaction between material degradation, user behaviour, and organisational conditions.

The most frequent types of the studied water damages originate from failures in internal pipe systems, including tap water, sewage, heating installations, and water-using appliances. These incidents can be understood through four main categories of underlying mechanisms. User-related actions and sabotage constitute a major source, including pulled water traps, opened valves, blocked drains, running taps, and improper use of the systems. Technical vulnerabilities, such as corrosion in ageing pipes, worn fittings, poor installation workmanship, and inaccessible pipes, and failures in appliances and heating system components was highlighted as a cause for the damages occuring in public buildings. Finally, organisational and design-related shortcomings, such as irregular inspections, lack of maintenance routines, gaps in alarm handling, and buildings not adapted to actual use, allow minor leaks to escalate. Together, these findings show that water damage arises from the interplay between behavioural factors, material degradation, installation weaknesses, and insufficient preventive controls.

The identified solutions show that effective prevention requires a combination of technical, organisational, and design-related measures adapted to specific building conditions. In high-risk environments such as schools, tamper-resistant fixtures and vandal-resistant installations are essential. In buildings with ageing systems, camera inspections, relining, and material replacement enable proactive maintenance. Moisture-tolerant materials reduce damage consequences, particularly in care facilities. Digital solutions, such as leakage alarms, sensors, and automatic shut-off valves, could limit the damages when combined with clear response routines. Organisational improvements, including structured inspections, defined responsibilities, and standardised procedures, are also necessary to ensure effective implementation. Together, these measures strengthen system robustness, improve detection, and support consistent preventive practices.

Overall, the study identifies the causes of water damage in public buildings and evaluates feasible preventive solutions across building types. The findings show that effective strategies must account for operational demands, material vulnerabilities and organisational conditions, directly addressing the research questions. Significant potential for reducing both costs and damage impact lies in targeting high-risk contexts and severe events. A combination of systematic maintenance, adapted technical design, digital monitoring and clear alarm workflows is required to shift from reactive damage management toward preventive and resilient building operation.

From a facility management perspective, the findings highlight the importance of integrating water-damage prevention into day-to-day building operation, maintenance planning and asset management. Effective prevention depends not only on technical solutions, but also on inspection routines, communication processes, condition assessments and long-term investment decisions. The study therefore contributes to the facility management literature by demonstrating how organisational practices and operational strategies influence both the occurrence and consequences of water damage in public buildings.

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Paper VIII [redacted]

Climate impact of water damage in public buildings: linking water leakage time with lifecycle emissions

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Highlights

- Water damage can exceed the initial bathroom construction impact.
- Leakage duration strongly influences repair-related emissions
- Early detection reduces climate impact and repair needs
- Water-damage emissions should be included in LCAs
- Prevention improves resource efficiency and cleaner production

Abstract

Water damage is a frequent and costly problem in buildings, yet its contribution to lifecycle greenhouse-gas emissions is rarely considered. This study quantifies the climate impact of water damage in bathrooms of public buildings by combining a material-based life cycle assessment (A1-A3) with simulated leakage and repair scenarios. A reference bathroom (5 m² floor area) was analysed using four common floor and wall material configurations and three leakage scenarios representing minor, moderate, and severe damage. The assessment includes replacement of damaged building materials and drying processes. However, replacement of plumbing systems, sanitary fixtures, electrical installations, transport (A4), construction and installation activities (A5), and end-of-life processes were excluded. The results show that water damage can generate substantial emissions, ranging from 26-35 $kgCO_2e$ for minor damage to 140-247 $kgCO_2e$ for moderate damage and 454-749 $kgCO_2e$ for severe damage. In several cases, emissions from a single damage event were comparable to or exceeded the initial construction impact of the bathroom. The findings demonstrate a strongly non-linear relationship between leakage duration and climate impact, whereby relatively small delays in detection lead to disproportionately large increases in emissions due to expanded repair scope and prolonged drying requirements. Technical measures such as leakage detection systems and automatic shut-off devices were found to have considerable potential to reduce emissions by limiting damage escalation. By linking water-damage development, repair requirements, and climate impact, the study extends conventional building life cycle assessments and highlights the importance of accounting for damage-related emissions in sustainability evaluations. The findings show that water-damage prevention can contribute to cleaner production, improved resource efficiency, and reduced lifecycle greenhouse-gas emissions in public buildings.

Keywords

water damage; LCA; public buildings; climate impact; technical solutions; lifecycle emissions

1. Introduction

1.1 Background

Water damage is one of the most frequent and costly categories of building and building-service-system defects, causing substantial economic losses, operational disruptions, and material degradation throughout the building lifecycle (Mundt-Petersen et al., 2026; Mundt-Petersen et al., 2023; Milion et al., 2021; Weeks and Leite, 2021; Yarnold et al., 2021; Mattsson et al., 2026b; Mattsson et al., 2024). In Sweden alone, the annual cost of water damage has been estimated to exceed 12.6 billion SEK, primarily due to failures in water supply, sewage, and heating systems, as well as defects in bathroom waterproofing installations (Mattsson et al., 2024; Mattsson et al., 2026b). Beyond the direct financial consequences, water damage generates considerable environmental impacts. Damage remediation commonly requires demolition, drying, replacement, and reconstruction of building components, resulting in additional material consumption, energy use, and greenhouse-gas emissions that would

otherwise be avoided. Water damage can substantially reduce the overall sustainability performance of buildings. Water damage is also a widespread problem. In Sweden, approximately 57 000 water-damage claims, in insured residential buildings were reported in 2024, corresponding to insurance reimbursements exceeding 4.5 billion SEK, while previous studies have highlighted that moisture-related deficiencies are widespread in the Swedish building stock (Gustavsson et al., 2022). Furthermore, previous research found that on average 13% of municipally owned buildings experience at least one water-damage incident annually, with particularly high occurrence rates in nursing and care facilities (up to 68%) and in schools (27%) (Mattsson et al., 2026b). Since insurance statistics exclude many uninsured, self-financed, and unreported incidents, the actual extent of water damage is likely substantially greater than indicated by claims data alone (Gustavsson et al., 2022; Boverket, 2018; Mundt-Petersen et al., 2026; Mundt-Petersen et al., 2023).

At the same time, the construction sector faces increasing pressure to reduce its climate impact, with current mitigation efforts primarily targeting emissions associated with material production and construction processes. Life cycle assessment (LCA) has become the dominant method for evaluating these impacts, yet assessments often focus on early lifecycle stages while emissions associated with the operational phase remain less explored (Dixit et al., 2010; EN 15978, 2019). This creates an important gap in understanding the full life-cycle environmental impact of buildings, particularly regarding unexpected events such as water damage. Wet rooms, defined as spaces supplied with water and therefore exposed to a higher risk of leakage and flooding, such as bathrooms, are particularly vulnerable. Bathrooms generally have relatively high embodied carbon compared with other interior spaces due to their multilayered construction systems, including ceramic and cement-based materials (Cabeza et al., 2014; Petrovic et al., 2021). Even limited moisture intrusion may necessitate the replacement of several construction layers, generating substantial emissions from repair and reconstruction activities. In public buildings, where extensive floor areas, complex usage patterns, and large property portfolios can delay damage detection, the consequences may be even more severe.

Previous studies have shown that water damage is typically caused by a combination of technical, organisational, and user-related factors, including aging infrastructure, corroded pipes and connections, installation deficiencies, blocked drainage systems, prolonged water exposure in care facilities, inadequate maintenance practices, and shortcomings in inspection and communication routines (Chong and Low, 2006; Mattsson et al., 2026a; Mattsson et al., 2026b). Interview-based research has further demonstrated that sabotage and intentional misuse constitute important causes of water damage in schools, where facility managers reported recurring incidents involving the deliberate removal of water traps and manipulation of valves (Mattsson et al., 2026a). As one practitioner explained:

"*Intentional damage… often we have had to close the toilet for several days for the pupils to understand the consequence.*"

Another facility manager noted:

"*Elementary school (age 6 to 15) is where a lot of vandalism happens. But it is also very much in pre-school (age 3 to 5). And that is perhaps the most frightening thing.*"

Several mitigation measures have therefore been proposed, including leakage detection systems, automatic shut-off devices, improved inspection routines, and design strategies that limit damage propagation (Mattsson et al., 2026a). Previous studies indicate that the effectiveness of such measures depends largely on reducing leakage duration and enabling rapid intervention. However, interview findings suggest that organisational constraints often limit their effectiveness in practice. Practitioners highlighted how delayed access, unclear responsibilities, and shortcomings in monitoring systems may substantially increase damage extent:

"*By the time we enter, the flat may already be flooded...*"

"*Alarms go to the burglar system in some sites; when that fails, nobody knows who should respond to a water alert."*

"*When inspections slip, we pay for it later. Leaks that could have been caught early turn into big clean-ups."*

Similarly, other interviewees described how delayed detection can significantly worsen damage:

"*In many cases the incident is first noticed by the care staff, not the resident. If access is delayed, the water damage is already extensive when we arrive*."

"Stoppages in care units are daily occurrences, often objects flushed that should not be there."

Conversely, the interviews also illustrate the potential benefits of technical mitigation measures. One practitioner described an automatic shut-off solution connected to the lighting system:

"*After five minutes it shuts off... maybe 50 litres run out, and that is easy to clean up. It does not become a cubic metre that leaks through the whole building. Before, it could run for two hours...*"

These findings suggest that both technical and organisational factors influence not only the occurrence and extent of water damage but also its environmental consequences by affecting the duration of leakage, the extent of damage, and ultimately the amount of materials, energy, and reconstruction work required following an incident. Water damage therefore constitutes an important but often overlooked source of environmental impact, as remediation frequently requires demolition, drying, and reconstruction processes that repeat a substantial share of the original construction emissions (Cabeza et al., 2014; Tagg et al., 2010). These impacts are driven primarily by material replacement and, to a lesser extent, energy-intensive drying processes, which can last from days to weeks depending on material properties and moisture penetration (Tagg et al., 2010). Previous research has also highlighted the importance of considering life-cycle impacts beyond initial construction. For example, Petrovic et al. (2021) demonstrated that maintenance, repair, and replacement activities represent a substantial share of long-term building impacts, particularly for building components with high performance requirements such as bathroom systems. These findings suggest that emissions associated with repairs may be significant over the building lifecycle and therefore warrant greater attention in environmental assessments.

Despite this, water damage is rarely explicitly inclueded into LCA studies, which commonly rely on predefined maintenance schedules and neglect unexpected damage events, potentially leading to an underestimation of lifecycle emissions (Cabeza et al., 2014; Dixit et al., 2010). Although previous studies have improved understanding of the causes, prevention, and economic consequences of water damage, its implications for greenhouse-gas emissions remain poorly understood. In particular, limited knowledge exists regarding how damage severity and leakage duration influence climate impacts and to what extent mitigation measures can reduce emissions associated with repair and remediation. This is especially relevant for public buildings, where recurring water damage and delayed detection may substantially increase repair-related emissions. This study addresses this gap by quantifying the climate impact of water damage in wet rooms and evaluating how damage severity and technical mitigation measures influence lifecycle greenhouse-gas emissions.

1.2 Problem statement and research gap

Current climate assessment frameworks primarily focus on emissions from material production and construction processes (A1–A3), while emissions associated with use-phase (B) events such as water damage and repair are rarely included. This omission is particularly relevant in bathrooms, where damage often requires replacement of multiple construction layers, resulting in additional lifecycle emissions. Although previous research has identified key causes and preventive measures for water damage, the environmental consequences of different damage scenarios remain poorly understood (Mattsson et al., 2026a). Consequently, there is limited knowledge linking water-damage severity, repair requirements, and associated climate impacts.

1.3 Aim and research questions

The aim of this study is to examine the climate impact of water damage in bathrooms within public buildings and to assess how damage development and repair strategies influence lifecycle greenhouse gas emissions. By integrating material-based climate calculations with simulated water damage scenarios, the study seeks to provide a more comprehensive understanding of the environmental

consequences of water damage throughout the building lifecycle. Building on previous research that identified the causes of water damage and potential mitigation measures in public buildings (Mattsson et al., 2026a), the present study extends this line of research by quantifying the climate implications of water-damage development and repair. In particular, the study focuses on how the severity of water damage, driven by factors such as leakage volume, exposure time, and detection delay, affects the extent of repair work and associated emissions. The following research questions are studied:

I. RQ1: What is the climate impact of water damage in bathrooms in public buildings under different material configurations and damage scenarios, and how does this impact compare with the initial construction-related emissions of the bathroom?

II. RQ2: How do leakage duration, damage severity, and resulting repair requirements influence lifecycle greenhouse-gas emissions?

By addressing these research questions, the study contributes to a more holistic perspective on building sustainability, highlighting the importance of integrating damage-related emissions into climate assessments and supporting the development of more resilient and resource-efficient building systems.

2. Methodology

2.1 Study framework

This study adopts an integrated framework that combines material-based climate assessment with simulated water-damage scenarios to quantify the climate impact of water damage in bathrooms. First, a baseline life cycle assessment (LCA) of a reference bathroom was conducted to determine the embodied emissions associated with different material configurations (A1–A3). Second, three water-damage scenarios of increasing severity were modelled to represent typical leakage events in public buildings and to assess how leakage volume, damage extent, repair requirements, and drying processes influence greenhouse-gas emissions. By linking material-related emissions, damage development, and repair activities, the framework enables comparison between the climate impact of initial construction and that of water-damage repairs. The functional unit is one water-damage event affecting a bathroom in a public building, including all material replacement and drying activities required to restore the bathroom to its original functional condition.

2.2 Case description

The case study is based on a reference bathroom representing a typical sanitary space in public buildings with no exterior walls. The reference bathroom was assumed to be designed and constructed in accordance with current Swedish building regulations and industry guidelines, including the Swedish Building Regulations (BBR) (Boverket, 2024) and the requirements of Säker Vatten (Säker Vatten, 2026). The bathroom therefore represents a code-compliant wet-room construction with waterproof floor and wall systems intended to prevent moisture penetration under normal operating conditions. The bathroom contains a toilet and washbasin and is designed as a wet room with waterproof floor and wall systems. The analysed room measures 2.2m × 2.2m floor area with a ceiling height of 2.4m. The total analysed surface area includes a 5m² floor and 20m² of inner wall area, excluding the door opening. The reference case was selected to reflect bathroom configurations commonly found in schools, offices, healthcare facilities. Public buildings also include care facilities for mentally impaired. Two floor systems (ceramic tiles and PVC flooring) and two wall systems (ceramic tiles and painted surfaces) were evaluated to represent common construction practices in public buildings. The construction systems were modelled as multilayer assemblies consisting of surface materials, bonding layers, waterproofing membranes, and supporting structures. The selected layout and material configurations do not represent a specific building but a generic reference case that enables comparison of different water-damage and repair scenarios under consistent boundary conditions. A timber floor structure was assumed in the reference case, acknowledging that water-damage events are not necessarily confined to surface materials and waterproofing layers. Previous studies have shown that leakage can reach and damage underlying structural elements despite the presence of intended waterproof barriers due to deficiencies (Mundt-Petersen et al., 2026, Gustavsson et al., 2022).

2.3 Material and climate data

The material-related climate impact of the reference bathroom was quantified using a simplified life cycle assessment (LCA) approach focusing on the product stage (A1–A3). The analysed constructions were defined as multilayer assemblies for both floor and wall systems, with representative global warming potential (GWP) values ($kgCO_2e/m^2$) assigned to each material layer. The material categories included surface finishes (e.g., ceramic tiles or PVC flooring), bonding layers, waterproof membranes, levelling compounds, and supporting structures such as boards, insulation, and timber framing. Two alternative material configurations were evaluated for both floor and wall constructions. For floors, ceramic tile systems and PVC flooring systems were analysed, while walls were modelled using either ceramic tile systems or painted surfaces. These combinations reflect common bathroom construction practices and provide a basis for assessing how material selection influences climate impact.

Climate data were primarily based on generic emission factors from established construction LCA databases and values used in Swedish building climate declarations, thereby reflecting datasets commonly applied in regulatory climate calculations and industry practice (Petrovic et al., 2021, Boverket, 2026). Where suitable generic data were unavailable, environmental product declarations (EPDs) complying with EN 15804 were used to derive representative emission factors for specific materials (The International Epd System, 2026, The International Epd System, 2025, Saint-Gobain Sweden AB, 2025, The International Epd System, 2024, The International Epd System, 2023, Swedish Institute for Standards, 2019). This approach ensured consistent and comparable results across the analysed scenarios while maintaining relevance to contemporary construction practice. The GWP ranges presented in Table 1 do not necessarily originate from a single source but represent reasonable intervals derived from multiple data sources, including national climate databases and EPDs for comparable products. The applied values were selected as representative values within these intervals for use in the scenario calculations. The total climate impact was calculated by multiplying the GWP values per square meter (Table 1) by the corresponding surface areas of the floor (5 m²) and walls (20 m²) in the reference case. The resulting values represent the baseline embodied emissions of the bathroom and form the basis for the subsequent analysis of damage-related emissions and repair scenarios.

Table 1. Global Warming Potential (GWP, A1–A3) for selected materials and applied GWP-values and source of the applied EPD for each material.

Material	**Representative GWP range (A1-A3)** ($kgCO_2e/m^2$)	**Applied GWP (A1–A3)** ($kgCO_2e/m^2$)	**Source**
Ceramic tiles (floor/wall)	8 – 14	12	EPD-IES-0028945:001 (The International Epd System, 2026)
PVC flooring	6	6	IVL / Swedish National Board of Housing, Building and Planning (generic values) (Boverket, 2026)
Adhesive	1	1	IVL / Swedish National Board of Housing, Building and Planning (generic values) (Boverket, 2026)
Tile adhesive (mortar)	1.5 – 2.2	2	EPD IES 0005320:001 (2025) (The International Epd System, 2025)
Waterproof membrane (foil)	1.5 – 2.5	2	EPD IES 0009963:001, Environdec (The International Epd System, 2023)
Levelling compound	3 – 4.5	4	EPD-IES-0009539:001 (The International Epd System, 2024)
Timber floor structure	30	30	IVL / Swedish National Board of Housing, Building and Planning (generic values) (Boverket, 2026)
Painted surface (paint + filler)	1.5	1,5	IVL / Swedish National Board of Housing, Building and Planning (generic values) (Boverket, 2026)
Liquid-applied waterproofing membrane	1.5	1,5	IVL / Swedish National Board of Housing, Building and Planning (generic values) (Boverket, 2026)
Wet room board (gypsum-based)	2.8 – 3.2	3	EPD SP 00393 (Gyproc) (Saint-Gobain Sweden AB, 2025)

Timber studs + insulation	1.5 – 3.0	2	IVL / Swedish National Board of Housing, Building and Planning (generic values) (Boverket, 2026)

2.4 Reference scenarios

To establish a baseline for comparison, four reference scenarios were defined representing different combinations of commonly used material systems for floors and walls in bathrooms. These scenarios reflect typical constructions in public buildings and enable evaluation of how material selection influences the initial climate impact. The materials and the corresponding GWP-value of each surface material scenario is presented in Table 2-3.

Table 2. GWP (A1–A3) of the different materials for the different reference flooring scenarios.

Ceramic flooring	**GWP (**$kgCO_2e/m^2$)	**Plastic flooring**	**GWP (**$kgCO_2e/m^2$)
Ceramic tiles	12	PVC flooring	6
Tile adhesive	2	Adhesive	1
Waterproof membrane (foil)	2	Levelling compound	4
Levelling compound	4	-	
Sum	**20**	**Sum**	**11**

Table 3. GWP (A1–A3) of the different materials for the different reference wall scenarios.

Ceramic walls	**GWP (**$kgCO_2e/m^2$)	**Painted walls**	**GWP (**$kgCO_2e/m^2$)
Ceramic tiles	12	Painted surface (paint + filler)	1.5
Tile adhesive	2	Liquid-applied waterproofing membrane	1.5
Liquid-applied waterproofing membrane	1.5	Wet room board (gypsum-based)	3
Wet room board (gypsum-based)	3	Timber studs + insulation	2
Timber studs + insulation	2	-	
Sum	**20,5** $\mathbf{kgCO_2e/m^2}$	**Sum**	**8** $\mathbf{kgCO_2e/m^2}$

The analysed configurations include two alternatives for floor systems, ceramic tiles and plastic flooring, and two alternatives for wall systems, ceramic tiles and painted surfaces. By combining these options, four reference scenarios are obtained:

- (i) ceramic floor with ceramic walls
- (ii) ceramic floor with painted walls
- (iii) plastic floor with ceramic walls
- (iv) plastic floor with painted walls.

For each scenario, the total climate impact is calculated based on the material compositions defined in Section 2.3 and the corresponding surface areas of the reference bathroom.

2.5 Water damage scenarios

To analyse the climate impact of water damage, three representative leakage scenarios of increasing severity are defined. The scenarios are based on typical internal water leakage events in public buildings, such as failures in water supply systems, appliances, or plumbing connections and stoppages in sewage systems, and are characterised by the volume of water released and the resulting level of damage. The analysed scenarios correspond to leakage volumes of approximately 50, 300, and 600 liter, representing minor, moderate, and severe damage events. These volumes are used as proxies for different detection times, assuming a continuous leakage rate of 10 l/min, and reflect variations in how quickly a fault is identified and stopped. A typical design flow rate for a washbasin is approximately 0.17 l/s (10 l/min), which is consistent with the flow levels commonly used for water fixtures in accordance with the Swedish Safe Water (Säker Vatten) industry recommendations for the sizing of domestic water

distribution systems (Säker Vatten, 2026). The scenarios therefore implicitly capture the influence of detection delay on damage development. Each scenario is associated with a specific level of material impact and corresponding repair actions. The minor damage scenario (50 liter) represents surface-level exposure, typically limited to localised wetting of floor finishes, allowing for technical drying and minor repair. The moderate damage scenario (300 liter) corresponds to a critical threshold where water reaches wall interfaces and penetrates underlying layers, requiring removal and reconstruction of floor systems and partial wall assemblies. The severe damage scenario (600 liter) represents extensive water intrusion affecting both floor and wall systems, and potentially structural components, leading to large-scale demolition and near-complete reconstruction of the bathroom. The assumption that damaged materials are removed and replaced is consistent with Swedish remediation practice stated in legal requirements. A scientific and legal review conducted by RISE (Bloom, 2023) concluded that water-damaged materials should be removed when there is a risk of adverse effects on human health.

The review further found that the use of chemical treatment products as an alternative to material removal is generally not recommended, as available evidence indicates limited effectiveness while potentially increasing the concentration of pollutants in indoor air. Consequently, material removal and replacement are assumed to be the primary remediation strategy in all scenarios where moisture damage has affected building materials. In addition to material replacement, each scenario includes technical drying processes, with durations increasing in proportion to the extent of moisture penetration. Drying is modelled as continuous energy use over defined time periods, reflecting typical remediation practices. By linking leakage volume to damage extent, repair scope, and drying requirements, the defined scenarios enable a systematic evaluation of how increasing damage severity affects total climate impact. This approach also allows for analysis of threshold effects, where small increases in leakage volume result in disproportionately larger repair needs and associated emissions.

2.6 Repair and drying assumptions

Repair actions for each damage scenario are defined based on the extent of moisture penetration and the requirement to restore the functional integrity of bathroom systems. The assumptions reflect typical repair practices in which damaged materials are removed and replaced to ensure that waterproofing and structural performance are not compromised. For minor damage, repair is limited to localised replacement of surface materials, primarily affecting a small area of the floor, 1m^2. The repair includes partial removal of the surface layer and restoration of the affected section, combined with technical drying. For moderate damage, repair involves complete replacement of the floor system, 5m^2 and partial reconstruction of lower wall sections, in total 5 m^2 of the 20 m^2. This reflects cases where water penetrates beyond surface layers and reaches the connections between floor and wall systems, requiring removal of multiple layers to ensure proper drying and functionality. For severe damage, repair is assumed to involve near-complete reconstruction of the bathrooms surface material, including full replacement of floor and wall systems and, where relevant, parts of the supporting structure. For the severe damage scenario, reconstruction of the affected structural floor assembly was also assumed. The climate impact of structural replacement was calculated using the GWP value for the timber floor structure presented in Table 1 (30 $kgCO_2e/m^2$). This represents cases where water intrusion affects multiple construction layers and makes partial repair technically unfeasible.

In addition to material replacement, all scenarios include technical drying processes to remove moisture in materials that are not replaced. Drying is modelled as continuous electricity use from professional drying equipment, including dehumidifiers and air-circulation systems. A constant power demand of 1,5 kW is assumed as a representative value for a typical drying setup used in moisture remediation. The value is applied as a modelling assumption to enable consistent comparison between repair scenarios, while recognising that actual energy demand depends on equipment type, moisture conditions and building characteristics (Brander, 2012, Fuktcentrum, 2026, Munters, 2026). Electricity-related greenhouse gas emissions are calculated using an emission factor, for Swedish electricity mix, of 0,059 $kgCO_2e/kWh$, based on values published by the Swedish Environmental Protection Agency (Naturvårdsverket) for climate impact calculations (Naturvårdsverket, 2026). Drying times following water damage vary considerably depending on material type, moisture content, climatic conditions and

construction design (Forensics, 2025, Zhou et al., 2024, Boardman et al., 2020). Experimental and modelling studies show that the drying behaviour of gypsum- and wood-based assemblies is strongly influenced by relative humidity, material thickness and moisture redistribution within the structure (Zhou et al., 2024, Boardman et al., 2020, Arfvidsson et al., 2017). In this study, drying durations increase with damage severity, ranging from approximately 7 days for minor damage to 42 days for the severe cases. The total climate impact of each scenario is calculated as the sum of emissions from material replacement and energy use during drying.

2.7 Limitations

This study is based on a simplified modelling approach and therefore includes several limitations. First, the climate assessment is restricted to the product stage (A1–A3), and does not include transport, construction processes, or end-of-life stages. Second, the analysis is based on a representative case study of a single bathroom, which limits generalization to other building types, sizes, and construction systems. The material compositions and repair assumptions reflect typical conditions in public buildings as established in interviews with municipalities in (Mattsson et al., 2026a), but variations in design, construction quality, and maintenance practices may influence the actual climate impact. Third, water damage is modelled using deterministic scenarios based on predefined leakage volumes and repair extents. In reality, water damage events are stochastic and influenced by multiple factors such as building usage, system conditions, and response time. As a result, the study does not capture the full variability or probability of different damage events. Finally, technical solutions are represented indirectly through their impact on detection time and damage severity, rather than by modelling specific technologies in detail. While this approach enables generalization and comparison across scenarios, it does not account for performance differences between specific systems or their implementation costs.

3. Results

3.1 Climate impact of reference bathroom

The reference case of the climate impact of the construction of the bathroom (A1-A3) varies significantly depending on the selected material configuration for floor and wall systems. The calculated results showed that total carbon emissions range from approximately 215 to 510 $kgCO_2e$ for the analysed 5 m^2 public bathroom, described in Table 4.

Table 4. Total carbon emissions (A1–A3) for different surface material scenarios (case i-iv).

Scenarios of different surfaces materials (Cases**)**	**GWP** (A1-A3) $kgCO_2e/m^2$	**Area (**m^2)	**Total carbon emissions** ($kgCO_2e$)
Case i			
Ceramic flooring	20	5	100
Ceramic wall systems	20,5	20	410
Sum			**510**
Case ii			
Ceramic flooring	20	5	100
Painted wall systems	8	20	160
Sum			**260**
Case iii			
Plastic flooring	11	5	55
Ceramic wall systems	20,5	20	410
Sum			**465**
Case iv			
Plastic flooring	11	5	55
Painted wall systems	8	20	160
Sum			**215**

The highest climate impact is observed for the scenario with ceramic floor and ceramic wall systems, with a total impact of approximately 510 $kgCO_2e$. This is primarily driven by the large surface area of the walls and the high carbon intensity of ceramic-based assemblies, including tiles, adhesives, and associated layers. In contrast, the lowest impact is obtained for the configuration combining plastic

flooring and painted wall systems, with a total of approximately 215 $kgCO_2e$, representing a reduction of about 58% compared to the highest-emission scenario.

3.2 Climate impact of water damage

The assumed water leakage represents a typical pipe failure in a bathroom, corresponding to damage types identified in previous work, such as corrosion, connection failures, or deliberate damage to water supply or sewage systems (Mattsson et al., 2026b, Mattsson et al., 2026a). A constant leakage rate of 10 l/min is assumed, and three scenarios are defined based on the duration of leakage before detection and shut-off: 5, 30, and 60 minutes, corresponding to 50, 300, and 600 liter, respectively. All leakage scenarios are assumed to result in moisture intrusion into the construction requiring repair. While this represents a conservative assumption, it enables a consistent analysis of how leakage duration, and thus detection time, affects damage development and climate impact. Each scenario is modelled as a single event during the building lifetime.

3.2.1 Minor damage (50 L)

For the minor damage scenario (50 liter), the damage is assumed to remain largely superficial, with limited moisture penetration into the construction. Repair actions consist of localized replacement of surface materials (approximately 1 m^2) combined with technical drying over approximately 7 days (168 h). The estimated climate impact ranges between 26 and 35 $kgCO_2e$, depending on surface material scenario (cases), as described in Table 5. A significant share of this impact is associated with energy use for drying rather than material replacement. Compared to the baseline construction impact (215–510 $kgCO_2e$), the additional emissions from minor damage represent a relatively small increase.

Table 5. Climate impact of the different damage cases with varying material cases, the leakage volume of 50l and affected areas (floor, wall, and structure). The table presents estimated climate impact from materials (A1–A3) and from drying, based on 1.5 kW electricity use. Total impact is the sum of material and drying emissions for each case.

Surface material scenario	**Leakage volume** (l)	**Damaged area, flooring** (m^2)	**Damaged area, wall** (m^2)	**Damaged area, structure** (m^2)	**Climate impact of materials** (A1–A3) ($kgCO_2e$)	**Drying time** (h)	**Climate impact of drying** ($kgCO_2e$)	**Total climate impact** ($kgCO_2e$)
i (ceramic/ceramic)	50	1	0	0	**20**	168	15	**35**
ii (ceramic/painted)	50	1	0	0	**20**	168	15	**35**
iii (pvc/ceramic)	50	1	0	0	**11**	168	15	**26**
iv (pvc/painted)	50	1	0	0	**11**	168	15	**26**

3.2.2 Moderate damage (300 L)

For the moderate damage scenario (300 liter), the water level exceeds the waterproofing upstand at the floor, wall interface, allowing moisture to penetrate the construction. This results in more extensive damage affecting both floor systems and lower wall sections. Repair actions include complete replacement of the floor (5 m^2), partial reconstruction of the wall (approximately 5 m^2), and technical drying over approximately 21 days (504 h). The estimated climate impact ranges between 140 and 247 $kgCO_2e$, depending on material configuration, as described in Table 6. This represents a substantial increase compared to the minor damage scenario and corresponds to a significant share of the initial construction impact. The results indicate that once critical thresholds are exceeded, damage transitions from surface-level to structural, leading to a rapid increase in repair scope and associated emissions.

Table 6. Climate impact of the different damage cases with varying material cases, the leakage volume of 300l and affected areas (floor, wall, and structure). The table presents estimated climate impact from materials (A1–A3) and from drying, based on 1.5 kW electricity use. Total impact is the sum of material and drying emissions for each case

Surface material scenario	**Leakage volume** (l)	**Damaged area, flooring** (m^2)	**Damaged area, wall** (m^2)	**Damaged area, structure** (m^2)	**Climate impact of materials** (A1–A3) ($kgCO_2e$)	**Drying time** (h)	**Climate impact of drying** ($kgCO_2e$)	**Total climate impact** ($kgCO_2e$)
i (ceramic/ceramic)	300	5	5	0	**203**	504	45	**247**
ii (ceramic/painted)	300	5	5	0	**140**	504	45	**185**
iii (pvc/ceramic)	300	5	5	0	**158**	504	45	**203**
iv (pvc/painted)	300	5	5	0	**95**	504	45	**140**

3.2.3 Severe damage (600 L)

For the severe damage scenario (600 liter), extensive water intrusion occurs, resulting in significant moisture penetration into floor and wall systems and, in some cases, the supporting structure. The assumed water level (~12 cm) leads to widespread damage and, potentially, moisture spread to adjacent areas. Repair actions are assumed to involve near-complete reconstruction of the bathroom, including full replacement of floor and wall systems and drying of the underlying structure. In addition to the replacement of surface materials, reconstruction of the underlying timber floor structure was assumed where moisture penetration reached structural elements. The climate impact of structural replacement was calculated using the representative GWP value of 30 $kgCO_2e/m^2$ for the timber floor structure presented in Table 1. Assuming replacement of the entire 5 m^2 floor area, this corresponds to an additional impact of approximately 150 $kgCO_2e$, which contributes substantially to the total emissions in the severe damage scenarios. This additional structural replacement is one of the main reasons for the marked increase in climate impact compared with the moderate damage scenario. Technical drying is modelled over approximately 42 days (1008 h). The estimated climate impact ranges between 454 and 749 $kgCO_2e$, depending on material configuration, as described in Table 7. In several cases, this exceeds the initial construction impact of the bathroom.

Table 7. Climate impact of the different damage cases with varying material cases, the leakage volume of 600l and affected areas (floor, wall, and structure). The table presents estimated climate impact from materials (A1–A3) and from drying, based on 1.5 kW electricity use. Total impact is the sum of material and drying emissions for each case

Surface material scenario	**Leakage volume** (l)	**Damaged area, flooring** (m^2)	**Damaged area, wall** (m^2)	**Damaged area, structure** (m^2)	**Climate impact of materials** (A1–A3) ($kgCO_2e$)	**Drying time** (h)	**Climate impact of drying** ($kgCO_2e$)	**Total climate impact** ($kgCO_2e$)
i (ceramic/ceramic)	600	5	20	5	**660**	1 008	89	**749**
ii (ceramic/painted)	600	5	20	5	**410**	1 008	89	**499**
iii (pvc/ceramic)	600	5	20	5	**615**	1 008	89	**704**
iv (pvc/painted)	600	5	20	5	**365**	1 008	89	**454**

3.3 Comparison: construction vs damage

A comparison between initial construction impact and damage-related emissions shows that a single water damage event can result in climate impacts comparable to, or exceeding, the emissions from the original construction of the bathroom. While the baseline climate impact ranges between 215 and 510 $kgCO_2e$, the most severe damage scenarios reach up to 749 $kgCO_2e$, effectively representing a repetition of the initial embodied emissions. Even moderate damage scenarios account for a substantial share of construction-related emissions. A key finding is the strongly non-linear relationship between leakage duration and climate impact. As illustrated in Figure 1, climate impact increases disproportionately with leakage volume, indicating a non-linear relationship between damage extent and repair-related emissions. Small increases in leakage time (5 minutes to 30 or 60 minutes) lead to disproportionately large increases in emissions, as critical damage thresholds are exceeded and repair requirements escalate. The results also emphasise the importance of detection time. While minor damage results in limited additional emissions (approximately 20–40 $kgCO_2e$), delays that allow the leakage to continue for longer

periods lead to rapid escalation of climate impact (approximately 150–250 $kgCO_2e$ for moderate damage and over approximately 500 $kgCO_2e$ for severe damage), as described in Table 8.

Table 8. Range of total climate impact (A1–A3), including the impact from drying energy (kW), for different leakage volumes and material combinations.

Leakage volume (l)	**Baseline climate impact** ($kgCO_2e$) **for surface layer cases i-iv**	**Range of climate impact** ($kgCO_2e$) **for surface layer cases i-iv**
50	215 – 510	26 – 35
300		140 – 247
600		454 - 749

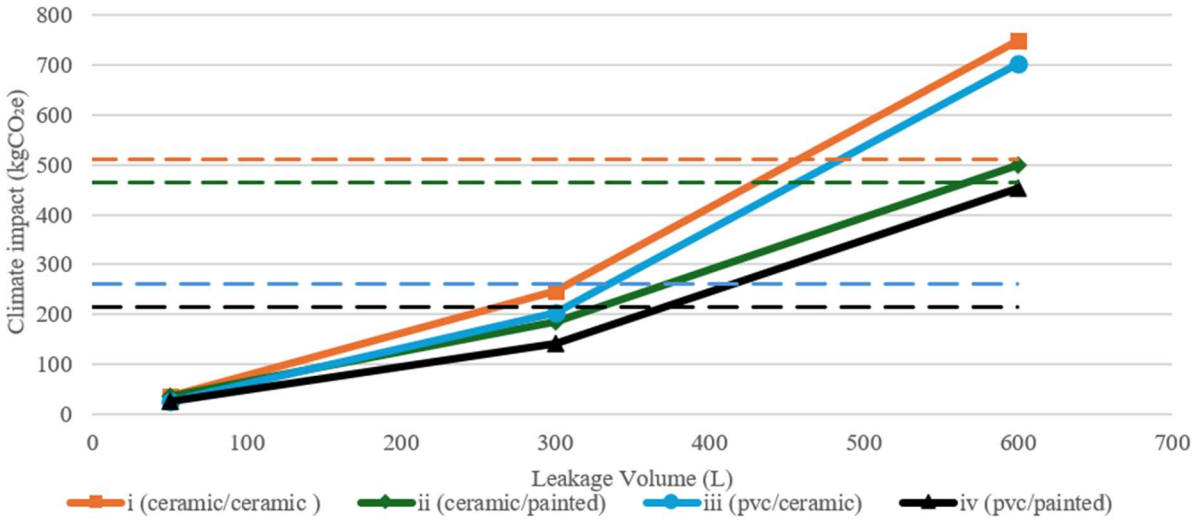


*Figure 1. Climate impact ($kgCO_2e$) of one water damage as a function of leakage volume for four bathroom construction systems. Dashed lines indicate the baseline climate impact of each construction, while solid lines represent repair climate impact of **one water damage** including repair-related emissions at different leakage volumes.*

4. Discussion

The results demonstrate that early detection and rapid intervention can substantially reduce the climate impact of water damage. Climate impacts increased from 26–35 $kgCO_2e$ for minor damage to 454–749 $kgCO_2e$ for severe damage, highlighting a strongly non-linear relationship between leakage duration and emissions. Small reductions in detection time can prevent damage from exceeding critical thresholds and thereby avoid extensive material replacement and prolonged drying. Technical solutions such as leakage sensors and automatic shut-off systems are therefore particularly effective, as they limit leakage volumes and reduce the likelihood of damage escalation. These findings indicate that measures traditionally implemented to reduce costs and operational risks may also provide significant climate benefits, especially in public buildings where water-damage events occur frequently. Although a single water-damage event may appear small in relation to total building lifecycle emissions, the results should be interpreted in the context of the high occurrence rate of water damage in public buildings. Previous research reported that approximately 13% of public buildings experience at least one water-damage event annually (Mattsson et al., 2026b). Consequently, the cumulative climate impact of water damage across large building portfolios may become substantial over the building lifecycle.

The results can be directly linked to the causes and mitigation strategies identified in previous work. Factors such as limited inspection routines, complex building layouts, and organisational barriers often lead to delayed detection, allowing leakage to continue for extended periods. The implementation of technical measures, such as leakage sensors, flow monitoring systems, and localized shut-off functions, enables earlier detection and faster response, can thereby reduce leakage volumes and limiting damage extent. In addition to active detection systems, robust design strategies and material choices could also influence the climate impact of water damage. Systems that allow for localized repair or limit moisture propagation could reduce the need for complete reconstruction. However, the results indicate that operational factors, particularly detection time, are more critical than initial material selection in

determining the overall climate impact of damage events. From a lifecycle perspective, the findings also demonstrate that technical solutions traditionally justified by cost savings or risk reduction also provide substantial climate benefits. This perspective is also supported by Petrovic et al. (2021), who demonstrated that maintenance and replacement activities contribute substantially to the lifecycle emissions of Swedish residential buildings. While their study focused on economic performance, the present results indicate that unplanned water-damage repairs may also represent a significant source of lifecycle greenhouse-gas emissions. In buildings with frequent water damage events, such as schools and healthcare facilities, these benefits accumulate over time and can significantly reduce total lifecycle emissions. Overall, the analysis shows that effective water damage prevention and mitigation strategies should be considered as part of climate reduction efforts in the building sector. By linking technical solutions to measurable reductions in emissions, the results provide a basis for integrating damage prevention into sustainability assessments and decision-making processes.

The results also link common causes of water damage to their associated climate impacts. Previous research has identified sabotage, inadequate maintenance, and organisational deficiencies as key drivers of water damage in public buildings (Mattsson et al., 2026a). These factors often increase leakage duration by delaying detection and intervention, thereby increasing the risk of damage escalation. As demonstrated in the analysed scenarios, prolonged leakage can lead to substantially higher repair needs and climate impacts. Climate performance is influenced not only by technical systems but also by maintenance practices, organisational routines, and response procedures. Effective prevention therefore requires a combination of technical solutions, proactive maintenance, and efficient management processes.

The findings also have important implications for material selection and design strategies in buildings. Traditionally, material choices are often evaluated based on their initial embodied carbon. However, the results indicate that robustness and damage tolerance may be more critical factors in reducing lifecycle emissions when water damage is considered. Materials and systems that are sensitive to moisture and require full replacement even after minor exposure contribute disproportionately to emissions in damage scenarios. In contrast, robust materials that can withstand moisture exposure or be locally repaired without extensive demolition can significantly reduce the climate impact of water damage events. This shifts the focus from minimizing initial CO_2 emissions to optimizing long-term performance under real-world conditions. Furthermore, constructions that limit moisture propagation, such as compartmentalized assemblies or water-resistant interfaces, can prevent damage from spreading beyond the initial leakage point. As the results show, preventing escalation is crucial due to the non-linear increase in emissions. Therefore, design strategies that reduce the likelihood of crossing critical damage thresholds can have a substantial climate benefit. This suggests that life cycle assessments (LCA) should more explicitly account for the probability and consequences of damage events. Materials with slightly higher initial emissions may still result in lower overall climate impact if they reduce repair frequency, extent, or complexity. At the same time, certain replacements may be unavoidable to ensure occupant health, safety, and compliance with regulatory requirements. Design decisions should incorporate both durability and repairability as key parameters in addition to embodied carbon. The same perspective is likely to become increasingly important for building service systems, which often contribute substantially to repair scope and replacement needs following water damage. A proposal has been put forward to include building service systems in future whole-life carbon assessment frameworks, although sufficiently detailed and standardized LCA data are not yet widely available. As such data become available, future assessments should evaluate not only the embodied carbon of these systems but also their durability, repairability, and contribution to damage-related emissions. Furthermore, the present study is limited to the product stage (A1-A3) and does not include emissions associated with transport to site (A4), construction and installation processes (A5), end-of-life stages, or the replacement of building service systems such as pipes, valves, sanitary installations, and electrical systems. Since these elements are frequently affected during water-damage remediation and may contribute substantially to the total environmental burden, the reported climate impacts should therefore be regarded as a lower-bound estimate of the actual climate impact of water damage. This is particularly relevant for severe damage scenarios, where replacement of building service systems, transport activities, installation work, and other downstream lifecycle processes may significantly increase the total greenhouse-gas emissions beyond the values presented in this study.

4.5 Limitations and uncertainties

Several limitations and uncertainties should be acknowledged. The analysis is based on predefined assumptions regarding leakage volumes, detection times, repair strategies, and drying processes. While these scenarios were designed to represent typical water-damage events, actual outcomes may vary depending on building type, construction system, climate conditions, and response time. Uncertainties are also associated with the emission factors and material data used in the climate calculations, as actual emissions may vary with production methods, transportation distances, and local construction practices. The modelling of drying processes relies on simplified assumptions regarding energy use and drying duration. Furthermore, the analysis focuses on direct emissions from material replacement and drying and does not include indirect effects such as operational disruption, transport, temporary relocation, or secondary damage. Finally, technical solutions were represented through their influence on leakage duration and damage extent rather than through detailed modelling of specific systems. The results should be interpreted as indicative estimates of the magnitude of climate impacts rather than precise predictions.

5. Implications for Cleaner Production

The results highlight that cleaner production in the built environment requires an integrated approach combining design, operation, policy and circularity. At the design stage, material selection should prioritize not only low embodied carbon but also durability, moisture resistance, and reparability, as fragile materials can lead to disproportionately high lifecycle emissions when damaged. Designing for modularity and localized repair, through accessible installations and replaceable components, further reduces the need for extensive demolition. From an operational perspective, reducing detection time is critical: leakage sensors, flow monitoring, and automated shut-off systems can significantly limit leakage duration and prevent escalation into high-impact damage scenarios, thereby avoiding resource-intensive repairs and energy-demanding drying processes. At the policy level, current climate assessment frameworks risk underestimating emissions by excluding damage events; incorporating maintenance, repair, and resilience into climate declarations and adopting a full lifecycle perspective would better reflect actual environmental impacts and incentivize preventive strategies. These implications are reinforced by the broader context in which around 13% of public buildings have been shown to experience water damage each year in average (Mattsson et al., 2026b), indicating that such events are common rather than exceptional. Since several construction materials are finite, frequent replacement due to damage represents a significant loss of resources. Moreover, water damage affects indoor environmental quality and human health, while also imposing substantial economic costs through repairs and disruptions, resources that could otherwise be allocated to preventive and sustainable investments. Finally, adopting circular principles, favoring partial repair over total replacement and enabling reuse of unaffected materials, can substantially improve resource efficiency and reduce emissions, positioning water damage prevention and management as a key element of cleaner production and long-term sustainability in the building sector.

6. Conclusions

This study addresses a key knowledge gap by explicitly linking (i) the occurrence and severity of water damage, (ii) the resulting repair processes, and (iii) the associated climate impact. The results demonstrate that water damage in bathrooms of public buildings can lead to substantial greenhouse gas emissions, primarily driven by material replacement and energy-intensive drying. Across the analysed cases, the total climate impact ranges from approximately 26–35 $kgCO_2e$ for minor damage, to 140–247 $kgCO_2e$ for moderate damage, and up to 454–749 $kgCO_2e$ for severe damage, depending on material configurations. While the size of the leakage varies, water damage consistently represents a non-negligible contribution to lifecycle emissions. A key finding is the strongly non-linear relationship between leakage volume, damage extent, and climate impact. Minor damage, resulting from early detection, leads to limited emissions due to localized repair needs. However, relatively small delays in detection can cause a disproportionate increase in emissions, as moisture penetrates deeper into the construction. In moderate scenarios, emissions increase to approximately 150–250 $kgCO_2e$, while severe scenarios exceed 500 $kgCO_2e$, reflecting extensive demolition, full material replacement, and prolonged drying. This highlights clear threshold effects, where transitions between damage levels drive rapid escalation in climate impact. The study further shows that technical solutions, such as leakage

detection systems, flow monitoring, and automated shut-off mechanisms, have significant potential to reduce emissions. By limiting leakage duration and preventing damage escalation, these measures can avoid the substantial increase in emissions associated with moderate and severe damage. In doing so, they directly address the identified gap by demonstrating how preventive and responsive strategies reduce both damage extent and lifecycle emissions. Overall, the findings demonstrate that water damage should not be treated as a marginal issue but as an integral component of building sustainability. Integrating damage scenarios, repair processes, and preventive strategies into life cycle assessments and design decision-making is essential to better reflect real-world impacts. This enables decision-makers to prioritise investments in robust materials, technical systems, and resilient design solutions, thereby supporting more effective alignment with long-term climate targets.

Credit authorship contribution statement

Christian Mattsson contributed to conceptualization, methodology, formal analysis, investigation, data curation, visualization, and writing of the original draft. Birgitta Nordquist contributed through conceptualization, methodology, review and editing as well as supervision. Petter Wallentén contributed to conceptualization, methodology and review as well as supervision. Dennis Johansson, Ulla Janson, and Hans Bagge contributed to the conceptualization of the project and supervision.

Declaration of competing interest

The author(s) declared no potential conflicts of interest concerning the research, authorship, and/or publication of this article.

Acknowledgements

The authors would like to thank the participating municipalities and property managers for their valuable contributions to this research through interviews, discussions, and the sharing of experiences related to water-damage occurrence, causes, and mitigation strategies in public buildings. Their insights provided an important foundation for the assumptions, damage scenarios, and repair strategies analysed in this study. This research was conducted in collaboration with industry partners Säker Vatten AB and AB Rörläggaren, together with Lund University. Financial support from SBUF (the Development Fund of the Swedish Construction Industry) under Grant No. 14 360 is gratefully acknowledged. The funding source had no involvement in the study design, data analysis, interpretation of results, manuscript preparation, or the decision to submit the article for publication. The authors declare that they have no competing interests.

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