Reducing water damage by using a holistic approach to costs, occurrence and solutions in buildings

Christian Mattsson

LICENTIATE DISSERTATION
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Title and subtitle: Reducing water damage by using a holistic approach to costs, occurrence and solutions in buildings

Abstract: A large amount of water damage cases and resources are annually reported and spent on water damage in Sweden from cases occurring in buildings from building services such as tap water-, sewage, heating systems, household appliances such as refrigerators, freezers and dishwashers and inadequate waterproof membranes in wet rooms. These water damage cases in buildings cause several problems in the built environment regarding economic, environmental, and social aspects of sustainability such as unhealthy indoor environments due to higher levels of moisture, mold growth, and redundant usage of building materials and resources in reparations and renovations of water damaged constructions, immense amounts of monetary resources spent annually by both residents, building owners and insurance companies to restore the buildings to their designed purpose.

This thesis aimed to reduce water damage occurrence and costs in buildings by outlining a holistic approach to the aspects of sustainability, occurrence, costs and solutions. Using qualitative and quantitative methods to analyze the state-of-the-art water damage research field, this thesis conducted several analyses to determine the occurrence, costs and solutions of water damage in the buildings. To reduce the impact and effects of water damage in buildings this thesis used empirical statistical data, parametric analysis, and a holistic approach regarding factors such as building purpose/type, extent of occurrence and causes, effects of the damage, different stakeholders and different solutions. A model was proposed regarding key figures, water damage causes, age distribution of reported damage cases, and estimated repair costs depending on the water damage cause and origin, to consider during the different phases, design, construction and operation, of the building.

The results of the thesis found that there exists a gap in the research and data collection of water damage occurrence, costs and consequences in buildings such as multi-family and non-residential buildings. The research conducted often includes the studied type of water damage cases in this thesis; building service systems, appliances and waterproof membranes, within the fields of building pathology and building defects but does not explicitly study the causes, associated costs and occurrence from different water supply systems and different origins within the building. The consequences of water damage from building services and installations, such as environmental and social impact are not often regarded.

The associated costs of water damage for the studied part of the building stock, were calculated to amount to approximately 1.1 billion € per year (12.6 billion SEK) including repairs of water-damaged buildings, single-, multi-, and public buildings, and insurance costs covered by the residents, such as deductible and age reduction costs. Solutions identified, that could be a part of the solution to reduce the occurrence, cost and consequences of water damage, were both passive and active technical solutions together with structures and information regarding the management and operation during the different phases of the building life cycle. The model presented causes and water damage cases, reported by the insurance industry, with the costliest repairs occurring due to corrosion, age/wear, and freezing damage, followed by faulty waterproof membranes and connection of membranes to drains and then refrigerators/freezers and dishwashers. Moreover, the expected time before water damage was reported was found to be most frequent in the first 10-year period after installation for several water damage causes reported in single-family buildings.

The thesis concluded, with the use of the holistic approach and the presented model of monetary resources spent on water damage and the associated costs, that if actions are taken to reduce water damage cases the immense resources that are annually allocated to water damage could be reduced, it could also reduce the unnecessary use of resources in replacing and repairing damaged material with existing service life, it also could decrease the associated costs, decrease the moisture, and water levels in buildings and could have the potential to improve the sustainability in the building sector and allocate the resource to other areas such as measures to improve the indoor environment and reducing the carbon emissions.

Key words: Water damage, building defects, tap water, costs, sewage, heating, leakage

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Christian Mattsson

LUND
UNIVERSITY

Building Services, LTH
Lund University
P.O. Box 118
SE-221 00 LUND
Sweden

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Lund, September 2023
Christian Mattsson

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Abstract

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Sammanfattning

Det rapporteras många fall och spenderas årligen stora mängder av resurser på vattenskador i byggnader i Sverige. Vattenskador som uppkommer på grund av läckage och utströmning av vatten från installationer så som tappvatten-, avlopp- och värmesystem, utrustning så som kylskåp, frysar och diskmaskiner samt läckande tätskikt i våtrum. Vattenskador från dessa system orsakar allvarliga problem i byggnader. Hållbarhetsaspekter, såsom ekonomiska, miljömässiga eller sociala, påverkas negativt av vattenskador, exempelvis försämrat inomhusklimat, förhöjd risk för fukt- och mögel i konstruktionen, överflödigt användande av material och resurser vid reparation av vattenskador, samt stora mänger av monetära resurser som spenderas årligen på att åtgärda och förebygga vattenskador av både boende, byggnadsägare och -förvaltare samt försäkringsbolag för att återställa byggnaderna och dess funktion.

Syftet med denna avhandling var att reducera antalet och kostnaden för vattenskador genom ett helhetsperspektiv på hållbarhet, antal skador, kostnader och lösningar på vattenskador. Genom användning av både kvalitativa och kvantitativa metoder för att analysera befintlig forskning och kunskap, kunde orsaker, kostnader och lösningar för vattenskador undersökas och analyseras. Tillsammans med helhetsperspektivet, som syftade till parametrar som användning av byggnader, olika aktörer, orsaker, skadeeffekter och lösningar, genomfördes det även analys av empirisk statistik och analys av olika påverkan från olika parametrar. Utifrån detta förslogs en modell där nyckelvärden så som skadeorsaker, installationsålder vid skada, uppskattad reparationskostnad beroende på skadetyp och orsak presenterades för att kunna användas i olika skeden av byggnadens livscykel, skeden så som planering-, produktion- och driftskede för att motverka och uppskatta vattenskadornas omfattning, orsak och reparationskostnad.

Från resultatet kunde det konstateras att det fanns en brist av forskningsresultat och datamaterial för orsaker, kostnader och effekter av vattenskador i flerfamiljshus och för byggnader ej avsedda för bostäder, såsom offentligt ägda och förvaltade byggnader. De vattenskador som har analyserats i denna avhandling från installationer, utrustning och tätskikt, inkluderades ofta inom forskningsområdena byggnadsbrister och defekter i tidigare studier. Detta medförde att vattenskadorna studerades med mindre fokus på vattenskadornas omfattning, ursprung, orsak och reparationskostnad. Helhetsperspektivet var även sällan studerat, exempelvis miljöpåverkan från skadorna och eventuella effekter på inomhusmiljön.

Kostnaden för reparationer av vattenskador i det studerade byggnadsbeståndet villor, flerfamiljshus och offentliga byggnader samt försäkringskostnader och självrisk och åldersavdrag, för boende och byggnadsägare uppskattades i denna avhandling till 1.1 miljard € (12.6 miljarder SEK) per år. För att minska dessa skador, kostnader och effekter av vattenskador studerades och identifierades åtgärder. Dessa åtgärder var både passiva och aktiva tekniska lösningar för att stoppa läckage samt vikten av information och kunskap om vattenskadors uppkomst, orsaker och kostnader i branschen under samtliga skeden under en byggnads livscykel. Genom att presentera en modell, där vattenskadeorsaker och reparationskostnader integrerades kunde de olika orsakerna analyseras och modelleras utifrån vilken skada som bidrog med till högst kostnader beroende på vilken reparation som krävdes. Korrosion, ålder/slitage samt frysskador på ledningssystemet bidrog till högst reparationskostnader följt av otäta tätskikt i våtrum samt felaktiga anslutningar mellan tätskikt och golvbrunn, vilket var följt av utrustningsskador i kylskåp/frysar och diskmaskiner. Dessutom presenterades intervall på ålder av installationer när skador inträffade, vilket visade att de flesta av de rapporterade vattenskadorna i villor inträffar under den första 10års perioden efter installation.

Sammanfattningsvis visar resultaten i avhandlingen att, genom ett helhetsperspektiv och den presenterade modellen för monetära resurser som spenderas på vattenskadeorsaker, att om åtgärder och lösningar vidtas för att minska antalet vattenskador kan de enorma resurserna som årligen spenderas reduceras. Detta skulle även innebära att den överflödiga användningen av resurser och material för att ersätta, återställa och reparera skadade byggnader minskas. Genom att minska vattenskadorna och kostnaderna av dem finns det även potential för att förbättra inomhusmiljöer, genom reducerad fukt-och mögelrisk från vattenskador samt att bidra till en mer hållbar byggsektor. En minskning av kostnaderna för vattenskadorna skulle även kunna innebära en frigöring av resurser som skulle kunnat användas till annat, exempelvis andra åtgärder som ökar inomhusmiljökvaliteten eller minskning av koldioxid-utsläppen.

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*

Submitted to Indoor and Built Environment

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*

Presented at E3S Web of Conferences, 2021 Cold Climate HVAC and Energy 2021 - Tallinn, Estonia. Duration: 18 – 21 April 2021

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

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

Presented at the 17th International Conference of the International Society of Indoor Air Quality & Climate - Kuopio, Finland. Duration: 12-16 June 2022

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*

Presented at the ASHRAE and SCANVAC HVAC Cold Climate Conference 2023 – Anchorage, Alaska, United States. Duration 5 – 10 March 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*

Presented at 2nd International Conference on Moisture in Buildings (ICMB23) – London, UK. Duration 3 – 4 July 2023

Paper VI: Water damage occurrence and cost in public buildings in Sweden – a case study

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

Submitted to Developments in the Built Environment

1 Introduction

Water damage that originates from building services and installations is causing problems that account for large amounts of resources every year in direct defects to the built environment, and it further causes the use of resources that are not included in the measurement of the direct defects to cost estimations, such as building delays, health effects to residents and inefficient usage of building material.

In Sweden, water damage that occurs from leaking pipes, connections, or valves in the tap water, sewage, or heating systems, inadequate waterproof membranes, and appliances such as dishwashers, and refrigerators is the defect in homes that amount to the largest sum of reimbursements from insurance companies [1]. In single-family buildings, it was estimated by the Swedish insurance companies in 2021[1] that annual insurance reimbursements amount to 4.4 billion SEK (440 million € [2])[1]. Similar trends, from corresponding buildings and leakages, are reported in countries such as Denmark and Norway [3, 4]. In international studies, from North America and Asia, the problem of moisture from building services is not reported to the same extent. However, studies identify water leakage from tap water and sewage as a major cause of building defects, significantly impacting overall building quality [5]. As such, there is a need for an international effort to reduce water leakage-related defects in building services in order to enhance the quality of the built environment and minimize the material usage required to repair water damage.

Water damage in buildings could occur due to several reasons and defects in buildings. One common reason is leakage through the building envelope which could cause moisture or rain from the outdoor environment to leak into the building [6]. Another is condensation of indoor moisture, produced by occupants, or indoor humidity, condensing in the building envelope. Another one, which is the subject of this thesis, is leakage of water from water services, such as tap water, sewage, or heating, or from appliances, such as refrigerators or dishwashers and inadequate water-proof membranes, in wet rooms. All of these defects are caused by water or moisture leaking into parts of the building that it´s not designed for and to achieve a good built- and indoor environment the defects in the building sector need to be improved and addressed regarding reducing the occurrence, causes and consequences of the defects.

To reduce costs and problems caused by water, an important aspect to consider is how the building and its technical systems should be designed, built, and operated to handle undesirable water and how to minimize the occurrence of such water loads from building services and wet rooms. Even if a building could be completely protected from water and moisture damage it would, with the highest certainty, be too expensive and would be hampered by other functional requirements. This is why a holistic approach is needed that regards water as a load considering different parts of the building process, from planning to use over a whole life cycle and communication and interaction with all involved stakeholders.

Reducing water damage occurrence in buildings and costs of repairs require solutions that improve the sustainability of the building sector regarding economic, environmental and social aspects. The building sector accounts for approximately one-third of global energy- and process-related carbon emissions [7]. In Europe, the sector also accounts for half of all raw materials extracted, half of the total energy use, one-third of all water use, and one-third of all waste generated [8]. Several actions across the entire value chain are needed to reduce the environmental impact and in doing such a transition to a sustainable sector regarding the building sector's social, economic, and environmental aspects. In paying attention to the social and environmental aspects together with the economic perspective of the building sector a more sustainable and resources-effective sector could be achieved. Furthermore, the European Union estimates that adopting greater material efficiency practices could result in saving approximately 80% of greenhouse gas emissions associated with material extraction, manufacturing of construction products, and construction and renovation of buildings [8]. These emissions are estimated to be 5 – 12% of total national greenhouse gas emissions. This emphasizes the crucial role that material efficiency plays in reducing greenhouse gas emissions, particularly in the construction and building sector [8]. In studying repairs and construction material usage and efficiency regarding defects and damage cases in buildings and constructions, must be included. In terms of annual reimbursements from insurance companies in Sweden, the payout to insurance takers from damage from water leakage was the largest by approximately 1.5 times larger than fire-related damage cases, which was second. Furthermore, insurance reimbursement for water damage was 3.6 times larger than all-risk insurance, which was in third [1].

To reduce greenhouse gas emissions and material usage, defects occurring in buildings both during their life cycle and during their construction and design need to be limited [9-11]. Defects deteriorate the quality of the building and generally demand repairs or renovation to the building or a part of the building to restore the building to its designed and designated purpose or function. Defects are frequently occurring in buildings due to moisture that originates from water within or outside of the structure and can be caused by the age of the installation, wear, and tear, and impacts from occupants of poor-quality materials [9, 11]. Sources of moisture in buildings are several and do occur both from external sources, such as precipitation, outdoor humidity, and from the soil, interior sources such as built-in moisture in the building material, indoor moisture from occupants and residents, and leakage from installations and building services and through leakage in the building envelope [12]. Measures for both reducing the causes and effects of water damage are required. Repair causes carbon emissions for the exchanged materials and used resources, i.e., a climate impact load that would not have been needed if the damage had not occurred. One case study of water damage in a single-family building estimated the impact to be 250 to 750 kgCO_2e per water damage [13].

Social aspects that are affected by water damage include indoor air quality and a healthy indoor environment for the occupants and the building's user. Studies show that water damage and water that leaks and doesn't get noticed could cause mold growth and moisture in homes and have shown an increased likelihood of respiratory diseases and adverse health effects, such as asthma, respiratory infections, allergic reactions, and eczema [14-16]. Furthermore, the public health agency of Sweden reported in 2017 that 19 % of the respondents in their study live in residents where they had visible moisture damage, mold, or smell of mold growth [17].

In effect, this could lead to consequences for the residents living under such conditions. Consequences such as sick leave, impaired health and life quality and costs for medical care together with the insurance costs, for example deductible cost. If the building isn´t covered by insurance or the insurance does not cover the repair the cost for the resident could be significant. On average a water damage occurring in a single-family building, in Sweden causes damage costs, often repair/restore costs, of approximately 49 000 SEK (4 450 € [2]) per damage case [18, 19]. Some studies suggest an average repair cost of a water damage of 80 000 - 133 000 SEK (7 100 – 11 800 € [2]) per damage occurring in multi-family buildings. While insurance or building owners may cover the economic impact of water damage, there are still many uncertainties surrounding the costs of water damage and its effects on social and environmental sustainability. Thus, it is important to consider a more comprehensive approach to managing water damage that further considers sustainability and through that could reduce the occurrence and cost of water damage and advocate for holistic solutions.

To increase sustainability, regarding economic, environmental, and social aspects, the occurrence, costs and consequences of water damage in buildings need to be reduced. The repair costs of the reported cases are increasing and are the largest, regarding annual insurance reimbursements, in Sweden [1]. The water damage cases occurring in rooms without waterproofing is increasing [20] which is causing problems that could be related to the large number of residential buildings with moisture problems. Avoiding moisture problems from water damage cases requires knowledge and information of risks and causes of the different systems, tap water, sewage, heating, appliances and waterproofing, depending on different buildings, -usage, -constructions, and -age including several different actors, such as building owners, residents, managers, and designers. However, this knowledge is often not regarded for water damage specifics but for building defects and other problems in the built environment. Furthermore, the potential consequences of water, such as costs for different stakeholders, health implications and carbon emissions of the repairs, are not often studied explicitly regarding water damage from different building services and installations. Hence, there is a need for detailed studies that consider these sustainability aspects of water damage. This thesis therefore intends to outline which aspects to address and to explore some of these aspects.

1.1 Aim

The research presented in this thesis has an overall aim to reduce water damage occurrence and costs in buildings by outlining a holistic approach to the aspects of sustainability, occurrence and costs and solutions.

One aim is to evaluate and analyze scientific literature and databases regarding water damage occurrence, cost and consequences.

Another aim is to examine what costs are associated with water damage occurring in buildings due to leaking pipes, connections, appliances, and inadequate waterproof membranes for different stakeholders.

Furthermore, the study aims to study existing solutions regarding reducing the effects of water damage and find the potential economic payback time of implementing such solutions.

This thesis finally aimed to present a model, based on empirical water damage data and research findings for the building sector where water damage occurrence and costs could be determined with input parameters, such as building age, construction and different tap water systems.

With the literature, databases, associated costs and possible solutions analyzed the model presented in this thesis aims to be used by different stakeholders throughout the lifecycle of the buildings to reduce the occurrence, costs and consequences of water damage in buildings.

1.2 Limitations

The water damage and effects that are not studied and investigated are moisture and water damage caused by factors outside the building (e.g., flooding and leaks through the building envelope) or by building physical reasons (e.g. mold growth caused by condensation in the foundation, wall, or cold attic). Included water damage is caused by or has an origin from faulty:

- Pipe and connections, water damage caused by unexpected flow or leakage from the tap- or wastewater or heating systems.
- Appliances, equipment or installations, water damage caused by unexpected flow or leakage from installations in buildings, for example, refrigerators, freezers, dishwashers, or washing machines on rooms without floor drain/-s
- Waterproof membrane, water damage caused by leakage or moisture-penetration in waterproofing membranes installed in rooms equipped with floor drain/-s.

This limitation is commonly used in reporting water damage in single-family buildings, one example is the water damage statistics in Sweden [1, 18]. Furthermore, the result of the study is derived from buildings in Sweden and the Nordic countries, Denmark and Norway, but implementation and effects of the results could be applied internationally by taking into regard the specific circumstances applying to that country. Several of the problems discussed in this thesis are concerns that apply in countries outside Nordic countries, and similar studies could be conducted using the methods used in this study.

1.3 Research questions

The research presented in this thesis was conducted through 2 scientific journal papers and 4 scientific conference proceedings to answer the 4 following research questions, all with the overall aim to reduce water damage occurrence and costs and finding sustainable solutions:

I. To what extent do the existing international and national literature and statistical data on occurrence and costs describe the causes, consequences, and costs of water damage occurring in buildings due to leaking pipes, connections, appliances, and inadequate waterproof membranes?

II. What costs are associated with water damage occurring in buildings due to leaking pipes, connections, appliances, and inadequate waterproof membranes for different stakeholders?

III. What existing solutions could be used to reduce the occurrence, cost and consequences of water damage in buildings and what could the potential gain of such solutions regarding costs and occurrence of water damage be?

IV. How can parameters such as occurrence, costs and consequences of water damage in different buildings be modeled with the aim of reducing the amount and extent of water damage occurring in buildings due to leaking pipes, connections, appliances, and inadequate waterproof membranes?

2 Research methods

To achieve the goal of reducing water damage in buildings several different aspects need to be addressed. By this is will be possible to fully address the problem and reduce occurrence of water damage and its associated costs. The findings in this thesis are derived from the use of a holistic approach concerning water damage occurrence, costs, and solutions. The holistic approach was needed because of the many different aspects concerning the research subject, including different building purposes, different water damage characteristics and extent, several stakeholders, building sustainability, causes and problems, and several costs to the stakeholders derived from the damage. Thus, a holistic approach was needed along with several different research methods to determine the status of the field, analyze the existing statistical data and suggest different actions and measures to reduce both the occurrence of and thereby generated costs of water damage in buildings. The research study present a model that can be used as an approach to predict water damage occurrence, cause and costs in existing buildings. An overview of the parameters regarded in the holistic approach is presented in Figure 1.

The thesis aims to suggest a holistic approach that includes all affecting/relevant factors regarding water damage in buildings and to address some of these concerning costs, occurrence and solutions. To achieve this, the different aspects were:

- Different buildings and building purposes where water damage occurs.
- Different water damage characteristics and types.
- Stakeholders involved or affected by the water damage.
- The extent of the water damage cases in the building stock, statistics and known cases.
- Causes and origins of water damage.
- Effects and problems derived and originated from the water damage, regarding the building, users, sustainability and energy.
- Costs derived originated from the water damage, affecting the building owner, manager, resident or the insurance company.
- Different solutions, actions or measures implemented, in different stages of the building's lifecycle, to reduce the effect, cost and occurrence of water damage.

Figure 1. Overview of the parameters regarded in the holistic approach of reducing water damage occurrence, cost and consequences.

2.1 Thesis content

This thesis presents results from six papers to answer the research questions expressed in the introduction. These papers are referred to as Paper I – VI and are appended in this thesis. Each of these appended papers has detailed methods, results and conclusions enclosed and this thesis is a summary of the study in which the appended papers are included. The different methods used are summarized in this chapter. Key results from the papers are presented and discussed in the following chapters. The thesis consists of the following papers that use the methods and study the subjects described below:

Paper I: 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.

Paper II: A parametric analysis of empirical water damage statistics in order to review water damage cases that occurred in cold outdoor climates. This was done by a literature review of both scientific literature and retrievable cases from practical experience along with a parametric analysis of weather data and water damage data in Sweden.

Paper III: 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 material and quantitative methods to attain material on costs from insurance companies and in multi-family buildings. Quantitative methods that were used was questionnaire, interview, and discussions with stakeholders. The gathered data was analyzed using extrapolation and estimation to present a cost of each studied cost-category.

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

Paper V: Similarities, differences, and tendencies of causes and occurrence of water damage in the Nordic countries were studied using a questionnaire answered by representatives in the Nordic countries

Sweden, Norway, Denmark, Finland and Iceland. Answers from the questionnaire in combination with the estimated reimbursement (cost) per inhabitant in each studied country constituted the basis for the analysis of similarities, differences, and tendencies.

Paper VI: Analysis of water damage occurrence and cost in public buildings in Sweden, using real estate data and 5-year damage data from a larger municipality to extrapolate and estimate the extent of water damage in publicly owned, managed, and operated buildings.

The papers included in this thesis are all conducted with several authors acting as supervisors to the projects and the doctoral student and all authors have contributed in the preparation of the papers. The doctoral student did manage all calculations and data throughout the papers and this thesis.

In summary, the methods used in the appended papers and this study are presented in Table 1.

Table 1. Methods used in appended Papers I-VI.

Methods used	**Paper I**	**Paper II**	**Paper III**	**Paper IV**	**Paper V**	**Paper VI**
Literature review	X	-	X	-	-	-
Qualitative analysis	X	-	-	-	X	-
Quantitative analysis	X	X	-	X	-	-
Parametric analysis	-	-	X	X	X	X
Extrapolation of data	-	-	-	X	-	X

Throughout the thesis costs will be presented in Swedish krona (SEK) and euro (€) with the conversion rate of 1 € = 11.3037 SEK as of April 2023 [2].

2.2 Review of literature and data (RQ I)

The first research question regarding the state-of-the-art of the field and the available data was determined using both quantitative and qualitative methods in reviewing literature and finding relevant databases within the scope of the study. The appended papers intended to answer the first research question are Paper I – II and V. The quantitative method used in the literature review aimed to determine the literature distribution and what research fields the published material was included in. The qualitative review was performed to review the state-of-the-art of water damage in regard to the status of the field and to determine what causes are prominent and highlighted in the field, in addition to this the costs associated with the water damage cases were also reviewed. Furthermore, studies of consequences and effects were reviewed to determine the effects of moisture and water in buildings. As the final study object, the study included a review of strategies and methods for the prevention of water damage in buildings to determine what measures were used that have shown a positive outcome in reducing water damage and defects in the built environment.

The statistical data included in the study is derived from the water damage statistics gathered by insurance companies in Sweden, companies managing or operating building compounds, municipalities and industry organizations. Organizations used for gathering data are the Swedish water damage center (Vattenskadecentrum), the Swedish insurance industry organization (Svensk Försäkring), Statistics Sweden (SCB), The Swedish real property register by the Land Survey Authority (Lantmäteriet).

The Swedish water damage center (Vattenskadecentrum) annually publishes a detailed examination and analysis of the water damage cases in insured single-family buildings in Sweden. The report compiles insurance damage reports and together with a detailed inspection protocol analyzes water damage causes and occurrences that occurred during the studied year. Alongside this, the center publishes data regarding common causes of water damage divided into three categories, *pipes and connections*, *appliances* and *waterproof membranes*.

In addition to the detailed analysis of water damage in insured single-family buildings, carried out by Vattenskadecentrum, the insurance industry organization Swedish insurance (Svensk Försäkring [21]) publish statistics on defects in different insurance categories, of which water damage is included, with less detail of the cause of the defect. In difference to the report by the Swedish water damage center (Vattenskadecentrum) do Svensk Försäkring add insurance reimbursements paid to cover the costs of the defects. This data is not specific to single water damage cases but is instead a comprehensive database of the number of insurance cases and reimbursed amount for those cases that were reported to the insurance companies during the chosen year. Hence, only reported insurance cases are included in this dataset, and no specific data on specific cases can be exported. The data in the dataset is based on and divided into insurance principles, presented below, and the defects are categorized as *water damage that occurred from water that occurred due to leakage, moisture or freezing from waterpipes or other reasons that were not natural damage* [21]. The data is gathered each year and dates back to 1985. The insurance principles included are [21]:

- Home insurance
- Dwelling and property insurance
- Leisure home and property insurance
- Property and company insurance
- Other insurance

These insurance principles where property insurance is included cover both the property and the building whilst home insurance often is used in combination with property insurance for single-family buildings, such as dwellings, detached houses and leisure homes cover the personal property.

The building stock in Sweden is comprised of buildings designated for living, conducting business, social services, culture, and leisure buildings. The residential building stock is comprised of single-family and multi-family buildings and homes together with other buildings where the building purpose varies and is categorized as special housing or other buildings [22]. The building purpose of the buildings is described by Statistics Sweden [22] as the designed usage, usually whether the building is used as a home for families, vacation homes, care or elderly home, etc. Data on the residential building stock is gathered by Statistics Sweden (SCB) and are described and comprised of:

- Single-family buildings refer to residential-detached one- or two-family houses, including terraced houses but excluding vacation homes.
- Multi-family buildings refer to residential apartment buildings with three or more apartments.
- Special housing refers to residential housing for the elderly/disabled, students, and other specialized housing.
- Other buildings in the building stock are buildings not explicitly designed for residential purposes but still include residential apartments, such as buildings intended for commercial or public use [22].

The building's form of tenure is usually described as further dividing the residential building stock. These tenures are as described by Statistics Sweden [23], apartments are used to describe one resident or home:

- Tenancy apartments refer to apartments not owned by the resident but leased from the building owner or the managing company.
- Condominium apartments refer to apartments owned by the resident, but the building is owned by housing cooperatives.
- Tenant-owned apartments refer to apartments owned by the resident.

Furthermore, to determine the building years of Swedish buildings Statistics Sweden [22] was used, to enable an analysis of the expected lifetime of installations and building services, such as pipes and connections, the building year together with the expected service life was examined, to be able to comprehend leakages and be able to plan for maintenance and renovations.

To examine the nonresidential building stock the real property register was used. This register includes buildings not intended for residential use such as public buildings, schools, offices, and culture [22, 24]. The Real Property Register uses building purposes and detailed building purposes to describe the purpose/use of the buildings which in this study were categorized into the 4 categories listed in Table 3. Table 2 describes the detailed building purposes for which 1 – 24 were used. The residential buildings would be registered as 30 – 35 in the real property register and 40 – 99 were not studied in this study.

Table 2. Detailed building purposes used in the Real property register *[24]*

DETAILED BUILDING PURPOSES	
01 = Indoor aquatic center	**20 = Sports hall**
02 = Fire station	**21 = University**
03 = Bus station	**24 = Multi arena**
05 = Animal hospital	30 = Detached house
07 = Care center	31 = Detached houses chain houses
08 = High school	32 = Terraced houses
09 = Ice rink	33 = Multi-family building
10 = Railway station	35 = Small house with several apartments
11 = Municipal building	40 = Other manufacturing industry
12 = Correctional institution	42 = Industrial hotel
13 = Cultural building	47 = Metal- or machine industry
14 = Police station	48 = Textile industry
16 = Riding house	49 = Wood products industry
17 = Societal, association, community building	53 = Other industrial building
18 = Hospital	99 = Unspecified
19 = School	

The detailed building purpose described in Table 2 is divided into the categorization, of schools, nursing, and care homes, offices and premises and culture and leisure buildings. The purposes, used in this study are described in Table 3 together with the number of buildings included in the real property register.

Table 3. Detailed building purposes are categorized into building categories.

Building category	**Detailed building purposes described in the Real Property Register**	**Number of buildings in the Real Property Register [24]**
Schools	8, 19, 21	7 206
Nursing, and Care homes	5, 7, 18	520
Offices and Premises	2, 3, 9, 10, 11, 12, 14, 16	1 518
Culture and Leisure buildings	1, 13, 17, 20, 24	3 382
		Σ 12 626
Residential buildings	30-35	-
Industries	40-53	-
Unspecified	99	-

International data was derived from datasets from housing organizations and insurance companies. Water damage data, such as occurrence, cost and causes, was found from the Norwegian insurance industry organization Finans Norge [3], the Danish insurance and pension industry organization Forsikring & Pension [4], the German Insurance Association (GDV) [25] and the American housing study (AHS) U.S. Census Bureau [26].

2.3 Water damage associated costs (RQ II)

The second research question regarding costs of water damage included several different costs such as the repairs, renovation and insurance costs associated with restoring buildings to their designated function with a good indoor environment and air quality without moisture problems. The appended papers intended to answer the second research question is Paper III–VI. To create an overview of the associated costs of a water damage an analysis of the insurance statistics was conducted and the different associated costs of water damage were determined regarding different stakeholders. The studied stakeholders were the building occupant, resident, manager or owner and the insurance company. The studied costs in this thesis associated with water damage are such costs related to the reparation or the drying of moisture from the water damage. Other costs associated with the effects of living or spending longer periods in a building with high levels of moisture, mold and smell of mold were not studied.

The costs of water damage in Sweden, Denmark and Norway are most often referred to as the reimbursement for the monetary losses due to repairs of the building because of the water-damaged material that needs to be replaced [1, 3, 4]. These reimbursements, from the insurance companies, cover the repair of the damage caused in the insured building. These reimbursements are reported similarly in the Nordic countries, Sweden, Norway and Denmark where the number of reported cases and the reported total reimbursements are presented annually. A difference between the country's methods for reporting cases exists in categorizing the reported cases. In Sweden, the cost and occurrence statistics from the residential building stock are categorized in *different insurance principles* and depending on if the *water damage occurred from water that occurred due to leakage, moisture or freezing from waterpipes* or *other reasons that were not natural damage* [21]. Causes are reported in the detailed water damage report as, described in Table 4.

Table 4. Categories used in the detailed water damage report by the Swedish Vattenskadecentrum for describing water damage causes.

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

In Norway, it´s used a categorization depending on the *cause of the water damage*, e.g., failure of the product, corrosion and freezing [3]. Detailed causes used in Norway are described in Table 5.

Table 5. Categories used in Finans Norge [3] for describing causes of water damage.

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

In Denmark, the categorization used is based the on the *cause of the water damage*, e.g., *water damage that originates due to hidden pipes and connections* and *water damage that originates due to other reasons than hidden pipes and connection and exterior influence* [4], described in Table 6.

Table 6. Categories used in Denmark for describing water damage causes[4]

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

Once the differences were determined a comparison between the water damage in these countries could be made, in a number of reported water damage cases and reported costs. The reported reimbursements and the number of water damage cases in the studied countries are from the insurance industry. The data provided by the insurance industry is derived from a large dataset with established methods for data gathering. The reported cases and reimbursements from the insurance industry, by Svensk Försäkring [1] is regarded, in this study, to be representative of the single-family buildings and special housing (amounting to approximately 2.1 and 0.3 million apartments [22]) in Sweden. The causes of these water damage cases, described in the report by Vattenskadecentrum [20], is also used as a basis for evaluating solutions and measures to reduce the occurrence and costs of water damage. To conduct a comprehensive analysis, as of this study, of the associated costs of water damage in buildings, several more costs need to be considered.

Multi-family buildings are often operated and managed by a company or a cooperative of the residents. How the set up for operation is made depends on the form of the lease, which could be tenancy, condominium, or ownership of the apartment. To determine the extent of water damage and the repair costs, this study included the aspects of management. This was made by examination of previous reports of water damage costs in multi-family buildings and completed this information with a questionnaire, in which building managing companies got to answer questions regarding data and experience of water damage occurrence and costs. In estimating key figures, both gathered from previous studies [19] and from this thesis (appended paper III), of an assumed cost of a water damage per apartment in the multi-family building stock (approximately 2.6 million apartments [22]), together with the likelihood of water damage occurrence, the key figures could be extrapolated to correspond to an estimation of annual repair costs spent on repair, renovation or restoration of water damage in the studied multi-family buildings. The building stock of multi-family buildings was estimated in apartments, using data from the Official Statistics of Sweden [22].

For public-owned, -managed, and -operated buildings, such as schools, nursing, care homes, offices, premises, and culture and leisure buildings the occurrence and costs for the repair of water damage were in this study estimated using similar extrapolation methods as for multi-family buildings. Water damage data from a larger Swedish municipality were used to establish key figures of water damage occurrence and cost per year and building of the different studied buildings purposes, schools, nursing/care homes, offices/premises and culture/leisure buildings. The extrapolation was conducted by multiplying the key figures of occurrence and cost per building and year (estimated in appended paper VI, derived from the studied municipality) for the different building categories with the number of buildings in the real property register. The estimated number of water damage cases in Sweden was calculated using the occurrence of reported water damage cases in the studied municipality to represent the entire building stock for each respective building category. When the occurrence was estimated the average, minimum and maximum estimated costs for water damage cases derived from the municipality's data were used to estimate the costs for Sweden per year. By this, an estimation of the buildings in Sweden could be done using extrapolation with the building stock of similar buildings with the same usage and purpose. For public-owned buildings the Swedish real estate register was used by Lantmäteriet [24].

Water damage causes more expenses than just the repair of the water-damaged material. There are costs concerning the insurance, such as deductible and depreciation and the age reduction costs that the building owner needs to cover to be reimbursed for the damage. Deductible cost is the amount that the insurance holder is responsible for paying for the loss to be reimbursed by the insurance company, in short the deductible is subtracted from the reimbursement depending on the insurance terms and conditions. The depreciation or age reduction is the cost that the insurance holder needs to cover depending on the age of the damaged material due to its decreasing value over time, often paid similarly to the deductible cost [28-32]. Insurance reimbursements that the insurance companies deliver to the insurance customer if the water damage occurs within the boundaries of the current insurance company’s terms and conditions and if the building where the water damage occurs is covered by insurance. As a customer with insurance for your home, you are eligible to pay the deductible cost and possibly the age reduction and deprecation cost because of damage that the water damage caused [28-30, 32, 33]. These costs were evaluated by analysis of different Swedish insurance companies. The included Swedish insurance companies were Dina Försäkringar [28], Folksam [29], IF [30], Moderna Försäkringar [32], Länsförsäkringar [33]. In addition to these insurance principles discussions with the insurance companies were conducted in order to establish key figures that could be used to estimate the costs associated with home- and property insurance.

The cost associated with having insurance for the building owners, the annual premiums paid by insurance customers in order to have an insurance if a water damage would occur, was examined from Swedish insurance statistics [34]. Because of the lack of data on a number of insured buildings in Sweden the insurance premiums for home insurance, dwelling and property insurance were examined. Included in these premiums are the insurance to get reimbursed for water damage together with several other reimbursements. Thus, it is not the whole sum of the premiums that are allocated to water damage reimbursement, but it is still a cost that the building owner needs to cover to be eligible to receive reimbursement if water damage occurs [28-32].

Water damage occurring in or in the adjacent walls or floor of a wet room for example could cause large and costly repairs because of the waterproofing demands of a wet room, which demands replacement of materials under the waterproofing and new sealant to the not damaged waterproof layer. Whilst water damage in a room without waterproofing such as a kitchen could be less costly to repair because of the often less comprehensive waterproof layer in the construction needed in rooms that are not considered wet rooms, but the damage could cause a need for a larger and more material needing repair [35]. To include figures such as these where actual costs of damage repair scenarios included the report by Björk, et al. [19] used together with key figures established in estimations of water damage associated costs in single- and multi-family buildings.

To answer the research question, a summary of the results established in the studies was conducted to estimate the annual amount of water damage associated cost. This was done by adding the reimbursement of damage in the studied different type of buildings, the estimated annual premiums paid by households with insurance, together with deductible, deprecation and the age reduction costs.

2.4 Solutions to reduce the occurrence, costs and consequences of water damage (RQ III)

The third research question, regarding solutions that could have the potential to reduce the occurrence of water damage, cost and effects of water damage was studied in this thesis. The appended papers intended to answer the third research question is Paper IV–V. In appended paper IV four different actions/measures were examined regarding and aiming to identify and suggest preventive cost-effective and sustainable measures of maintenance and operation phase that had potential be implemented, or advocated for, by the building owner, manager, or insurance company.

The four studied actions/measures to avoid water damage were waterproof underlays, water monitoring devices, water leak switches and water leak alarms. The waterproof underlays are used below or under appliances, with the function of directing water to flow out from beneath the appliance into a visible area where the water leakage is discovered by occupants. Without the underlay the water could flow into the building construction and cause damage. The water monitoring device studied is a device that is installed at the inlet pipes of a building. The device is constructed to monitor the water flow in the building and create an overview of the system. It should be able to automatically shut off the water flow for the building if a leakage, small or large, is discovered in the building. The water leak switches studied were devices that are installed locally to detect and stop water leakages from e.g., appliances. It consists of a switch and a water-sensitive sensor. The switch is connected between the appliance's main supply pipe and the distribution service pipe to the appliance. The water leak alarms studied were devices that are placed on the existing pipe system, 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.

Once the four different actions/measures were selected, data was collected regarding what cases of water damage they could prevent or reduce in relation to the water damage data available, data from the Swedish water damage center (Vattenskadecentrum [20]) was used to represent the damage cases in Sweden. The study further regarded what the installation cost of the action/measure was (investment cost) and finally what the payback time would be if installed regarding the assumptions and limitations in the study.

The payback calculation was conducted by an estimation of the risk of water damage using the number of reported water damage cases within the specific water damage category that the action/measure was assumed to prevent (estimated occurrence in apartments per year (n)). The probable damage cost was calculated by multiplying the percentage of apartments with damage per year (%) and the estimated damage repair costs (SEK) estimated in previous studies and presented in chapter 2.3 of this study. Finally, the payback calculation was estimated by dividing the probable damage cost per year without an action (SEK/year) with the investment cost (SEK). The equations for the calculation are presented in Equation 1 and 2.

$$(1)\ Probable\ damage\ cost = Estimated\ occurrence\ per\ apartment\ and\ year\ *\ repair\ cost$$

$$(2)\ Payback\ time = \frac{Probable\ damage\ cost\ per\ year\ without\ action}{Investment\ cost}$$

Other solutions, that were determined through the state-of-the-art review, were to reduce the water damage occurrence, costs and consequences together with other defects by increasing the knowledge in the field through informed and guided design, management, and organizational structures. To analyze the possibility of such solutions a questionnaire was electronically sent out to industry organizations, insurance companies and universities in Nordic countries, Sweden, Denmark, Norway, Finland and Iceland, with the purpose of gathering information about documentation, gathering, reporting, extent, and presentation of water damage statistics. Answers from the questionnaire and water damage data from each country, similarities, differences, and tendencies could then be analyzed. The 5 countries were chosen because of similarities in building types, climate and insurance structures.

2.5 Additional parameter analysis and modeling of costs from different causes (RQ IV)

The fourth research question regarding which parameters could be included in a model for reducing the occurrence, costs and consequences of water damage was answered using the previous results presented in this thesis and appended papers. The additional analysis that this thesis presents is an outline for the model which was intended to be used as a guideline to assess the consequences of water damage and the possible risk of occurrence and costs in different buildings studied in this thesis. Firstly, the input parameters, occurrence and costs were determined using the detailed water damage report by Vattenskadecentrum [20] and the different water damage costs were determined in this thesis and appended papers. The studied data from Vattenskadecentrum [18], [20, 36] was collected between the years 2020 – 2022. These years were chosen to represent the current problems with water damage and the causes of water damage in Sweden. Alongside the causes, information on service life (years after installation to damage was reported) was gathered to demonstrate the different studied causes' service life before damage could be expected, according to the water damage statistics available in Sweden. This was done using data from the water damage center which, as previously mentioned, is gathered from insured single-family buildings. In order to conduct this demonstration of common causes and expected service life and answer the research question this detailed data is needed. For this study it´s used to represent other types of buildings as well and therefore it could be differences in the occurrence and causes of water damage in other buildings than the buildings where the data is derived from. The studied data is divided into 3 origins of the water damage, used by Vattenskadecentrum [20], and causes of damage as described in Table 7.

Table 7 Categories used to describe water damage cases in origin and causes of the water damage [20].

Origin of water damage	**Pipe and connections**	**Appliances**	**Waterproof membrane (divided into wall and floor-originated damage)**
Causes	Corrosion	Fridge/freezer	Faulty membrane
	Age/wear	Dishwasher	Connection to drain
	Freezing	Water heater	Joint
	Faulty installation	Washing machine	Connection to pipe
	Faulty material	Ice machine	Joint wall/floor
		Aquarium	Fasteners
		Other*	Mechanical infringement

*Other causes in the appliance such as causes determined by the inspectors occurring in pipes and connections to the appliances, that are not included in the category pipes and connections, according to Vattenskadecentrum [20].

To determine which factors could impact and cause water damage to single-family buildings the report by Vattenskadecentrum [20] was used. In this thesis, different costs associated with water damage repairs have been determined depending on which rooms in the buildings the damage occurs in and what repairs of a typical damage in such rooms demand in terms of costs. By using these costs, presented in Table 14, together with the detailed water damage data, a new aspect of which causes are the costliest in relation to the occurrence was analyzed. In the additional analysis the categories associated with the costs, presented in Table 14, are modified to apply to the damage categories used by Vattenskadecentrum.

- Water damage with an origin from *pipes and connections* could occur in all parts/rooms of the building, hence the costs used in this study to estimate the costs of the causes are the average water damage costs derived from the water damage statistics gathered by the insurance industry, called other spaces (average repair cost insured single-family buildings) was estimated to 49 000 SEK (4 300 €) [1, 37].

- Water damage with an origin from *appliances* did 2022 most commonly occurred in kitchens [20] but did as well occur in rooms with a waterproof membrane. But because of the waterproof membrane and the drain, a water damage occurring in such rooms was assessed in this study to cause damage in a smaller extent than the estimated repair costs of kitchens. Therefore the repair cost estimation from the case study by Björk, et al. [19], a leakage from a tap water faucet of 30 500 SEK (2 700 €) [19, 37] was used for estimating water damage repair costs from appliances.

- Water damage occurs in rooms with a *waterproof membrane* but where the waterproof membrane is inadequate, and water still causes damage, the costs in this study are estimated to be an average of the two estimations of repair costs in waterproof rooms by Björk, et al. [19]. This is done because of the difference in the amount of water damage cases occurring in a wet room with tiles – leakage through a membrane with an estimated repair cost of 93 000 SEK (8 300 €) [19, 37] and in a wet room with a plastic mat - leakage through a membrane with an estimated repair cost of 60 000 SEK (5 300 €) [19, 37] is not known. Hence the average repair cost of the two estimated costs by Björk, et al. [19] of 76500 SEK (6 800 €) is used in this study.

The costs associated with the repair of the water damage depending on the damaged material that needs to be repaired were multiplied by the number of cases occurring in each cause category, Table 7. The result derived from this calculation is a model that could be used, in addition to the annual occurrence of water damage causes and its distribution between rooms, depending on origins etc., to weigh the costs that the different water damage causes are associated with. Thus, additional data are added to understand the occurrence, cost and consequences of water damage in buildings which solutions could be based upon and target specific costly water damage causes. Finally, the percentage of the estimated costs in relation to the total costs and the percentage of reported causes are calculated.

3 Results

The following chapter presents an overview of the results in the papers included in this thesis and research project, following the research questions. Starting with a comprehensive review of relevant literature and previous research, analyzing the state-of-the-art in the field. Continuing with outlining the major findings and results of the research project, which examined the costs of water damage in buildings and proposed solutions and measures to reduce these costs. The results and key findings from the appended papers are presented. This chapter provides an analysis of the research conducted, highlighting the significance of the study's contributions to the field of water damage occurring from pipe systems, appliances and waterproof membranes in buildings and suggestions on how prevention measures could be implemented and how management and operation of the building could implement the findings of this project in buildings to reduce the costs and occurrence of water damage.

3.1 Review of previous research and obtainable datasets (RQ I)

The quantitative review of the field resulted in 39 relevant studies published after 1995 in the studied databases Scopus and Web of Science (Figure 2, see appended Paper I Table 3-6). Figure 3 shows the geographical distribution of the found papers, approximately 50 % of the found literature was conducted in Europe, followed by Asia with 25 % of the found literature.

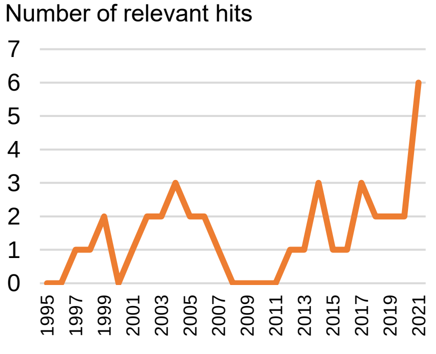

Figure 2 Relevant hits found in the literature review (Scopus and WoS)

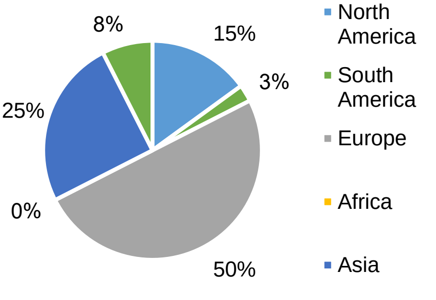

Figure 3. Geographical distribution of the found papers

The major finding of the literature review was that water damage occurring from causes studied in this project was highly limited to the Nordic countries, Sweden, Denmark and Norway. The study concluded that research on water damage is often not limited to the building services, pipes, connections, appliances and water-proof membrane, as the scope of this project but rather is included in defect analysis, as a part of the building pathology field, in the built environment, with water damage being one source of many defects. However, the studies (Paper I and VI) showed that water damage-related problems, such as leaking pipes and fault installation of water services, were some of the most common defects studied or was the defect with the highest impact, regarding the found causes for the building defects, on the results of the studies found. To further nuance the findings and to analyze the research field, 4 subject areas were chosen to divide the findings. These areas were construction defects, automation in buildings, quality in construction and moisture analysis and both illustrate the focus areas of the found literature and the field and illustrated the differences of defect and water damage research geographically, see Figure 3 in appended Paper I. This showed a large research emphasis on quality in construction and moisture analysis in Europe and a larger emphasis of construction defect analysis in Asia.

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 solution of reducing the amount, cost, and effects of defects, including water damage. Shortcomings in parameters such as these were found to be the most studied causes of defects in studies such as [9, 11, 38-41]. The key findings from the literature review were that to improve the overall building sector and decrease the number of defects occurring in the sector, key decisions need to be based on more knowledge of building defects. One solution to decrease the number of water damage is informed and guided structures throughout the construction and operation phase of the building [5].

In the empirical statistical review of water damage statistics in the Nordic countries, conducted in appended paper II, the differences in the statistic gathering within the Nordic countries, Sweden Denmark and Norway were determined. Significant differences were found in the categorization of water damage causes, but statistics could be found in such as detailed degree that it allowed for further analysis of the occurrence, causes and costs in the studied countries. In the study the correlation between freezing caused water damage and the cold climate in the Nordic countries was studied. Freezing caused water damage was shown to increase during a cold period of time in Sweden and Norway, see Figure 4, and there was found to be a correlation between the two parameters, deviation from the mean winter temperature and the ratio of freezing caused water damage of 0.59 – 0.61, see Figure 5, which indicated some correlation but other factors could not be excluded, such as building practice [42].

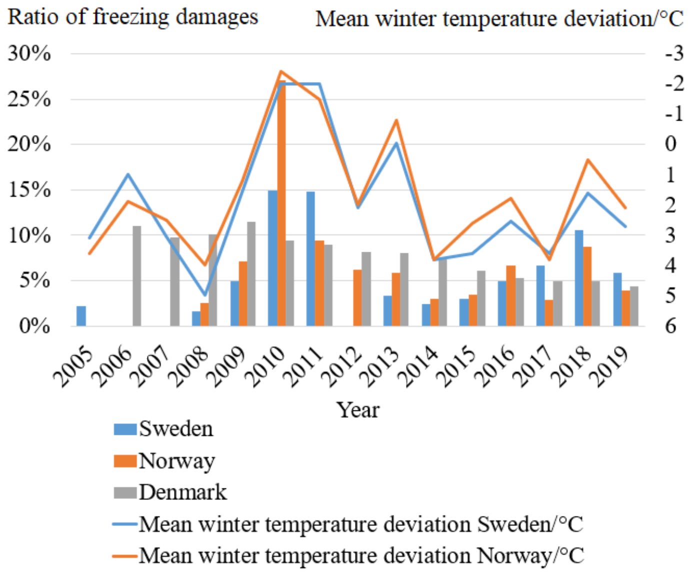

Figure 4. Ratio of water damages due to freezing in relation to the mean winter temperature deviation for the Nordic countries between 2005 and 2019 [42]

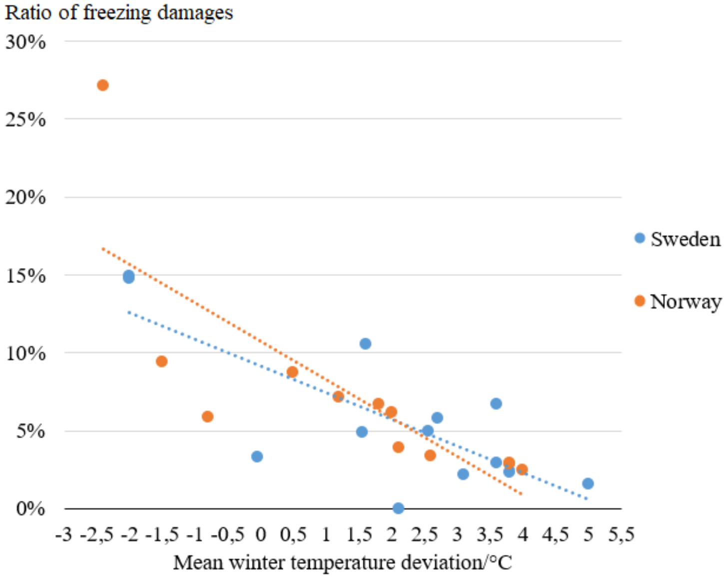

Figure 5. Correlation between the mean winter temperature deviation and the percentage of freezing caused water damage (R^2 = 0.59 Sweden, R^2 = 0.61 Norway) [42].

The qualitative analysis of the literature concluded that the status of the occurrence of water damage is researched in the field of building pathology and detail as defects. However, statistics and data on causes, origins, and costs of water damage, as described in the scope of this study, were not found in international sources. These could have provided a comparative determination of different countries' status concerning water damage and provided further knowledge into effective solutions and building practices. However, the causes that are prominent and frequently mentioned in the found literature, concerning building design and construction quality are very much applicable to reducing the amount of water damage cases, using studied methods to improve the quality of the built environment and the construction phase of the buildings. Likewise, are the studies found concerning the moisture effects of water in buildings.

The cost of defects for an organization or building project in terms of delays, rework, and economic losses was found to be described well in the found 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, but a holistic approach, one that covers multiple cost categories in different building types, such as multifamily buildings and premises, offices and schools was found to be lacking both internationally and in the Nordic countries.

3.1.1 Water damage occurrence and costs data in Sweden

In Sweden, the availability of water damage statistics is strongly dependent on the home- and building insurance industry. One explanation for this is the over 20-year publication of the water damage report (Vattenskaderapport), published by Vattenskadecentrum [18]. The report has during the years increased in included water damage cases, as can be seen in Figure 6. The report does include detailed statistics of what the included water damage cases are caused by (shown as (—) in Figure 6), what room in the buildings the damage occurred (shown as (–●–) in Figure 7) in and how old the system or appliance was once the damage occurred. The increase in number of included water damage cases in the report started in 2017. However, the distribution of reported cases between pipe- and connections, appliances and waterproof membranes has not significantly changed. The percentage of reported cases of water damage in appliances, 28 % in 2022, has slightly increased over the period whilst the percentage of reported cases in the waterproof membrane, 13% in 2022, category decreased. With this increase in reported cases due to appliances the reported amount of water damage cases in kitchens has also increased and became the room with the largest percentage of reported water damage cases (35% in 2022) [20].

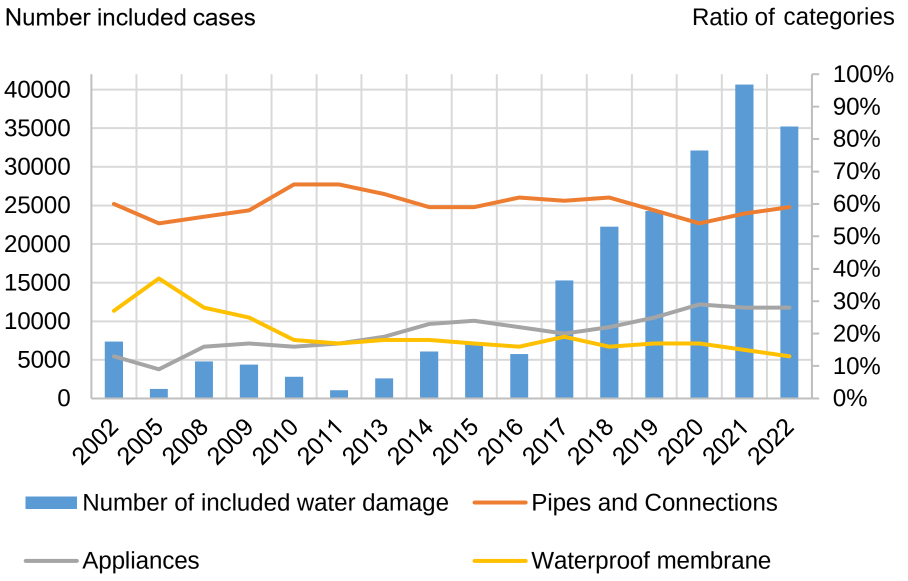

Figure 6. Left axis, number of included water damage cases in the water damage report from Vattenskadecentrum [20]. Right Axis, distribution of water damage causes (——).

From the data presented in Figure 6, it can be seen that the number of reports has increased significantly, starting from the year 2017. Water damage cases reported to occur from appliances is the category with and continuously increasing trend, which could be an effect of more water-connected equipment in rooms without waterproofing, such as kitchens [20]. The same trend can be found in Figure 7, where water damage cases in kitchens are the rooms with the most reported cases in single-family buildings.

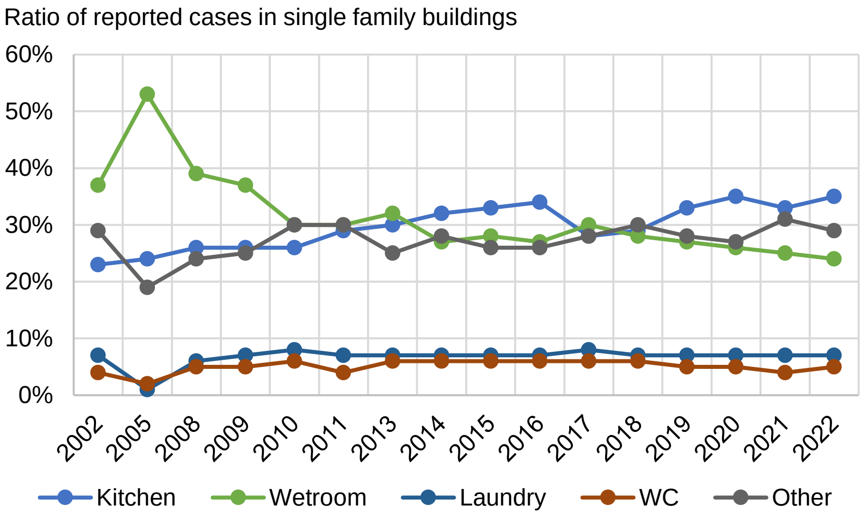

Figure 7. Distribution of reported water damage cases depending on different rooms in single-family buildings [20].

In 2022, the water damage cases that occurred in the pipe and connections category that was included in the water damage report, occurred in buildings with an age distribution of the different water distribution systems presented in Figure 8. The different service ages described indicate that there is a large amount of the water damage cases that occur early after installation. 43 % of the reported tap-water system related water damage cases did 2022 occur the first 10 years after installation. This trend can also be seen in the other categories and is similar to previous reports in the VASKA project.[43], where there is a large amount of water damage cases in the first 10 years and then a decrease until the end of expected service life is reached, often 50 years [44]. However, it is not preferable to have this distribution and findings from the literature review, [5], indicate that the problem is not isolated to Sweden.

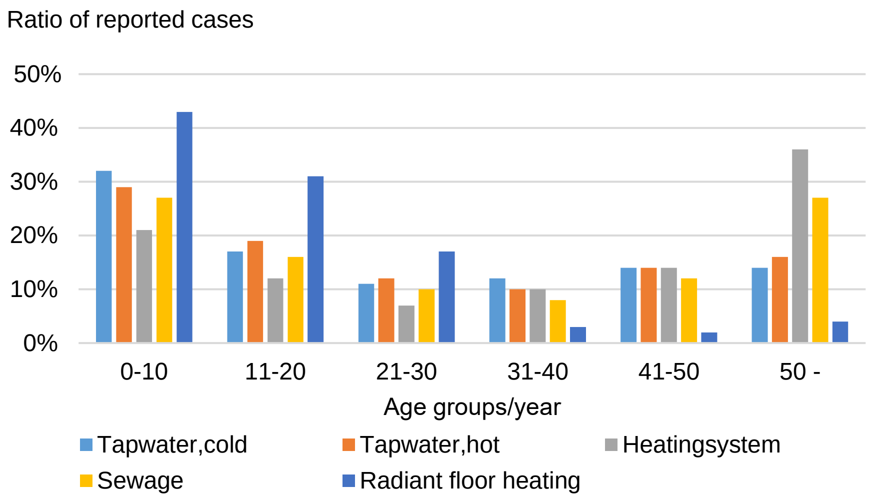

Figure 8. Age of pipe and connection systems when water damage occurred in 2022 is divided depending on the type of system. Each system divided in intervals of years after installation [20].

The number of reported cases, divided by insurance principle and total reported water damage cases, is presented in Figure 9. The reimbursed amount of the water damage cases is presented in Figure 10, divided into insurance principle and in total reported reimbursement for water damage cases. From the figures, it could be seen that the number of reported cases to the Swedish insurance industry has decreased in Sweden since 1985 but has increased since 2015. The reported reimbursements are also increasing but have been doing so since 1985, on average 2.0 % per year since 1985 [1].

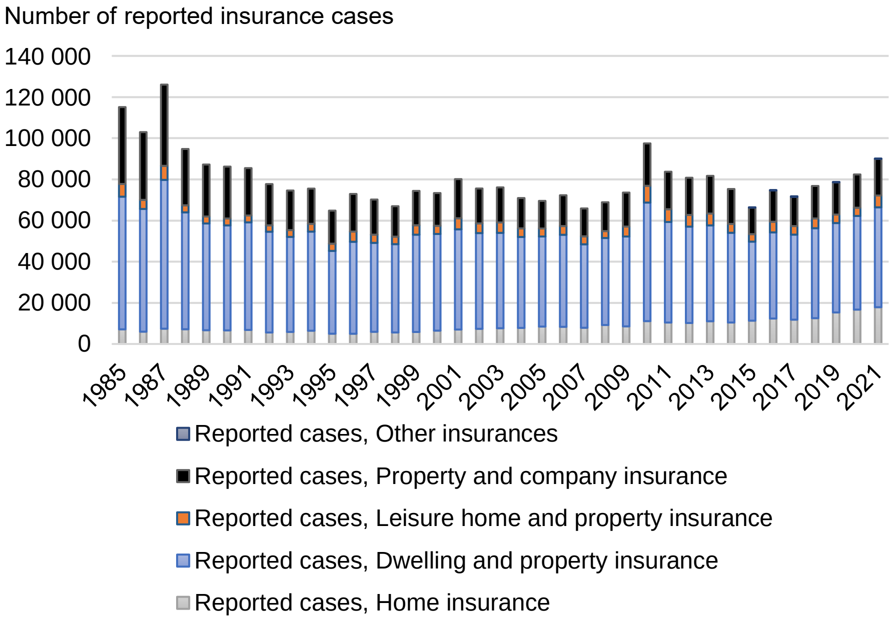

Figure 9. Number of reported water damage cases in Sweden to the included insurance companies in Svensk Försäkring [21].

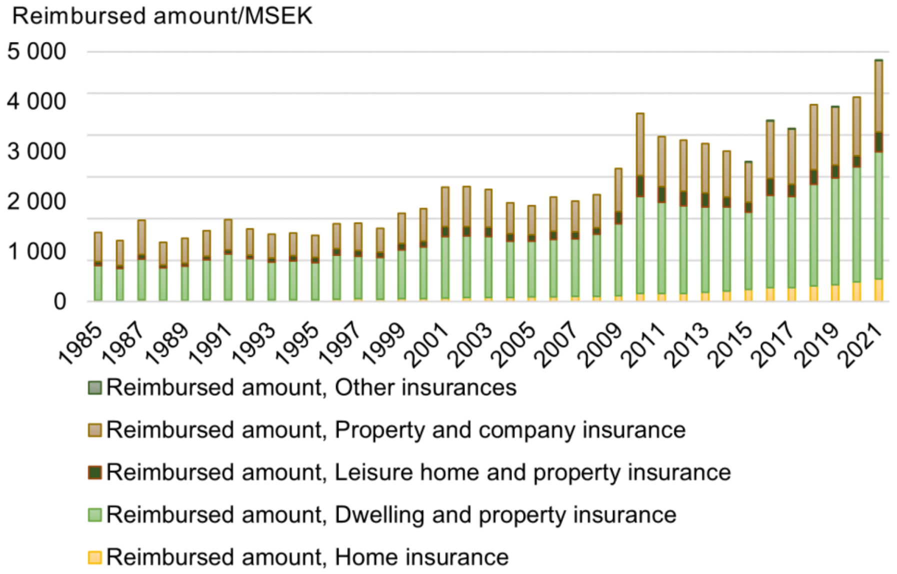

Figure 10. Reimbursed amount (MSEK) of reported water damage cases in Sweden to the included insurance companies in Svensk Försäkring [21]. The presented reimbursements are not adjusted for inflation.

In short, the reported amount of water damage-related cases by Svensk Försäkring [21] in 2022 was approximately 89 500 with reimbursement of approximately 4.97 billion SEK (425 million € as of mid-2023 [2]). Of which 35 000 of these cases were included in the detailed water damage report 2022, because of the level of detail in the damage reporting demanded to be included in the detailed report by Vattenskadecentrum [20]. In this detailed report of water damage in mostly single-family buildings the pipes and connections are the main cause of the occurring cases and appliances, such as refrigerators, freezers, and dishwashers have increased the most of the three damage categories. The increase in water damage cases in kitchens could be explained by the total increase but pipes and connections were however the largest categories of water damage in kitchens by 2022 [20], as can be seen in Figure 7.

Using these two statistical databases creates an overview of the causes and costs of water damage in Sweden for the buildings included in the report and the buildings covered by the insurance principles. The detailed water damage report (Vattenskaderapport) states that dwellings and leisure homes are the main sources on which the report is based upon, with approximately 35 000 reports included [20]. The reason for this is the reporting of water damage cases in other buildings, such as multi-family buildings and publicly owned buildings, is not carried out in the same system or is not reported to the insurance companies but is repaired or reimbursed by the building owner or managing company without the involvement of the insurance industry [20]. For buildings such as these, there are no statistic-gathering organizations such as Svensk Försäkring, which leads to a significant amount of uncertainty of occurrence and costs of water damage in other buildings than insured single-family buildings and those included in the statistics presented above. In order to determine the coverage of the water damage statistics in Sweden the building stock needs to be analyzed with regards to the empirical data that is gathered by the insurance industry.

3.1.2 The Swedish residential and nonresidential building stock

In total, the residential buildings in Sweden were estimated by Statistics Sweden [23] in 2022 at 5.16 million apartments divided by the building purposes in Table 8. The residential building stock distribution is presented in Figure 11.

Table 8. Number of residential apartments in Sweden divided into the form of tenure and building purpose [23]

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%

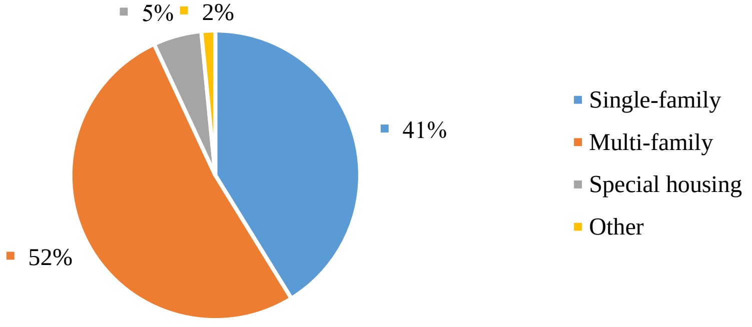

Figure 11. Distribution of residential buildings in Sweden 2022 [23].

In line with this distribution of the Swedish building stock and the data provided by the insurance companies and industry organizations, the water damage statistic coverage in Sweden could be estimated. The Swedish insurance industry reported in 2022 approximately 89 500 water damage cases from the insurance principles, home insurance, dwelling and property insurance, leisure home and property insurance, property and company insurance and other insurance principles. These reports of water damage are derived from the same statistical data as the water damage report is based upon and the same limitations apply, the data is derived from residential single-family buildings. So, the building types included in these statistics are single-family buildings and special housing with all the forms of tenures listed in Table 8, approximately 2.1 million apartments and 0.3 million in special housing. If estimated that these 2.1 and 0.3 million single-family apartments are covered by insurance and the damage cases that occur in these buildings are included in the data by Svensk Försäkring [1], Vattenskadecentrum [20] the number of apartments included in the water damage statistics could be estimated to be 47% of the Swedish residential building stock, by dividing the single-family apartments and special housing apartments (2.1 + 0.3 million) by the total number of residential buildings in Sweden (5.16 million).

The residential building stock divided per building year (the statistics do not include the special housing building purpose, hence the exclusion), is presented in Table 9 and Figure 12.

Table 9. The residential apartment stock´s age is divided into building purposes, excluding the special housing [23].

Building Year	Single-family	Multi-family	Other	Total
-1930	417 909	214 082	16 831	**648 822**
1931-1940	140 763	158 105	5 332	**304 200**
1941-1950	137 673	245 918	4 607	**388 198**
1951-1960	164 890	399 711	8 627	**573 228**
1961-1970	290 434	583 569	11 014	**885 017**
1971-1980	427 257	299 618	6 942	**733 817**
1981-1990	216 088	196 463	6 299	**418 850**
1991-2000	99 596	127 645	3 788	**231 029**
2001-2010	115 262	114 150	4 481	**233 893**
2011-2020	89 926	264 906	4 936	**359 768**
2021-	16 238	65 893	373	**82 504**
Not specified	9 233	5 209	6 385	**20 827§**
SUM	2 125 269	2 675 269	79 615	

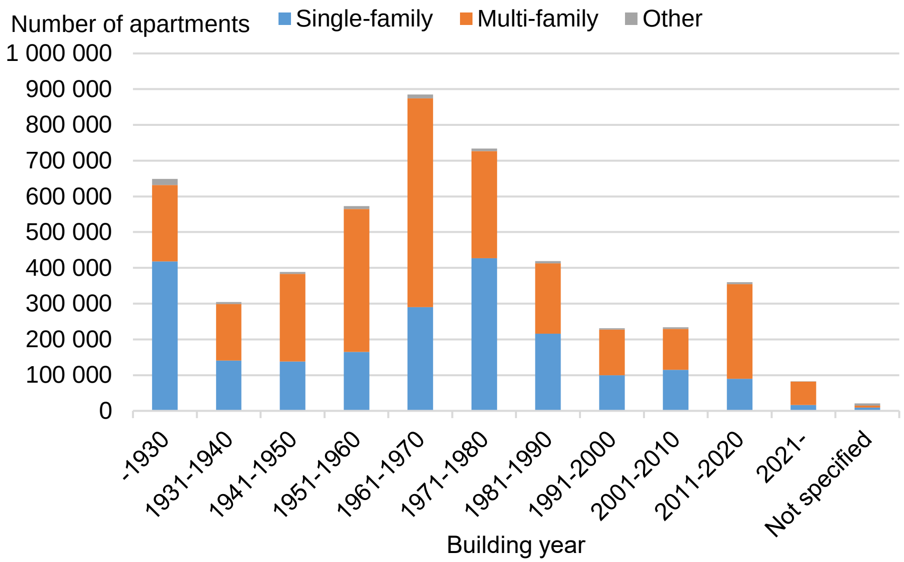

Figure 12. The residential building stock´s building age is divided into building purposes, excluding the special housing [23].

The building stock that is not intended and used for residential purposes such as public buildings, schools, offices, and culture is not included in the statistics presented above. The building stock of these nonresidential buildings consists of approximately 12 600 buildings with a distribution of building purposes described in Figure 13 and appended in Paper VI.

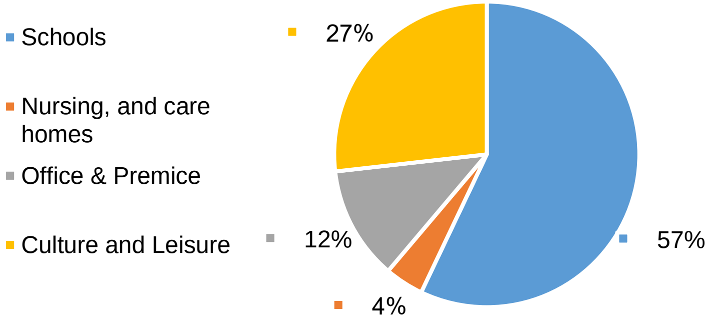

Figure 13. The distribution of non-residential Swedish public building stock is divided into 4 building categories [24].

3.1.3 International datasets

In the Nordic countries, Denmark and Norway, insurance companies have a similar role as the insurance companies in Sweden, the occurrence of damage and the reimbursement are reported, and annual statistics are presented in a national database. However, each country excludes and includes different causes of water damage. The Norwegian statistics publishing company Finans Norge categorized depending on the cause of the water damage, e.g., defective product, faulty design, wrongful installation, user fault, tear and age, corrosion, stop in sewages, and freezing [3]. The Danish water damage statistics publishing company Forsikring & Pension categorizes in a system based on the cause of the water damage, e.g., the water damage that originates due to hidden pipes and connections and water damage that originates due to other reasons than hidden pipes and connection and exterior influence [4].

In continental Europe, the issue of water damage in buildings, within the scope of this study, has been found in the literature review (paper I) in the form of scientific papers. The papers found, conducted in the UK, Spain and Italy, studied the effects of defects, water damage among others, in both inspection techniques to reduce energy losses [45], defects occurring because of design faults in the maintenance face of the building [40, 46, 47] and legal disputes after the fact of defects (water leakage included) [40]. Datasets of exclusively incorporated water damage in statistics, similar to the datasets found in the Nordic countries were not found. However, a report from 2012 from the German Insurance Association (GDV) [25] of costs and occurrence was found in Germany, with approximately 1 million tap water damage cases reported per year with a reported cost of 2 billion euros [25]. This indicates that the problem does occur outside of the Nordic countries and is causing damage but there is a gap in the scientific research concerning what resources and effects water damage in buildings is causing.

In the rest of the world, the literature review (paper I) found similar results as those for continental Europe, that defects and specifically water damage, in the scope of this study, are studied in the larger research field of building pathology. Several research papers were found concerning defects, where water damage occurring from leaking pipes, connections, or valves in the tap water, sewage, or heating systems was often a prominent cause. Water damage from inadequate waterproof membranes, and appliances such as dishwashers, and refrigerators were not found to be studied to the same extent. Finding of databases of statistics from insurance companies, corporations or governments were not found, except in the U.S where a comparison of leakages from inside/outside of the building structure was found. The percentage of leakages from outside the structure was shown to be frequently higher than leakages from inside the structure with approximately 2 - 3% annually, see Figure 14 [26]. In comparison Sweden where damage from water damage from outside the structure is only a fraction of the water damage that occurs from inside of the structure (In 2021 water damage inside the structure was approximately 90 000 and water damage that occurred due to factors from outside the structure was approximate 16 600 [1]).

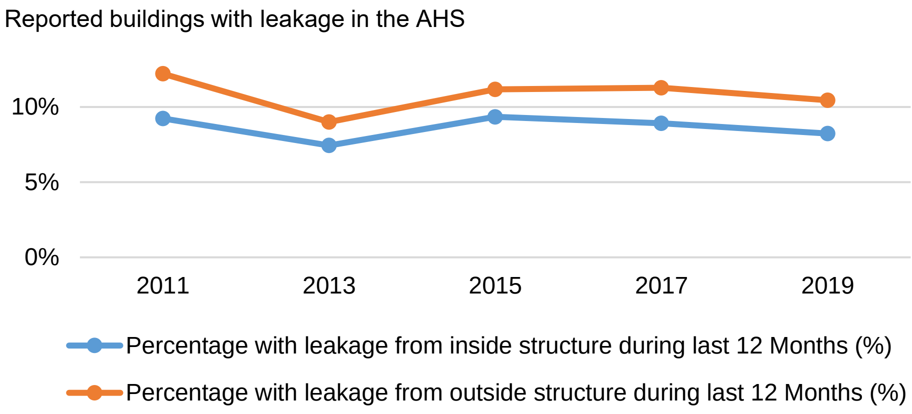

Figure 14. The amount of water leakage cases from inside and outside the structure reported in the American housing study (AHS) *U.S. Census Bureau [26]*.

3.2 Water damage associated costs (RQ II)

The associated costs of water damage in buildings occurring from leaking pipes, connections, appliances, and inadequate waterproof membranes were found to be such that occur from the repair, renovation, and restoration of the water-damaged material in the building and the costs associated with the insurance or the building owner depending on the building principle, see Table 10 for cost category and which stakeholder is responsible for the different costs. Besides these costs, described in Table 10, there are costs associated with living in buildings with higher levels of moisture, mold, or moisture problems. These costs, that could affect the resident/occupant, are such as health effects due to living or spending longer periods of time in a building with high levels of moisture [14-16]. In addition to these problems there could be other costs associated with moisture in homes that have not to date been associated with regards to water damage, some examples of this are reduced salary due to sick leave, medicine, hospital and medical expenses, reduced life quality, and temporary housing arrangements.

The different direct costs examined in this thesis are presented in Table 10 along with the stakeholder that is eligible to cover the amount required for the damage caused, these are usually the insurance company, the building owner/manager or the resident/occupant of the building or apartment.

Table 10. Different cost categories associated with water damage and the responsible stakeholders for the different costs.

Different cost categories	Insurance company	Building owner/manager	Building resi-dent/occupant
Reimbursement of damage	X	X	-
Insurance premiums	-	X	X
Deductible cost	-	-	X
Age reduction	-	-	X
Depreciation	-	-	X
Cost of repair (covered or not covered by insurance)	-	X	X

Insurance reimbursements paid by the insurance companies to cover the cost of water damage cases that occurred in insured residential buildings in Sweden, Denmark and Norway are presented in Table 11 together with the reported amount of occurred water damage cases in such buildings.

Table 11. Reported sum of water damage cases and reimbursement in insured single-family buildings in Sweden, Denmark and Norway.

	Sweden [1]	Denmark [4]	Norway [3]
Reported water damage cases	90 000	125 000	104 000
Reported reimbursement cost	420 000 000 €	360 000 000 €	510 000 000 €

Water damage that occurs in buildings with lower statistical coverage is still repaired and causes costs and other effects but, like other countries, the Nordic countries do not have a joint knowledge of the extent of this damage. Some examples of buildings with this lower statistical coverage are multi-family residential buildings and publicly owned and managed buildings. The costs in multi-family residential apartments were estimated using a report by Björk, et al. [19] where the repair cost for isolated water damage cases was assessed to the interval of 80 000 – 133 000 SEK (7 700 – 12 800 €) per water damage. Furthermore, the authors assessed a cost of 170 € per apartment and year for water damage in Sweden in the studied apartments. The study carried out (Paper III) in this project concluded that the costs for water damage per apartment and year were in the interval of 250 – 2700 SEK (24 – 260 €) for the 3 studied building managing companies, which included both tenancy and residential-owned apartments. Which for Sweden would result in an estimated annual cost for repairs of water damage, if the estimated costs of 170 € per year was used, within the scope of this project, to 421 million € per year for the 2.68 million apartments in the category multi-family apartments in Table 8.

In public-owned and managed buildings the estimate was based on data from 2017 – 2022 gathered in a large municipality in Sweden. The reported number of water damage cases during the studied years is presented in Figure 16 and the repair costs are presented in Figure 15.

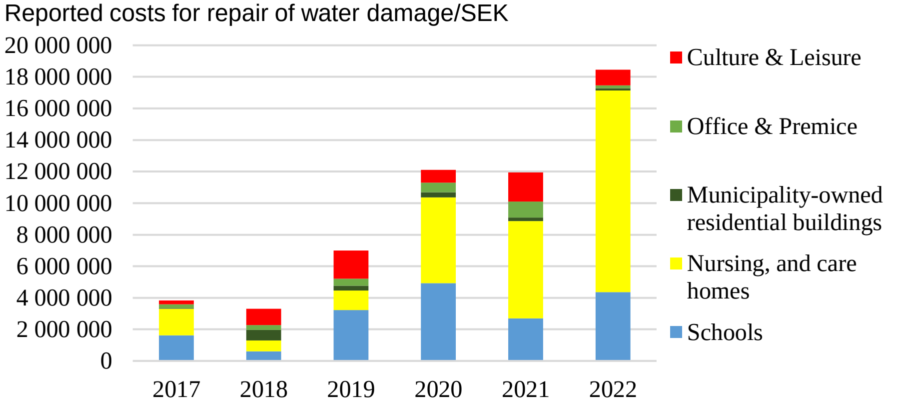

Figure 15. The studied municipality´s reported renovation/repair costs were divided into years and in 5 different categories.

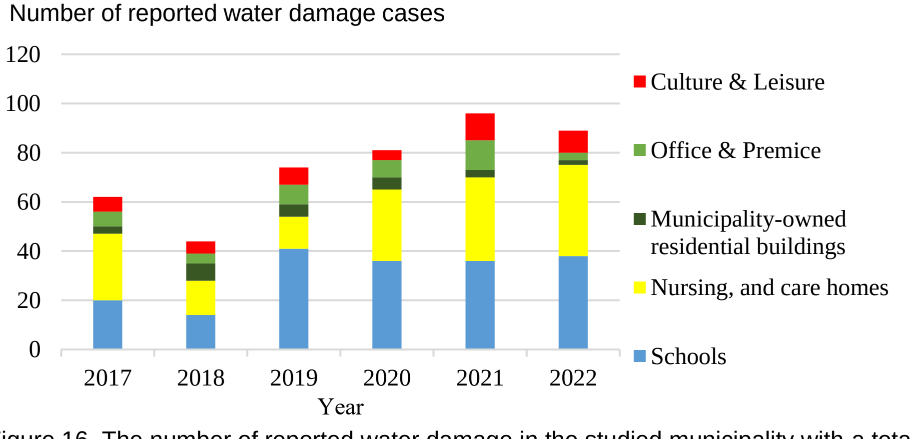

Figure 16. The number of reported water damage in the studied municipality with a total of 408 buildings in management.

The repair cost interval for a water damage in the studied municipality was established with the results presented in Table 12. It could be determined that the average repair costs in the studied municipality are significantly higher than for residential single-family buildings (49 000 SEK (4 450 € [2]) but often in the same range as the estimations of water damage repairs in multi-family buildings (80 000 – 133 000 SEK (7 700 – 12 800 €) [19, 37]).

Table 12. Estimated average repair costs per building category derived from the studied municipality.

Building category	Average repair cost per water damage (2017-2022)	Lowest annual average repair cost per water damage (2017-2022)	Highest annual average repair cost per water damage (2017 – 2022)
Schools	90 100 SEK (7 960 €)	35 700 SEK (3 140 €)	137 000 SEK (12 050 €)
Nursing, and Care homes	181 800 SEK (16 060 €)	49 500 SEK (4 360 €)	345 500 SEK (30 400 €)
Municipality-owned residential buildings	67 900 SEK (5 995 €)	11 700 SEK (1 030 €)	96 300 SEK (8 470 €)
Offices and Premises	70 400 SEK (5 920 €)	41 700 SEK (3 670 €)	87 700 SEK (7 720 €)
Culture and Leisure buildings	159 200 SEK (14 065 €)	40 600 SEK (3 580 €)	255 000 SEK (22 440 €)

These figures from the studied municipality were then extrapolated regarding the 12 626 public-owned nonresidential buildings in the real property register, schools, nursing and care homes, offices and premises and culture and leisure buildings, to 1.38 billion SEK (122 million €) per year in water damage repair costs. With regards to uncertainties and year-to-year variation, the estimation could vary in the span of 0.48 – 2.2 billion SEK (43 – 191 million €) per year. The costs per water damage in each building category in the studied municipality were estimated and presented in Table 12. These figures together with data on the non-residential building stock from the real property register in Sweden, see Figure 13. The different estimated water damage repair costs in non-residential buildings, divided into the different building categories, are presented in Figure 17 where the average repair cost is presented together with the estimated interval depending on year-to-year variation in the data gathered in the studied municipality.

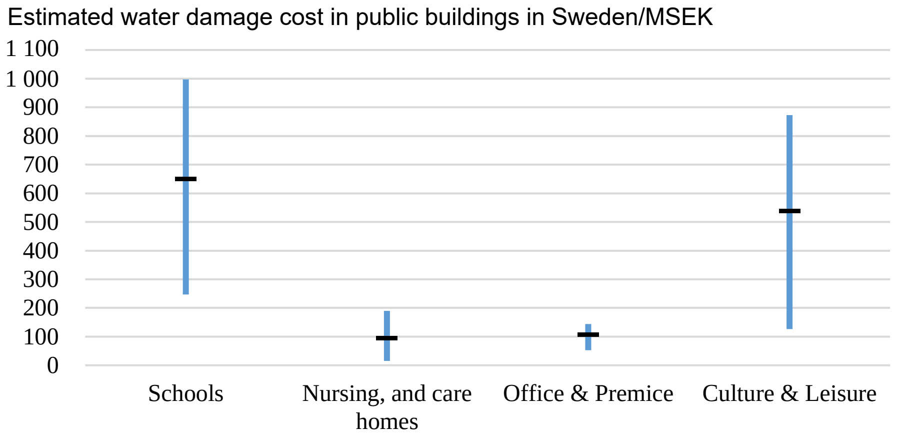

Figure 17. The estimated water damage repair cost in schools, nursing and care homes, offices and premises, and culture and leisure buildings, with the variation that could exist on an annual basis. (-) indicate the average estimated value.

The occurrence of water damage in public buildings in Sweden was estimated to occur in a total of 2 090 buildings per year with an annual variation in cases between 1 100 –2 840. The extrapolation was conducted using the Swedish building stock which consists of 12 626 buildings in the categories studied in the real property register and the number of buildings with reported water damage cases in the studied municipality, see Figure 16. The average is presented together with the estimated interval depending on year-to-year variation in the data gathered in the studied municipality, see Figure 18.

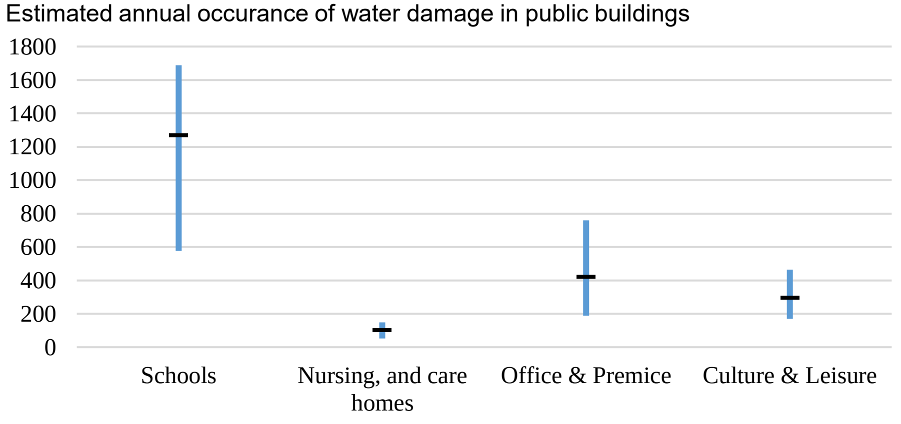

Figure 18. The estimated water damage occurrence in schools, nursing and care homes, offices and premises, and culture and leisure buildings, with the variation that could exist on an annual basis. (-) indicate the average estimated value.

The deductible, deprecation and the age reduction costs were estimated in appended Paper III and are summarized in Table 13. These costs do only occur in buildings covered by an insurance which cover the property and the dwelling, in this study single-family buildings. These costs were established from gathering of insurance policies in Sweden, to determine the cost per damage and then extrapolate with regards to the number of water damage cases reported that had a water damage reimbursed by an insurance company included in data by Svensk Försäkring [1]. In the study conducted based on data from 2020, 82 400 water damage cases were reported to the insurance companies, which was assumed to correspond for the amount of damage cases in the insured building stock.

Table 13. Estimated deductible cost, depreciation, and age reduction cost per damage in Sweden.

Deductible cost	**Depreciation and the age reduction**
332 – 965 € per damage	936 – 2 520 € per damage
59.8 million € in total per year	77.1 million € in total per year

In a demonstration of the differences in repair costs Björk, et al. [19] examined what a repair would cost in a wet room with different surface layers and in a kitchen. The study evaluated the cost of typical 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, the cost entails together with the material, transport, taxes, and installation consisting of replacing the waterproof membrane and the surface layers. The water damage that was studied that occurred in the kitchen was a leakage beneath the sink that arose from the tap water faucet. The repair consisted of replacing parts of the whole floor surface layer and parts of the supporting structure. Adding to these costs of a single water damage repair the average reimbursed amount from insurance companies in single-family buildings and the estimation of a water damage in a multi-family building, the repair cost was estimated to 80 000 – 133 000 SEK (7 000 – 11 770 €) by Björk, et al. [19] (106 500 SEK (9 500€) on average) [37], described in Table 14.

Table 14. Estimation of repair costs of water damage in different rooms [1, 19, 48]

Studied room for repair	Estimated repair cost
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 – Leakage from tap water faucet	2 700 (€ 30 500 SEK)
Other Spaces (average repair cost insured single-family buildings 2021)	4 300 € (49 000 SEK)
Multifamily buildings	9 500 € (106 500 SEK)

In summary, the total costs associated with water damage are in this study, using established key figures, water damage statistics and extrapolation to the studied building stock (insured single-family buildings, multi-family apartments, public-buildings, deductible costs and depreciation and age reduction for insured buildings) estimated to amount to 1,1 billion euros per year, detailed breakdown is presented in Table 15.

Table 15. Breakdown of estimated associated costs for water damage in Sweden 2021

Cost category	Estimated cost, million €/year (million SEK/year)
Repair, renovation or restoration costs	-
Single-family apartments	420 (4 820) [1]
Multi-family apartments	421 (4 850) [48]
Public buildings	122 (1 380) [49]
Deductible cost	59.8 (670) [48]
Depreciation and the age reduction	77.1 (872)[48]
Σ	1 100 (12 590)
Insurance premiums (Home, Dwelling and property insurance)	6 490 (73 370) [34]

3.3 Solutions to reduce the occurrence, costs and consequences of water damage (RQ III)

In this thesis 4 potential solutions to minimize the effects of water damage were examined, both measures that activity stops the flow of water when a leakage is noticed and measures that passively direct the flow to a more visible area to make the leakage visible to a resident. 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 passive 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. The studied measures in this thesis are presented in Table 16 and appended paper IV. In the table the investment costs including retail price, an installation by a contractor, and VAT, the way of indication of water leakage is carried out, the estimated occurrence of the damage which the measure is chosen to prevent (%) in buildings and the assigned costs category which the measure is chosen in this study to reduce depending on the damage cause and occurrence. The active and passive way of indicating a leakage is used to describe if the measure actively can stop a leakage if it is noticed by the measure. The passive indication way of a measure was meant to demonstrate that the measure only makes the leakage more noticeable to the resident/occupant. The measure is not designed to stop the flow of the leakage.

The estimated occurrence in buildings per year was estimated using the statistics from the water damage report by Vattenskadecentrum [20], where key figures were chosen to represent which damage cases that the studied measure could prevent. For the underlays was the damage cases that occurred due to 15% of the faulty appliances that were reported missing water-proof underlays (in 2021 701 cases). The water monitoring devices were assumed to be able to reduce and/or prevent the water damage that occurs due to faults in the tap-water system, both cold and hot water, both for the pipes, connections, which accounted for approximately 33% of the damage in 2021 in Sweden (12 285 cases). Water leak switches and water leak alarms were each 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 (11 386 cases). In using these figures and establishing the number of cases that could be reduced using a measure the estimated occurrence could be determined by dividing the number of cases that could be reduced with a measure with the total number of single-family buildings in Sweden (2.1 million, see Table 8).

Table 16. 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.

Studied measure	**Underlays (3 units)**	**Water monitoring devices (7 units)**	**Water leak switch (2 units)**	**Water leak alarms (8 units)**
Investment cost	300 SEK (27 USD)	10 500 SEK (930 USD)	4 700 SEK (420 USD)	460 SEK (41 USD)
Way of indicating leakage	Passive	Active	Active	Passive
Assumed water damage category that could be prevented (number of cases 2021)	Appliances without underlays (701 [18])	Tap-water (hot and cold) (12 285 [18])	Appliances (11 386 [18])	Appliances (11 386 [18])
Estimated occurrence of water damage in buildings per year	0.03% (1 out of 1225 dwellings in Sweden)	0.58% (1 out of 155 dwellings in Sweden)	0.54% (1 out of 185 dwellings in Sweden)	0.54% (1 out of 185 dwellings in Sweden)
Assigned cost category	Kitchens 30 500 SEK (2 700 USD) Other Spaces 49 000 SEK (4 400 USD) Multifamily buildings 106 500 SEK (9 500 USD)	Kitchens 30 500 SEK (2 700 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) Wet room with a plastic mat 60 000 SEK (5 300 USD)	Kitchens 30 500 SEK (2 700 USD) Other Spaces 49 000 SEK (4 400 USD) Multifamily buildings 106 500 SEK (9 500 USD)	Kitchens 30 500 SEK (2 700 USD) Other Spaces 49 000 SEK (4 400 USD) Multifamily buildings 106 500 SEK (9 500 USD)

With this data established the probable water damage cost per year without any measure taken could be estimated depending on the different measures, damage repair costs and the estimated occurrence of water damage per year. These estimated costs are presented in Table 17 and established using Equation 1.

Table 17. 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)	-	-

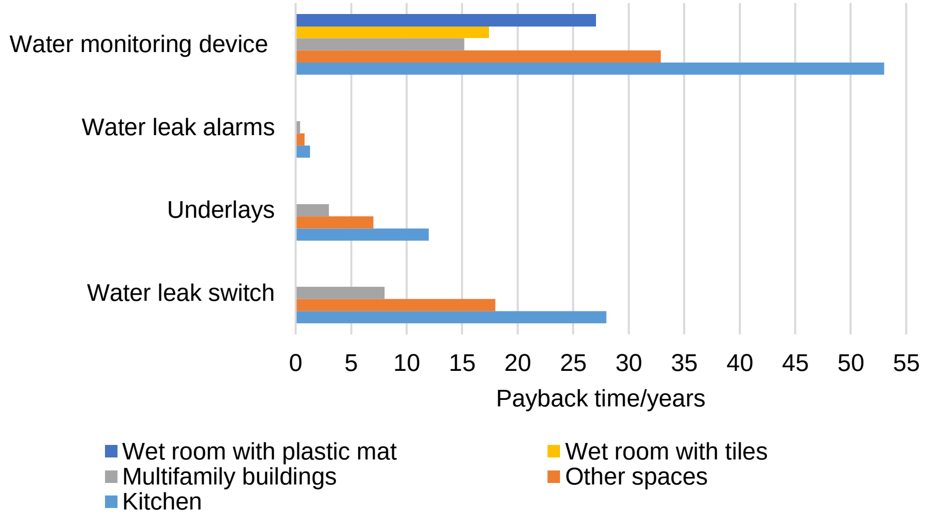

Figure 19. The estimated payback time of water monitoring devices, water leak alarms, underlays, and water leak switch investments is divided by the different water damage cost categories [37].

The payback times were estimated, using Equation 2, for different actions/measures, presented different intervals for the 4 studied actions/measures. 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. For water monitoring devices the expected payback time is an average of 30 years. Figure 19 presents the results from the study where 5 different expected cost scenarios are used presented previously in Table 14 (appended paper IV).

The study showed that water leak alarms had the shortest payback time, approximately 10 months after the installation, mostly because the action was estimated to reduce or prevent a higher number of cases the payback time was shorter. The combination of active and passive actions and measures could also be beneficial to study in more detail to evaluate how the different measures complement each other. Furthermore, to determine the potential to reduce water damage occurrence, cost and effects of actual practical tests over time would be beneficial to conduct. The method used in the study implies that a higher investment cost would lead to a longer payback time. If the start of the leakage and the time of the leakage detection, by the occupant, building manager, or the device, could be reduced, the cost and effects could most certainly be significantly reduced. This whilst a larger detection rate of leakage without any or little damage to the building would increase the occurrence of cases. Hence the costs and effects are important parameters to analyze.

To reduce the occurrence, cost and consequences of water damage cases this thesis studied the similarities, differences and tendencies in water damage reporting, statistics and documentation in 5 Nordic countries. This study, appended in paper V, resulted in key findings that could outline what is needed to be done to increase collaboration and learnings from each other. Some of the key findings were that the reporting of water damage occurrence and costs is conducted similarly, by the insurance industry, but there are differences in the categorization of damage causes and occurrence which contributes to less comparable statistics. The building regulations, codes, and insurance policies are similar and aim to reduce similar defects in the industry. The similarities in reimbursement cost per inhabitant can be seen in the studied countries, with an approximate cost of 31 – 94 € per inhabitant and year for water damage cases [27]. To conclude, the similarities and tendencies found regarding ongoing work to reduce the occurrence, costs and effects of water damage in the studied countries and the potential to further extend the cooperation between the countries, could potentially be beneficial in finding solutions to reduce water damage cases.

4 Additional parameter analysis and modeling of costs from different causes (RQ IV)

The following chapter presents an additional analysis of the results presented in this thesis. By presenting different parameters that could impact building owners, managers or operators' decision-making regarding preventing water damage occurrence, costs and consequences, this chapter demonstrates different causes and service life of systems. Making it possible to identify causes which consists of the largest part both in terms of number of water damage cases and repair costs for them and when to address them with regards to expected service age. Furthermore, this chapter outlines an estimation of repair costs allocated to the different reported and studied causes in the water damage report [18, 20], Vattenskadecentrum [36]. This estimation outlines causes that demand further solutions or implementing existing solutions to reduce the costs associated with water damage. This could add knowledge to the detailed water damage causes and occurrences that the water damage report examines.

4.1 Input parameters

The studied input parameters for the reported water damage causes are; age distribution of the reported water damage cases, the different causes of water damage reported in the report, and the occurrence divided in different rooms (kitchen, wet room and other areas in buildings) and costs established in this thesis.

4.1.1 Occurrence

The occurrence of water damage reported in the water damage report is divided into the 3-damage categories. In this thesis, this additional analysis presents the outline of which cases are reported in Sweden and adds the context of the known distribution of water damage cases occurring in insured buildings, it was further intended to act as guidelines for decision-makers when deciding on preventive actions to find effective solutions that could minimize the risk of water damage occurring and causing damage.

4.1.1.1 Pipe- and connection systems

Number of reported cases, presented in Figure 6, in the category, pipes and connections was reported to have a distribution of causes according to Figure 20 where the combined distribution of the causes from [18], Vattenskadecentrum [20], [36] between 2020 – 2022 is presented.

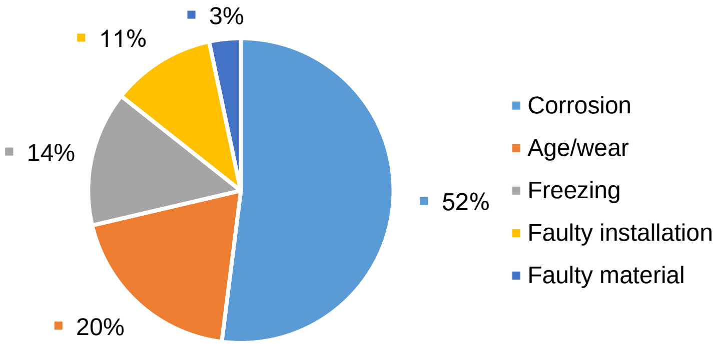

Figure 20. Distribution of water damage causes in the category pipes and connections between 2020 – 2022 [18, 20, 36].

Corrosion and age/wear consisted of 72% of the reported cases in the studied years.

4.1.1.2 Appliances

Number of reported cases, presented in Figure 6, in the category appliances were reported to have a distribution of causes according to Figure 21 Figure 20where the combined distribution of the causes from [18], Vattenskadecentrum [20], [36] between 2020 – 2022 is presented.

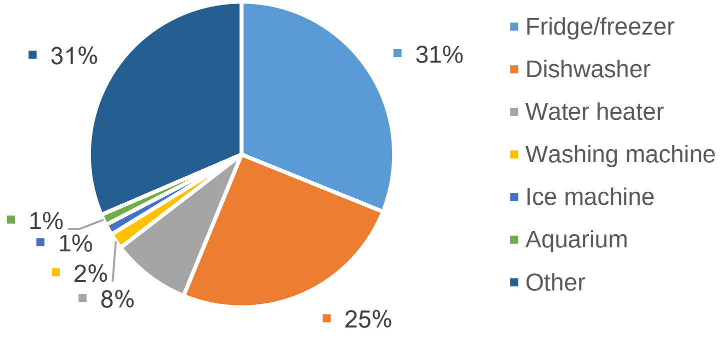

Figure 21. Distribution of water damage causes in the category appliances between 2020 – 2022 [18, 20, 36].

56 % of the reported water damage cases from appliances occurred due to faulty fridges/freezers or dishwashers.

4.1.1.3 Waterproof membrane

Number of reported cases, presented in Figure 6, in the category waterproof membrane was reported to have a distribution of causes according to Figure 22 and Figure 23 where the combined distribution of the causes from [18], Vattenskadecentrum [20], [36] between 2020 – 2022 is presented.

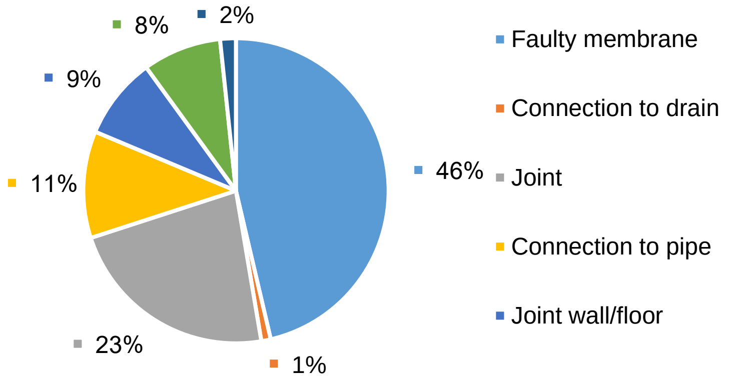

Figure 22. Distribution of water damage causes occurring from wall membranes between 2020 – 2022 [18, 20, 36].

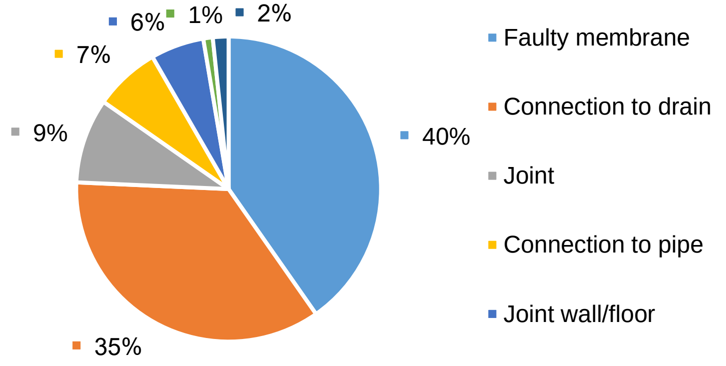

Figure 23. Distribution of water damage causes occurring from floor membranes between 2020 – 2022 [18, 20, 36].

Faulty membranes and the connection to the drain are the main cause of water damage occurring from waterproof membranes in floors, accounting for 75% of the reported cases. Faulty membranes and the joint between membranes are the main cause of water damage occurring from waterproof membranes in walls, accounting for 69% of the reported cases.

4.1.2 Age distribution

The age distribution of the reported cases is presented in the different damage categories, pipe- and connection systems, appliances and waterproof membranes.

4.1.2.1 Pipe- and connection systems

The age distribution of the reported cases in the water damage report within the damage category of pipe- and connection systems [18, 20, 36] is presented in Figure 24 - Figure 28. The average number of cases included in the report was 35 990 [18, 20, 36].

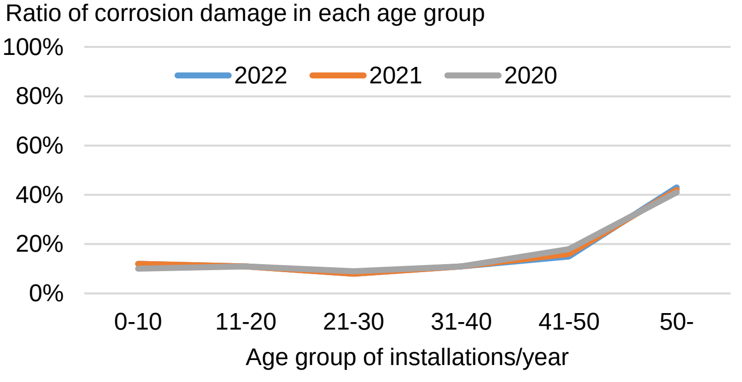

Figure 24 Age distribution of reported water damage cases that occurred because of corrosion summarized for 2020-2022 respectively [18, 20, 36]. (Corrosion accounted for approximately 29.4% of the reported cases 2020-2022)

From the age distribution of corrosion related damage cases it can be determined that there is an increase after approximately 40 years after installation, which could be expected, but important for building owners to acknowledge, when there is a large portion of the building stock in Sweden at or above the age of 40. This could be one explanation of why almost 30% of the reported cases have the cause of corrosion.

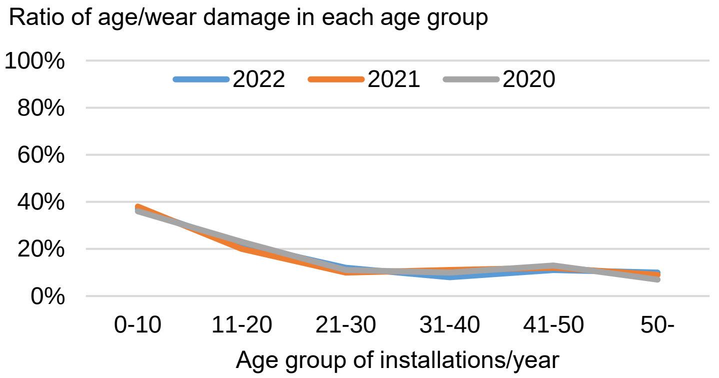

Figure 25. Age distribution of reported water damage cases that occurred because of age/wear summarized for 2020-2022 respectively [18, 20, 36]. (Age/wear accounted for approximately 10.9% of the reported cases 2020-2022)

The age/wear reported causes have an unexpected distribution of several cases reported to have causes where the service life of the product has been reached during the first 10 years after installation even though the service life of pipe and connections usually is longer than that if installed correctly, cold tap-water pipes between 90 – 200 years as example [44].

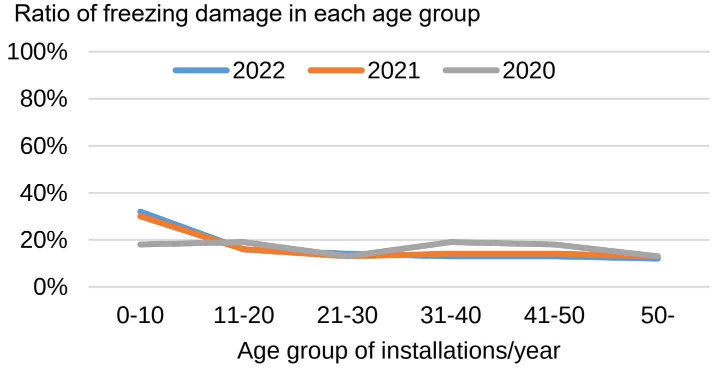

Figure 26. Age distribution of reported water damage cases that occurred because of freezing summarized for 2020-2022 respectively [18, 20, 36]. (Freezing damage accounted for approximately 8.3% of the reported cases 2020-2022)

Freezing damage does not have any outstanding result and as previously mentioned there is a correlation between how cold the climate is and the number of freezing-related damage cases [42]. Hence the age distribution could vary, and no conclusions could be drawn solely on the age distribution.

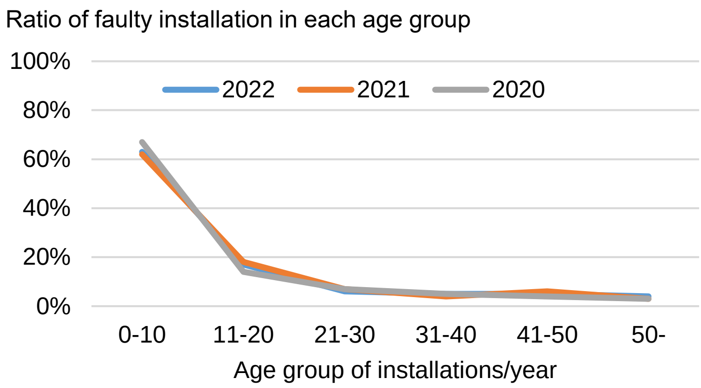

Figure 27. Age distribution of reported water damage cases that occurred because of faulty installation summarized for 2020-2022 respectively [18, 20, 36]. (Faulty installation accounted for approximately 6.2% of the reported cases 2020-2022)

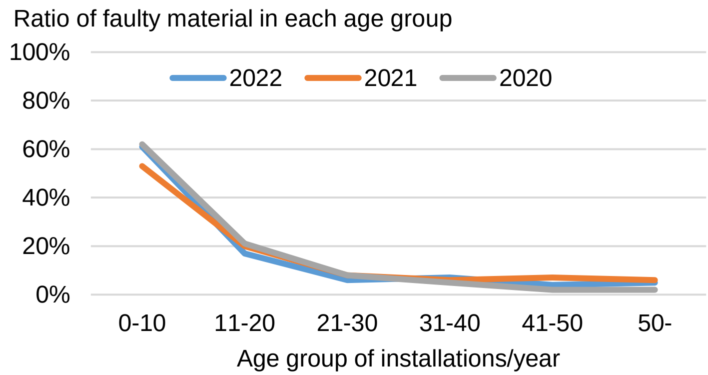

Figure 28. Age distribution of reported water damage cases that occurred because of faulty material summarized for 2020-2022 respectively [18, 20, 36]. (Faulty material accounted for approximately 1.9% of the reported cases 2020-2022)

The age distribution of faulty installation and material is as expected, to occur in the first 10 years after the installation, since if pipe and connections are not installed correctly and the material is faulty the designed purpose of the pipes and connections could not be expected to not cause a leakage. This could be faulty or damaged material that never should have been installed or installations where important parts of the system were not installed, for example sealant between connections and pipes.

4.1.2.2 Appliances

The age distribution of the reported cases in the water damage report within the damage category of appliances [18, 20, 36] is presented in Figure 29 - Figure 31.

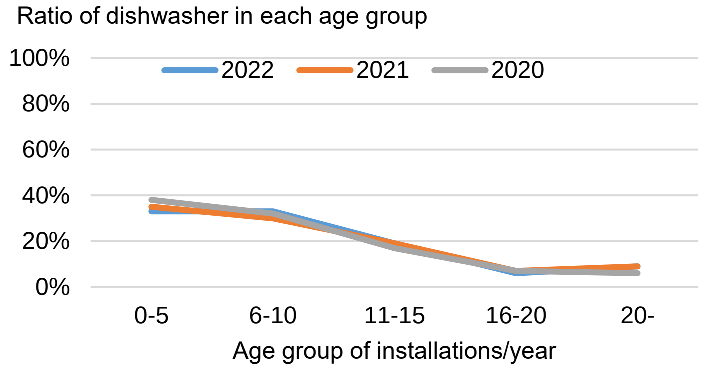

Figure 29. Age distribution of reported water damage cases that occurred because of dishwashers summarized for 2020-2022 respectively [18, 20, 36]. (Dishwasher accounted for approximately 7.1% of the reported cases 2020-2022)

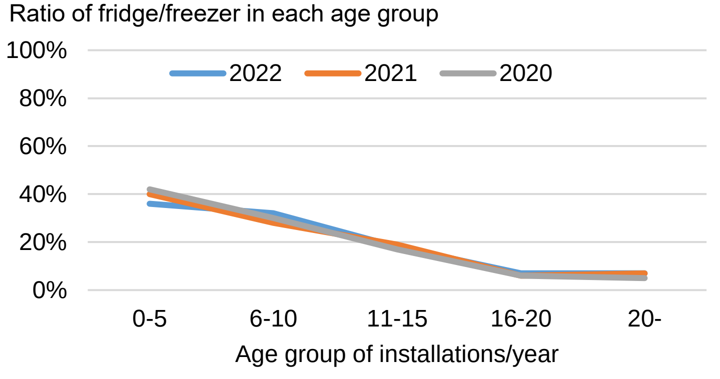

Figure 30. Age distribution of reported water damage cases that occurred because of refrigerators and freezers summarized for 2020-2022 respectively [18, 20, 36]. (Fridge/freezer accounted for approximately 8.8% of the reported cases 2020-2022)

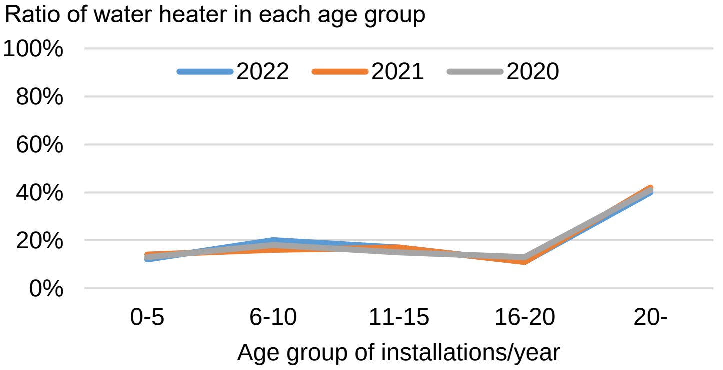

Figure 31. Age distribution of reported water damage cases that occurred because of water heaters summarized for 2020-2022 respectively [18, 20, 36]. (Water heater damage accounted for approximately 2.4% of the reported cases 2020-2022)

The age distribution reported for water damage cases that occurred because of faulty appliances indicates that dishwashers and fridges and freezers cause water damage often during the first 10 years after installation. This is a worrying trend regarding sustainability, but it also indicates that homeowners need to be aware of this and use the appliances according to the manufacturer's guidelines and follow industry rules to reduce the risk of water damage. Water heaters or heat pumps combined with a water heater show an age distribution of a more desirable outcome where most of the reported damage cases occur after 20 years of service life.

4.1.2.3 Waterproof membrane

The age distribution of the reported cases in the water damage report within the damage category of the waterproof membrane [18, 20, 36] is presented in Figure 32 and Figure 33. In difference to the other categories the age distribution for waterproof membranes is not presented in the detailed causes but depends on if the leakage occurred through a membrane on the floor or the wall.

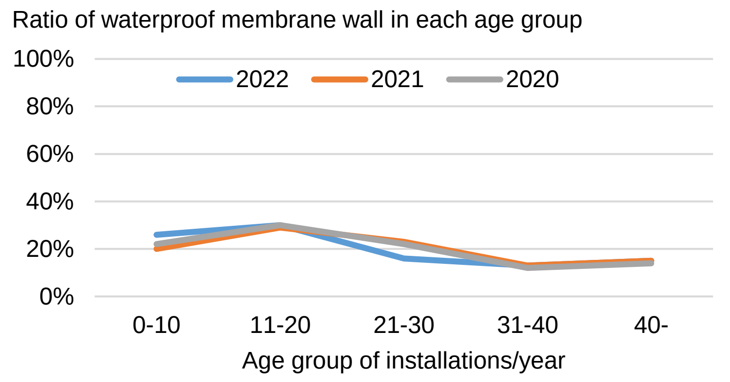

Figure 32. Age distribution of reported water damage cases that occurred because of water causing damage through the wall of waterproof membranes summarized for 2020-2022 respectively [18, 20, 36]. (Waterproof membrane, wall accounted for approximately 3% of the reported cases 2020-2022)

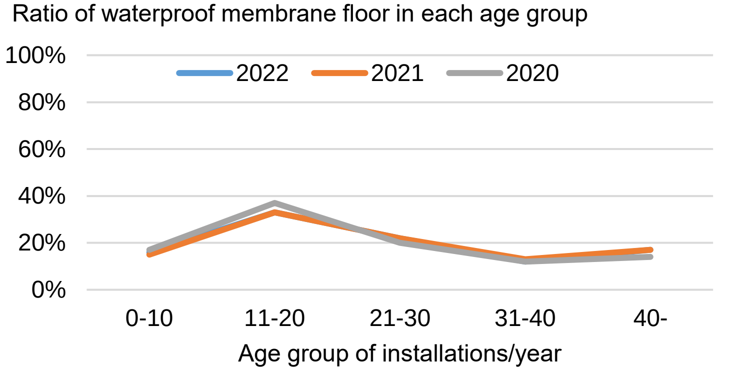

Figure 33. Age distribution of reported water damage cases that occurred because of water causing damage through the floor of waterproof membranes summarized for 2020-2022 respectively [18, 20, 36]. (Waterproof membrane, floor accounted for approximately 12% of the reported cases 2020-2022)

The waterproof membranes have a slight increase in reported damage cases during 11-20 years after installation, about 35-40 % for the floor membranes. Which could indicate that after this period of time the membranes need to be inspected, in areas where it's possible, connection to drain for example, to reduce the number of cases. However, the demand of waterproofing wet areas in Sweden started with industry rules in 1993 [50] which could indicate that it is these building, built after the introduction the rules, where water damage from the membranes are reported.

4.2 Modelling of water damage costs

The model of water damage repair costs in this thesis is presented below. Table 18 shows the estimated cost for pipe and connections presented along with the reported number of cases, per category and reported cases in total. Table 19 presents the appliances and Table 20 presents the waterproof membrane divided into wall- and floor-mounted membranes. Total estimated cost per year was estimated using the number of reported cases and the estimated cost of repair per damage, thus only costs for reported water damage cases are estimated in the total estimation, i.e. no extrapolation was conducted.

Table 18. Estimation of costs from the reported pipe and connection associated causes.

	Number of reported cases*	Reported cases per damage cate-gory**	Re-ported cases in total	Estimated cost of repair per damage	Total estimated costs per year (million SEK)
Pipe and Connections	**20 430**	**100%**	**57%**		**1 001 (88.5 M€)**
Corrosion	10 534	52%	29%	49 000 SEK (4 300 €)	516
Age/wear	3 897	19%	11%		191
Freezing	3 111	14%	8%		152
Faulty installation	2 216	11%	6%		109
Faulty material	671	3%	2%		33

*Calculated as an average of cases included in the [18, 20, 36].
**From Figure 20.

Table 19. Estimation of costs from reported appliances associated with causes.

	Number of re-ported cases*	Reported cases per category**	Reported cases in total	Estimated cost of repair per damage	Total estimated costs per year (million SEK)
Appliances	**10 185**	**100%**	**28%**		**310 (27 M€)**
Fridge/freezer	3 154	31%	9%	30 500 SEK (2 700 €)	96
Dishwasher	2 539	25%	7%		77
Water heater	848	8%	2%		26
Washing machine	166	2%	0%		5
Ice machine	116	1%	0%		4
Aquarium	116	1%	0%		4
Other	3 212	31%	9%		98

* Calculated as an average of cases included in the [18, 20, 36].
** From Figure 21

Table 20. Estimation of costs from reported waterproof membrane-associated causes

	Number of re-ported cases	Reported cases per category	Reported cases in total	Estimated cost of repair per damage	Total estimated costs per year (million SEK)
Waterproof membrane	**5 378**	**100%**	**15%**		**411 (36.4M€)**
Wall	**1 079**	**20%**	**3%**		**82**
Faulty membrane	499	46%	1%	76 500 SEK (6 800 €)	38
Connection to drains	11	1%	0%		1
Joint	242	23%	1%		19
Connection to pipes	122	11%	0%		9
Joint wall/floor	95	9%	0%		7
Fasteners	90	8%	0%		7
Mechanical infringement	19	2%	0%		1
Floor	**4 300**	**80%**	**12%**		**329 (29.1 M€)**
Faulty membrane	1 734	40%	**5%**	76 500 SEK (6 800 €)	133
Connection to drains	1 526	35%	**4%**		117
Joint	387	9%	1%		30
Connection to pipes	301	7%	1%		23
Joint wall/floor	242	6%	1%		18
Fasteners	43	1%	0%		3
Mechanical infringement	72	2%	0%		5

*Calculated as an average of cases included in the [18, 20, 36].
** From Figure 22 and Figure 23.

Table 18-20 and Figure 34 can be used as a supporting documents for different actors in the building sector, such as designers, contractors, building owners, building maintenance and operation personnel, inventors of technical solutions, when deciding on which actions to take and which causes to focus on when trying to prevent water damage cases from occurring. For some actors, the number of reported cases may be of interest, in finding new solutions where the cases are noticed or stopped before the repair cost amounts to the estimated average repair cost. For some actors, cases with the highest/high total costs can guide what actions are needed to reduce the total number of costs spent to repair water damage. These tables also added a view of the reported cases than the detailed water damage report by Vattenskadecentrum [20], where the repair cost distribution is presented and offers a different way of determining where the actions are needed to reduce both the occurrence, cost and effects of water damage. However, it is important to emphasize that this model is based on reported cases in Sweden, which is only a part of the building stock, namely single-family buildings. Once the estimation of costs associated with the causes the different causes could be compared against each other to determine which causes do cause the largest repair costs, see Figure 34. Furthermore, the relation between the reported amount of water damage cases and the estimated repair costs determined to find which causes in the water damage report is the costliest. In doing so, it demonstrated where solutions and actions should be taken to reduce the costs of water damage.

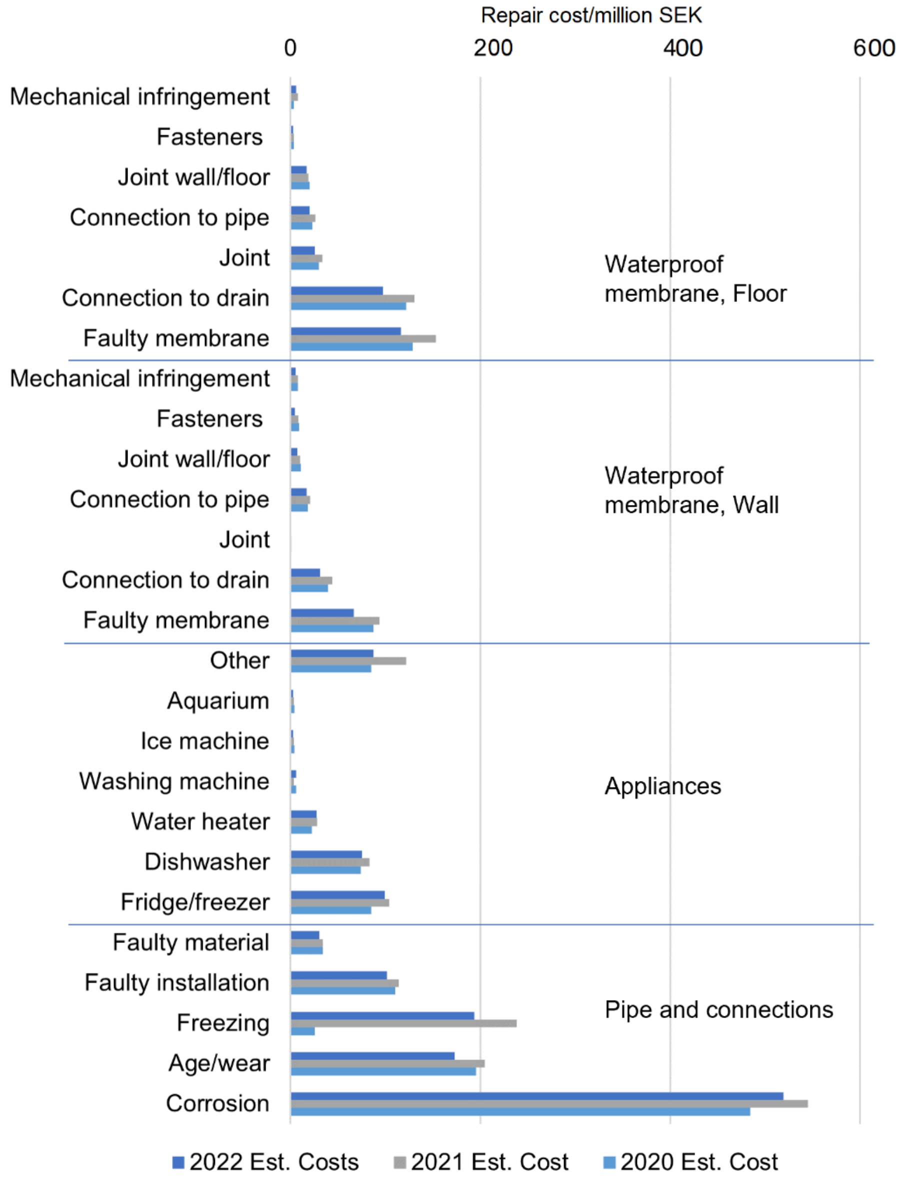

Figure 34. Summary of the estimated repair costs divided into causes and damage categories.

The relation between the number of reported water damage cases in the water damage report and the estimated costs is presented in Figure 35. From the figures, it could be determined that pipe and connections account on average, in the studied years (2020 – 2022), for 58% of the water damage cases and 57% of the estimated costs. Appliances account on average, in the studied years (2020 – 2022), for 28% of the water damage cases and 18% of the estimated costs. Waterproof membranes account on average, in the studied years (2020 – 2022), for 15% of the water damage cases and 24% of the estimated costs.

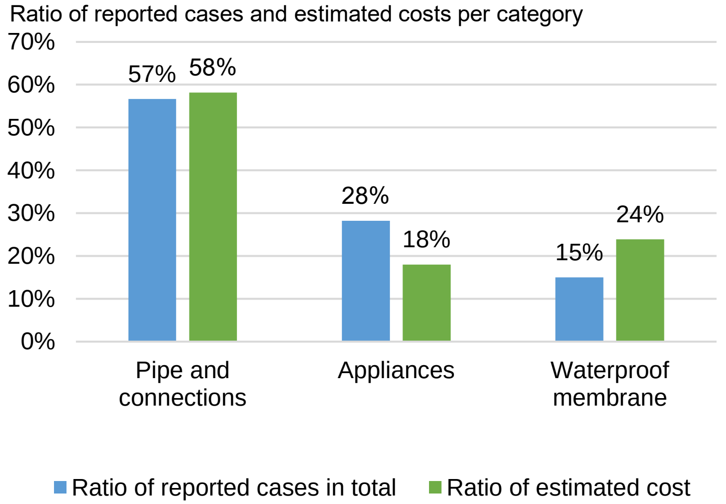

Figure 35. Comparison of the average percentage of reported cases in the water damage report and percentage of the estimated costs during 2020 and 2022.

This model presented above presents the significant repair costs that the different causes presented in the water damage report cause according to the repair cost estimations conducted in this thesis. Corrosion in pipes and connection is the costliest with an estimated repair cost of 516 million SEK (45.6 million €) per year. Followed by age/wear, freezing related causes in the pipe and connection systems but following these are the faulty membranes and connection to drains in the waterproof membranes in floors, which is significant because of the number of cases reported in these categories only accounted for 5 % and 4 % of the total reported damage cases whilst corrosion (29%) and damage caused in with high total estimated repair costs, such as waterproof membrane repairs, were reported to occur in higher frequency. Figure 35, demonstrates the difference in number of reported water damage cases, included in the water damage report, and the repair costs estimated in this study. The pipe and connection category are similar whilst the appliances have a significantly lower percentage of the estimated costs than the reported number of cases.

Waterproof membranes had the opposite results. This could be a result of the estimations made in the repair costs, but the results further highlight the importance of avoiding water damage that causes large costly repairs, for example repairing structures in wet rooms and restoring the water sealing and connections to drains in wet rooms with for example ceramic tiles. By implementing actions and measures to indicate and monitor the water systems and following government and industry rules and regulations, the costs could have the potential to be decreased. However, the cost of the repairs after a water damage cases needs to be further examined to fully determine what measures could be implemented.

5 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.

5.1 Literature and data

Water damage in buildings was demonstrated through the results of this thesis to be an international and national issue, causing severe effects and costs on buildings and the built- and indoor environment. Even though, in international research, it was found to be studied through the building pathology field including among other building defects, and not exclusively studied as in the Nordic countries, Sweden, Norway and Denmark. In these countries water damage that occurs from leaking pipes, connections, or valves in the tap water, sewage, or heating systems, from inadequate waterproof membranes, appliances such as dishwashers, and refrigerators to a large extent is studied as a single research topic [5]. However, in international studies, found in this thesis, in which defect analysis was conducted water damage or leaking pipes and connections was a frequent problem and water damage, as studied in this thesis, often was regarded as having a high level of impact on buildings and the built environment in counties other than the Nordic counties [5, 9, 39, 41, 51, 52].

In the analysis and search for datasets in which water damage occurrence, cost, and causes were documented, few sources were found. Estimations from Germany [25] and the U.S. [26] could be found where similar limitations as of this study applied, but no insurance data or other datasets were found that could be compared to the insurance data found in Sweden, Norway and Denmark. Thus, the estimations and results presented in this thesis were derived from the Swedish insurance and industry-gathered data and from cases in buildings in Sweden. Detailed data regarding water damage occurrence and causes in insured single-family buildings was gathered by the Swedish Water Damage Center, Vattenskadecentrum [20], and the reimbursement costs of the reported water damage cases in insured single-family buildings were gathered by the Swedish insurance industry company Svensk Försäkring [1]. This data is gathered from these two organizations and is compiled from insurance claims where water damage has occurred. Thus, the number of buildings included was expected to be large, the majority of insured homes and properties in Sweden, but no exact number of included homes and properties could be determined from the data sources, it´s only the number of reported insurance claims included. This number of insured buildings in Sweden is probably not shared by the insurance companies due to different regulations from the companies.

5.2 Water damage associated costs

The associated costs of water damage were further analyzed in this thesis, because of the limited amount of water damage-related costs that were found in the review. The documented costs determined before this study were the annual insurance reimbursements from the insurance companies to the homeowners with insurance, such as Svensk Försäkring [1] and estimations of key figures regarding costs for different water damage cases in multi-family buildings such as the figures presented by Björk, et al. [19]. The result of this thesis adds to these documented costs and presents an estimation of several costs and which stakeholder is eligible to cover the cost. It could be determined that the costs that aren´t included in the data often were the costs covered by the building owner or the resident. For example, the insurance premiums, the deductible costs, and the costs associated with living in a building with moisture problems other than the repair costs. It has also been shown to increase the risk of negative health effects [14-16]. The cost and effects of living in a building with a high level of moisture are not studied in this thesis but it is likely to be a significant cost to consider when conducting estimations of water damage associated costs. The associated costs studied in this thesis were estimated regarding both what repairs of water damage causes for costs in material and work and furthermore the insurance-related costs were examined.

The contribution to the field that this thesis presents is the holistic approach where costs in different buildings are studied and compared to each other. The holistic approach referenced in this thesis is an approach to includes and describe affecting and relevant factors, see Figure 1, and addresses some of these, regarding occurrence, cost and solutions to water damage, in the thesis. Furthermore, an estimation of the associated costs in the studied building stock was presented to amount to approximately 1,1 billion euros per year. This estimation was made with data gathered during 2020 to 2023. To be able to compare data from different years, which could fluctuate depending on factors such as a cold or a warm winter for example as examined in Mattsson, et al. [42], certain figures needed to be set over time. One figure that was estimated to be set was the average reimbursement for insured single-family buildings of 4 300 € (49 000 SEK). This estimation is relatively low compared to the figure

2022, see Figure 36. Thus, the estimation could be an underestimation of the actual water damage associated cost, not regarding parameters not studied which also would increase the estimated cost, such as health-related costs, construction delays, drying out moisture from water-damaged buildings, and sick leave.
Knowing that water damage cases, occurring from systems, installations and building services in buildings in the studied part of the building stock, are the insurance damage that causes the largest sum of reimbursements per year in Sweden, approximately 420 million €. Adding this analysis of additional buildings, multi-family- and non-residential public buildings, and associated costs, deductible, depreciation and age reduction, to this figure (1.1 billion € (12.6 billion SEK)) it becomes comparable in size to almost double the insurance reimbursements for nature-related damage cases in buildings during 2015 – 2022 in Sweden, such as flooding, rain and wind, which amounted to approximately during the period 620 million € (7 billion SEK) [53].

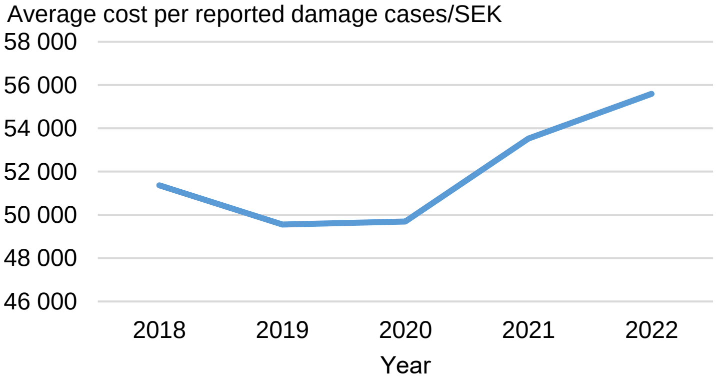

Figure 36. The average reported costs per water damage in Sweden [1].

5.3 Solutions to reduce the occurrence, cost and consequences of water damage

To reduce the occurrence, cost, and consequences of water damage in buildings it has been established throughout this thesis that measures must be taken to reduce the increasing trend of both occurrence and repair costs. Actions have been taken regarding building regulations, industry rules, and insurance policies both from the industry and from research contributions such as [5, 20, 35, 41]. However, few measures have been taken in the maintenance and operation phase. Therefore, some of the existing technical measures were studied regarding the economic payback potential the measures could have.

Implementing measures to reduce the risk and limit the possibility of water damage in existing buildings, the potential of reducing the overall number of water damage cases and associated costs could be large. In order to demonstrate the benefits of such measures this thesis conducted a payback analysis of 4 measures using empirical water damage data and estimated repair costs for different water damage cases. This demonstrated that the studied measures, water leak alarms, waterproof underlays, water leak switches, and water monitoring devices, separately had a payback time between 10 months and 30 years. Considering the service age of different pipe and connection systems, presented in Chapter 4, the reported water damage cases occurring from tap water systems were 43 % of the reported cases less than or 10 years old when the damage occurred. A similar trend could be found in water damage cases caused by appliances in kitchens where water damage cases occur from relatively new appliances.

The reported age distribution of the water damage cases occurring in Sweden, especially the large share of reported cases occurring in less than 10-year-old appliances, is notable. Relatively newly installed appliances, systems, components and material with a short service time could be expected to have the smallest share of reported damage cases, regarding the age distribution. The fact that it is the contrary must be acknowledged and addressed by actors in the building sector. Examining the reason for this shortfall is one important future research area. The reason behind this, whether it is caused by insufficient design, manufacturing, construction or inadequate material quality or other reasons must be identified to be able to address the problems and reduce the occurrence of water damage cases. Installing for example water monitoring devices that could reduce the damage and the possibility of it, in tap-water systems, several of the reported causes could have the potential to be reduced. Furthermore, the costly repairs that were estimated for each cause, (described in the Swedish water damage report [20]) a solution such as this could have an impact on both existing buildings and new buildings, dealing with corrosion, age/wear, and freezing but also faulty material. However, this solution is not the end of all problems, but it could together with other solutions be a part of the method of reducing the occurrence and costs of water damage. For example, the water damage that occurs because of appliances, more and more frequently occurring according to the industry [20], sewage, heating systems, and through inadequate waterproof membranes is not as affected by such devices because of the measuring of tap water flow which the device uses.

Instead, other solutions are needed, for example solutions presented in the studies regarding defect analysis. The solutions presented in these studies were structures and management in the planning, design, construction, maintenance, and operation phases aimed to improve the knowledge of water damage consequences to enable informed and guided decisions to be made [5, 9, 11, 39, 41, 42, 46, 54]. For these decisions to be made to such an extent that they are effective and actually decrease the impact of water damage consequences more research is needed regarding the holistic approach, which this study presented and used, even though there are more perspectives to study, for example, health effects from water damage regarding different water systems, effects of water damage, such as carbon emissions from the repairs of different damage cases.

By studying solutions, actions and measures that could contribute to increasing sustainability factors, such as economic, environmental, and social aspects, several different factors were found to be less researched upon. 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, faster 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 [14, 15], and in doing so improve the indoor air quality. By studying the environmental aspects of water damage even more factors could be added to the holistic approach needed to fully improve the built environment. Different repair strategies for repair or restoring buildings damaged by moisture or water could possibly be improved upon by implementing actions and strategies such as selective repairs of specific areas known to be damaged, which could decrease the usage of resources, such as material, energy and carbon emissions. Furthermore, a need for tools to assess the built environment was found, so that building owners can assess if they have structures, building services or installations coming to an end of their service life or where the age distribution of the reported damage cases, as presented in the model, chapter 4, of this thesis. Together with the estimated repair cost it could be used to motivate a preventive measure or inspection of the specific system to prevent future damage.

5.4 Additional analysis, model

The model presented in this thesis regarding the repair costs of the documented and reported water damage causes in Sweden was meant as an additional tool to assess the reported water damage cases. The model is intended to be used in combination with other parameters presented to create a holistic approach to water damage occurrence, cost, and consequences in buildings, even though all parameters presented in Figure 1 are not included in the results. The intended usage of the model is, based on existing knowledge of causes and new data of associated costs per water damage caused, in different building types, different building and installation ages, and for different stakeholders, to be used by different stakeholders during a building service life. Through the planning, design, construction, operation, and renovation/demolition phases of a building, the model and its parameters could be used to assess the risk, cost, and possible occurrence and cause of water damage. In doing so the determined lack of structures and informed guided decisions in the building phases, which were determined to be a part of the solution in reducing defects in the building sector [5], could be improved with more comprehensive data to use as a basis in decisions together with already established material to determine which building constructions/technology and risk constructions regarding water damage risk, associated costs and consequences to be avoided.

By using and presenting this model the number of water damage cases, its occurrence, cost and causes could possibly be decreased by demonstrating the factors and presenting important parameters regarding costs and occurrence. To increase the possibility that the results and data, presented in the model are used and implemented in the industry, which could be needed for actual decreasing figures, regarding cost and occurrence, tools, digital or industry regulations could be implemented where the data is included and accessible. For example, a digital twin of the buildings, including the current life span for all components, could possibly be an effective tool together with data on known and costly defects and damage cases, causes and risk for damage to occur. Such a digital tool could be used by both stakeholders actively and those with knowledge of the buildings and stakeholders without, such as residents. The inclusion of these actors could increase the knowledge of the systems and the risks that the systems could be facing just by knowing what systems the building has and what the risks of those systems are, according to the data both by the industry and by this thesis for example.

5.5 Data and limitations

The statistics of number of reported water damage cases in insured single-family buildings are established and have been conducted for a large share of the building stock, with the assumption that water damage cases, in terms of the reported causes of water damage, that occur in single-family buildings are likely to also occur in other buildings as well. The causes reported in single-family buildings were therefore used when assessing and analyzing actions to reduce the water damage cost, occurrence, and effects for the whole residential building stock. The assumption was made because the data on water damage occurrence, cause and costs in other types of buildings is limited. Whether this assumption is valid cannot be decided upon because of the limited available data and information in these other buildings. The conditions in other types of buildings may differ due to other types of usage, building design and technique which may affect the occurrence of water damage. However, this assumption was made because the data collected in the single-family buildings do have a large and established coverage of different damage types, causes and is documented to an extent that no other data, found in this thesis, is. The costs on the other hand are different depending on factors such as the structure of the building, whether the damage occurs in a room covered with a water-proof membrane and a floor drain or not, and depending on the design of the building [9, 19, 41, 43, 51, 55]. The repair cost of water damage repairs was found to be different in different kinds of buildings and rooms, for example, the public-owned and managed buildings and residential buildings. The estimation for a repair in a single-family building was estimated at 49 000 SEK (4 300 €), whilst the other building types were significantly higher, up to 80 000 – 133 000 SEK (7 700 – 12 800 €) for multi-family buildings. An explanation for this difference could be the comprehensive cost and occurrence data in insured single-family buildings that the industry in Sweden has, which could lead to a lower average repair cost estimation of such damage cases in relation to the less comprehensive estimations of water damage repair costs in other buildings. The estimation used for water damage repairs in multi-family buildings was derived from qualitative surveys with building owners, managers, and operators, such as [19]. Meaning not as a large basis for the estimations as the insured single-family buildings had. Thus, the estimation of what a repair entails in costs when occurring in a multi-family building is higher (80 000 – 133 000 SEK (7 700 – 12 800 €), however the repair cost in multi-family building could be higher. Because water damage in a single-family building only causes damage in one apartment and one structure whilst water damage in a multi-family building could affect several apartments and therefore cause larger and more costly repairs.

However, more research on the variation in costs is needed for example different causes, depending on the size of the apartment or the home (m^2). This would allow for more precise estimations regarding the total associated costs, however with the data accessible and studied in this thesis the estimations present new information to the field to use and regard when making decisions on renovation of existing buildings, what possible water damage causes could occur depending on the input parameters in the model, such as building age, likelihood of certain damage cases and estimated repair costs. Furthermore, the estimation of damage repair costs was derived from the databases in Sweden, from previous research, and quantitative methods to access information from the industry and the building owners. In using these methods data was collected from other sources, such as building owners, managers and operation companies (see appended paper III) and a municipality (appended paper VI), with experience and knowledge in the field. This was a strategy used to access other datasets with data gathered from established methods, such as the insurance industry. The insurance industry gathers data on water damage occurrence and causes from damage inspectors with knowledge and education to assess the causes of defects. Adding to this is the large number of single-family buildings included in the insurance industry´s data, if not accessed this large number of buildings would not have been possible to access and include in the study.

Finally, to reduce the occurrence, associated costs and consequences of water damage it is important to consider several different parameters; how a building, its components, and technical equipment should be designed, constructed, and operated to handle water leakages and how the buildings users, residents, and owners are operating and using the building to reduce the potential of water damage. Even though a building could be completely protected from water damage, it would be too expensive and could constrict and limit other functional demands. This is why a holistic approach is needed when considering what measures and actions could be used to reduce the occurrence, costs, and consequences of water damage considering different parts of the building process, from design to use over a whole lifecycle and interaction with all different stakeholders. Considering all of these aspects, there are data and information that could be used to further extent to reduce the effects and consequences of water damage but it could be implemented and integrated to reach and be used by more stakeholders in the building industry which could have the potential to improve the sustainability, regarding environmental, economic and social aspects, in the building industry, the built environment and the indoor environment. In doing so, the immense costs that annually are allocated to water damage could be reduced which could contribute to fewer repairs and the unnecessary use of resources in replacing and repairing damaged material with otherwise existing service life, which also could decrease the associated costs, decrease the moisture, and water levels in buildings and could have the potential to improve the sustainability in the building industry and sector. Resources that could be used in other areas rather than restoring/repairing water-damaged material, such as improving the indoor environment or reducing the carbon emissions in the sector.

6 Conclusions

The following chapter presents the conclusions from this thesis and the appended papers. Outlining the chapter are the concluding remarks on the research questions stated in the thesis with the overall aim of answering questions and providing research to reduce the water damage occurrence, and costs and finding sustainable solutions.

RQ I: - *To what extent do the existing international and national literature and statistical data on occurrence and costs describe the causes, consequences, and costs of water damage occurring in buildings due to leaking pipes, connections, appliances, and inadequate waterproof membranes?*

Water damage occurring in buildings has been included in the literature and there are statistical data on occurrence and costs but it´s often embedded in the larger field of building pathology and building defects. The statistical coverage of water damage occurrence, cost, and causes was found to a large extent to be gathered by insurance companies in Sweden, Norway and Denmark for insured single-family buildings. There was found to exist a gap in the research and statistics regarding the occurrence, cost, causes and consequences, of water damage cases occurring in residential buildings such as multifamily buildings and in non-residential buildings, such as schools and offices.

Sustainability factors, such as carbon emissions of the repair caused by water damage in buildings and moisture in homes and its consequences regarding water damage from different systems have not been comprehensively studied in the research identified in this thesis. Sustainable solutions, regarding environmental, economic, and social aspects, for water damage could potentially reduce costs and consequences for residents, building owners, and management and insurance companies, and reduce the climate impact of the building sector. More attention needs to be paid to the consequences and effects of water damage from various origins.

RQ II: - *What costs are associated with water damage occurring in buildings due to leaking pipes, connections, appliances, and inadequate waterproof membranes for different stakeholders?*

The costs associated with water damage regarded in this study were insured single-family buildings, multi-family apartments, public buildings, deductible costs, and depreciation and age reduction for insured buildings. These associated costs could be estimated to amount to 1,1 billion euros per year using established key figures derived from water damage statistics and using extrapolation of key figures regarding the studied building stock of Sweden, which included insured single-family buildings, multi-family residential buildings, non-residential buildings such as schools, offices, premises, culture and leisure buildings and nursing and care homes included in the real property register.

The studied associated cost did not include all the societal costs derived from higher moisture levels in buildings, such as sick leave, hospital costs, loss of income, and costs in delays due to time loss in drying out water damage cases in construction. The extensive costs however substantiate, especially considering the health impacts, that actions reducing the amount and costs of water damage must be given attention.

RQ III: - *What existing solutions could be used to reduce the occurrence, cost and consequences of water damage in buildings and what could the potential gain of such solutions regarding costs and occurrence of water damage be?*

Throughout the thesis, two types of solutions were introduced regarding the reduction of water damage occurrence, costs, and consequences. These were:

- Informed and guided decisions in the planning, design, construction, and management phases of the building. Together with organizational structures and industry guidelines to reduce and prevent defects and water damage cases in the early stage of the building and/or construction phase were found to be a part of the solution in the studied literature.

- Active and passive technical solutions that could be integrated into the water systems with the function of indicating, stopping, or directing leaking water where it could be stopped instead of damaging the building. The economic payback was evaluated with the results varying. For passive 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. Note that passive measures do not stop the flow of water without other actions, whilst active measures have the capacity of stopping the flow or water in case of a noticed leakage. Active 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. However, the payback time of these measures was only studied for each measure separately, if combined the payback and the effect of the solutions could possibly be improved.

Additionally, it was identified a need for data and information regarding water damage occurrence, cost and causes and parameters specific to a building, such as building systems, construction, building age, and building-specific installations and technology to be implemented in a system or a digital tool in which could be used in existing and new buildings where the user, manager, owner or operator could access and use the information together with the building specifics in order to actively comprehend and prevent, using established water damage knowledge and information. This could potentially have a large impact in reducing the occurrence, cost and consequences of water damage which addresses the holistic approaches suggested in this thesis.

RQ IV: - *How can parameters such as occurrence, costs and consequences of water damage in different buildings be modeled with the aim of reducing the amount and extent of water damage occurring in buildings due to leaking pipes, connections, appliances, and inadequate waterproof membranes?*

Finally, to answer the final research question regarding modeling the studied parameters to present an overview of different water damage causes, repair costs and age distribution of the reported water damage cases several different key figures were presented, alongside new data on what the reported water damage causes means in terms of repair costs. From the model, it could be concluded that the costliest repairs were water damage caused by the pipe and connections (58% of the estimated costs and 57 % of the reported cases), including corrosion, age/wear, and freezing. Followed by water damage cases reported to occur due to inadequate waterproof membranes (24% of the estimated costs but only 15% of the reported water damage cases), including faulty membranes and connection to drains in the waterproof membranes on floors. Appliances constitute (18% of the estimated costs but accounted for 28% of the reported water damage cases).

Together with this modeling of repair costs of reported water damage cases the age distribution was presented where it could be concluded that several of the reported water damage cases do show that water damage is frequently reported to occur during the first 10 years after installation, including age/wear, faulty installation, faulty material in the pipe and connections systems, dishwashers, fridges/freezers in the appliance category and wall and floor mounted waterproof membranes.

7 References

[1] Svensk Försäkring. "Inträffade skador för hushåll och företag." https://www.svenskforsakring.se/statistik/hem--villa-foretags--och-fastighetsforsakring/intraffade-skador-per-ar/ (accessed 2022-09-22, 2022).

[2] InforEuro. "Exchange rate (InforEuro)." European Commisson. https://ec.europa.eu/info/funding-tenders/procedures-guidelines-tenders/information-contractors-and-beneficiaries/exchange-rate-inforeuro_en (accessed 2023-04-19, 2023).

[3] Finans Norge. "Vannskadestatistikk (VASK),."Finans Norge. (accessed).

[4] Forsikring & Pension. "Vandskader, Udviklingen i antallet og erstatninger for vandskader." Insurance & Pension Denmark. (accessed.

[5] C. Mattsson, B. Nordquist, D. Johansson, P. Wallentén, and H. Bagge, "A quantitative and qualitative state-of-the-art literature review of water damage occurring from pipes, appliances, and wet rooms in buildings," 2023.

[6] C.-E. Hagentoft, *Introduction to building physics*. Lund: Studentlitteratur, 2001.

[7] IEA. "Buildings." IEA. https://www.iea.org/reports/buildings (accessed 2023).

[8] European Commission. "Buildings and construction." https://single-market-economy.ec.europa.eu/industry/sustainability/buildings-and-construction_en (accessed 2022-09-24.

[9] W. K. Chong and S. P. Low, "Latent building defects: Causes and design strategies to prevent them," (in English), *J. Perform. Constr. Facil.*, Article vol. 20, no. 3, pp. 213-221, Aug 2006, doi: 10.1061/(asce)0887-3828(2006)20:3(213).

[10] S. Lee, S. Lee, and J. Kim, "Evaluating the impact of defect risks in residential buildings at the occupancy phase," *Sustainability (Switzerland)*, Article vol. 10, no. 12, 2018, Art no. 4466, doi: 10.3390/su10124466.

[11] P. E. Josephson and Y. Hammarlund, "Causes and costs of defects in construction a study of seven building projects," *Automation in construction*, Article vol. 8, no. 6, pp. 681-687, 1999, doi: 10.1016/S0926-5805(98)00114-9.

[12] J. Arfvidsson, I. Samuelson, and L.-E. Harderup, *Fukthandbok: praktik och teori*. Halmstad: Bulls Graphics, 2017.

[13] B. Petrovic, T. Lindkvist, J. Pettersson, and J. Apel, "Klimatpåverkan från vattenskador i kök och badrum," Dalarnas försäkringsbolag,, 2022-6-16 2022.

[14] R. Becher, A. H. Høie, J. V. Bakke, S. B. Holøs, and J. Øvrevik, "Dampness and Moisture Problems in Norwegian Homes," *International Journal of Environmental Research and Public Health*, vol. 14, no. 10, 2017, doi: 10.3390/ijerph14101241.
[15] Institute of Medicine, *Damp Indoor Spaces and Health*. Washington, DC: The National Academies Press (in English), 2004, p. 368.
[16] W. J. Fisk, Q. Lei-Gomez, and M. J. Mendell, "Meta-analyses of the associations of respiratory health effects with dampness and mold in homes," presented at the Indoor Air, Aug, 2007.
[17] Folkhälsomyndigheten, "Miljöhälsorapport 2017," Folkhälsomyndigheten, folkhalsomyndigheten.se, 2017.
[18] Vattenskadecentrum, "Vattenskador i Sverige 2021," Vattenskadecentrum, 2022.
[19] F. Björk, H. Lind, R. Kling, and K.-E. Larsson, "Vattenskador på bostäder–omfattning och kostnader: Slutrapport av ett uppdrag från Boverket," Kungliga Tekniska högskolan, 2018.
[20] Vattenskadecentrum, "Vattenskador i Sverige 2022," Vattenskadecentrum.se, 2022.
[21] Svensk Försäkring. "Statistik om skador inom hushåll och företag." SAS Visual Analytics 7.5. (accessed).
[22] Statistics Sweden. "Bostadsbestånd." SCB. https://www.scb.se/hitta-statistik/statistik-efter-amne/boende-byggande-och-bebyggelse/bostadsbyggande-och-ombyggnad/bostadsbestand/#_Dokumentation (accessed 2023).
[23] Statistics Sweden. "Antal lägenheter efter region, hustyp och upplåtelseform (inklusive specialbostäder). År 1990 - 2020." SCB. https://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__BO__BO0104__BO0104D/BO0104T04/ (accessed 2022-01-19.
[24] Lantmäteriet. *Real Property Register* Lantmäteriet, 2022-04-18.
[25] Gesamtverband der Deutschen Versicherungswirtschaft e.V., "Kleines Leck, großer Schaden,
So schützen Sie sich vor Leitungswasserschäden," GVD.de, 2012.
[26] U.S government (2022). *American Housing Survey (AHS)*,. [Online] Available:https://www.census.gov/programs-surveys/ahs/data/interactive/ahstablecreator.html?s_areas=00000&s_year=2011&s_tablename=TABLE5&s_bygroup1=4&s_bygroup2=1&s_filtergroup1=1&s_filtergroup2=1&s_show=S
[27] Official Statistics of Sweden. "Population statistics." https://www.scb.se/be0101-en (accessed 2021-05-31, 2022).
[28] Dina Försäkringar. "Villa 2018." (accessed).
[29] Folksam. "Försäkringsvilkor Hem och Villa." (accessed).
[30] IF. "Hemförsäkring Försäkringsvillkor." (accessed).

[31] Länsförsäkringar, "Villkor för villahemförsäkring," 2021.
[32] Moderna Försäkringar. "Försäkringsvillkor för hem, villa och fritidshus." (accessed).
[33] Länsförsäkringar. "Vilkor för villaförsäkring." (accessed.
[34] Svensk Försäkring. *Försäkringsmarknaden*, Svensk försäkring, 2023-08-16, doi: https://statistik.svenskforsakring.se/SASVisualAnalyticsViewer/VisualAnalyticsViewer_guest.jsp?reportName=Innehåll%20Från%20A%20till%20Ö&reportPath=/SF/Extern&appSwitcherDisabled=true&reportViewOnly=true.
[35] Säker Vatten, "Branschregler: Säker Vatteninstallation 2021:1," Säker Vatten, 2020. [Online]. Available: https://www.roxx.se/v/yqtfn
[36] Vattenskadecentrum, "Vattenskador i Sverige 2020," Vattenskade centrum, 2021. [Online]. Available: http://www.vattenskade centrum.se/rapporter
[37] C. Mattsson, B. Nordquist, D. Johansson, H. Bagge, and P. Wallentén, "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," presented at the ASHRAE and SCANVAC HVAC Cold Climate Conference 2023, Anchorage, Alaska, USA, 2023.
[38] H. Abdul-Rahman, C. Wang, L. C. Wood, and Y. M. Khoo, "Defects in affordable housing projects in Klang valley, Malaysia," *J. Perform. Constr. Facil.*, Conference Paper vol. 28, no. 2, pp. 272-285, 2014, doi: 10.1061/(ASCE)CF.1943-5509.0000413.
[39] M. Y. L. Chew, "Defect analysis in wet areas of buildings," *Construction and Building Materials*, vol. 19, no. 3, pp. 165-173, 2005, doi: 10.1016/j.conbuildmat.2004.07.005.
[40] M. Sassu and A. De Falco, "Legal Disputes and Building Defects: Data from Tuscany," (in English), *J. Perform. Constr. Facil.*, Article vol. 28, no. 4, p. 8, Aug 2014, doi: 10.1061/(asce)cf.1943-5509.0000520.
[41] J. Yarnold, S. Banihashemi, C. Lemckert, and H. Golizadeh, "Building and construction quality: systematic literature review, thematic and gap analysis," (in English), *Int. J. Build. Pathol. Adapt.*, Review; Early Access p. 23, 2021, doi: 10.1108/ijbpa-05-2021-0072.
[42] C. Mattsson, B. Nordquist, D. Johansson, P. Wallentén, and H. Bagge, "Water damages in HVAC, tap water and sewage systems in cold climates," in *E3S Web of Conferences*, Estonia, 2021, vol. 246, 2021, doi: 10.1051/e3sconf/202124612001.
[43] J. Andersson and R. Kling, *Bygg vattenskadesäkert : VASKA visar vägen : ett beprövat sätt att spara pengar, hälsa och miljö*. Stockholm: Byggforskningsrådet, 2000.

[44] K. Stråby and L.-E. Fiskum, "Levetider for vann- og avløpsrør i bygninger," Sintef, 2021.
[45] M. H. Shariq and B. R. Hughes, "Revolutionising building inspection techniques to meet large-scale energy demands: A review of the state-of-the-art," *Renewable and Sustainable Energy Reviews,* Review vol. 130, 2020, Art no. 109979, doi: 10.1016/j.rser.2020.109979.
[46] N. Forcada, M. Macarulla, A. Fuertes, M. Casals, M. Gangolells, and X. Roca, "Influence of Building Type on Post-Handover Defects in Housing," *J. Perform. Constr. Facil.,* vol. 26, no. 4, pp. 433-440, 2012/08/01 2012, doi: 10.1061/(ASCE)CF.1943-5509.0000225.
[47] N. Forcada, M. Macarulla, M. Gangolells, M. Casals, A. Fuertes, and X. Roca, "Posthandover Housing Defects: Sources and Origins," *J. Perform. Constr. Facil.,* vol. 27, no. 6, pp. 756-762, 2013/12/01 2013, doi: 10.1061/(ASCE)CF.1943-5509.0000368.
[48] C. Mattsson, B. Nordquist, D. Johansson, H. Bagge, and P. Wallentén, "Cost performance analysis of water damages for sustainable prevention measures.," presented at the 17th International Conference of the International Society of Indoor Air Quality & Climate, Kuopio, Finland, 2022.
[49] C. Mattsson, B. Nordquist, D. Johansson, U. Janson, P. Wallentén, and H. Bagge, "Water damage occurrence and cost in public buildings in Sweden - a case study," 2023.
[50] (2007). *Byggkeramikrådets branschregler för våtrum*. [Online] Available: https://wwwbkrse.cdn.triggerfish.cloud/uploads/2015/10/branschregler2007.pdf
[51] A. Olanrewaju, Y. Y. Tan, and S. N. Soh, "Defect characterisations in the Malaysian affordable housing," (in English), *Int. J. Build. Pathol. Adapt.,* Article; Early Access p. 30, 2018, doi: 10.1108/ijbpa-11-2018-0095.
[52] E. Plebankiewicz and J. Malara, "Analysis of defects in residential buildings reported during the warranty period," *Applied Sciences (Switzerland),* Article vol. 10, no. 17, 2020, Art no. 6123, doi: 10.3390/app10176123.
[53] Svensk Försäkring. "Naturskador." https://www.svenskforsakring.se/statistik/hem--villa-foretags--och-fastighetsforsakring/naturskador/ (accessed 2022).
[54] F. Olubodun and T. Mole, "Evaluation of defect influencing factors in public housing in the UK," *Structural Survey,* vol. 17, no. 3, pp. 170-178, 1999, doi: 10.1108/02630809910291352.

[55] M. J. Carretero-Ayuso, A. Moreno-Cansado, and J. García-Sanz-Calcedo, "Occurrence of faults in water installations of residential buildings: An analysis based on user complaints," *Journal of Building Engineering*, vol. 27, p. 100958, 2020/01/01/ 2020, doi: https://doi.org/10.1016/j.jobe.2019.100958.

8 Appended papers

Paper I

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

Christian Mattsson[1*], *Birgitta* Nordquist[1], *Dennis* Johansson[1], *Hans* Bagge[2] *and Petter* Wallentén[2]
[1]Division of Building Services, Department of Building and Environmental Technology, Faculty of Engineering, Lund University, Box 118, 221 00, Lund, Sweden
[2]Division of Building Physics, Department of Building and Environmental Technology, Faculty of Engineering, Lund University, Box 118, 221 00, Lund, Sweden
*Corresponding author: christian.mattsson@hvac.lth.se

Abstract

Water damage affects both residents and buildings. Issues include moisture, repair costs, and climate impact. Research is needed to reduce and limit the extent and effects of water damage. This study aimed to determine the state of the art of the water damage field and find gaps in the research. Literature distribution, the status, consequences, effects, and the 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 proven as a part of the solution to reducing the amount and effect of defects and could effectively 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.

Introduction

Water damage in buildings occurs for many reasons. Some examples are flooding, water infiltration through the building envelope, often rainwater, and water vapor diffusion into walls and roofs. This paper is limited to water damage occurring indoors from leaking pipes, connections, or valves in the tap water, sewage or heating systems, inadequate waterproof membranes, and appliances such as dishwashers, refrigerators, or freezers in buildings. In Sweden, insurance companies in 2021 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 2021 amounted to 4.4 billion SEK (approximately 440 million Euro) in 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] In terms of reimbursements paid by insurance companies, water damage represented the largest cost in Sweden in 2021.[1] In Norway and Denmark, corresponding amounts of water damage and costs can be found, indicating that water damage is a problem across Nordic countries[4-6]. 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 [5-9]. 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's 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 the residents include 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 the water-damaged material.[17] Such consequences contradict the 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 4.4 billion SEK in 2021, 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 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 seems to be limited. Research results, experience, and outcomes from this research could also benefit the building industry.

To determine the state of the art of 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 industry) and those studied within the research community. Finally, the study aimed to further research that could support industry and the scientific community to find new methods and techniques for reducing the impact and consequences of water damage.

Method

The comprehensive examination of the field was undertaken through a state-of-the-art 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. The water damage included in this study originated from leaking pipes, connections, or valves in the tap water, sewage or heating systems. In addition, leakage from inadequate waterproof membranes in wet rooms was considered, as was leakage from appliances. Appliances are such 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. The review was conducted using both quantitative and qualitative analyses.

Quantitative analysis

The methodology used in the quantitative analysis follows the ten steps of a literature review described by Säfsten and Gustavsson.[20] They are:

(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 determine the state of the art of 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 the multiple searches. 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, e.g., "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[21], was also determined 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 through state-of-the-art theory and 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, Salehi [22], strong coverage of literature that dates back to 1990 written in English. Scopus, in contrast, offers a wider range of journals and literature.[22] 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 present time deemed to be more relevant.

The brief analysis of the relevant literature (6) was carried out by analyzing and scrutinizing the literature to determine the degree of relevance to the subject and in accordance with the aim of the paper. The 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, e.g., leaking pipes or connections from tap water, sewage, drainage, and heating systems, and inadequate waterproof membrane. 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 the found literature, also described as the analysis of the result and the content (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 percentage 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 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 analyzed 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 are 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), and Vattenskadecentrum (Water damage center). 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 that were developed for the study. These topics are commonly used in evaluating water damage and could be used to determine the state of the art of the field of water damage, allowing comparisons to be made and conclusions drawn.

- *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 damage 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 of the state of the art. 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 state of the art. 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 state-of-the-art 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 where the damage occurred, and column 5 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.

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*

Literature distribution

Figure 1 presents 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 increased, as did the number of relevant hits, in the later years, 2019 – 2021. There was also a large increase in the percent 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.

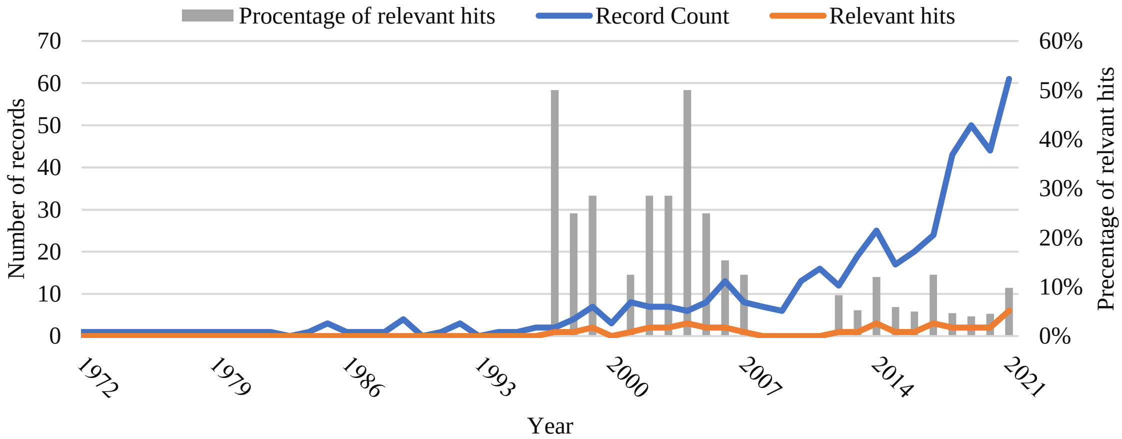

Figure 1. Number of records found and relevant hits in Web of Science and Scopus databases

The searches resulted in a total of 451 hits of which 39 were deemed relevant for the study and within the study's limitations. Web of Science resulted in 9 relevant hits out of 115, and Scopus resulted in 30 out of 336. The rate of relevant to non-relevant hits was from 7% to 9% in the individual databases and 8.6% when combining the search results. The keywords that generated the most relevant hits were defect*, build* and cost*, which gave rise to a large number of records that weren't relevant to this study, making the sifting to determine relevancy necessary.

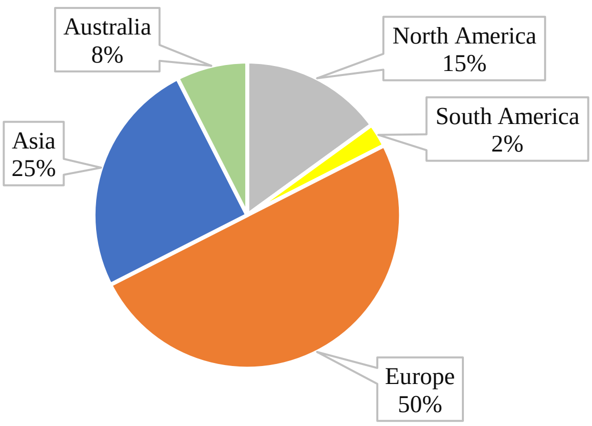

Figure 2. Geographical distribution of relevant records found in literature searches

Figure 2 presents the geographical distribution of relevant hits in terms of where they were published. The geographical distribution relative to the subject areas – construction defect analysis, automation in buildings, quality in construction, and moisture analysis – is presented in Figure 3.

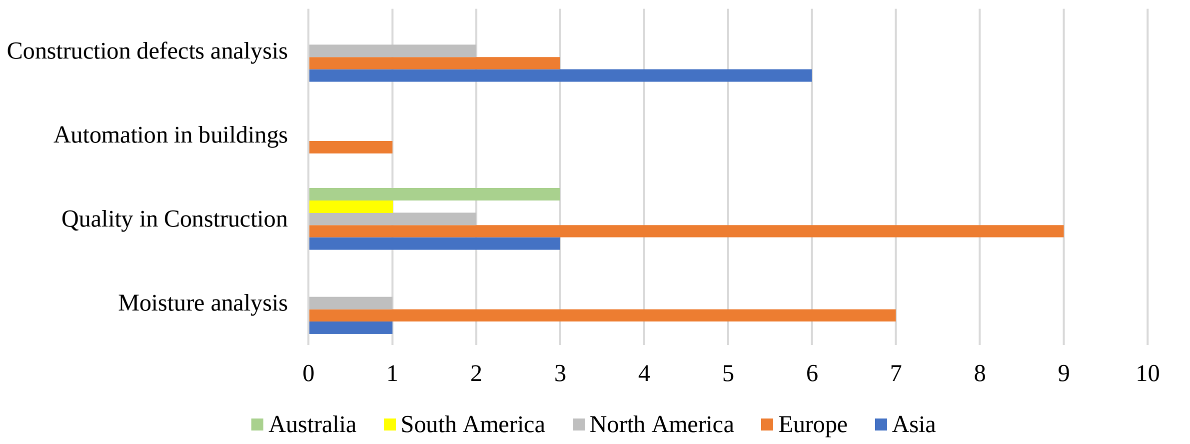

Figure 3. The geographical distribution of relevant records divided into the subject areas, construction defect analysis, automation in buildings, quality in construction, and moisture analysis

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 4 shows the distribution of these methods across the papers. Three publications types were also identified, namely conference paper, review and article. Figure 5 shows the percentages represented in the relevant hits.

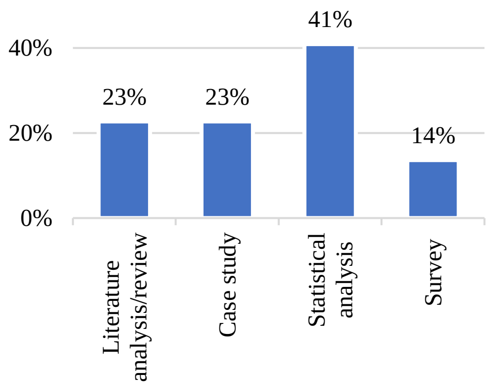

Figure 4. Literature distribution by method used

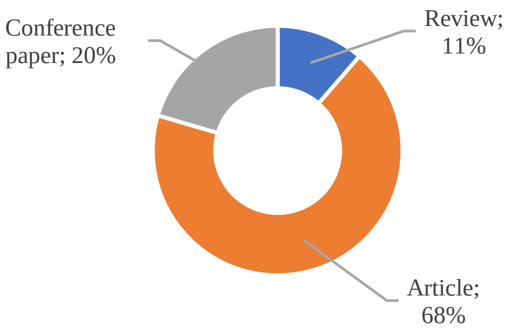

Figure 5. Literature distribution by publication type.

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 6.

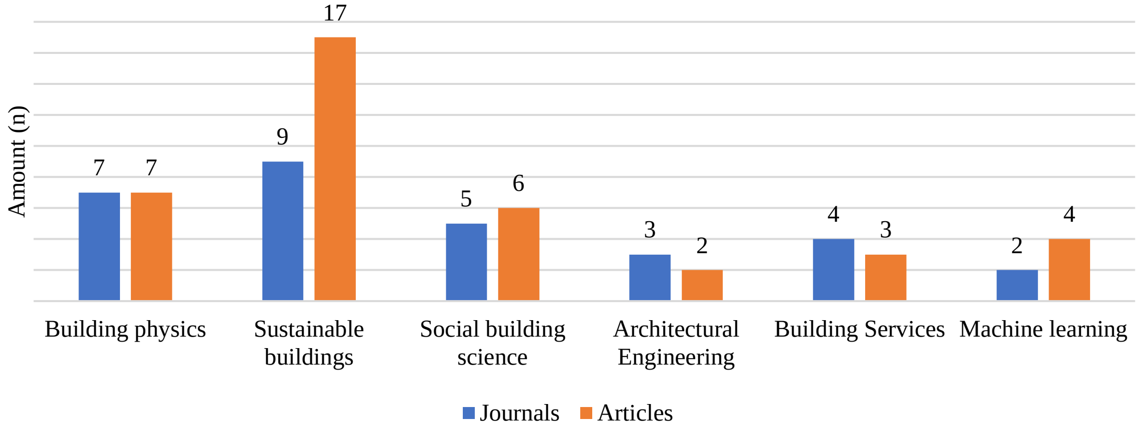

Figure 6. Scientific fields represented in the journals and the number of journals and articles in each field

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.

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, 23, 24]	101 (3)	Singapore	National University of Singapore
Forcada, Núria [13, 25, 26]	72 (3)	Spain	Universitat Politècnica de Catalunya
Low, Sui Pheng [27, 28]	195 (2)	Singapore	National University of Singapore
Lee, Sanghyo [29, 30]	49 (2)	South Korea	Hanyang University
Faqih, Faisal [31] Zayed, Tarek [31]	5 (1) 348 (1)	Hong Kong	Hong Kong Polytechnic University
Abdul-Rahman, Hamzah [11]	105 (1)	Malaysia	Universiti Malaya
Chong, Wai Kiong Oswald [27]	67 (1)	US	Arizona State University
Becher, Rune [15]	62 (1)	Norway	Norwegian Institute of Public Health
Josephson, Per Erik Bertil[32]	22 (1)	Sweden	Chalmers University of Technology
Lee, Sanghoon [29]	21 (1)	South Korea	Hanyang University
Morelli, Martin [33] Brandt, Erik [33]	15 (1) 18 (1)	Denmark	Aalborg University
Beasley, Kimball J.[34]	18 (1)	US	Wiss, Janney, Elstner Associates, Inc.
Hammarlund, Yngve [32]	7 (1)	Sweden	Chalmers University of Technology
Andersson, Johnny V. [35]	7 (1)	Sweden	Scandiaconsult International
Kaunisto, Tuija [36]	6 (1)	Finland	Satakunta University of Applied Sciences

Qualitative analysis

The qualitative analysis was conducted to determine the state of the art 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 that studies the status of the field is presented in Table 3.

Table 3. Studies that examine the cause of water damage 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" [24]	Survey	Asia
"Defect characterisations in the Malaysian affordable housing" [37]	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" [29]	Statistical analysis	Asia
"Evaluating the Impact of Defect Risks in Residential Buildings at the Occupancy Phase" [30]	Review	Asia
"Water seepage in multi-storey buildings" [38]	Review, statistical analysis	Asia
"Posthandover Housing Defects: Sources and Origins" [13]	Statistical analysis	Europe
"Assessment of construction defects in residential buildings in Spain" [26]	Statistical analysis	Europe
"*Analysis of Defects in Residential Buildings Reported during the Warranty Period*" [39]	Statistical analysis	Europe
"Causes and costs of defects in construction a study of seven building projects" [32]	Statistical analysis	Europe
"Evaluation of defect influencing factors in public housing in the UK" [40]	Survey, statistical analysis	Europe
"Water damages in HVAC, tap water, and sewage systems in cold climates"[4]	Review, statistical analysis	Europe
"Contemporary and traditional wall-system failures" [34]	Review	North America
"Latent building defects: Causes and design strategies to prevent them" [27]	Statistical analysis, review	North America
"Facility Defect and Cost Reduction by Incorporating Maintainability Knowledge Transfer Using Maintenance Management System Data" [41]	Review	North America
"Auditing the indirect consequences of rework in construction: a case based approach" [42]	Case study	Australia
"Building and construction quality: systematic literature review, thematic and gap analysis" [43]	Review	Asia, Australia, Europe, North America, South America

Residential buildings, e.g.,[12, 26, 30, 39, 44], and affordable housing e.g., [11, 37] are studied throughout the found literature, but defects and water damage in other buildings, such as offices, premises, or public buildings are not 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.[7] In Chew and De Silva [12], the quality of wet areas is studied, and conclusions are 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 e.g., [12, 23, 24 27, 33], 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,[7] there are only few such studies, and more attention should be paid in the future.

Causes that are prominent and frequently mentioned are building design and construction quality e.g., [11-13, 23, 24]. Abdul-Rahman, Wang [11] studied defects in affordable housing projects in Malaysia to identify, 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, Wang [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 [24] 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 is also mentioned in studies of high-rise residential buildings in Singapore.[12, 23] By assessing maintainability and the factors 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, Macarulla [13, 25, 26] 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 multi-family 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.”.[25] 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 concludes that there is a strong correlation between post-handover housing defects and workmanship, inspection/checking 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.[26] Statistics and data on 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.

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

Health	**Method used**	**Origin of the study**
"Dampness and Moisture Problems in Norwegian Homes" [15]	Statistical analysis	Europe
"Drying behaviour and microbial load after water damage" [45]	Statistical analysis	Europe
"Humid Buildings – The Construction Remedy" [46]	Case study	Europe
"Estimating effects of moisture damage repairs on students’ health—a long-term intervention study" [47]	Survey	Europe
“Meta-analysis of the associations of respiratory health effects with dampness and mold in homes” [48]	Statistical analysis, review	North America
Climate impact	**Method used**	**Origin of the study**
"Building rehabilitation versus demolition and new construction: Economic and environmental assessment" [49]	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" [50]	Survey, statistical analysis	South America
Costs	**Method used**	**Origin of the study**
"*A construction quality costs quantifying system for the building industry*"[28]	Case study	Asia, North America
“Facility Defect and Cost Reduction by Incorporating Maintainability Knowledge Transfer Using Maintenance Management System Data” [41]	Review	North America
"Auditing the indirect consequences of rework in construction: a case based approach" [42]	Case study	Australia
"Water damages in HVAC, tap water, and sewage systems in cold climates" [4]	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

The health aspects of moisture and its effects and consequences have been studied by Becher, Høie [15], Andersson [46], Fisk, Lei-Gomez [48], and Haverinen-Shaughnessy, Pekkanen [47], among 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.[48] Becher, Høie [15] concluded that crawl spaces, basements, in-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 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, e.g., sewage and heating water?

Studies that evaluated the climate impact of water damage were those by Alba-Rodríguez, Martínez-Rocamora [49] and Milion, Alves [50]; 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, Lindkvist [51] 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.[51] 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.[51] Notwithstanding these estimations, more research is needed to understand the climate impact of water damage in different kinds of buildings – such as dwellings, multifamily 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.[28] Also considered are the correlations between preventative maintenance, corrective maintenance, and emergency work [41], and the consequences in terms of cost of rework.[42] 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 e.g., [2, 5, 6, 52], but a holistic approach, one that covers multiple cost categories in different building types, such as multifamily building 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.

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

Solutions in the design phase	Method used	Origin of the study
"Performance of Lightweight Wet-Room Floor with Two Waterproof Membranes" [33]	Statistical analysis	Europe
"Latent building defects: Causes and design strategies to prevent them" [27]	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" [50]	Survey, statistical analysis	South America
Solutions in the construction phase	**Method used**	**Origin of the study**
"A formalism for utilization of sensor systems and integrated project models for active construction quality control" [53]	Case study	North America
"A comparative review of building component rating systems" [31]	Review	Asia
Solutions in the operation phase	**Method used**	**Origin of the study**
"Revolutionising building inspection techniques to meet large-scale energy demands: A review of the state-of-the-art" [54]	Review	Europe
"Use of a surface emissions trap for improving the indoor air quality by efficient exposure reduction" [55]	Case study	Europe
"Facility Defect and Cost Reduction by Incorporating Maintainability Knowledge Transfer Using Maintenance Management System Data" [41]	Review	North America

Design phase strategies and methods are the following: additional waterproofing and changing traditional building methods, as described by Morelli and Brandt [33]; moisture trapping zones and leakage-stopping systems to prevent leaks flowing into dry areas, as described by Chong and Low [27]; and methods to support the decision-makers in sustainable choices, described by Milion, Alves.[50] 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 [53] and methods for assessing building components during inspection.[31] In the operation phase, strategies and methods to prevent water damage are mapping the building structure to make water leakages and other defects visible[54] and designing buildings that allow and facilitate maintenance.[41]

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, such as [33, 53], that could be implemented in the design and operation phases. Studies of measures that actively stop water from flowing or indicate when leakage occurs and 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.[7] In the operation phase, usually the longest period of a building, it is the residents/occupants or building manager who are responsible for the building and its installations, services, and systems. However, in contrast to the designer and constructor, 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.

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 [27] and water leakage [24], 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 periods between 1997-2007 and 2017-2021 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. The number of relevant hits indicates that research on water damage was increasing during 2021, which could mean that both research and the occurrence of defects was increasing, but this is yet to be determined. 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 defect 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 the defects or the water damage on the 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, e.g., in Nordic countries [5-7], but additional research could have an impact on reducing the costs of water damage. Furthermore, the articles found in this study selected to represent the state of the art, reveal the field of water damage to be 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, e.g., [27, 31, 43], 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.

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 can be found in [46, 48] and examples of water damage affecting the building physics are recorded in.[24, 43] 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. 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, e.g., [56, 57]. 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, e.g.,[15, 16, 46, 48]. 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 buildings from leaking pipes, connections, or valves in the tap water, sewage or heating system, inadequate waterproof membranes, and appliances has been studied. 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 and reviewed using a state-of-the-art method 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 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 the 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, more attention needs to be paid to 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.

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.

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Note

Authors' contribution All authors contributed equally in the preparation of this manuscript.

References

1. Svensk Försäkring. Inträffade skador för hushåll och företag, https://www.svenskforsakring.se/statistik/hem--villa-foretags--och-fastighetsforsakring/intraffade-skador-per-ar/ (2022)

2. Svensk Försäkring. Statistik om skador inom hushåll och företag, (2022).

3. SCB. Bostadsbestånd, http://www.scb.se/bo0104 (2022).

4. Mattsson C, Nordquist B, Johansson D, et al. Water damages in HVAC, tap water and sewage systems in cold climates. In: *E3S Web of Conferences* Estonia, 2021.

5. Finans Norge. Vannskadestatistikk (VASK), (2022).

6. Forsikring & Pension. Vandskader, Udviklingen i antallet og erstatninger for vandskader., (2022).

7. Vattenskadecentrum. *Vattenskador i Sverige 2021*. 2022. Vattenskadecentrum.

8. Vattenskadecentrum. *Vattenskador i Sverige 2020*. 2021. Vattenskadecentrum.

9. Vattenskadecentrum. *Vattenskadeundersökningen 2019: Ledningssystem, utrustning, tätskikt, våtrum*. Vattenskadecentrum, 2020, p.23.

10. Sassu M and De Falco A. Legal Disputes and Building Defects: Data from Tuscany. *J Perform Constr Facil* 2014; 28: 8. Article. DOI: 10.1061/(asce)cf.1943-5509.0000520.

11. Abdul-Rahman H, Wang C, Wood LC, et al. Defects in Affordable Housing Projects in Klang Valley, Malaysia. *J Perform Constr Facil* 2014; 28: 272-285. DOI: 10.1061/(asce)cf.1943-5509.0000413.

12. Chew MYL and De Silva N. Factors Affecting Water-Tightness in Wet Areas of High-Rise Residential Buildings. *Architectural Science Review* 2002; 45: 375-383. DOI: 10.1080/00038628.2002.9696953.

13. Forcada N, Macarulla M, Gangolells M, et al. Posthandover Housing Defects: Sources and Origins. *J Perform Constr Facil* 2013; 27: 756-762. DOI: 10.1061/(ASCE)CF.1943-5509.0000368.

14. Strangfeld C and Klewe T. Hygrometric Moisture Measurements Based on Embedded Sensors to Determine the Mass of Moisture in Porous Building Materials and Layered Structures. 2021, p. 213-225.

15. Becher R, Høie AH, Bakke JV, et al. Dampness and Moisture Problems in Norwegian Homes. *International Journal of Environmental Research and Public Health* 2017; 14. DOI: 10.3390/ijerph14101241.

16. Institute of Medicine. *Damp Indoor Spaces and Health*. Washington, DC: The National Academies Press, 2004, p.368.

17. Karlsson A, Rattfelt A, Eerola P, et al. *Återbruksguiden för installationer*. 2022.

18. European Parliament CotEU. DIRECTIVE 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 May 2010 on the energy performance of buildings. *Official Journal of the European Union* 2010.

19. Nations U. Transforming our world: the 2030 Agenda for Sustainable Development. In: Assembly G, (ed.). United Nations, 2015.

20. Säfsten K and Gustavsson M. *Forskningsmetodik för ingenjörer och andra problemlösare*. Studentlitteratur AB, 2019, p.336.

21. Hagentoft C-E. *Introduction to building physics*. Lund: Studentlitteratur, 2001.

22. Aghaei Chadegani A, Salehi H, Md Yunus MM, et al. A comparison between two main academic literature collections: Web of science and scopus databases. *Asian Social Science* 2013; 9: 18-26. Article. DOI: 10.5539/ass.v9n5p18.

23. Chew MYL and De Silva N. Maintainability problems of wet areas in high-rise residential buildings. *Building Research and Information* 2003; 31: 60-69. Article.

24. Chew MYL. Defect analysis in wet areas of buildings. *Construction and Building Materials* 2005; 19: 165-173. DOI: 10.1016/j.conbuildmat.2004.07.005.

25. Forcada N, Macarulla M, Fuertes A, et al. Influence of Building Type on Post-Handover Defects in Housing. *J Perform Constr Facil* 2012; 26: 433-440. DOI: 10.1061/(ASCE)CF.1943-5509.0000225.

26. Forcada N, MacArulla M, Gangolells M, et al. Assessment of construction defects in residential buildings in Spain. *Building Research and Information* 2014; 42: 629-640. Article. DOI: 10.1080/09613218.2014.922266.

27. Chong WK and Low SP. Latent building defects: Causes and design strategies to prevent them. *J Perform Constr Facil* 2006; 20: 213-221. Article. DOI: 10.1061/(asce)0887-3828(2006)20:3(213).

28. Low SP and Yeo HKC. A construction quality costs quantifying system for the building industry. *International Journal of Quality and Reliability Management* 1998; 15: 329-349. Article. DOI: 10.1108/02656719810198926.

29. Kim B, Ahn Y and Lee S. LDA-based model for defect management in residential buildings. *Sustainability (Switzerland)* 2019; 11. Article. DOI: 10.3390/SU11247201.

30. Lee S, Lee S and Kim J. Evaluating the impact of defect risks in residential buildings at the occupancy phase. *Sustainability (Switzerland)* 2018; 10. Article. DOI: 10.3390/su10124466.

31. Faqih F and Zayed T. A comparative review of building component rating systems. *Journal of Building Engineering* 2021; 33. Review. DOI: 10.1016/j.jobe.2020.101588.

32. Josephson PE and Hammarlund Y. Causes and costs of defects in construction a study of seven building projects. *Automation in construction* 1999; 8: 681-687. Article. DOI: 10.1016/S0926-5805(98)00114-9.

33. Morelli M and Brandt E. Performance of Lightweight Wet-Room Floor with Two Waterproof Membranes. *Journal of Architectural Engineering* 2019; 25. DOI: 10.1061/(asce)ae.1943-5568.0000363.

34. Beasley KJ. Contemporary and traditional wall-system failures. *J Perform Constr Facil* 2001; 15: 42-45. Article. DOI: 10.1061/(ASCE)0887-3828(2001)15:2(42).

35. Andersson J and Kling R. *Bygg vattenskadesäkert : VASKA visar vägen : ett beprövat sätt att spara pengar, hälsa och miljö*. Stockholm: Byggforskningsrådet, 2000.

36. Määttä J and Kaunisto T. Leakage accidents of the water supply systems in small houses. *VTT Tiedotteita - Valtion Teknillinen Tutkimuskeskus* 1997: X-42.

37. Olanrewaju A, Tan YY and Soh SN. Defect characterisations in the Malaysian affordable housing. *Int J Build Pathol Adapt* 2018: 30. Article; Early Access. DOI: 10.1108/ijbpa-11-2018-0095.

38. Wong JTY and Hui ECM. Water seepage in multi-storey buildings. *Facilities* 2005; 23: 595-607. DOI: 10.1108/02632770510627570.

39. Plebankiewicz E and Malara J. Analysis of defects in residential buildings reported during the warranty period. *Applied Sciences (Switzerland)* 2020; 10. Article. DOI: 10.3390/app10176123.

40. Olubodun F and Mole T. Evaluation of defect influencing factors in public housing in the UK. *Structural Survey* 1999; 17: 170-178. DOI: 10.1108/02630809910291352.

41. Weeks DJ and Leite F. Facility Defect and Cost Reduction by Incorporating Maintainability Knowledge Transfer Using Maintenance Management System Data. *J Perform Constr Facil* 2021; 35. Article. DOI: 10.1061/(ASCE)CF.1943-5509.0001569.

42. Love PED. Auditing the indirect consequences of rework in construction: a case based approach. *Managerial Auditing Journal* 2002; 17: 138-146. Article. DOI: 10.1108/02686900210419921.

43. Yarnold J, Banihashemi S, Lemckert C, et al. Building and construction quality: systematic literature review, thematic and gap analysis. *Int J Build Pathol Adapt* 2021: 23. Review; Early Access. DOI: 10.1108/ijbpa-05-2021-0072.

44. Stephan A and Stephan L. Life cycle water, energy and cost analysis of multiple water harvesting and management measures for apartment buildings in a Mediterranean climate. *Sustainable Cities and Society* 2017; 32: 584-603. DOI: 10.1016/j.scs.2017.05.004.

45. Zegowitz A, Peixoto de F, João M.P.Q V, et al. Drying behaviour and microbial load after water damage. *Structural Survey* 2016; 34: 24-42. DOI: 10.1108/ss-07-2015-0032.

46. Andersson JV. Humid buildings - The construction remedy. *Indoor and Built Environment* 2003; 12: 217-219. Conference Paper. DOI: 10.1177/1420326X03035162.

47. Haverinen-Shaughnessy U, Pekkanen J, Nevalainen A, et al. Estimating effects of moisture damage repairs on students' health—a long-term intervention study. *Journal of Exposure Science & Environmental Epidemiology* 2004; 14: S58-S64. DOI: 10.1038/sj.jea.7500359.

48. Fisk WJ, Lei-Gomez Q and Mendell MJ. Meta-analyses of the associations of respiratory health effects with dampness and mold in homes. *Indoor Air*. 2007/07/31 ed. 2007, p. 284-296.

49. Alba-Rodríguez MD, Martínez-Rocamora A, González-Vallejo P, et al. Building rehabilitation versus demolition and new construction: Economic and environmental assessment. *Environmental Impact Assessment Review* 2017; 66: 115-126. Article. DOI: 10.1016/j.eiar.2017.06.002.

50. Milion RN, Alves TDCL, Paliari JC, et al. Cba-based evaluation method of the impact of defects in residential buildings: Assessing risks towards making sustainable decisions on continuous improvement activities. *Sustainability (Switzerland)* 2021; 13. Article. DOI: 10.3390/su13126597.

51. Petrovic B, Lindkvist T, Pettersson J, et al. *Klimatpåverkan från vattenskador i kök och badrum*. 2022-06-16 2022. Dalarnas försäkringsbolag,.

52. U.S. Census Bureau. American Housing Survey (AHS),. 2022.

53. Akinci B, Boukamp F, Gordon C, et al. A formalism for utilization of sensor systems and integrated project models for active construction quality control. *Automation in Construction* 2006; 15: 124-138. Article. DOI: 10.1016/j.autcon.2005.01.008.

54. Shariq MH and Hughes BR. Revolutionising building inspection techniques to meet large-scale energy demands: A review of the state-of-the-art. *Renewable and Sustainable Energy Reviews* 2020; 130. Review. DOI: 10.1016/j.rser.2020.109979.

55. Larsson L, Markowicz P and Mattsson J. Use of a surface emissions trap for improving the indoor air quality by efficient exposure reduction. In: *6th International Building Physics Conference (IBPC)* Torino, ITALY, Jun 14-17 2015, 6th international building physics conference (ibpc 2015), pp.1224-1226.

56. Säker Vatten. *Branschregler: Säker Vatteninstallation 2021:1*. 2020. Säker Vatten.

57. United States Department of Housing and Research UDOoPDa. *Moistureresistant homes : A Best Practice Guide and Plan Review Tool for Builders and Designers With a Supplemental Guide for Homeowners*. U.S. Department of Housing and Urban Development, 2006, p.112.